Sustainability of vegetable fibres in construction

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Abstract: This chapter discusses the performance of vegetable fibres that are important in international trade and are of interest as construction materials. The chapter is focused on fibres extracted from non-wood plants and their wastes such as sisal, coconut, bamboo, sugar cane bagasse, banana and jute. The availability of the fibres and their extraction depends on manufacturing and processing these fibrous raw materials for different uses. General applications of vegetable fibres as reinforcing elements are connected to both polymeric and cementitious matrices. The chapter also contains an example of the application of vegetable fibres as reinforcement in cement-based composites for building and infrastructure construction. The mechanical and physical performances of non-conventional composites are evaluated in both the newly formed state and after exposure to weathering conditions.

Key words: composite, fibre cement, general applications, mechanical performance, physical characteristics, processing, vegetable fibre.

3.1 Introduction

Sustainability is a concept of increasing concern all over the world in view of the shortage of natural resources and energy, the generation of several types of solid wastes and gas emissions from various sources. The rational use of vegetable fibre can be an alternative solution for the production of durable and more sustainable goods. Fibres obtained from the various parts of plants are known as vegetable fibres. These fibres are classified into three categories depending on the part of the plant from which they are extracted: bast or stem fibres (jute, malva, banana, flax); leaf fibres (sisal, pineapple, screw pine) and fruit fibres (cotton, coir, oil palm) (Wood, 1997).

Fibre resources such as bamboo, sisal, coir and banana, and those from agricultural residues are called natural non-wood fibre resources. The four main fibre material resources from plants are: (a) natural non-wood fibre resources; (b) bamboo; (c) agricultural residues and (d) recycled fibre (waste paper). These fibres have been used to produce clothing, ropes and cordage, sacks, canvas, fishing nets, brushes and sewing thread; and also pulp, paper and building products such as plaster products, fibre-cement sheeting, fibre-reinforced concretes, fibre-reinforced plastics and insulating materials.
The traditional non-wood fibres can be used to produce high-quality writing and specialty papers. Global paper use has increased more than six times over the latter half of the twentieth century, and has doubled since the mid-1970s. About 93% of today’s paper comes from trees, and paper production is responsible for about one-fifth of the total wood harvest worldwide. A sheet of writing paper might contain fibres from hundreds of different trees that have collectively travelled thousands of kilometres from forest to consumer.

In recent years, vegetable fibres have been increasingly used as reinforcement in polymer composites. With their low cost and high specific mechanical properties, they can represent a good, renewable and biodegradable alternative to the most common synthetic reinforcement, i.e. glass fibres (Li et al., 2000; Herrera-Franco and Valadez-González, 2005; Doan et al., 2007; Tomczak et al., 2007; Zini et al., 2007).

The fibre reinforcement of building materials has been practised since early ages and its application in the civil construction industry took a large leap forward, with the introduction of asbestos cement in the world market, at the beginning of the twentieth century; however, its durability and mechanical properties are still not fully understood. Materials based on vegetable plants and alternative cements are well known and should be more intensely used as local building materials. Advantages can include low cost, energy efficiency, control of residues and contamination, thermal comfort and principally the achievement of eco-friendly materials (Agopyan, 1988; Coutts, 1988; Agopyan et al., 2005; Coutts, 2005; Savastano and Warden, 2005).

There is also substantial knowledge regarding the materials and techniques required for the construction of earth buildings containing vegetable plants (non-wood and wood fibres). Unfortunately, current performance codes are much more focused on modern materials and in several cases construction materials based on natural earth are found to be out of conformity in relation to these performance codes, even for special uses in rural areas (Agopyan, 1988; Coutts, 1988; Plessis, 2001).

The main objective of the present chapter is to discuss the performance of the vegetable fibres relevant to civil construction applications. The availability of the fibres and their extraction are closely related to the manufacturing and processing of the fibrous raw materials for different uses. The chapter also contains an example of the application of vegetable fibres as reinforcement in cement-based composites for building and infrastructure construction.

### 3.2 Availability and extraction

There are three basic procedures for extracting vegetable fibres (for example, jute, malva, banana, sisal): retting, chemical treatment and mechanical decortication. The fibre bundles have traditionally been extracted by a microbiological process known as retting, in which the combined action of microbial enzymes and water
decomposes the non-fibrous material surrounding the fibre bundles, enabling them to be loosened for manual extraction (Wood, 1997). The fibres produced by the retting process are still encrusted with high amounts of lignin and hemicellulose which affect the quality of the fibre. For the production of textiles, the fibres are often subjected to chemical treatment to remove these adhering compounds. Decortication is a process where the fleshy leaves are first trimmed to remove the spines and then passed through decortication machines that crush them between rollers and scrape them against a bladed drum. During the scraping stages water is sprayed on to the leaves to assist in the separation of fleshy material from the fibre. For some purposes the bast fibres can be extracted from green or dried stem material simply by mechanical means with no pre-treatment required (Wood, 1997).

Some advantages and disadvantages of vegetable fibres for building components can be highlighted as follows.

The advantages of vegetable fibres include:

- low specific weight, which results in higher specific strength and stiffness than glass; this is particularly beneficial in components designed for bending stiffness;
- they are a renewable resource, the production requires little energy and carbon dioxide is used while oxygen is given back to the environment;
- can be produced with low investment at low cost, which makes the material an interesting product for developing countries;
- good thermal and acoustic insulating properties in building applications.

The disadvantages of vegetable fibres are:

- variable quality, depending on unpredictable influences such as weather;
- moisture absorption, which causes swelling of the fibres;
- restricted maximum processing temperature;
- lower durability, which can be considerably improved by fibre treatments;
- price can fluctuate depending on harvest yield or agricultural politics.

Many researchers are working to mitigate the disadvantages of vegetable fibres and to modify their characteristics in order to optimize their performance as reinforcement in composite technology. Table 3.1 gives details of some commercially available vegetable fibres. The selection was made based on physical and mechanical properties, cost, durability in natural wet environments and production. As they are natural products, the fibres are heterogeneous and therefore the coefficients of variation in some properties are very high. The characteristics of E-glass and polypropylene fibres are included in Table 3.1 for comparison purposes.

### 3.3 Manufacturing and processing of raw materials

Treatment is required to turn just-harvested plants into fibres suitable for composite processing. For example, in the case of flax, the first step is retting (as described...
Table 3.1 Physical and mechanical properties of vegetable, E-glass and polypropylene fibres

<table>
<thead>
<tr>
<th>Fibres</th>
<th>Density (g/cm³)</th>
<th>Tensile strength* (MPa)</th>
<th>MOE (GPa)</th>
<th>Elongation at failure (%)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jute (Corchorus capsularis)²</td>
<td>1.36</td>
<td>400–500</td>
<td>17.4</td>
<td>1.1</td>
<td>250</td>
</tr>
<tr>
<td>Coir (Cocos nucifera)b</td>
<td>1.17</td>
<td>95–118</td>
<td>2.8⁴</td>
<td>15–51</td>
<td>93.8</td>
</tr>
<tr>
<td>Sisal (Agave sisalana)b</td>
<td>1.27</td>
<td>458</td>
<td>15.2</td>
<td>4</td>
<td>239</td>
</tr>
<tr>
<td>Banana (Musa cavendishii)²</td>
<td>1.3</td>
<td>110–130</td>
<td>–</td>
<td>1.8–3.5</td>
<td>400</td>
</tr>
<tr>
<td>Bamboo (Bambusa vulgaris)b</td>
<td>1.16</td>
<td>575</td>
<td>28.8</td>
<td>3.2</td>
<td>145</td>
</tr>
<tr>
<td>E-glassc</td>
<td>2.5</td>
<td>2500</td>
<td>74</td>
<td>2–5</td>
<td>–</td>
</tr>
<tr>
<td>Polypropylenec</td>
<td>0.91</td>
<td>350–500</td>
<td>5–8</td>
<td>8–20</td>
<td>–</td>
</tr>
</tbody>
</table>

*Tensile strength strongly depends on type of fibre, being a bundle or a single filament.
MOE, Modulus of elasticity.

in Section 3.1); this is a controlled retting process to get rid of the pectin that connects the fibre bundles to the wood core of the stem. During harvesting, pretreatments and processing, the handling of the material plays an important role in fibre quality. Failure spots on the fibres can be induced, which cause a reduction of the tensile strength. This section describes the manufacturing and processing methods that are widely available and commonly used for vegetable fibres.

3.3.1 Sisal fibres

The sisal plant and its products have proved, over centuries of natural and commercial production, that they can serve mankind as a sustainable renewable resource; the plant is used for cordage and for woven, pharmaceutical and building products. Figure 3.1 shows some production stages in the cordage industry that generate residues of sisal. The sisal (Agave sisalana) fibres are easily obtained from the leaves of the Agave plants. Sisal is produced in South America (e.g. Brazil and Venezuela), Africa (e.g. Tanzania, Kenya and Madagascar) and Mexico, where it originated. Central American countries also produce small amounts of this fibre. In 2004, the annual production of fibre in Brazil was about 139 700 tonnes, making it the largest producer of sisal in the world. The Brazilian production is concentrated in the states of Bahia (87%) and Paraíba (7.4%), both located in the northeast region of the country (Andrade, 2006). Nowadays, sisal leaves are also being used by the pulp and paper industry and there have been many attempts to use it in cementitious (Savastano et al., 2005) and polymeric (Fung et al., 2003; Chand and Jain, 2005) materials.
The procedure of decortication of the sisal fibre is very crude and it can be dangerous for the workers if they do not use proper procedures for this operation. Thousands of simple machines powered by diesel engines are spread throughout the sisal plantations. These machines mechanically separate the fibres from the mucilage, but about 40% of the fibres, the short ones, remain in the mucilage residues. The acidity of the fibres is neutralized simply by washing in water; the fibres are bleached in the sun. During processing, a further 10% of the fibres are lost as residues. Therefore only 3%, by weight of leaves, is recovered as long fibres.

The global market for sisal fibres has remained strong, after improving through 2003 and 2006. Brazil has benefited from China’s growing import demand. There is a high demand African sisal for various non-traditional applications. In Africa the prices increased from around US$750 per tonne in early 2003 to stabilize at around US$1010 through 2006. In Brazil, the price increased from US$400 during 2002 to around US$780 in the second half of 2006 (FAO, 2006).
3.3.2 Coir fibres

Coconut is a tall cylindrical-stalked palm tree, reaching 30 m in height and 60–70 cm in diameter. It is a tropical plant for low altitudes. It needs sunshine and a soil rich in calcium and phosphorus and is thus generally suitable for cultivation in sandy, sea-shore areas (Agopyan, 1988; FAO, 2002). Although coconut cultivation is concentrated in the tropical belts of Asia and East Africa, it is also found in Latin America on a smaller scale; coconut is cultivated on a commercial basis in Brazil (Tomczak et al., 2007). The most important part of the tree is its fruit, which is egg-shaped and about 30 cm long and 25 cm in diameter. The more external layer of the fruit is thin and smooth: its fibrous mesocarp is 3–5 cm thick and the endocarp is very hard. The fruit has a large central cavity that contains a sweet liquid (coconut water). The number of fruits per tree varies, depending strongly on soil conditions (Agopyan, 1988).

Brazil produces about 1.5 billion coconuts (Cocos nucifera L.) annually, mainly in the northeast region, in a cultivated area of 273,810 ha. Coconut fibres (coir) can be extracted from either immature or mature fruits (Fig. 3.2). They are lignocellulose fibres obtained from the mesocarp of the coconut fruit, which constitutes about 25% of the nuts. They are one of the least expensive of the various natural fibres available in the world. They are not brittle like glass fibres, they are responsive to chemical modification and are non-toxic. However, the waste from their disposal causes environmental problems (Tomczak et al., 2007).

Coir fibre production is normally rudimentary, old-fashioned equipment crushes the husk and separates the fibres. Some industries have modern equipment that can separate long fibres (of more than 110 mm in length) suitable for brushes and threads. Asasutjarit et al. (2007) carried out research into the development of coir-based, lightweight cement boards. They were used as building components for energy conservation. John et al. (2005) also conducted a comparative study on the microstructure of both new and in-use aged blast-furnace slag cement reinforced with coir fibre. Aged samples came from the internal and external walls of a 12-year-old house built in São Paulo, Brazil that remained in an acceptable condition after this period under normal utilization. The panels of the house were produced using 1:1.5:0.504 (binder:sand:water, by mass) mortar reinforced with 2% of coir fibre by volume. After 12 years, the cement was fully carbonated. Fibres removed from the old samples seem to be undamaged when examined using scanning electron microscopy. Qualitative determination of lignin content by Wiesner reaction suggested that the old samples had a lower content of guaiacyl lignin units. Nevertheless, the total lignin content of the old fibres when measured by the acetyl bromide method was comparable with that reported in literature. No significant difference was found in the lignin content of fibres removed from external walls and those removed from internal walls.

As a by-product generated in the fabrication of other coconut products, coir fibre production is largely determined by demand. Abundant quantities of coconut husk
3.2 (a) Coconut plantation in northeast region in Brazil, (b) deposits of coconut husk, (c) detail of the fibres in the coconut husk and (d) extracted coir fibre.

imply that, given the availability of labour and other inputs, coir producers can adjust relatively rapidly to market conditions and prices. It is estimated that approximately 10% of husks are utilized for fibre extraction, satisfying a growing demand for fibre and coir products. Production of coir fibre takes place in small- or medium-sized units, mainly in India, Sri Lanka and Thailand. During the 1990s, production in India expanded by 8.2% annually in order to meet domestic demand, while in Sri Lanka, a major exporter of coir fibre, production contracted due to weakening export and domestic demand. In the medium term it is projected that global production will increase from an average of 534 000 tonnes in 1998–2000 to 640 000 tonnes in 2010. Most of the expansion in production is likely to take place in India, with some modest growth in Sri Lanka (FAO, 2002; FAO, 2003a).

3.3.3 Bamboo fibres

Throughout wide areas of the world, bamboo plants serve many purposes. The bamboo culture in the Americas and Asia is ancient. In these areas the largest, most
pure and densest bamboo forests and the best and largest number of giant species were found. The natives of this area also developed the best constructions technologies for bamboo houses and bridges and became skilled builders. Nowadays, there are many applications for bamboo in different fields of aeronautical, chemical, civil, electrical, hydraulic, nautical and mechanical engineering (Hidalgo-Lopez, 2003; Ghavami, 2005; Yamashita et al., 2007; Lo et al., 2008).

Sixteen countries in Asia reported a total of 24 million ha of bamboo resources, while five African countries reported 2.8 million ha. It is estimated that ten Latin American countries may have over 10 million ha of bamboo resources, taking the world total to some 37 million ha or roughly 1% of the global forest area. However, the figures represent only rough estimates and include pure bamboo forests, bamboo mixed with other species (in which bamboo is not necessarily predominant) and bamboo on other land (also pure or mixed with other trees or crops) (FAO, 2005). National and local trade is probably a few times higher. There are numerous other examples of the importance of bamboo for national economies and international trade; however, reliable statistics are still lacking. Most of the economic activities related to bamboo are not recorded officially. They are site-specific, highly diverse and present challenges for official data collection.

The growing industrial and environmental importance of bamboo requires the development of more comprehensive statistics on bamboo resources, utilization and trade. In 2005, the World Customs Organization (WCO) approved the Food and Agricultural Organization of the United Nations (FAO) proposal to introduce 16 new harmonized system codes, including bamboo pulp, panels, furniture and shoots. The new codes will have a profound long-term effect on bamboo statistics and will facilitate bamboo trade and development (FAO, 2005).

About 75 genera and 1250 species of bamboo are found in different countries of the world. *Bambusa vulgaris* is the best known and most widely used species in Asia. For building, *Guadua angustifolia* Kunth is also used and is a common plant in Latin America, especially in Colombia, Peru and Ecuador (Agopyan, 1988; Hidalgo-Lopez, 2003). Bamboo is the most important non-wood forest product and in India it is known as the ‘poor man’s timber’. In China, it is the valuable raw material for the booming bamboo industry (FAO, 2005).

Over the last 15–20 years, bamboo has developed as an exceptionally valuable and often superior substitute for wood. Bamboo-based panels and boards are hard and durable and may successfully substitute the hardwood products. Bamboo may replace wood in many industrial applications and thereby contribute to the saving and restoration of the world’s forests. Pulp and paper manufacture from bamboo is expanding (Hidalgo-Lopez, 2003; FAO, 2005). Fig. 3.3 shows some steps in the production of bamboo paper.

Fresh bamboo materials softened by high temperature can be manufactured into fibres for textile production. Bamboo fibre is hollow inside and, thus, it results in breathable fabrics. The texture of bamboo fibre and hemp, silk or wool fibres results in fabrics with better performances than those made from other commonly
used fibres. As China is one of the biggest bamboo producers in the world, bamboo utilization is significant to the development of China’s pulp industry. Bamboo is the second most important fibre material for pulp making in China, and its production is estimated at approximately 177 000 tonnes (Dhamodaran et al., 2003; INBAR, 2004).

The length of bamboo fibre is much longer than the length of hardwood (e.g. eucalyptus) fibre and this also results in a stronger pulp. However, as pulping conditions are very similar for both eucalyptus and bamboo, they can be pulped together. This mixed pulping (for example in a chemical process) gives a stronger pulp than if the hardwood is pulped separately (Stig Andtbacka, 2005).

3.3.4 Sugar cane bagasse fibres

Sugar cane bagasse is a lignocellulosic fibre residue obtained from sugar cane culm (Fig. 3.4), after the culm is milled and the juice is extracted. The average composition of sugar cane is 65–75% water, 11–18% sugars, 8–14% fibres and 12–23% soluble solids. The cane basically consists of juice and fibre (Santaella,
3.4 Sugar cane plantation (photograph by Loan T. Le).

2007). The sugar cane bagasse has the following composition (by weight): cellulose, 41.8%; hemicellulose (as pentosan), 28.0%; lignin, 21.8% (Bilba et al., 2003).

There are roughly 130 countries that are responsible for between 74 and 77% of the global sugar cane production; about 191 countries are registered as producers. Developing countries currently account for about 67% of world production (1998–2000). In addition, production is becoming more concentrated in certain countries. In 1980, the top ten producers accounted for 56% of global production; by 2004, they accounted for 69%. World sugar consumption is expanding, reflecting rising incomes and shifts in food consumption patterns. Developing countries account for more than 67% of current global sugar consumption – particularly in Asia – and are expected to be the primary source of future demand growth. Brazil is the major player and the most competitive supplier in the world sugar market, with the lowest production costs both in field and factory. The country has significantly increased its exports over the last 5 years, driven by record production and by deregulation of the sugar and ethanol sectors (FAO, 2007).

Other applications for parts of the sugar cane and its residues are being studied with the objective of generating a sustainable life cycle of production. There are successful examples of cement-based materials reinforced with plant fibres produced at very low cost and with high potential as building materials in poor areas. In Cuba, the Technical Centre for Construction and Materials, with the help of the Cuban Institute for the Research of Sugar Cane By-products, has developed sugar cane husk–cement panels, similar to those produced from chip wood bonded with cement. Panels of up to 1.20 m² have been produced and have been found to be...
useful for construction purposes. Agopyan (1988) has presented several propositions involving the use of pressed sugar cane bagasse for the production of panels and sheets. In the future it is possible that the availability of bagasse will increase due to the general interest in the production of bio fuels based on sugar cane.

3.3.5 Banana fibres

Bananas are grown in all tropical regions and play a key role in the economies of many developing countries. Banana plantations were cultivated over an area of some 9 million ha in 2000. World production averaged 92 million tonnes per annum in 1998–2000 and it was estimated at 99 million tonnes in 2001. The bulk of world banana production (almost 85%) comes from relatively small plots or backyard gardens (FAO, 2003c). In many developing countries, the bulk of the banana production is self-consumed or locally traded (FAO, 2003a; FAO, 2003c).

World banana exports are projected to reach almost 15 million tonnes in 2010, rising by approximately 28% with respect to the volume exported in the base period 1998–2000 (FAO, 2003). The average annual increase was predicted to be between 1 and 2% from 2001 to 2005. The opening of the European Community market in 2006 was expected to be reflected by a rise in exports of some 5% that year. In subsequent years the growth was predicted to return to a more moderate rate of 2% per annum. The projected growth of exports in the 2000–2010 decade is lower than the expansion observed in the previous decade. Global exports rose by 48% from an annual average of 7.8 million tonnes in 1988–1990 to some 11.7 million tonnes in 1998–2000. The slower rate of growth projected for 2000–2010 can be explained by both supply and demand. On the supply side, structural adjustments have been made by banana producers in the wake of low prices at the end of the 1990s (FAO, 2003a). The three leading exporting countries are Ecuador, Costa Rica and Colombia. In Asia, the main exporter is the Philippines; in Africa, Cameroon and Côte d’Ivoire; and in the Caribbean, the Dominican Republic and the Windward Islands (FAO, 2003b; FAO, 2003c).

Banana is a perennial crop that grows quickly and can be harvested all year round and its plants reproduce asexually by shooting suckers from a subterranean stem. The shoots have vigorous growth and can produce a ready-for-harvest bunch in less than 1 year. Suckers continue to emerge from a single mat year after year, making bananas a perennial crop. The importance of bananas as a food crop in tropical areas cannot be underestimated. Bananas fall into two categories:

(a) cooking bananas, including plantains and other sub-groups of varieties such as Pisang Awak in Asia;

(b) dessert or sweet bananas, where the Cavendish cultivars are prominent with a 47% share of global banana production; almost all bananas traded worldwide are Cavendish (Fig. 3.5).

Approximately 26% of the total Cavendish crop is exported, and 8 out of 10 bananas exported originate from Latin America.

The banana plant has long been a source of fibre for high quality textiles. In
3.5 Banana Cavendish fruit.

Japan, the cultivation of banana for clothing and household use dates back to at least the thirteenth century. In the Japanese system, leaves and shoots are cut from the plant periodically to ensure softness. The harvested shoots must first be boiled in lye to prepare the fibres for the making of the yarn. These banana shoots produce fibres of varying degrees of softness and yielding yarns. Textiles can be produced with differing qualities for specific uses. For example, the softest, innermost fibres are desirable for kimono and kamishimo clothing; this traditional Japanese banana cloth-making process requires many steps, all performed by hand (Kijoka Banana Fiber Cloth Association, http://www.kougei.or.jp/english/crafts/0130/f0130.html, 2007).

Banana fibre is also used in the production of banana cellulose and paper. Soffner (2001) compared two different types of pulping processes applied to wastes from the banana stem, the grain stalk that supports the banana fruits. For banana stem pulping, a CaO process can be considered a technical alternative for pulp production, with delignification rates similar to the NaOH process.
The use of banana fibres as a reinforcement in cement composites has shown enormous potential in the field of recycled materials and supports their utilization in the sustainable production of building components for civil construction (Coutts, 1990; Savastano et al., 2005).

Banana fibres can be used with man-made or natural polymers to provide a wide range of useful composites in textiles (including geotextiles and non-wovens), particle and other boards, chemical and thermosetting polymer-containing goods, and filters; as well as having several uses in transportation, building industry and agriculture. These applications are of increasing interest as in the future all biocomposites will have to be recyclable and fully biodegradable (Kozlowski, 2000).

3.3.6 Jute fibres

Jute is a long, soft, shiny vegetable fibre that can be spun into coarse, strong threads. It is produced from plants in the genus Corchorus, family Malvaceae (Agopyan, 1988). Jute is one of the cheapest vegetable fibres and it is second only to cotton in the amount produced and the variety of its uses. Jute fibres are composed primarily of the plant materials cellulose (major component of plant fibre) and lignin (major component of wood fibre). It falls into the bast fibre category (fibre collected from the bast or skin of the plant) along with kenaf, industrial hemp, flax (linen) and ramie. The industrial term for jute fibre is ‘raw jute’. The fibres are off-white to brown and 1–4 m long.

Jute was growth for many centuries in Bengal before it became known to the West in the eighteenth century (Fig. 3.6). Small quantities were imported into Europe and America, but it was only in the nineteenth century that serious attention was given to jute as a textile fibre (Wood, 1997). Although, jute is not a typical American plant, Brazil is producing it on a large scale, mainly in the Amazon region. The plant grows quite easily in wet and warm areas, and it is harvested 130 days after planting. The average productivity varies from 1500 to 2000 kg/ha (Agopyan, 1988).

The fibres are separated by maceration or decortication. However, for large-scale production only mechanical decortication is suitable, and this kind of equipment is not available in Latin American countries. The fibres are used alone or blended with other types of fibres (cotton, for example) to make twine and rope (Sreenath et al., 1996). Jute butts, the coarse ends of the plants, are used to make inexpensive cloth. Conversely, very fine threads of jute can be separated out and made into imitation silk. As jute fibres are also being used to make pulp and paper, and with increasing concern over forest destruction to obtain the wood pulp used to make most paper, the importance of jute for this purpose may increase. Jute has a long history of use in the sackings, carpets, wrapping fabrics (cotton bale) and construction fabric manufacturing industries.

Ramakrishna and Sundararajan (2005) reported experimental investigations
into the resistance to impact loading of cement mortar slabs reinforced with jute; four different fibre contents (0.5, 1.0, 1.5 and 2.5% by weight of cement) and three fibre lengths (20, 30 and 40 mm) were investigated. Ordinary Portland cement was used as the binder. The results obtained showed that the addition of the cellulose fibres increased the impact resistance to 3–18 times that of the reference (i.e. plain) mortar slab.

Jute is predominantly a rain-fed annual crop. Its cultivation is labour-intensive, but it requires relatively small quantities of other inputs, such as fertilizer and pesticides, and can be carried out on smallholdings. For all these reasons, jute production is increasingly concentrated in Bangladesh, India, China and Thailand, which between 1998 and 2000 together accounted for more than 95% of the world production, compared with a share of 90% in the early 1970s (FAO, 2003a).

3.4 General uses of vegetable fibres

In most developing countries in Africa, Asia and Latin America, the sustainable production of vegetable fibres fulfils a major economic role which is confirmed by its large contribution to the gross domestic product (GDP) and to the employment rate.

When determining the properties of vegetable fibres, it is advisable to keep in mind that one is dealing with natural products with properties that are strongly
influenced by their growing environment. Temperature, humidity and the compo-
sition of the soil and of the air affect the height of the plant, the mechanical
properties and the density of its fibres. In addition, the way in which the plants are
harvested and processed results in a variation of properties. For this reason it is
very difficult to use vegetable fibres, but due to their low costs they are being
widely applied in many areas of the economy.

Nowadays, vegetable fibres form an interesting alternative to the glass fibres
that are the most widely applied fibre in the composite technology industry. The
use of fibres such as coir, hemp, jute or sisal in this industry so far is small since the
availability of a durable semi-finished product with constant quality is often a
problem. Recent research and development have shown that these aspects can be
improved considerably. The knowledge that vegetable fibres are cheap and have a
better stiffness per weight than glass fibres, which results in lighter components,
has resulted in a growing interest in vegetable fibres.

Secondly, the environmental impact of these fibres is smaller since the vegetable
fibre can come from a renewable resource. The main drawback of using hy-
drophilic vegetable fibres as reinforcement in polymer composites is the lack of
adhesion with most common thermoplastic matrices which have an intrinsic
hydrophobic character. Several methods have been applied to overcome this
inconvenience. Typically, physical and chemical modifications of fibres and
matrices have been performed in order to obtain similar surface properties for the
composite constituents.

Hemp, sisal, jute and flax are the fibres most commonly used to reinforce
polymers such as polyolefins, polystyrene, epoxy resins and unsaturated polyesters (Li et al., 2000; Arbeiaiz et al., 2005; Bourmaud and Baley, 2007; Doan et al., 2007; Yuanjian and Isaac, 2007). Most of the present applications are in the
automotive sector and include composite parts produced by means of thermoforming or thermo-compression moulding techniques. The vegetable fi-
bres are in the form of mats and the matrix is a thermoset or thermoplastic
polymer. Recent developments in natural fibre-reinforced composites point –
for economical reasons – towards the use of the more versatile and faster
injection-moulding techniques. The main disadvantage associated with processing through extrusion/injection moulding is the drastic decrease of fibre length
(caused by the high mixing energy applied) and the consequent reduction of
reinforcing effect.

In several industrialized and developing countries, cellulose fibres derived from
hardwood or softwood are used for the production of cement composites by
adaptation of the former asbestos-cement production processes. Asbestos cement
still represents around 74% of the approximately 200 million m² of fibre–cement
composites produced yearly in Central and South America, mostly as corrugated
roofing elements, as estimated by Heinricks et al. (2000). In the case of developing
countries, there is an enormous need for houses, schools, hospitals and public
service buildings. Therefore, even in periods of economic difficulty, there is a
Table 3.2 General prices for E-glass and vegetable fibres
(Brouwer, 2001)

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Price/kg (US$), raw</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass</td>
<td>1.3</td>
</tr>
<tr>
<td>Flax</td>
<td>1.5</td>
</tr>
<tr>
<td>Hemp</td>
<td>0.6–1.8</td>
</tr>
<tr>
<td>Jute</td>
<td>0.35</td>
</tr>
<tr>
<td>Ramie</td>
<td>1.5–2.5</td>
</tr>
<tr>
<td>Coir</td>
<td>0.25–0.5</td>
</tr>
<tr>
<td>Sisal</td>
<td>0.6–0.7</td>
</tr>
</tbody>
</table>

major need for the application of these vegetable fibres to accelerate the production of composites with adequate performance (Agopyan, 1988).

Vegetable fibres are low cost (Table 3.2). When consideration is given to the variety and abundance of vegetable fibres, of adequate length, available in developing regions, including residues (such as those from agro-industries), the challenge is to facilitate the application of these fibres in civil construction. However, it is first necessary to improve their durability in composites (Mohr et al., 2004).

Changes in the fibre and fibre–cement interfacial region due to environmental interactions can affect the long-term performance of cement-based composites reinforced with natural fibres. A significant cause of changes in composite properties is pulp fibre degradation as a result of environmental interactions or changes in the fibres themselves due to their presence in the strongly alkaline matrix (Mohr et al., 2004).

According to Savastano and Pimentel (2000), there is a considerable range of short-length fibre residues that can not be used for textile or cordage industries, but which are still adequate for the reinforcement of composites. These authors proposed the following steps for the use of these residues based on information collected in technical visits: (a) general identification of the agricultural production; (b) identification of residues, including correlation with main products and production processes; (c) amount of residues available and other possible uses with actual demands; (d) local availability and requirements for transportation or processing; (e) market value of the residue; (f) physical and mechanical properties of composites and components.

3.5 Case study: vegetable fibre in cement-based composites

The main objective of the present section is to discuss the performance of several non-conventional materials based on cementitious matrices with emphasis on vegetable fibre-cement studies. Construction materials and elements are evaluated
Table 3.3 Physical properties of sisal Chemi-thermomechanical pulp and fibre

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappa number</td>
<td>32</td>
</tr>
<tr>
<td>Canadian standard freeness (mL)</td>
<td>650</td>
</tr>
<tr>
<td>Fibre length (length weighted) (mm)</td>
<td>1.65</td>
</tr>
<tr>
<td>Fibre width average (µm)</td>
<td>13.5</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>122</td>
</tr>
</tbody>
</table>

*Sonsino, et al.* (2001) conducted a collaborative work between Universidade de São Paulo (USP), Brazil and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia. The main objective of the study was to develop asbestos-free fibre cements based on residues from agriculture and pig iron fabrication in Brazil. The processing of these construction materials was based on technologies previously developed in CSIRO in collaboration with industrial partners in Australia.

### 3.5.1 Raw materials

Ground, granulated, blast furnace slag (GGBS) was employed as the main component of an alternative binder. Ground agricultural gypsum and construction-grade hydrated lime were used as activators in the proportions of 0.88:0.10:0.02 (GGBS: gypsum: lime) by mass as previously discussed (Oliveira et al., 1999). Sisal (*Agave sisalana*) field by-product was selected from a variety of Brazilian fibrous residues on the basis of availability and the relatively low levels of contamination. Chemi-thermomechanical (CTM) pulping procedures, based on the suggestions of Higgins (1996), were employed in the preparation of the sisal fibres. The main physical attributes of the sisal CTM pulps are summarized in Table 3.3.

### 3.5.2 Composite preparation

Cement-composite pads reinforced with 8% sisal CTM pulp, were prepared in the laboratory using a slurry vacuum dewatering technique. The selection of fibre contents was based on the optimum levels found in a similar study published by Savastano et al. (2000). Pads were pressed simultaneously at 3.2 MPa for 5 min.

On completion of the initial saturated air cure for the period of 7 days, pads were then allowed to air cure in a laboratory environment at 23 ± 2 °C and 50 ± 5%
relative humidity prior to the performance of mechanical and physical tests at a total age of 28 days. Additional pads were allocated for exposure for up to 60-month periods of weathering in temperate Australian and tropical Brazilian environments (Table 3.4). Corresponding sets of pads were stored continuously in the laboratory over the same periods to provide specimens for the determination of reference properties at the different ages.

### 3.5.3 Test methods

Three-point bending tests were performed for the determination of modulus of rupture (MOR), modulus of elasticity (MOE) and toughness. A span of 100 mm and a deflection rate of 0.5 mm/min were used for all tests in an Instron model 1185 testing machine. Fracture energy was calculated by integration of the load–deflection curve to the point corresponding to a reduction in load carrying capacity to 50% of the maximum observed. For the purpose of this study, the toughness was measured as the fracture energy divided by specimen width and depth at the failure location. The mechanical test procedures employed are described in greater detail by Savastano et al. (2000). Water absorption and bulk density values were obtained from tested flexural specimens following the procedures specified in ASTM C 948–81 (ASTM, 2000).

The experimental data were subjected to one-way analysis of variance using Tukey’s multiple comparison method to determine the significance of observed differences between sample means at the 95% confidence level ($\alpha = 0.05$).

### 3.5.4 Weathering conditions

After 28 days, composites of each formulation were placed in a rack facing the Equator at an angle of inclination of 45° to age naturally in the temperate environment of Melbourne, Victoria, Australia (37° 49′ S latitude). Corresponding
Table 3.5 Mechanical and physical properties (± standard deviation) of composites at 28 days

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Fibre content (% by mass)</th>
<th>MOR (MPa)</th>
<th>Toughness (kJ/m²)</th>
<th>MOE (GPa)</th>
<th>Water absorption (% by mass)</th>
<th>Bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil</td>
<td>–</td>
<td>8.1 ± 2.2</td>
<td>0.03 ± 0.01</td>
<td>11.6 ± 1.7</td>
<td>17.6 ± 0.9</td>
<td>1.84 ± 0.03</td>
</tr>
<tr>
<td>Sisal</td>
<td>8</td>
<td>18.4 ± 1.4</td>
<td>0.85 ± 0.10</td>
<td>5.9 ± 0.5</td>
<td>32.9 ± 0.6</td>
<td>1.33 ± 0.01</td>
</tr>
</tbody>
</table>

The short-term water absorption and bulk density values of the composites with sisal pulp were 33% by mass and 1.3 g/cm³ respectively (Table 3.5). The plain GGBS matrix, produced using a process analogous to that reported in the present study for composites, was found to have a water absorption of 18% and bulk density of 1.8 g/cm³, confirming the influence of the cellulose fibres on the volume of capillary voids in fibre cements.

Figures 3.7 and 3.8 show decreasing strength and increasing toughness with time for the composites maintained in laboratory environment. There was a tendency of stabilization of the mechanical properties after the first four initial.

As shown in Fig. 3.7, the external exposure of fibre cement to temperate weather resulted in considerable reduction in flexural strength, which dropped to 4 MPa after 60 months. In the case of tropical weather, the same formulation presented a strength of 1.5 MPa after the same period of time due to even more severe degradation. Both flexural strength and toughness (Figs 3.7 and 3.8) measurements indicated that tropical weather (São Paulo, Brazil) affected the microstructure of the composites more intensely than temperate weather (Victoria, Australia) after the fourth month of exposure. The loss in mechanical strength of composites...
3.7 Sisal CTM pulp in GGBS. Variation in composite modulus of rupture (MOR) with age and conditions of exposure.

3.8 Sisal CTM pulp in GGBS. Variation in composite toughness with age and conditions of exposure.
subjected to either natural weathering or ageing under a controlled environment is attributable to matrix carbonation. Such a mechanism (Wang et al., 1995; Taylor, 1997) consumes calcium ions from hydration products and hence causes weakening of the composites.

Qualitative evaluation using an indicator solution of 2% phenolphthalein in anhydrous ethanol revealed that the aged composites were completely carbonated. The greater severity of the effect of the natural environment on composite properties can be attributed to interfacial damage resulting from volume changes of the porous and hygroscopic vegetable fibres inside the cement matrix (Savastano and Agopyan, 1999).

As shown in Fig. 3.8, the composites aged for 60 months in laboratory conditions demonstrated toughness values similar to or even higher than composites tested at 28 days. In general, the improvement in toughness can be linked to the reduction in MOR and MOE, according to the expected compromise between strength and ductility in such composites. Values of toughness after 60 months of weathering in external environments indicate that the integrity of the fibres within the GGBS matrix has been significantly reduced by decomposition. In a previous study of sisal, malva and coir strands in ordinary Portland cement (OPC) matrix, Savastano and Agopyan (1999) reported reductions of at least 50% in toughness after only 6 months in a laboratory environment. Tolêdo Filho et al. (2000) and Bentur and Akers (1989) noted similar embrittlement in aged vegetable fibre–OPC composites and found that it could be directly attributed to the petrifaction of the reinforcement through the migration of hydration products to the fibre lumens and pores.

3.5.6 Production of roofing tiles using vegetable fibre cement

Savastano et al. (1999) and Roma et al. (2008) developed roofing tiles, reinforced with sisal pulps, based on the Parry Associates process (United Kingdom) for moulding by densification and vibration, with intensive use of labour. Undulate roof tiles were produced with dimensions of approximately 500 × 275 mm, thickness between 8 and 10 mm, and format similar to ceramic roofing tiles (Fig. 3.9).

Roma et al. (2008) reported that the exposure to a tropical climate caused a severe reduction in the mechanical properties of the composites. This behaviour can be attributed to alkaline attack and petrifaction of the natural fibre and progressive micro-cracking of the cement matrix. The toughness of the vegetable fibre-cement fell to between 53 and 68% of that of non-aged composites after approximately 4 months under natural tropical weathering. The high porosity associated with water absorption of at least 30% by mass is expected to play a significant role in this undesirable behaviour. The refinement of pore structure or the combined use of vegetable and synthetic fibres for reinforcement may be effective approaches to material optimization.
3.9 (a) Transference of a newly manufactured flat pad for the mould with corrugated format. (b) Corrugated roofing tile on mould. (Courtesy of Luiz Carlos Roma Jr.)

The small roofing tiles reinforced with sisal pulp can be made by an alternative process of sucking and pressing, as patented by Savastano (2002) (Fig. 3.10(a)). In this process the mixture with the cement raw materials can be prepared with approximately 40% solids. The slurry is transferred to the storage container located in the upper part of the equipment shown in Fig. 3.10(a). This container is moved by an automated system for the transference of the mixture to a casting chamber with approximate dimensions of 500 mm long, 275 mm wide and 8 mm thick. The dewatering system in the lower part of the chamber is applied for 30 s to drain the excess water while the undulate tile is formed and pressed by pneumatic pistons (Fig. 3.10(a), arrows 1 and 2). Afterwards, negative pressure is applied to the upper device for an additional 30 s (Fig. 3.10(b), arrow 3). This device, after horizontal displacement, puts the roofing tile in a mould (Fig. 3.10(c), arrow 5) and the cformed roofing tile can be transferred from the moulding chamber to the undulate mould conferring its final shape (Figs 3.10(c) and 3.10(d)).

The results show that maximum load for roofing tiles reinforced with sisal pulp, and prepared by the process of sucking and pressing, is approximately 50% higher than the maximum load associated with tiles produced by the Parry Associates process. This result suggests that the roofing tiles formed by the process of sucking and pressing present better densification and consequently lower porosity.

3.6 Conclusions

In 2006, the UN General Assembly declared 2009 the International Year of Natural Fibres. This decision will contribute to the Millennium Development Goals by further developing the efficiency and sustainability of these agricultural industries that employ millions of people in some of the world’s poorest countries, according to the FAO.
3.10 (a) Process of sucking and pressing (arrow 1) and dewatering to withdraw the excess water through the moulding chamber (arrow 2); (b) inverted suction using the upper device (arrow 3) and withdrawal of the roofing tile from the moulding chamber (arrow 4); (c) horizontal displacement of the equipment (arrow 5) and refilling the chamber with a mixture (arrow 6); (d) formed roofing tile on the undulate mould (Tonoli, 2006).

The use of vegetable fibres is increasing throughout the world but mostly in developing countries situated in tropical and subtropical climates. The fibres are used primarily for the production of bags, ropes, baskets and mats, in newer bio-based composites and as a source for paper making. Vegetable fibres offer several advantages – their renewable origin, worldwide availability, low costs, low production energy requirements, reduced equipment wear, biodegradability – over man-made fibres such as glass, carbon and aramid.

The use of vegetable fibres as a source of raw material in polymer and cement-based materials not only provides a renewable resource, but also generates a non-food source of economic development for farming and rural areas and brings new trends in composite materials. However, knowledge, durability, and suitable cost-effective design and fabrication techniques for manufacture should be developed.

The consumption of building components made of hybrid fibre cement rein-
forced with vegetable and synthetic fibres is increasing rapidly, especially in developing countries. Vegetable fibres, which are widely available, can be used as convenient materials for the reinforcement of a brittle matrix. In addition, different types of building components can be produced as low-cost, lightweight products for non-load-bearing, hollowed walls panels, ceiling plates and roofing tiles (Agopyan et al., 2005).

The scientific research has demonstrated that vegetable fibres can be a useful material in the transformation of recycling waste. In particular, the use of alternative materials for the complete (e.g. GGBS) or partial replacement of conventional OPC-based composites can be a helpful approach for appropriate solutions in rural construction. The result can be the production of cost-efficient building elements, with low consumption of energy, that are suitable for developing areas. Potential solutions to housing and rural infrastructure demand can be achieved through the adaptation of already known technologies to overcome the problem of durability, which is the main drawback of these composites.

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Sustainability of vegetables fibres in construction


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