

# **STUDY REPORT**

**No. 192 (2008)**

## **Bio-derived Polymers and Composites**

**N.J. Marston**



The work reported here was funded by Building Research Levy.

© BRANZ 2008  
ISSN: 1178-4938

## **Acknowledgments**

This work was funded by the Building Research Levy.

# **Bio-derived Polymers and Composites**

## **BRANZ Study Report SR 192**

**N.J. Marston**

### **Reference**

Marston N.J. 2008 'Bio-derived Polymers and Composites'. *BRANZ Study Report 192*. BRANZ Ltd, Judgeford, New Zealand.

### **Abstract**

Presented in this report are a review of materials and an initial study to examine the performance and potential of bio-derived polymers (plastics) and composite materials for the building industry. Interest in, and utilisation of, bio-derived polymer materials in consumer products has steadily grown over the last five years. Their potential for a reduced environmental footprint, bio-compatibility and bio-degradability are advantages for an increasing number of diverse applications from packaging through to medical devices and electronics. However, this is a complex subject area and this study report presents only a brief overview of the materials that are currently available.

Overseas, bio-derived products are becoming readily available. The use of these materials, particularly in packaging, is also on the increase in New Zealand. Their potential for use in construction has not been investigated to any great extent. The durability performance of these materials has been characterised to some extent under the conditions typically encountered in buildings. The properties of these materials will always be a balance of durability against bio-degradability and so it is clear that more systematic experimental work is required. Given this background, the aim of this project is to examine the potential, performance and availability of bio-derived polymer and composite products within New Zealand.

Following a comprehensive literature review it is observed that some knowledge exists regarding mechanical properties and property retention. The review highlights that, because the majority of the products are derived from natural products, the properties are strongly influenced by the growing environment of the feedstock materials.

It is promising that local suppliers are already offering bio-derived polymer products, albeit targeted exclusively at bio-degradable packaging applications. By way of a preliminary experimental study, using bio-derived polymer materials sourced in this country, it is found that the physical properties reported in the literature were matched by the materials tested and these showed the expected drop-off of properties when exposed to just UV radiation for short periods.

BRANZ finds that bio-polymers and composites do have some potential for New Zealand's building industry. However, their application is likely to have to be restricted because of their bio-degradability. Hence, it is thought likely that the use of natural fibres will be limited to products using synthetic resin (derived from oil) as the matrix. Likewise, the use of bio-derived polymers will be limited to applications within the weathertight envelope of buildings. Consequently, the most accessible benefit to the construction industry from bio-derived materials is expected to be the adoption of bio-degradable packaging materials that will reduce the amount of construction-related waste that will persist in the environment.

To facilitate the adoption and acceptance of emerging bio-derived materials, further work is needed to better understand these trade-offs: durability against bio-degradability; manufacture of bio-derived materials and fuels against food supply; and life-cycle analysis of bio-derived resins against existing synthetic materials. To deliver this understanding, in a

timely fashion, it is recommended that effort be focused on assessing bio-derived polymer and composite materials against construction applications to define the materials that offer the maximum advantages to this country's commitment to long-term sustainable development.

### **Keywords**

Polymer, natural fibre, weatherability, durability, degradation, construction.

<b>Contents</b>	<b>Page</b>
<b>1. INTRODUCTION.....</b>	<b>7</b>
<b>2. BIO-DERIVED RESINS.....</b>	<b>10</b>
<b>2.1 Resins directly extracted from bio-mass.....</b>	<b>10</b>
<b>2.1.1 Polysaccharides .....</b>	<b>10</b>
<b>2.1.1.1 Starch.....</b>	<b>10</b>
<b>2.1.1.2 Cellulose .....</b>	<b>11</b>
<b>2.1.1.2.1 Cellulose acetate .....</b>	<b>11</b>
<b>2.1.1.3 Gums.....</b>	<b>11</b>
<b>2.1.1.4 Chitin/chitosan .....</b>	<b>11</b>
<b>2.1.2 Proteins .....</b>	<b>11</b>
<b>2.1.3 Lipids.....</b>	<b>12</b>
<b>2.1.4 Furfural alcohol and furan resins .....</b>	<b>12</b>
<b>2.2 Resins synthesised from bio-derived monomers.....</b>	<b>12</b>
<b>2.2.1 Polylactic acid (PLA).....</b>	<b>12</b>
<b>2.2.2 Other polyesters.....</b>	<b>13</b>
<b>2.2.3 Polyurethanes .....</b>	<b>13</b>
<b>2.2.4 Acrylics.....</b>	<b>13</b>
<b>2.2.5 Polyolefins.....</b>	<b>13</b>
<b>2.3 Resins produced directly by organisms.....</b>	<b>13</b>
<b>2.3.1 PHA.....</b>	<b>13</b>
<b>2.3.2 Bacterial cellulose (BC) .....</b>	<b>14</b>
<b>3. NATURAL FIBRES .....</b>	<b>14</b>
<b>3.1 Fibre types.....</b>	<b>15</b>
<b>3.2 Fruit fibres.....</b>	<b>15</b>
<b>3.2.1 Cotton .....</b>	<b>15</b>
<b>3.2.2 Coir (coconut fibre) .....</b>	<b>15</b>
<b>3.3 Grass fibres.....</b>	<b>15</b>
<b>3.3.1 Bamboo.....</b>	<b>15</b>
<b>3.3.2 Elephant grass.....</b>	<b>15</b>
<b>3.4 Leaf fibres.....</b>	<b>15</b>
<b>3.4.1 Sisal .....</b>	<b>16</b>
<b>3.4.2 Pineapple leaf fibre (PALF) .....</b>	<b>16</b>
<b>3.5 Stem fibres .....</b>	<b>16</b>
<b>3.5.1 Flax .....</b>	<b>16</b>
<b>3.5.2 Hemp .....</b>	<b>16</b>
<b>3.5.3 Jute.....</b>	<b>16</b>
<b>3.5.4 Kenaf .....</b>	<b>16</b>
<b>3.5.5 Ramie.....</b>	<b>17</b>
<b>3.6 Cellulosic fibres .....</b>	<b>17</b>
<b>3.6.1 Straw fibres.....</b>	<b>17</b>
<b>3.6.2 Wood fibres.....</b>	<b>17</b>
<b>3.7 Natural fibre properties.....</b>	<b>17</b>
<b>4. BIO-DERIVED MATERIAL RESEARCH IN NEW ZEALAND .....</b>	<b>18</b>

4.1	Bio-polymer Network Ltd (BPN).....	18
4.1.1	Films/coatings.....	18
4.1.2	Bio-plastics/bio-foams.....	18
4.1.3	Composites and natural fibres.....	18
4.1.4	Bio-derived thermosets and additives.....	19
4.2	Centre of Advanced Composite Materials (CACM).....	19
4.2.1	Natural fibre reinforcement.....	19
4.2.2	WPCs .....	19
4.3	Scion.....	19
4.3.1	Low density packaging.....	19
4.3.2	Adhesive polymer systems .....	20
4.3.3	Thermoplastics from carbohydrates .....	20
4.3.4	Wood fibre-bio-polymer composite materials.....	20
5.	BIO-DERIVED RESIN PROPERTIES .....	20
5.1	Literature properties.....	20
5.2	Testing .....	21
5.3	Test results.....	23
5.4	Conclusions.....	24
6.	BIO-DERIVED COMPOSITES PROPERTIES.....	24
6.1	Fibres in thermosetting composites .....	24
6.2	Fibres in thermoplastics .....	25
7.	EMERGING BIO-DERIVED MATERIALS IN THE INTERNATIONAL CONSTRUCTION INDUSTRY.....	26
7.1	Natural insulation.....	26
7.2	Floor coverings .....	26
7.3	Reinforcement of blocks and plaster.....	26
7.4	Surface coatings.....	27
7.5	Composite boards.....	27
8.	SUMMARY.....	27
9.	REFERENCES.....	29
	APPENDIX A GLOSSARY .....	34

Figures		Page
Figure 1	Origins of bio-derived plastics	10
Figure 2	Bio-derived material samples obtained for testing	22
Tables		Page
Table 1	Natural fibre properties compared to glass	17
Table 2	Generalised properties for the most common polymers used in construction	21

Table 3	Generalised properties for the most readily available bio-derived polymers	21
Table 4	Potential for substitution in interior applications based on physical properties	21
Table 5	Details of bio-derived materials tested	22
Table 6	Tensile properties of the NZ sourced samples	23
Table 7	Tensile properties of the NZ sourced samples after 500 light hours of QUV A exposure	23
Table 8	Percentage property retention after 500 light hours QUV A	23

# 1. INTRODUCTION

The conversion of bio-mass into useful materials, such as polymers (plastics) and composite reinforcements is finding increasing favour due to their perceived economic and environmental benefits. Using sunlight to grow feed materials and the role of photosynthesis in consuming CO<sub>2</sub> appears to offer potential advantages over conventional polymer materials, which are derived from fossil fuel. As a result bio-derived polymer materials are said to consume 60–70% of the energy required to produce similar conventional materials (Mohanty 2005). It is also possible that the production of these materials can utilise the bio-mass by-products of bio-fuel production (SRIC 2008), although the sustainability of some of these processes is perhaps unclear (EECA 2008).

While it is possible that their adoption will enhance global sustainability, it is clear that these materials can offer bio-compatibility and bio-degradability. As a result, bio-derived polymers are finding increased market interest. Currently, this is mainly as a packaging of foodstuffs, but other current, and growing, segments include medical devices and electronics.

Bio-derived polymers may be divided into three main categories, adopted by Plastics New Zealand (Hall 2006, Bradshaw 2007):

- those directly extracted from bio-mass
- polymers produced directly by organisms
- those synthesised from bio-derived monomers.

Meanwhile, three main categories of natural fibre composites can be defined as:

- composites where the natural fibre serves as a filler in commodity thermoplastics, such as polypropylene (PP)
- composites where longer fibres enhanced with compatibilisers and other additives attain additional strength and toughness in thermoplastics
- composites where natural fibres are used with thermosetting resins as designed elements within engineered components.

Composites using natural fibres and bio-derived resins are predicted to see rapid development and adoption into some market sectors in the next 10 years (Bradshaw 2007, NGCC 2008).

Some agricultural crops are already finding new uses in construction (NGCC 2008). Recent international developments include:

- use of natural fibres for reinforcing concrete and polymer composites
- hemp, flax and wool used in insulation materials
- straw-bale houses
- hemp-shive concretions with a lime binder used for wall construction
- linseed oil in natural paints and resins.

It is said that these materials were predominantly used as a replacement for conventional synthetic petroleum-based systems (NGCC 2008). However, in New Zealand in 2006 less than 1,000 tonnes (te) of bio-derived polymers were imported. This represents only 0.4% of all polymer feedstock used, approximately 240,000 te (Plastics NZ 2007). Note: as New Zealand has no domestic polymer production



(polymerisation) industry, all polymer feedstock must be imported. None of this bio-derived polymer is believed to have been directly used in construction.

However, the construction industry is a major user of polymer products. Approximately 43,000 te of conventional polymer feedstock was converted into products for use in construction in 2006. This was about 18% of all polymer processed in New Zealand (Plastics NZ 2007). The mass consumed has fallen, but the percentage has grown compared to 2005 when the figure was 47,800 te, equating to 16% of national consumption (260,000 te total polymer imports in 2005) (Plastics NZ 2006). The fall in feedstock imports and the reduction in total tonnes used in construction are believed to be the result of increased imports of finished products. These imported finished products are believed to contribute a further 17,000 te of polymer, bringing the total for polymer products used in construction to about 60,000 te in 2006.

PVC materials remain the major polymeric material used directly by the construction industry in New Zealand, with about 27,000 te being used domestically in 2006 (Plastics NZ 2007). This represents about 74% of all domestic PVC consumption in New Zealand, compared to 70% in 2005. This percentage has increased because the total PVC consumption has fallen due to lower demand from the agricultural sector (Plastics NZ 2007). Unplasticised PVC (uPVC) materials find applications in potable and waste water piping, spouting, ducting, cladding, windows and trims. Flexible, plasticised, PVC represents approximately 10% of PVC consumed (Plastics NZ 2007). Plasticiser additives modify the material properties for applications such as cable sheathing, flooring, seals and gaskets.

High density polyethylene (HDPE) usage in construction is significantly less than PVC, at approximately 5,900 te per annum (Plastics NZ 2007). This is approximately 15% of all HDPE used in New Zealand. HDPE materials find applications in waste water piping, building wrap, damp-proof membrane (DPM), ducting and trims. The reduced tonnage of HDPE used in 2006 vs 2005 might be the result of substitution by low density polyethylene (LDPE) and PP. Both these materials have been consumed in larger masses by construction products, as noted later.

Expanded polystyrene (EPS) is consumed in very high volumes by the construction industry, in the form of insulation. This volume translates into an annual mass consumed of approximately 3,800 te and represents about 58% of all EPS use in New Zealand (Plastics NZ 2007). EPS insulation is hidden, and so fit-for-purpose. Polystyrene has very poor resistance to solar radiation exposure.

LDPE has shown substantial growth recently and in 2006 was used directly in construction at the rate of about 4,500 te per annum (Plastics NZ 2007), compared to 2,500 te in 2005 (Plastics NZ 2006). In 2006, this equated to about 7% of national annual consumption, compared to 4% in 2005. This LDPE consumption will be almost entirely as DPM, as used below concrete slabs, although some substitution for HDPE products is also believed to play a role in increased consumption. Additionally, it is believed that a significant quantity will also be used in packaging of building materials that is not accounted for in the figures derived by Plastics New Zealand.

PP consumption by the construction industry has grown from 400 te per annum in 2005 to 1,500 te per annum in 2006 (Plastics NZ 2006, Plastics NZ 2007), being mainly used as DPMs, but also for building wraps. Some substitution for HDPE products is believed to play a role in this increased consumption.

Of course, other polymeric materials are used within the construction industry. While these account for only about 0.2% of annual total polymer usage in New Zealand some specific types are worthy of note. Polycarbonates (PC), polyesters (predominantly polyethylene terephthalate, PET) and polymethylmethacrylate (PMMA, acrylic) can be used as glazing materials which are exposed to the full effects of sunlight. Polyester is

used as thermal insulation. Nylons, polyesters and PP are used in carpets, which will be partially exposed to the effects of the sun after filtering by window glass.

While most (90%) of plastics production waste is re-used, via in-house recycling by plastic processors (Plastics NZ 2008), it is estimated that roughly 190,000 te of plastic materials annually are sent to landfill (Plastics NZ 2008a). It is said that this represents only about 7% of the waste stream, by weight. Currently, the majority of plastic landfilled is from packaging (60–80%), which has a short life-cycle from manufacture to disposal. As a result, a considerable effort has been made by the industry in recent years to increase recovery and recycling of plastics. This has delivered a reduction in landfilling of plastic waste in compliance with the New Zealand Packaging Accord 2004 (MfE 2008). Today, approximately 22% of all plastic converted in New Zealand (about 35,000 te) is recovered for recycling.

Plastic waste from construction will mainly be composed of waste packaging, left over material from the building process and material recovered during demolition. It is estimated that approximately 6,500 te per annum of plastic building waste will go to landfill (according to figures derived from data published by Reбри and MFE (Reбри 2008, MFE 2008a). This implies that plastic waste from construction amounts to <4% of the total plastic landfilled per annum and only about 0.2% of the total waste stream in New Zealand.

In the light of these plastic waste statistics, it is obvious why the packaging sector has been an early adopter of bio-derived materials that offer the potential to bio-degrade. It is probable that these waste-related drivers will also apply to the packaging of building products. However, the situation is different for plastic components used in construction. The majority of plastic building components are required by the New Zealand Building Code to remain durable for 15 years or more. This is the result of their use in applications that are difficult to repair or areas that are difficult to access. It is possible bio-derived materials would give a benefit of reduced emissions during manufacture and reduce the contribution of construction waste to materials that will persist in the environment. However, the adoption of any bio-derived material by the sector should be on the basis of establishing the risk of substitution is minimal.

Existing studies of bio-derived plastics and composites indicate that the materials are generally susceptible to water absorption and/or hydrolysis (Gupta 2007, Hajnalka 2006, Mehta 2006). This degradation by water could result from elevated levels of atmospheric moisture and could significantly reduce both the physical properties of the materials and their service life.

Therefore, it is expected that polymers from bio-derived materials, i.e. those that do not involve synthetic chemistry to produce monomers, will struggle to deliver the properties required for use in the exposed areas of buildings. In this context resistance to moisture and assurance of long-term durability will be important. Protection from moisture implies their use (currently) would need to be limited to applications within the weathertight interior of buildings. Some emerging applications in these areas are discussed in Section 7.

Recommended further reading in this area includes:

Mohanty M, Misra M and Drzal L. 2005. *Natural Fibers, Bio-polymers and Bio-composites*. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.

Wool RP and Sun XS. 2005. *'Bio-based Polymers and Composites'*. Elsevier, Amsterdam, The Netherlands.

## 2. BIO-DERIVED RESINS

Bio-derived polymers are, in some ways, regarded as an emerging technology. However, as discussed below, polymeric materials from animals and plants have been utilised for many years. Some of their names and uses are actually quite familiar.

Bio-derived polymers may be divided into three main categories (Hall 2006):

- those directly extracted from bio-mass
- those synthesised from bio-derived monomers
- polymers produced directly by organisms.

Some examples of materials within these categories are shown in Figure 1.

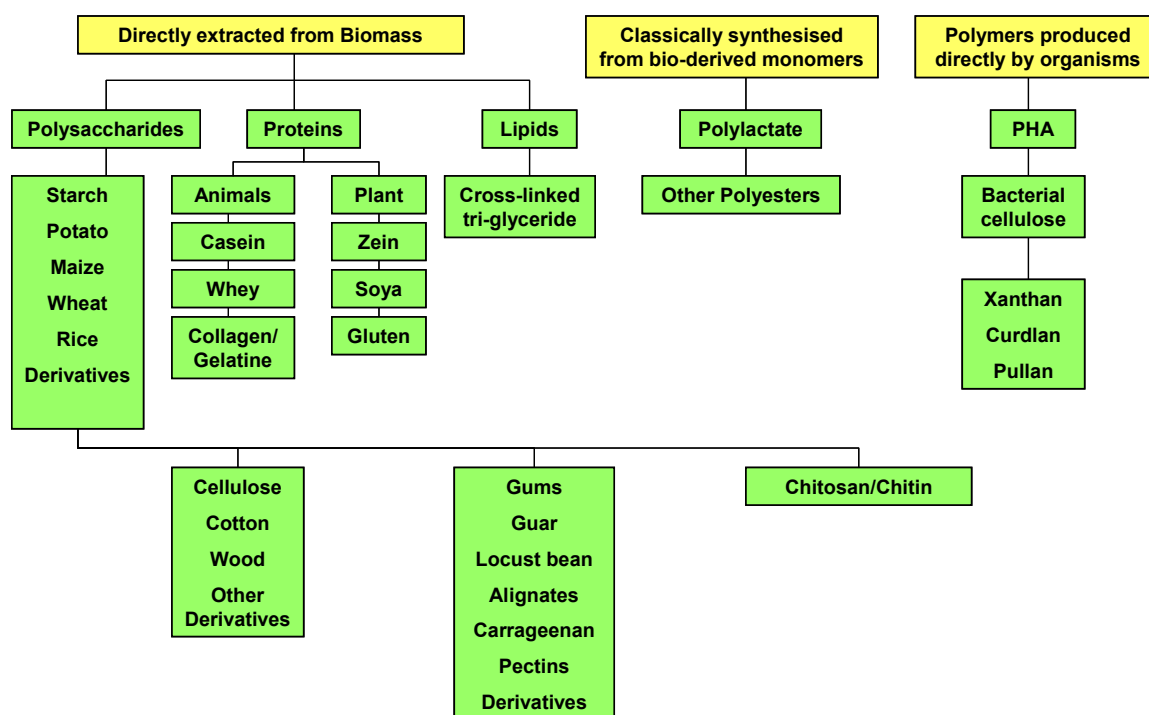


Figure 1. Origins of bio-derived plastics (Hall 2006)

The main materials from these categories are discussed in the following sections.

### 2.1 Resins directly extracted from bio-mass

Bio-mass, as a broad definition, is biological matter or material derived from living animals and plants.

Materials that can be extracted from bio-mass and used in the place of conventional polymeric materials include: polysaccharides, protein, lipids and furfural derivatives.

#### 2.1.1 Polysaccharides

Polysaccharides are the major component of carbohydrates such as cellulose and starch. Starch and cellulose are not plastics in their native forms. They are converted into plastics via processes such as functionalisation, extrusion cooking and plasticisation.

##### 2.1.1.1 Starch

Starch is the main carbohydrate storage product of plants. It is a complex polymer comprising a mixture of amylose and amylo-pectin polysaccharides. The properties of

starch vary according to the amylose/amylo-pectin ratio and hence according to the plant source. A major source of starch is corn but it can also be extracted from potato, wheat and rice.

The polymer is crystalline due to the presence of the amylo-pectin component. The two main disadvantages of starch are its water-solubility and poor mechanical properties. Hence, this polymer is suited to applications where long-term durability is not needed and where rapid degradation is advantageous. It is often processed as foam where it provides an alternative to polystyrene for use in the manufacture of food trays, moulded shaped parts or as loose packing filler.

### **2.1.1.2 Cellulose**

Cellulose is the major component of crop residues such as straw and is also the major component in wood fibres (Wool 2005). These fibrous materials will be discussed further in Section 3.

Cellulose can also be modified into cellulose esters, such as cellulose acetate.

#### **2.1.1.2.1 Cellulose acetate**

Cellulose acetate (a modified polysaccharide) has been prepared from a reaction between acid anhydride and cellulosic products derived from cotton linters, wood pulp, recycled paper or sugar cane.

The manufacturing process for cellulose acetate was first patented at the end of the nineteenth century and the polymer has found use in filaments, films and lacquers since that time. This bio-degradable polymer exhibits good toughness and a high degree of transparency, and as a result its most familiar uses are in clear sticky tapes and cine-film.

### **2.1.1.3 Gums**

Plant gums are exuded by some tree and plant varieties when they are damaged. These materials have been widely used in binding media, adhesives and as thickening materials in paints e.g. water colours. Globally, the most commonly used plant gums are gum arabic, gum tragacanth and cherry gum (Timar-Balazsy 1998).

As a result of their polysaccharide nature, gums are susceptible to photo-oxidation and undergo yellowing. They can also be attacked by fungi and bacteria, as their sugar-like structure can be a food source.

### **2.1.1.4 Chitin/chitosan**

Chitin is a polysaccharide found in the outer skeleton of insects, crabs, shrimps and lobsters and in the internal structures of other invertebrates. It has a similar structure to cellulose and has a high strength. The principle source of chitin is shellfish waste. Chitosan is a derivative of chitin and is tough, biocompatible and oxygen permeable. As a result it is used in bandages and sutures.

### **2.1.2 Proteins**

Proteins are built up of various combinations of 20 different amino acids. The different combinations of amino acids within the protein give each a unique structure and function. Proteins can vary greatly in chain length, giving molecular weights from a few hundreds to several millions.

Examples of proteins derived from animals include casein (used in adhesives), collagen (used in cosmetics), gelatine (used in food) and whey (used in food).

Plant proteins are amino acid polymers obtained mainly from oilseeds and grains. They are usually produced as by-products of producing oils or starches, but find applications in paper coatings (soybean protein) and food coatings (corn protein).

Proteins, particularly soy, are also considered a viable alternative to synthetic polymers in the manufacture of adhesives, packaging and binders (Mohanty 2005). However, their relatively low strength and higher moisture absorption may limit their applications.

### **2.1.3 Lipids**

A large number of bio-derived thermosetting resins can be formed from vegetable oils – by grafting hydroxyl, acrylate and maleate moieties or combinations of these onto the fatty acid triglyceride.

Vegetable oils can also be epoxidised to form a reactive component for bio-derived epoxy resins. The epoxidised oil (typically soybean or linseed oil) can also be further reacted to produce polyols and used with diisocyanates in polyurethane resin formulations.

Thermosetting polyester resins can be produced using many combinations of diols and diacids to form the polyester resin base, then cross-linked on addition of carboxylic acid curing agents.

Other naturally derived resins can be formed from cashew nut shell liquid (CNSL) which is extracted from the shell of cashew nuts as a by-product of the nut industry. The CNSL is rich in anacardic acid, which is converted to cardanol during the heated extraction process. Cardanol can be polymerised by free radical polymerisation, and condensation polymerisation between phenolic units can occur in the presence of aldehydes.

These two component resin systems are said to be suited to the same resin transfer moulding, vacuum bagging, sheet moulding and bulk moulding systems used in traditional thermoset composite manufacture.

### **2.1.4 Furfural alcohol and furan resins**

The pre-cursor to furfural alcohol and furan-based resins is furfural, a compound which is extracted from naturally occurring agricultural residues. Feedstock may be derived from sugar cane bagasse as well as corn cobs, wood products or cereal by-products.

Furan resins are usually used in heat curing thermosets, either in combination with urea-formaldehyde resin and phenol formaldehyde resin or with furfural alcohol. This later binder is preferred in some applications because of its low formaldehyde content, higher tensile strength and lower binder usage level (Chang 2003).

## **2.2 Resins synthesised from bio-derived monomers**

### **2.2.1 Polylactic acid (PLA)**

PLA is not a newly developed material and investigation of potential production techniques dates back as far as 1932 (Mohanty 2005). However, historically production costs have been a barrier to wider use.

Lactic acid is produced principally by microbial fermentation of sugars (Wool 2005, Mohanty 2005) and is then polymerised to produce PLA. PLA can be semi-crystalline or totally amorphous depending on the isomers of the lactic acid feedstock or lactide intermediates used in production. As a result, the number of potential structures for PLA are substantial.

L-lactic acid is the natural and most common form of the acid. D-lactic acid can also be produced by micro-organisms or through racemisation. Adding this D-lactic acid comonomer to the polymer backbone behaves similarly to a comonomer in other

polyester polymers and influences the kinetics of crystallisation – critical to some fabrication processes and applications (Mohanty 2005).

Of the PLA polymer family, poly-L-lactic acid (PLLA) has received most research attention. This is because the naturally occurring L-lactic acid is most widely produced. However, most commercial PLA polymers are co-polymers produced from mostly the L-lactide, with small amounts of feedstocks or intermediates of other isomers, and are made by bulk polymerisation with tin octoate catalyst.

Simplistically, the PLA family of polymers show some potential for use in construction since its processing and finished properties can be tuned by controlling the chemistry of the polymer chain. This control potentially could give the polymer durability to maintain mechanical strength without rapid hydrolysis, whilst maintaining good composting capability. However, this is provided that industrial, not domestic, composting techniques are always employed.

Current uses for this polymer group centre on medical applications such as implants, sutures, drug delivery systems and grafts.

### **2.2.2 Other polyesters**

Bio-polyesters can also be derived from fermentation of plant sugars. Commercial materials, derived from 1, 3-propanediol, offer an alternative to nylon and polyethylene terephthalate for fibre and fabric manufacture (Mohanty 2005).

### **2.2.3 Polyurethanes**

As already mentioned, epoxidised plant oil can be further reacted to produce polyols and used with diisocyanates in polyurethane resin formulations. Some manufacturers are experimenting with incorporating these bio-derived materials into conventional polyurethane foams in increasing amounts (MPW 2007).

### **2.2.4 Acrylics**

Acrylic manufacturers are positioning themselves to begin production from ethanol derived from cellulosic materials (MPW 2007a).

### **2.2.5 Polyolefins**

Some polyethylene manufacturers are positioning themselves to begin production from ethanol derived from sugar cane. Productionisation of this technology is currently planned for early in the next decade (MPW 2007b).

## **2.3 Resins produced directly by organisms**

A variety of resins are produced by organisms. Polyesters, polyhydroxy alkanoates (PHA), are produced by microbial processes in bacteria. Some bacteria can produce cellulose that can be recovered and used.

### **2.3.1 PHA**

The main PHAs are poly(3-hydroxybutyrate) (PHB) and poly(3-hydroxyvalerate) (PHV). Homopolymers and co-polymers of both are synthesised by microbes and accumulate in cells during growth.

PHB and its co-polymers are bio-degradable and bio-compatible. However, it has relatively poor thermal stability and low impact resistance.

Co-polymers of PHB with PHV have been found to be more flexible, mainly as a result of having a lower glass transition temperature.

Depending on the physical properties of the material, uses such as adhesives, stretch coatings, fibres and even rubber substitution are possible (Kosier 2006).

### **2.3.2 Bacterial cellulose (BC)**

Bacterial cellulose is a straight chain polysaccharide with the same chemical structure as cellulose that is derived from plants (Piao 2006). Bacterial cellulose has the advantage of being devoid of lignin, pectin and hemicellulose (Jonas 1998). This means that BC is high purity and has found applications in medical dressings, tissue engineering and nanocomposites (Czaja 2006, Svensson 2005, Grunert 2002).

## **3. NATURAL FIBRES**

Three main categories of natural fibre composites can be defined:

- composites where the natural fibre serves as a filler in commodity thermoplastics, such as polypropylene (PP)
- composites where longer fibres enhanced with compatibilisers and other additives attain additional strength and toughness in thermoplastics
- composites where natural fibres are used with thermosetting resins as designed elements within engineered components.

The major natural fibres types and species will be discussed in this section, but longer natural fibres will be focused on.

Long natural fibres are potential candidates to substitute as reinforcement for composite products in place of the customary synthetic fibres such as glass. It is estimated that about 2.3 million tonnes of glass fibres are used annually in various applications around the globe (NGCC 2008).

Natural fibres have a number of potential advantages over glass fibre:

- low density
- low cost
- high toughness
- acceptable specific strength properties
- good thermal properties
- lower embodied energy
- reduced tool wear
- reduced irritation to the skin and respiratory system
- low energy requirement for processing.

In addition, they may be bio-degradable or recyclable depending on the selected matrix. As a result some sources predict that the use of bio-derived polymers with natural fibre reinforcement could lead to a new generation of bio-degradable products suited to packaging and disposable applications (NGCC 2008). In New Zealand their adoption would, of course, pivot on the provision of more composting facilities. However, it is anticipated that industrial composting facilities will be installed in many urban areas over the coming decade in an effort to reduce the quantity of material going to landfill (Bury 2006).

Natural fibres, often referred to as vegetable fibres, are generally categorised depending on the part of the plant they are extracted from. However, when discussing the general properties of natural fibres, it should be borne in mind that these are natural products with properties that are strongly influenced by their growing environment. For example, temperature, humidity, the composition of the soil and the air all affect the

height of the plant, strength of its fibres, density etc. The way the plants are harvested and processed can also result in a variation of properties. These factors result in significant property variations when compared to synthetic fibre materials (glass, aramid and carbon).

The rapidly developing bio-derived polymer market has led to wide-ranging research on natural fibres in many matrices.

### **3.1 Fibre types**

### **3.2 Fruit fibres**

Fruit fibres are relatively short, light and hairy, and allow the wind to carry the seeds. These fibres will, most likely, find uses as fillers rather than reinforcements.

#### **3.2.1 Cotton**

Cotton fibres consist of seed hairs of the cotton plant. The cotton fruit bursts when mature to reveal a tuft of fibres 25–60 mm in length. Individual cotton fibres are up to about 3 mm in length. Cotton requires a large amount of water to grow and requires intensive fertilisation. These attributes can have an adverse environmental impact e.g. the evaporation of the Aral Sea.

Cotton is rather weak, when compared to other natural fibres. It can absorb up to 20% of its dry weight of water without feeling wet and is also a good heat conductor.

Cotton has traditionally been used for the manufacturing of clothes, carpets and blankets and is the backbone the world textile industry.

#### **3.2.2 Coir (coconut fibre)**

Coconut fibre is obtained from the husk of the fruit of the coconut palm. Coir is mainly produced in Asia. Individual coir fibres are only about 0.5 mm in length. After nine months of growth, the nuts are still green and contain white fibres, which are traditionally used for the production of yarn, rope and fishing nets. After 12 months of growth, the fibres are brown and have been used for brushes and mattresses.

The fibres are one of the toughest plant fibres available (Mohanty 2005). They are also light, and withstand heat and deterioration if exposed to salt water.

### **3.3 Grass fibres**

#### **3.3.1 Bamboo**

Bamboo fibres are regarded as a good candidate for composite materials. The fibres range in length from about 1 mm to nearly 5mm, depending on the species. The fibre's diameter also varies from about 10  $\mu\text{m}$  to 40 $\mu\text{m}$  (Liese 1998). Fibre surface treatment is known to critically affect the mechanical properties of the resulting materials and this has been studied in some detail (Mohanty 2005).

#### **3.3.2 Elephant grass**

Elephant grass is a large perennial that can grow more than 3 m high and is regarded as a pest in New Zealand (Biosecurity NZ 2007). Individual elephant grass fibres are about 1.1 mm in length. The properties of the fibres in thermoplastics, such as polyester, have been explored (Rao 2007).

### **3.4 Leaf fibres**

Leaf fibres are rough and sturdy and form part of the plant's transportation system.



### **3.4.1 Sisal**

Sisal produces sturdy and strong fibres that are very well resistant to moisture and heat. Sisal fibres are up to about 65 mm in length.

Sisal is grown in both Africa and South America. It has traditionally been used for rope, mats, carpets and cement reinforcement.

### **3.4.2 Pineapple leaf fibre (PALF)**

PALF is a lignocellulosic fibre that comprises mostly cellulose, polysaccharides and lignin. The fibres are very hygroscopic, while their high cellulose content gives them good mechanical properties. Primary fibre length is about 30 mm. The plant is mainly cultivated in tropical countries and traditionally PALF yarns have been used to manufacture fabrics, carpets and curtains.

## **3.5 Stem fibres**

Bast fibres are found in the stems of the plant providing the plant its strength. In the case of some tropical plant fibres, such as kenaf or ramie, it is possible to exploit the fact that the fibre bundles making the outer stem structure are continuous for the height of the stem in the manufacture of long fibre composites.

### **3.5.1 Flax**

Flax is a strong fibre with an increase of strength of 20% in wet conditions and it can absorb 20% water without feeling wet. Primary flax fibres are up to about 80 mm in length and elastic in nature, but degrade when exposed to sunlight. Flax has good heat conducting properties and is hard wearing and durable. However, constant creasing in the same place in sharp folds tends to break the fibres.

Internationally, flax production is centred in Europe, but clearly there has also been a long history of use of these materials in New Zealand. Flax has traditionally been used for the production of linen, canvas, rope and sacks.

### **3.5.2 Hemp**

A hemp yarn is strong and has the highest resistance of all natural fibres against water. However, it should not be creased excessively to avoid breakage. Hemp fibres are typically about 25 mm in length.

Internationally, hemp production occurs in Asia and Europe. The fibre has traditionally been used for the production of rope, fishing nets, paper, sacks, fire hoses and textiles.

### **3.5.3 Jute**

The fibres are extracted from the ribbon of the stem. The small fibres, about 5 mm long, are obtained by successively retting in water, beating, stripping the fibre from the core and drying. Due to its short primary fibre length, jute is the weakest stem fibre, although it resists rotting.

Internationally, jute production is centred in Asia. It has traditionally been used as packaging material (bags), carpet backing, rope, yarns and wall decoration.

### **3.5.4 Kenaf**

Kenaf is a strong fibre plant grown in tropical regions and is capable of continuous cropping. Kenaf production occurs in North America, Asia and Africa. The fibre strands, which are 1.5–3 m long, have traditionally been used for making rope, cordage, canvas, sacking, carpet backing, nets and table cloths. The primary kenaf bast fibre length is typically about 2.5 mm.

### 3.5.5 Ramie

Ramie is an expensive and durable fibre and can be dyed very easily. Ramie fibres average about 125 mm in length. Traditionally, it has been used in decorative fabrics. Internationally, ramie production is centred in Europe. Applications are curtains, wallpaper, sewing thread and furniture covers.

## 3.6 Cellulosic fibres

### 3.6.1 Straw fibres

Straw is produced in large quantities worldwide as a by-product of cereal growth. Straw from barley, maize, oats, rice, rye and wheat have provided large quantities of fibrous bio-mass which have traditionally been processed into boards, fuel and paper. Wheat straw fibres are about 1 mm in length.

### 3.6.2 Wood fibres

The chemical make-up of wood is complex and will not be discussed in detail here. Wood is made up of cellulose, hemicellulose, lignin and low molecular weight oleophilic extractables. The cellulose fibres are the primary structural component within the cell walls of the wood fibres and provide strength. Cellulose molecules are completely linear and bonding between molecules forms them into microfibrils. The hemicellulose primarily serves as a connecting agent that bonds the microfibrils into filaments. The lignin acts as a cement between the cellulose filaments providing stiffness to the wood.

Wood Plastic Composites (WPC) were developed in the mid-1980s, with the most successful application being the United States decking market (Mohanty 2005). Internationally, current WPC compositions comprise a broad range of materials from those manufactured from 100% post-consumer waste to those using pulped wood and engineering resins.

## 3.7 Natural fibre properties

Properties of natural fibres are presented in Table 1 and compared to the properties of glass fibre. However, it should be kept in mind that large variations of natural fibres properties exist due to natural growth-related variables. This variability is reflected by the inclusion of ranges for the majority of the natural fibre properties.

Table 1, Natural fibre properties compared to glass (NGCC 2008)

Fibre	Density [g/cm <sup>3</sup> ]	Strength [MPa]	Stiffness [GPa]	Elongation at break [%]	Moist absorption [%]	Price of raw fibre [US\$/kg]
Glass	2.55	2400	73	3	–	1.3
Coir	1.25	220	6	15–25	10	0.25–0.5
Cotton	1.51	200–800	12	6–12	8–25	1.5–2.2
Flax	1.4	800–1500	60-80	1.2–1.8	7	0.5–1.5
Hemp	1.48	550–900	70	1.6	8	0.6–1.8
Jute	1.46	400–800	10–30	1.5–1.8	12	0.35
Ramie	1.5	500–900	44	2	12–17	1.5–2.5
Sisal	1.33	600–700	38	2-3	11	0.6–0.7

## **4. BIO-DERIVED MATERIAL RESEARCH IN NEW ZEALAND**

Research into the development, properties and applications of bio-derived polymers and composites is well advanced in New Zealand academia and research institutes. Work to date has particularly focused on high volume applications, e.g. packaging, and utilisation of abundant New Zealand resources, such as wood-derived bio-mass.

### **4.1 Bio-polymer Network Ltd (BPN)**

Bio-polymer Network is a business and science collaboration established in 2003. It describes itself as a 'virtual institute' and contains substantial expertise from its shareholder companies, namely Scion, Crop & Food Research and AgResearch (BPN 2006).

Their two research areas are bio-polymer products (manufacture of core chemicals, tuning of functional performance, formulation and performance delivery) and bio-composite structures (natural fibre networks and composites, bio-derived matrices/bio-polymer formulations, impregnation and interfaces, foams/low density structures).

#### **4.1.1 Films/coatings**

Crop & Food Research has invented an easy, fast method to produce bio-degradable films from barley flour. The physical properties of the films are said to match or exceed the internationally reported values from other renewable resources. The films are said to withstand boiling water and hold a diverse range of additives within their structure.

In laboratory and field trials, the film forming solution has been sprayed directly on to soil to control weeds and pests. It is reported that the film was superior to other bio-degradable films used in the trial and comparable with commercial chemical solutions.

Potential applications for the extracts and films are seen as bio-plastics for agricultural production, water-proofing composite materials, controlled chemical release media and for lamination.

#### **4.1.2 Bio-plastics/bio-foams**

Work by Scion has examined the foaming of PLA, and other bio-plastics, with "green" blowing agents to produce bio-foams. A proprietary technology has been used to extrude or mould these materials to foam blocks. Possible applications for these products are seen as packaging, composite cores, loose fill, insulation and extruded foam sheets for packaging fresh food. Future applications in bio-medical products are also expected. Scion has also undertaken research into phenolic-based foams, low density fibre composites (with potential seen as insulation) and pulp thermoforming processes (targeted at applications in packaging, plates and containers).

#### **4.1.3 Composites and natural fibres**

Natural fibres for bio-composites have been researched, including hemp, linen flax, wood, wool and Harakeke/New Zealand flax. Unidirectional and random mat reinforcements have been studied.

Scion and AgResearch have examined different methods for preparing fibres and studied different processes for forming fibre networks, and AgResearch is said to have made a gilling machine for producing Harakeke fibres.

Scion has developed dry and wet (paper) based methods for mat forming and various liquid moulding methods to make composite parts and panels have been studied. The flexural, tensile, compression and impact properties of the composites have been tested and the behaviour of composite systems modelled. The interactions of the resins and fibres at a cellular level have also been examined.

As a demonstration of the high-performance characteristics of the bio-material technologies BPN has created a surfboard using Harakeke fibre bio-composite as a replacement for fibreglass. This 100% glass-free board has been made using a water-resistant bio-composite (Scion 2007).

#### **4.1.4 Bio-derived thermosets and additives**

Scion scientists have been investigating potential routes and possibilities for resins and additives for plastics from bio-resources. The bio-resin research into thermosets has two streams. In the near term Scion is looking at tannin-based formulations for preregs. It is also looking at epoxy/other resin substitutes.

Potential additives from bio-resources already identified include processing aids, UV and thermal stability, plasticisers and flame retardants.

In this area, Scion have already identified controlled degradation compounds that can accelerate or decelerate the bio-degradation of PLA in soil and additives to improve the impact strength of PLA.

### **4.2 Centre of Advanced Composite Materials (CACM)**

This Centre was established in 2002 and is a joint venture between the University of Auckland, Scion and other industrial participants.

The goal of this Centre is to bring together the complementary research capabilities of the University of Auckland, Scion and other partners in order to conduct research into advanced composite materials and manufacturing processes (CACM 2008).

Recent research includes the manufacture of composites from recycled thermoplastics and wood fibre, injection moulding and extrusion of wood fibre-thermoplastic composites and the manufacture and thermoforming of biocomposite sheets. Some specific details are given below.

#### **4.2.1 Natural fibre reinforcement**

Pilot scale extrusion and moulding equipment at the Centre has been used to probe the properties and performance of natural fibres in polyolefin matrices (Bhattacharyya 2002, Bhattacharyya 2003, Bhattacharyya 2004a). Work has also begun to examine the use of natural fibres in soil-cement mixtures (Jayaraman 2007).

#### **4.2.2 WPCs**

The centre has the processing equipment to produce pilot scale WPC sheet and test equipment to establish the properties of test materials. This has allowed the Centre to study the ability of wood fibre pre-treatment to enhance the performance of wood fibre-polypropylene composites (Bhattacharyya 2004). More recently the benefits of WPC materials have been examined in relation to conventional materials (Jayaraman 2007).

### **4.3 Scion**

Formerly known as Forest Research, Scion is focused on applying knowledge of wood and fibre to the development of new bio-materials from renewable plant resources.

Current research projects are focused on the areas of packaging, bio-derived adhesives, and generating thermoplastics from starch and WFCs.

#### **4.3.1 Low density packaging**

This research aims to identify new fibre-plastic composite packaging materials. The aim is to tune density by controlled foaming and hence to achieve superior performance relative to traditional packaging materials.

### **4.3.2 Adhesive polymer systems**

This research project is aimed at developing adhesive polymer systems (e.g. emulsion polymer) from biologically-based sources. Scion plan to synthesise these using "green" processing technology for use as resins in composite materials (Scion 2008).

Scion proposes to create a polymer series with a comparatively rigid internal structure, surrounded by a plastic layer so that the cured polymer series systematically varies in intrinsic rigidity. Their strategy to produce candidate materials is to utilise the characteristics of emulsion polymerisation processes to control the internal structure of polymer particles. Once produced, these materials will allow an insight into the effect of adhesive rigidity on the durability of the wood/adhesive interface.

### **4.3.3 Thermoplastics from carbohydrates**

This project is aimed at developing thermoplastics from carbohydrates, with an initial focus on starch. Bio-degradable starch-based plastics are already available, but are manufactured overseas, making them expensive for New Zealand producers. The main objectives are:

- replace petroleum raw materials with renewable resources
- develop a continuous reaction process
- produce potentially bio-degradable materials
- develop production for a New Zealand-based producer.

Other carbohydrates will also be investigated as part of the project. This includes the polymerisation of lactones from dehydrated monosaccharides.

### **4.3.4 Wood fibre-bio-polymer composite materials**

The aim of this research is to evaluate the performance of wood fibre-bio-polymer composite materials suitable for use in water-resistant packaging or moulded product forms (Scion 2008a). The project will investigate:

- composite materials manufacture
- mechanical testing
- modelling of performance characteristics.

The aim is to develop a bio-degradable alternative to polyethylene/polypropylene that is economically viable in the marketplace. Resistance to moisture will open up applications within construction.

## **5. BIO-DERIVED RESIN PROPERTIES**

### **5.1 Literature properties**

As already discussed in Section 2, the bio-derived thermoplastics possess mechanical properties and are sufficiently processible to be considered as replacements for conventional, oil-derived, polymers in some applications.

To better understand the potential of these materials in the construction sector it is essential to examine their mechanical performance. To do this, it is first necessary to examine the properties of polymeric materials that are widely used in construction.

LDPE, HDPE, PP and PVC together account for about 90% of polymer types used in construction in New Zealand (see Section 1).

Generalised properties for these materials are shown in Table 2.

**Table 2. Generalised properties for the most common polymers used in construction**

Property	LDPE	HDPE	PP	PVC
Density (g/cm <sup>3</sup> )	0.92	0.93–0.96	0.91	1.37
Tensile strength at yield (MPa)	7–12	15–31	19–42	45–50
Elongation at yield (%)	75	200–700	10–30	100
Flexural modulus (MPa)	150–300	500–1600	1500–2400	2200–2900
HDT (°C)	49	80	108	70

An assessment of the availability of bio-derived materials in New Zealand and Australia highlighted that PLA, cellulose, PHA and starch-based materials were being marketed and adopted into packaging applications. Samples of these materials were therefore available for evaluation. Approximate properties, derived from manufacturer's technical information, for these material types are shown in Table 3.

**Table 3. Generalised properties for the most readily available bio-derived polymers**

	PLA	Cellulose	PHAs	Corn Starch
Density (g/cm <sup>3</sup> )	1.25	1.25	1.25	1.35–1.45
Tensile strength at yield (MPa)	60	20–30	24–32	42–46
Elongation at break (%)	6	1–60	1.9–2.4	20–36
Flexural modulus (MPa)	3800	3300	1700–2700	1200
HDT (°C)	40–45, 135	77	56	

The ranges quoted for the property data presented in Table 3 reinforce that there are significant differences between materials from different manufacturers and different biological sources. The physical properties of the PLA, cellulose, PHA and starch-based materials were also assessed in relation to the mechanical and processing performance of LDPE, HDPE, PP and PVC. It should also be noted that these blanket designations of synthetic polymers group varied materials. The generalised potential for substitution in interior applications, based on mechanical properties, was assessed and is shown in Table 4.

**Table 4. Potential for substitution in interior applications based on physical properties**

	LDPE	HDPE	PP	PVC
PLA	✓	✓	✓	✗
Cellulose	-	-	-	✗
PHAs	-	✓	✓	✗
Starch	✓	✓	✓	✗

Key : ✓ possible, - doubtful, ✗ unlikely

Table 4 is derivative of a similar evaluation for substitution of packaging materials completed by other workers (Kosior 2006). The conclusions presented indicate that there is some potential for substitution of polyolefin materials within the building envelope.

## 5.2 Testing

The experimental work undertaken as part of this project was focused on examining the properties of bio-derived resin materials available in New Zealand.

Bio-derived resin materials from different manufacturers, produced from different feed materials and by different manufacturing processes, were obtained for this study. A photo of the materials obtained is shown in Figure 2 and a description of the materials is given in Table 5. These bio-derived resin parts were all intended as food packaging, which reflects the global trend of early adoption of these materials into the packaging of foodstuffs.



**Figure 2. Bio-derived material samples obtained for testing**

**Table 5. Details of bio-derived materials tested**

<b>Sample name</b>	<b>Generic matrix type</b>	<b>Manufacturing process</b>	<b>Thickness/mm</b>
PLA	PLA	Injection moulded	1.0
Cellulose	Bamboo pulp		1.0
Corn starch		Extruded	1.0
Potato starch		Proprietary	1.0

The as-received tensile properties of the bio-derived resin samples were tested for all the samples. The mechanical properties of these materials were also tested after 500 light hours of QUV A accelerated weathering.

Tensile testing was selected as it was decided that this would most effectively examine the effects of surface degradation on the mechanical properties of the materials.

Test coupons (10 x 100 mm) were cut from the samples and then conditioned at 23.0°C and 50% RH for 48 hours.

Post-conditioning, the test pieces were subjected to tensile strength testing. The tensile strength was determined over a gauge length of 50 mm with a cross-head rate of 10 mm/min.

Testing was carried out on a calibrated Instron Universal Testing Machine with a 10 kN load cell.

## 5.3 Test results

The bio-derived resin parts, listed in Table 5, were tested as-received. The tensile and elongation results obtained for the samples are presented in Table 6.

**Table 6. Tensile properties of the NZ sourced samples**

	PLA	Cellulose	Corn Starch	Potato Starch
Tensile strength at break (MPa)	70±4	22±2	52±2	3.3±0.6
Elongation at break (%)	29±2	40±8	60±4	1.8±0.3

The results obtained are generally as expected and agree with the generic results given in Table 3. These results indicate that the materials being marketed in New Zealand, for packaging applications, have generally similar tensile properties to equivalent material marketed internationally.

A Q-Panel QUV with UVA – 340 nm wavelength tubes – was used to provide a total light exposure time of 500 hours. The QUV was set for an irradiance of 0.68 W/m<sup>2</sup> at 340 nm. During the light cycle the cabinet temperature was maintained at 60°C. No condensation cycle was used as it was expected that this would severely degrade the samples.

The tensile and elongation results for the samples after 500 light hours of QUV A exposure are presented in Table 7.

**Table 7. Tensile properties of the NZ sourced samples after 500 light hours of QUV A exposure**

	PLA	Cellulose	Corn Starch	Potato Starch
Tensile strength at break (MPa)	6±2	14±2	11±0.3	2.9±0.5
Elongation at break (%)	23±6	36±10	46±3	1±0.2

The results obtained are presented as a percentage of initial values in Table 8.

**Table 8. Percentage property retention after 500 light hours QUV A**

	PLA	Cellulose	Corn Starch	Potato Starch
Tensile strength at break	9%	64%	21%	87%
Elongation at break	80%	90%	77%	52%

The samples all showed a decline in both tensile strength and elongation at break. This is as expected given the expected degradability of these materials.

The clear PLA samples became embrittled as a result of UV exposure and lost most of their tensile strength. The edges of the sample strips had bowed towards the UV lamps during exposure. These edges appeared milky, perhaps indicating more accelerated degradation due to higher UV levels and temperatures near the fluorescent lamps.

The bamboo pulp-based sheet retained much of its initial elongation at break after exposure, but lost about a third of its tensile strength.

The clear corn starch samples lost the majority of their mechanical strength due to micro-cracking. Micro-cracks are known to result from photo-oxidation and rapidly compromise the integrity of the sheet, as observed for clear polyolefins during outdoor exposure in New Zealand (Marston 2007).

Potato starch is known to undergo chemical changes when exposed to polarised light (Fiedorowicz 2002), and these findings mirror those found previously.



## **5.4 Conclusions**

The limited experimental programme completed as part of this project has confirmed the susceptibility of some bio-derived materials sourced in New Zealand to surface and mechanical property degradation when exposed to UV radiation alone. Based on reports of moisture-induced degradation in the literature, it is reasonable to expect that simultaneous exposure to moisture and UV radiation would have resulted in more rapid failures (Mohanty 2005, Lunt 1998).

In the testing completed the failure of the clear PLA, bamboo pulp and corn starch derived materials are believed to result entirely from degradation by UV radiation. The durability of these material types is clearly insufficient to give them any significant exterior service life in the New Zealand environment. This is as expected and also demonstrates that these materials are unlikely to persist in the environment if discarded outdoors.

Overall, it is expected that polymers from bio-derived materials, i.e. those that don't involve synthetic chemistry to produce monomers, will struggle to deliver the properties required for use in exposed areas of buildings. In this context resistance to moisture and assurance of long-term durability will be important. Protection from moisture implies their use (currently) must be limited to within the weathertight interior of buildings. However, this work also demonstrates that the most accessible benefit to the construction industry will be the adoption of bio-degradable packaging materials that will reduce the amount of construction-related waste that will persist in the environment.

In contrast, a switching of monomer feed materials, away from oil, is expected to have less effect on the properties of the materials manufactured. Polyolefins, polyurethanes and even acrylics manufactured in this way could possess similar properties and durability to the equivalent materials used today.

## **6. BIO-DERIVED COMPOSITES PROPERTIES**

### **6.1 Fibres in thermosetting composites**

Leaf and bast fibres are generally used in thermoset composite processing. A wide range of long natural fibres (sisal, PALF, flax, hemp, jute, coir, kenaf) have been studied in thermosetting matrices such as epoxy, polyester, polyurethane and phenolic resins (NGCC 2008).

Several different fibre lay-ups are possible, with non-woven mats combining low cost and ease of handling. For higher performance and greater precision in aligning fibres in the directions of the principle stresses, fibre can be used unidirectionally from tow or in woven textiles. Hand lay-up increases the cost of production, however for high end applications the benefits in terms of performance are greater.

Research on the fabrication of bio-composite panels from natural fibres (including hemp and jute) and unsaturated polyester resin by a novel panel manufacturing technique reported that the products were suitable for building and transport applications (Misra 2006).

Jute, jute-rice husk and jute-wheat husk composites have also been examined in a bio-derived epoxy polyurethane matrix (Mavani 2007). The resulting composites were thought to be useful for low load-bearing in construction industries and for marine applications.

Hybrid blends of natural and synthetic fibres have been studied by some workers. Bio-composite cores of industrial hemp or flax fibres with unsaturated polyester resin were combined with layers of woven jute, chopped glass or unidirectional carbon fabrics.

The resulting materials were said to show improved stiffness, strength and moisture-absorption stability, while flexural tests on laboratory-scale plates demonstrated enhanced structural behaviour (Burgueno 2005). The results were said to show that hybrids of natural fibre and synthetic fibres had adequate short-term performance and that they could efficiently compete with housing panels made from conventional structural materials (Burgueno 2005a).

## **6.2 Fibres in thermoplastics**

Natural fibres have already been widely adopted for use in reinforcing conventional thermoplastics in automotive applications (The Ecology Centre 2006). As long ago as 1942 Ford developed a prototype composite car made from hemp fibres (Mohanty 2005). It was never productionised due to the economics at the time. In Europe, the East German 'Trabant' (1950–1990) was produced with a body made from cotton fibres and a (thermosetting) polyester matrix (RAPRA 2002).

Adoption of natural fibres into luxury and mass market cars has increased over the last decade. The 2006 model Mercedes S-Class is said to use 43 kg of natural fibre reinforced thermoplastics in door cards, seat bases and other internal applications (DaimlerChrysler AG 2006). The key driver of reduced weight, compared to glass reinforced products, has seen natural fibre reinforced materials being adopted into more mass-market models. For example, the 2005 Ford Mondeo used PP reinforced with kenaf in its door linings (Ford 2005).

The potential life-cycle benefits of using natural fibres were reviewed in 2004 (Joshi 2004). This study concluded that natural fibre reinforced composites had four principle benefits over glass fibre reinforced systems:

- (1) natural fibre production has lower environmental impacts compared to glass fibre production;
- (2) natural fibre composites have higher fibre content for equivalent performance, reducing more polluting base polymer content;
- 3) the lightweight natural fibre composites improve fuel efficiency and reduce emissions in the use phase of the component, especially in auto applications; and
- (4) end-of-life incineration of natural fibres results in recovered energy and carbon credits.

Since then, further research has been reported that explores the reinforcement of bio-derived resins with natural fibres.

The use of flax fibre to reinforce PLA, PLLA, PHB, a proprietary bio-derived thermoplastic (polycaprolactone/starch blend), and bio-derived polyester has been researched. The tensile strength and Young's modulus of PLLA and PLA flax composites were reported to be greater than those of similar PP/flax fibre composites (Pillin 2007), while the specific tensile strength and modulus of flax fibre/PLLA composite was said to be very close to those of glass fibre polyester composites (Pillin 2007).

Kenaf fibre in PLLA also significantly increased the strength at failure to three times that of PLLA alone. The results showed a strong anisotropic effect, however further tests using a laminate with fibre oriented in four principal directions (0°, 45°, 90° and 135°) showed a greater improvement (Nishimo 2003).

## **7. EMERGING BIO-DERIVED MATERIALS IN THE INTERNATIONAL CONSTRUCTION INDUSTRY**

Various avenues are being explored to develop construction materials from bio-derived resources. These are discussed in the sections below.

### **7.1 Natural insulation**

A critical component of an efficient building is insulation. This is because such a large proportion of a building's energy requirement is expended "in-use", the vast majority for heating (or cooling) the living space (Isaacs 2006).

In Europe, crop-derived insulation materials are usually based on fibres. Products are already made from hemp and flax as well as from wood such as recycled newsprint, wood fibre and wood wool boards. Natural insulation materials are said to offer performance advantages over alternatives such as stone wool, glass wool and polymer foam. The rationale for this is that the thermal conductivity of mineral-based material is severely compromised by moisture whilst natural material continues to provide effective insulation even after absorption of up to 30% of its own weight in water (NGCC 2008).

In fact, this ability to absorb and desorb water vapour offers the potential to prevent accumulation of moisture at sites where it may cause damage (NGCC 2008).

Renewable products are claimed to store around twice as much heat as mineral alternatives, for an equivalent thickness and density, offering thermal buffering against swings in the external temperature (NGCC 2008). In addition, the flexibility of natural fibres makes them effective acoustic insulation agents.

In terms of their ecological profile, natural insulation materials appear to have lower embodied energy.

There is little adoption of crop-based insulation material in New Zealand. However, insulation products derived from wool have been used for over 30 years and insulation made from paper has also been used. Development of domestic markets through procurement policies or financial support for ecologically desirable products could change this. For instance, in Germany, renewable insulation materials attract government support of 40 Euros (approximately \$80) per cubic metre and have a significantly larger share of the market than in the United Kingdom where such incentives do not exist (NGCC 2008).

An insulation fibre product has been developed in the United Kingdom. It is made from hemp and waste cotton fibres. The product also contains 15% polyester fibres to give loft and stability. The hemp fibres used are grown without the use of herbicides and pesticides and the fibres are said to be extracted in a waste-free and chemical-free mechanical process (Plant Fibre Technology 2008).

### **7.2 Floor coverings**

Natural materials such as wool have a long history of use in carpets. In addition to these traditional materials, crop-based feedstocks are also used in manufactured floor coverings. For instance, linoleum is derived almost entirely from biological materials – mainly oxidised linseed oil mixed with rosin and wood flour pressed onto a jute backing.

### **7.3 Reinforcement of blocks and plaster**

Plant fibres, including straw and hemp, can be used to reinforce building blocks. For non-load-bearing interior walls, lightweight, unfired clay and sand blocks reinforced with straw are said to have good acoustic properties and the natural fibre also contributes temperature and humidity buffering (NGCC 2008).

A more robust building material is a hemp/lime mix. Two houses have been built using this technology by BRE in the United Kingdom. A thermographic survey showed significantly more heat loss through the walls constructed from conventional masonry (as used widely in the United Kingdom) compared with the hemp/lime houses. This decrease in heat loss was reflected in energy consumption in the hemp/lime houses (Yates 2003).

## **7.4 Surface coatings**

Globally, crop-derived surface coatings have seen a renaissance over recent years. This has been partly driven by regulation and market demand for “natural” materials, but also by their performance characteristics (NGCC 2008).

Linseed oil is widely used for timber treatments because its slow drying time enables the oil to penetrate more deeply than synthetic resins. It also forms a strong, but flexible, micro-porous skin which will accommodate contraction and expansion of surfaces in response to fluctuations in temperature or humidity as well as limited diffusion of moisture.

Linseed is probably the most widely used crop-derived component of surface coatings, however binders and thinners from soya and sunflower are also used (Stevens 2004). Solvents derived from citrus oils and lecithins from soya, maize and peanuts are also used (NGCC 2008).

## **7.5 Composite boards**

Many composite boards used in building are based on wood and synthetic resins e.g. particleboard, fibreboard and strandboard. These currently use synthetic binders e.g. phenolformaldehyde or urea formaldehyde resins. However, there is increasing interest among manufacturers and researchers in substitution of incumbent synthetic resins with types that offer the potential for derivation from bio-materials (El-Wakil 2007, Zhang 2007).

The use of compressed straw for construction is also being re-visited by United Kingdom-based company Stramit International. Their manufacturing process compresses the straw to make boards without the use of resin (Stramit 2008). Similar board products are also manufactured in Australia and have been used in a number of commercial projects (Ortech 2008).

# **8. SUMMARY**

The use of natural fibres in composite applications has increased significantly over the last two decades. The possibilities of utilising natural fibres and their associated composites are now being realised, and as a result there are now numerous examples where natural composites have found application in diverse industries from automotive, construction, packaging and leisure products.

Composite applications, to date, have leverage mainly off the lower cost, lower density and ease of processing of plant fibre articles over use of comparable glass fibres. Additionally, it is said that plant fibres offer high specific strength and modulus than glass fibres (Mohanty 2005). For these reasons, the use of natural fibres in products using synthetic resin (derived from oil) as the matrix is clearly an attractive option for the construction industry.

Bio-derived polymer uptake has mainly centred on the packaging industry where the high volumes, short product lifetime and the potential for bio-degradability have driven adoption.

However, existing understanding of bio-derived polymers and composites indicates that the materials are generally susceptible to water absorption and/or hydrolysis (Gupta 2007, Hajnalka 2006, Mehta 2006). This degradation by water could result from elevated levels of atmospheric moisture or weathertightness problems. Wetting of bio-derived materials could significantly reduce both the physical properties of the materials and their service life.

Therefore, it is expected that polymers from bio-derived materials, i.e. those that don't involve synthetic chemistry to produce monomers, will struggle to deliver the properties required for use in the exposed areas of buildings. In this context resistance to moisture and assurance of long-term durability will be important. Protection from moisture implies their use (currently) would need to be limited to applications within the weathertight interior of buildings, as reflected by the emerging applications discussed in Section 7.

Today, the most accessible benefit to the construction industry from bio-derived materials is the adoption of bio-degradable packaging materials. These are expected to reduce the amount of construction-related waste that will persist in the environment.

There is an emerging global recognition of the potential for bio-derived resins and composites. The South Africa Council for Scientific and Industrial Research has begun along the path of evaluating natural fibre composite materials for use in construction (van Wyk 2007). This is expected to continue as a programme of experimental work to better understand the potential of these materials.

This study has found that some initial research has been completed to characterise the properties and performance of bio-derived resins and composites. Some authors have obtained results that have prompted statements about the suitability of some materials for use in construction (see Section 6). The development of standards and codes for bio-derived materials are also progressing in a number of countries, but these are primarily focused on bio-degradability.

Globally the construction industry is in general dependent on codes, standards and regulations when making material choices. In most territories, and in New Zealand, bio-derived resins and composites are not referenced by these documents. This is not surprising given these materials are an emerging class, but it does stand in the way of their widespread use.

Development of an improved understanding of durability issues and recommended solutions for the potential problems involving the use of bio-derived materials in construction is needed to feed into code compliance documents.

Work should also incorporate evaluation of bio-derived materials when used across New Zealand over multi-year periods.

Ideally, any test methodology would have the capacity to determine property degradation rates as a function of composition and application over short exposure periods. It should also be capable of considering environmental conditions in a flexible manner, which would include both current architectural design and future best practice for optimum durability performance. These goals could be achieved through the development of verification techniques that varied as a function of application environment.

If warranted, the conclusions of the work would also lead to a development or revision of standards and, with the support of the bio-derived material producers, an increase in creative solutions available within the marketplace.

Finally, the availability of plant fibres and bio-derived polymers in the required quantities and sufficient quality are the key to fulfilling their potential. Currently,

international markets exist for a number of fibre and polymer types, as discussed in Sections 2 and 3, and this globalisation of material supply is expected to increase.

## 9. REFERENCES

Bhattacharyya D, Jayaraman K and Yuan XW. 2002. 'Plasma Treatment of Sisal Fibres and its Effects on Tensile Strength and Interfacial Bonding'. *Journal of Adhesion Science and Technology* 16(6): 703–727.

Bhattacharyya D, Jayaraman K and Yuan XW. 2003. 'Plasma Modification of Natural Fibres in Polypropylene Composites'. *International Journal of Plastics Technology* 6(1): 27–31.

Bhattacharyya D, Jayaraman K and Yuan XW. 2004. 'Effects of Plasma Treatment in Enhancing the Performance of Woodfibre-polypropylene Composites'. *Composites Part A: Applied Science and Manufacturing* 35(12): 1363–1374.

Bhattacharyya D, Jayaraman K and Yuan XW. 2004a. 'Mechanical Properties of Plasma-treated Sisal Fibre-reinforced Polypropylene Composites'. *Journal of Adhesion Science and Technology* 18 (9): 1027–1045.

Bio-polymer Network. 2006. *2006 Industry Workshop Summary* ([www.biopolymernetwork.com/BPN\\_SeminarSummary.pdf](http://www.biopolymernetwork.com/BPN_SeminarSummary.pdf) accessed 25 March 2008).

Biosecurity New Zealand. 2007. *Pests and Diseases* ([www.biosecurity.govt.nz/pest-and-disease-response/pests-and-diseases-watchlist](http://www.biosecurity.govt.nz/pest-and-disease-response/pests-and-diseases-watchlist) accessed 17 March 2008).

Bradshaw K. 2007. *Disruptive Technologies – A New Age for Plastics*. WasteMINZ Conference, Hamilton, New Zealand (7 November 2007).

Burgeueno R et al. 2005. 'Hybrid Biofiber-based Composites for Structural Cellular Plates'. *Compos Part A Appl Sci Manuf* 36(5): 581–593.

Burgeueno R et al. 2005a. Sustainable Cellular Bio-composites from Natural Fibers and Unsaturated Polyester Resin for Housing Panel Applications. *J. Polym. Environ.* 13(2): 139–149.

CACM. 2008. Centre for Advanced Composite Materials ([www.mech.auckland.ac.nz/Composites/CACM.html](http://www.mech.auckland.ac.nz/Composites/CACM.html) accessed 25 March 2008).

Chang KK. 2003. *Heat-cured Furan Binder System*. United States Patent US7125914.

Czaja W et al. 2006. Microbial Cellulose – The Natural Power to Heal Wounds. *Biomaterials* 27(2): 145–151.

DaimlerChrysler AG. 2006. *The New Mercedes-Benz S-Class: Design for the Environment*. DaimlerChrysler AG. Stuttgart, Germany (12 August 2006).

The Ecology Centre. 2006. *Automotive Plastics Report Card* ([www.ecocenter.org/sustainableplastics/AutoPlastics\\_full06.pdf](http://www.ecocenter.org/sustainableplastics/AutoPlastics_full06.pdf) accessed 20th September 2007).

El-Wakil NA et al. 2007. 'Modified Wheat Gluten as a Binder in Particleboard Made from Reed'. *Journal of Applied Polymer Science* 106(6): 3592–3599.

Energy Efficiency and Conservation Authority (EECA). 2008. NAME OF DOCUMENT? (www.eeca.govt.nz/eeca-library/renewable-energy/biofuels/summary/chris-purchas-08.pdf accessed 14 April 2008).

European Norm E13432. 2001. *Packaging – Requirements for Packaging Recoverable Through Composting and Biodegradation – Test Scheme and Evaluation Criteria for the Final Acceptance of Packaging*. European Committee for Standardisation, Brussels, Belgium.

Fiedorowicz M, Lii C and Tomasik, P. 2002. 'Physicochemical Properties of Potato Starch Illuminated with Visible Polarised Light'. *Carbohydrate Polymers* 50(1): 57–62.

Ford Motor Company. 2005. *From Bangladesh to a Mondeo, Kenaf Adds to Ford's Use of Ecologically-friendly Materials* ([http://media.ford.com/newsroom/release\\_display\\_foriframe.cfm?release=20953](http://media.ford.com/newsroom/release_display_foriframe.cfm?release=20953) accessed 20 March 2008).

Grunert M and Winter WT. 2002. 'Nanocomposite of Cellulose Acetate Butyrate Reinforced with Cellulose Nanocrystals'. *J. Polym. Environ.* 10: 28–30.

Gupta AP and Kumar V. 2007. 'New Emerging Trends in Synthetic Bio-degradable Polymers – Polylactide: A Critique'. *European Polymer Journal* 43: 4053–4074.

Hall W. 2006. *Standards and Labelling of Degradable Plastics* (Powerpoint presentation 'warwick-halls-presentation-australian-standard.ppt' from [www.plastics.org.nz](http://www.plastics.org.nz), 'Degradable Plastics' page accessed 20 March 2008).

Hajnalka H, Rácz I and Anandjiwala R. 2006. 'Development of Hemp Fibre – PP Non-woven Composites'. *Macromol. Symp.* 239: 201–208.

Isaacs et al. 2006. 'Energy Use in New Zealand Households: Report of the Year 10 Analysis for the Households Energy End-use Project (HEEP)'. *BRANZ Study Report 155*. BRANZ Ltd, Judgeford, New Zealand.

Jayaraman K et al. 2008. 'Life Cycle Assessment of Wood-fibre Reinforced Polypropylene Composites'. *Journal of Materials Processing Technology* NO ISSUE OR PAGE NUMBERS

Jayaraman K, Segetin, M and Xu X. YEAR? 'Harakeke Reinforcement of Soil-cement Building Materials: Manufacturability and Properties'. *Building and Environment* 42: 3066–3079.

Jonas R and Farah LF. 1998. 'Production and Applications of Microbial Cellulose'. *Polymer Degradation and Stability* 59: 101–106.

Joshi et al. 2004. 'Are Natural Fiber Composites Environmentally Superior to Glass Fiber Reinforced Composites?' *Composites Part A: Applied Science and Manufacturing* 35 (3): 371–376.

Kosior E, Braganca RM and Fowler P. 2006. *Lightweight Compostable Packaging: Literature Review*. The Waste & Resources Action Programme, Banbury, UK.

Liese W. 1998. *The Anatomy of Bamboo Culms*. International Network for Bamboo and Ratan, Eindhoven.

Lunt J. 1998. 'Large-scale Production, Properties and Commercial Applications of Polylactic Acid Polymers'. *Polymer Degradation and Stability* 59(1–3): 145–152.

Marston NJ and Jones MS. 2007. 'Weathering of Polymeric Materials in New Zealand'. BRANZ *Study Report 182*. BRANZ Ltd, Judgeford, New Zealand.

Mavani SI, Mehta NM and Parsania PH. 2007. 'Synthesis, Fabrication, Mechanical, Electrical and Moisture Absorption Study of Epoxy Polyurethane-jute and Epoxy Polyurethane-jute-rice/wheat Husk Composites'. *Journal of Applied Polymer Science* 106(2): 1228–1233.

Mehta G and Mohanty AK. 2006. 'Effect of Accelerated Weathering on Bio-composites Processed by SMC and Compression Molding'. *J. Polym. Environ* 14: 359–368.

MFE. 2008. *New Zealand Packaging Accord 2004–2009* ([www.mfe.govt.nz/issues/sustainable-industry/initiatives/packaging/](http://www.mfe.govt.nz/issues/sustainable-industry/initiatives/packaging/) accessed 17 April 2008).

MfE. 2008a. *National Waste Data Report* ([www.mfe.govt.nz/publications/waste/nat-waste-data-report-may97.html](http://www.mfe.govt.nz/publications/waste/nat-waste-data-report-may97.html) accessed 18 April 2008).

Misra M et al. 2006. *High Volume Production of Environmentally Friendly Bio-composites by Sheet Molding Compounding*. Proceedings of the American Chemical Society 21<sup>st</sup> Technical Conference, Dearborn, Michigan, USA, 17–20 September 2006.

Modern Plastics Worldwide. 2007. *Soybeans Make for Green PUR* (November).

Modern Plastics Worldwide. 2007a. *Bio-film Meets Demands for Agri-film Applications* (August).

Modern Plastics Worldwide. 2007b. *Sweet News for Polyethylene* (September).

Mohanty M, Misra M and Drzal L. 2005. *Natural Fibers, Bio-polymers and Bio-composites*. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.

Network Group for Composites in Construction. 2008. *Technical Sheet 08. Sustainable FRPs – Naturally Derived Resins and Fibres*. NGCC, Chesterfield, UK.

Nishimo et al. 2003. 'Kenaf Reinforced Bio-degradable Composite'. *Composites Science and Technology* 63(9): 1281–1286.

Ortech Industries. 2008. *Straw Panel Building Systems for Walls, Ceilings and Roofs* ([www.ortech.com.au](http://www.ortech.com.au) accessed 1 April 2008).

Piao H. 2006. *Microbial-derived Cellulose-reinforced Bio-composites*. Masters thesis, University of Canterbury, Christchurch, New Zealand.

Pillin I et al. 2007. 'Could Bio-polymers Reinforced by Randomly Scattered Flax Fibre be Used in Structural Applications?' *Composites Science and Technology* 67(3-4): 462–470.

Plant Fibre Technology. 2008. *Plant Fibre Technology Ltd* ([www.plantfibretechnology.com](http://www.plantfibretechnology.com) accessed 20 March 2008).

Plastics NZ. 2006. *Mass-Balance Survey (2005 Production)* ([www.plastics.org.nz/\\_attachments/docs/mass-balance-2005-1.pdf](http://www.plastics.org.nz/_attachments/docs/mass-balance-2005-1.pdf) accessed 28 June 2007).



Plastics NZ. 2007. *Mass-Balance Survey (2006 Production)* ([www.plastics.org.nz/\\_attachments/docs/mass-balance-2006-1.pdf](http://www.plastics.org.nz/_attachments/docs/mass-balance-2006-1.pdf) accessed 28 June 2007).

Plastics NZ. 2007a. *All About Plastics. What is PVC?* ([www.plastics.org.nz/](http://www.plastics.org.nz/) accessed 28 June 2007).

Plastics NZ. 2008. *NZ Plastics and the Environment* ([www.plastics.org.nz/page.asp?section=environment](http://www.plastics.org.nz/page.asp?section=environment) accessed 17 April 2008).

Plastics NZ. 2008a. *NZ Waste & Recycling Statistics* ([www.plastics.org.nz/page.asp?id=502](http://www.plastics.org.nz/page.asp?id=502) accessed 17 April 2008).

Rao K et al. 'Tensile Properties of Elephant Grass Fibre Composites'. *Journal of Material Science* 42(9): 3266–3272.

RAPRA. 2002. 'Natural and Wood Fibre Reinforcement in Polymers'. *Rapra Review Report* 13(8): Report 152.

Rebri. 2008. *What is Resource Efficiency?* (<http://www.rebri.org.nz/what/> accessed 18 April 2008).

Scion. 2007. *Annual Report 2007* ([www.scionresearch.com/Portals/0/ScionAnnualReport2007.pdf](http://www.scionresearch.com/Portals/0/ScionAnnualReport2007.pdf) accessed 25th March 2008).

Scion. 2008. *Molecular Composites – Polymer Systems* ([www.scionresearch.com/Default.aspx?PageContentID=196&tabid=240](http://www.scionresearch.com/Default.aspx?PageContentID=196&tabid=240) accessed 25 March 2008).

Scion. 2008a. *Molecular Composites – Woodfibre-biopolymer Composite Materials* ([www.scionresearch.com/Default.aspx?PageContentID=198&tabid=240](http://www.scionresearch.com/Default.aspx?PageContentID=198&tabid=240) accessed 25 March 2008).

SRIC. 2008. *Polymers from Bio-mass*. SRI Consulting, The Woodlands, TX, USA.

Stevens C and Verhé R. 2004. *Renewable Bioresources: Scope and Modification for Non-Food Applications*. Wiley, Hoboken, USA.

Stramit International. 2008. *Stramit Strawboard* ([www.stramit.co.uk/](http://www.stramit.co.uk/) accessed 1 April 2008).

Timar-Balazsy A, Eastop D and Járó M. 1998. *Chemical Principles of Textile Conversion*. Butterworth-Heinemann, Oxford, UK.

Van Wyk L. 2007. *The Application of Natural Fibre Composites In Construction: A Research Case Study*. Sixth International Conference on Composite Science and Technology, Durban, South Africa, 22–24 January 2007.

Wool RP and Sun XS. 2005. *Bio-based Polymers and Composites*. Elsevier, Amsterdam, The Netherlands.

Yates. 2003. *The Haverhill Hemp Houses* (<http://projects.bre.co.uk/hemphomes/> accessed 20 March 2008).

Zhang Y and Yu W. 2007. Current Status on Research and Development for Bio-based Adhesives in the Wood Industry. *China Adhesives* 16(6): 33–38.



## **APPENDIX A GLOSSARY**

### *Bio-derived*

Made from a biological source material.

### *Bio-compatible*

A material that is biologically compatible and does not produce a toxic, injurious or immunological response in living tissue.: As a result a material may be favoured for use in medical devices.

### *Bio-degradable*

A process where different micro-organisms break down organic matter and produce CO<sub>2</sub>, water, heat and humus (a relatively stable organic end product). It should be noted that bio-derived polymers may or may not be bio-degradable. Bio-degradability depends on the material composition and structure as well as the degrading environment.

### *Composites*

Composite materials are those composed of two, or more, distinct parts. This report is concerned with polymer composites where reinforcing fibres are combined with a polymer (plastic) matrix. The fibres provide strength and stiffness to the composite and are conventionally composed of glass, carbon or aramid.

### *Composting*

An industrial or small-scale (home composting) bio-degradation process which proceeds through three phases where different communities of micro-organism predominate during the composting phases.

### *Home composting*

Home composting implies that organic materials are transformed into humus by bacteria and other micro-organisms under aerobic conditions similar to industrial composting. There are, however, a number of major differences.

The time-scale is different – the composting cycle in industrial systems is composed of a three month thermophilic phase followed by a three month maturation phase. In home composting, such a time-scale may not be so crucial, as longer periods may be acceptable.

Control of humidity and temperature is another area of difference. It is expected that these parameters may be lower, due to heat exchange with ambient temperature and deficient aeration.

Little management of the compost is expected, whereby the compost is not turned and aerated. As a result, less heat is generated as part of the process. Indeed, the generation of heat significantly contributes to the ease and rate at which newly introduced material composts. It is unlikely that temperatures equivalent to industrial composting will be sustained in a home composting situation, particularly in the winter months and/or when the compost bin is not managed.

Overall, the altogether less efficient composting regime envisaged in a home composting environment places greater demands on the materials to be disposed of in this way at the end of their useful life.

### *Industrial composting*

Industrial composting implies proactive management of a compost site at which the compost is turned, aerated and bio-degradation is such that significant heat is generated as part of the process.

Attempts have been made to try to standardise a set of conditions, time-scales and degradation products which define if an item may be claimed to bio-degrade. For example, the European Standard for composting and bio-degradation of packaging materials, EN13432.

This standard is aimed at indicating the characteristics of the compostable packaging and defines a test method to verify the conformity of a packaging with the requirements. The standard gives conditions under which a test specimen should be conditioned to check bio-degradability.