Chapter 7
Cement Composites Reinforced with Vegetable Fibres

7.1 General

The use of construction and building materials made from renewable resources is generally regarded as an indispensable option so the construction industry can become more sustainable. That premise can not however be taken in absolute terms since not all situations involving the use of renewable resources like wood or other plant species are exempt from any environmental impact. This is the case of woods with high environmental impact through its transport over long distances or those that use large amounts of fertilizers, pesticides, fungicides or involving the destruction of ecosystems during the growth phase (Swanson and Franklin 1992; Powers 1999; Sample 2006; Burger 2009). One of the worst examples of this kind of ecological disaster can be found in the regions of Sumatra, Borneo, and Malaysia, where millions of square kilometers of rainforest were destroyed for the production of oil from palm three. This option endangered the survival of hundreds of species which include some mammals such as elephants, tigers, rhinos, and orangutans (UNEP 2007). Similar considerations can be made about the destruction of tropical forests to produce timber for industrial use or about the harvest of exotic woods at a rate higher than their natural regeneration. The use of toxic products for the protection of wood products, previously mentioned in Chap. 2, can not be considered a very sustainable option. A part from the aforementioned cases and as long as wood comes from certified forests (Rametsteiner and Simula 2003) it can be said that the resurgence of this material can only be viewed with an environmentally optimism. The use of wood species in the production of cement composites is particularly interesting for the construction industry. Furthermore, due to cancer health risks (Azuma et al. 2009; Kumagai and Kurumatani 2009) the Directive 83/477/EEC and amending Directives 91/382/EEC, 98/24/EC; 2003/18/EC and 2007/30/EC forbid the production of cementitious products based on fibre silicates (asbestos). Mineral fibres are now being replaced by synthetic fibres like polyvinyl alcohol (PVA) and polypropylene to produce fibre–cement products

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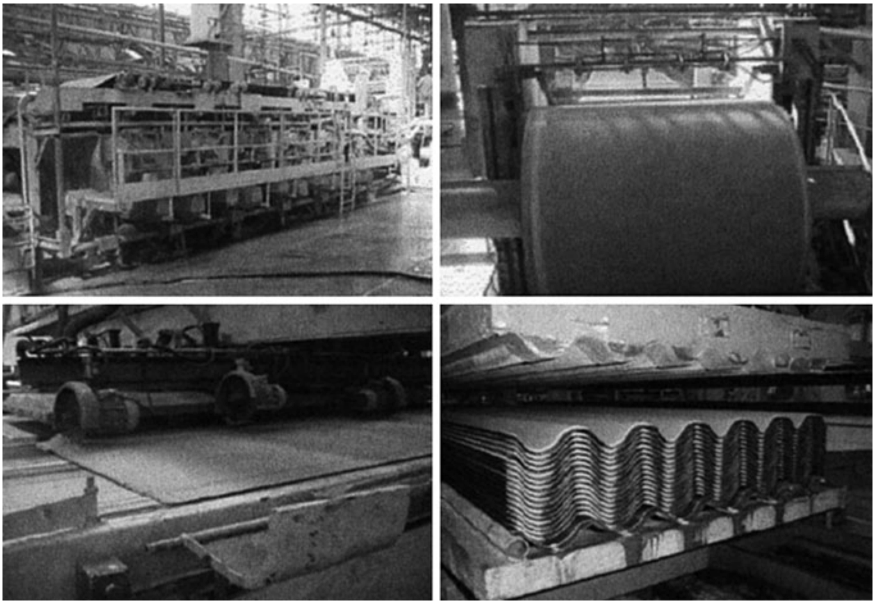

Fig. 7.1 Production of fibre–cement composites by the Hatschek process (Ikai et al. 2010)

using the Hatscheck process. An industrial process that represents 85% of fibre–cement composites production worldwide (Fig. 7.1).

However, production of PVA and polypropylene needs phenol compounds as antioxidants and amines as ultraviolet stabilizers and other additives acting as flame retardant which is not the right path to obtain more eco-efficient materials. This represents a large opportunity in the field of vegetable fibres cement based materials because they are as stronger as synthetic fibres, cost-effective and above all environmentally friendly. Therefore to promote the use of cementitious building materials reinforced with vegetable fibres could be a way to achieve a more eco-efficient construction. Another interesting possibility related to use of vegetable fibres encompasses the replacement of steel bars in reinforced concrete. Concrete is known for its high compressive strength and low tensile strength. The combined use of regular concrete and steel reinforced bars is needed to overcome that disadvantage leading to a material with good compressive and tensile strengths but also with a long post-crack deformation (strain softening). Unfortunately reinforced concrete has a high permeability that allows water and other aggressive elements to penetrate, leading to carbonation and chloride ion attack resulting in corrosion problems (Glasser et al. 2008; Bentur and Mitchell 2008). Steel rebar corrosion is in fact the main reason for infrastructure deterioration. Gjorv (1994) mentioned a study of Norway OPC bridges indicating that 25% of those built after 1970 presented corrosion problems. Another author (Ferreira 2009) mentioned that 40% of the 600,000 bridges in the USA were affected by corrosion problems and estimated in 50 billion dollars the repairing operations

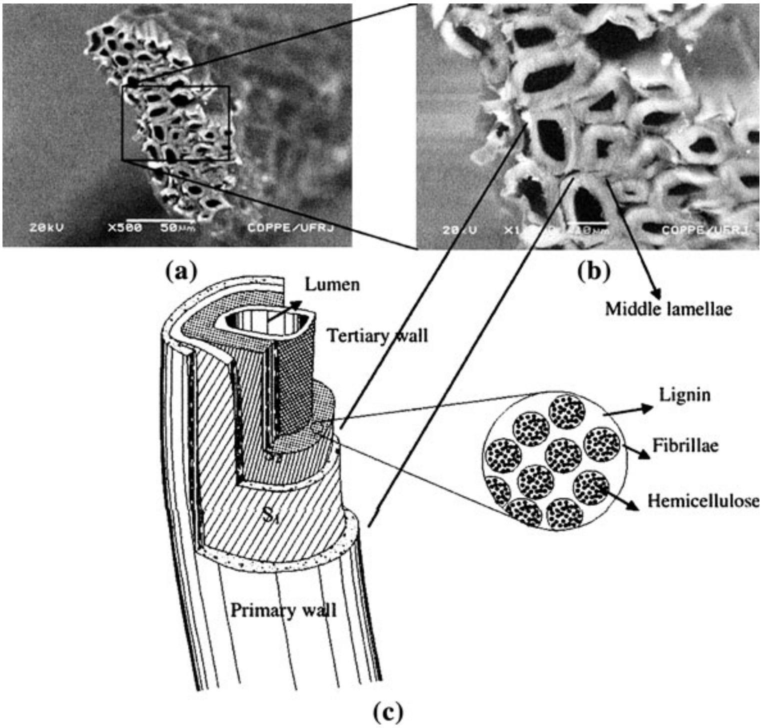

Fig. 7.2 Fibre–cell microstructure: **a** cross-section view showing the fibre–cells, lumens and middle lamellae, **b** magnification of the cross-section, and **c** schematic drawing showing the different layers of an individual fibre–cell (Filho et al. 2009)

cost. Since an average of 200 kg of steel rebar is used for each cubic meter of concrete structure it is clear that the replacement of reinforced steel rebar by vegetable fibres is a major step to achieve a more eco-efficient construction. On the other hand, reinforced steel is a highly expensive material, has high energy consumption and comes from a non renewable resource, while vegetable fibres are available almost all over the world (Brandt 2008).

7.2 Fibre Characteristics and Properties

Vegetable fibres are natural composites with a cellular structure. Different proportions of cellulose, hemi cellulose and lignin constitute the different layers. Cellulose is a polymer containing glucose units. Hemi cellulose is a polymer made of various polysaccharides. As for lignin it is an amorphous and heterogeneous mixture of aromatic polymers and phenyl propane monomers (John et al. 2005; Filho et al. 2009). Figure 7.2 shows the microstructure and a schematic representation of vegetable fibres. Different fibres have different compositions

Table 7.1 Composition of vegetable fibres (Arsene et al. 2007)

Fibre	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Extractives (%)	Ash (%)
Bagasse	21.8	41.7	28.00	4.00	3.50
Banana leaf	24.84	25.65	17.04	9.84	7.02
Banana trunk	15.07	31.48	14.98	4.46	8.65
Coconut coir	46.48	21.46	12.36	8.77	1.05
Coconut tissue	29.7	31.05	19.22	1.74	8.39
Eucalyptus	25.4	41.57	32.56	8.20	0.22
Sisal	11.00	73.11	13.33	1.33	0.33

Table 7.2 Properties of natural and synthetic fibres (Arsene et al. 2007)

Properties	Specific gravity (kg/m^3)	Water absorption (%)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Sisal	1,370	110	347–378	15.2
Coconut	1,177	93.8	95–118	2.8
Bamboo	1,158	145	73–505	10–40
Hemp	1,500	85−105	900	34
Caesar weed	1,409	182	300–500	10–40
Banana	1,031	407	384	20–51
Piassava palm	1,054	34–108	143	5.6
Date palm (Kriker et al., 2005)	1,300–1,450	60–84	70–170	2.5–4
Polypropylene	913	–	250	2.0
PVA F45 (Passuello et al., 2009)	1,300	–	900	23

(Table 7.1) therefore it is expected that their behavior inside a cement matrix could differ between them.

Natural fibres have a high tensile strength and a low modulus of elasticity (Table 7.2). Even so, their tensile performance can stand in a favorable manner with synthetic ones. One of the disadvantages of using natural fibres is that they have a high variation on their properties which could lead to unpredictable concrete properties (Swamy 1990; Li et al. 2006).

Pre-treatment of natural fibres was found to increase fibre reinforced concrete performance. Pulping is one of the fibre treatments that improve fibre adhesion to the cement matrix and also the resistance to the alkaline attack (Savastano et al. 2001b). Pulping can be obtained by a chemical process (kraft) or a mechanical one. Table 7.3 presents some pulping conditions for sisal and banana fibres.

Some chemical treatments lead to a higher mechanical performance than others (Pehanich et al. 2004). The pulping process through mechanical conditions has a lower cost (around half) when compared to the use of chemical conditions and has no need for effluent treatments (Savastano et al. 2001a). Some authors suggest the

Table 7.3 Sisal and banana kraft pulping conditions (Savastano et al. 2003)

Parameter	Sisal	Banana
Active alkali (as Na_2O) (%)	9	10
Sulphidity (as Na_2O) (%)	25	25
Liquor/fibre ratio	5:1	7:1
Temperature (°C)	170	170
Digestion time	~75–120 min temperature cook	~85–120 min temperature cook
Total yield (%w/w)	55.4	45.9
Screened yield (%w/w)	45.5	45.3

use of organofunctional silane coupling agents to reduce the hydrophilic behavior of vegetable fibres (Castellano et al. 2004; Abdelmouleh et al. 2004). But recently Joaquim et al. (2009) compared the performance of cementitious composites reinforced by kraft pulp sisal fibres and by sisal fibres modified by the organosolv process. They found out that the best mechanical performance was achieved by the composites with kraft pulp fibres. Arsene et al. (2007) suggests that using a pyrolisis process can increase the fiber strength by a factor of three.

7.3 Matrix Characteristics

Savastano et al. (2000) mentioned that acid compounds released from natural fibres reduce the setting time of the cement matrix. Fibre sugar components, hemi cellulose and lignin can contribute to prevent cement hydration (Bilba et al. 2003; Stancato et al. 2005). According to Sedan et al. (2008), fibre inclusion can reduce the delay of setting by 45 min. The explanation relies on the fact that pectin (a fibre component) can fix calcium preventing the formation of CSH structures. The interfacial transition zone (ITZ) between concrete and natural fibres is porous, cracked and rich in calcium hydroxide crystals (Savastano and Agopyan 1999). Those authors reported a 200 μm thick at 180 days. On the contrary other authors (Savastano et al. 2005a) reported that using vacuum dewatering and high pressure applied after molding led to a dense ITZ (Fig. 7.3a) also reporting that some fibers were free of hydration products Fig. 7.3b).

The use of water-repellents also leads to a good bond between natural fibre and concrete (Ghavami 1995). The mechanical treatment of the fibres also improves the bonding between the fibre and cement (Coutts 2005). Alkaline treatment of fibres improves their strength and also fibre-matrix adhesion (Sedan et al. 2008). Tonoli et al. (2009) compared cement composites with vegetable fibres previously submitted to surface modification with methacryloxypropyltri-methoxysilane (MPTS) and aminopropyltri-ethoxysilane (APTS). The results of cement composites with fibres modified by MPTS showing fibres free from cement hydration products while APTS based fibres presented accelerated mineralization which leads to higher embrittlement behavior of cement composites (Tonoli et al. 2009).

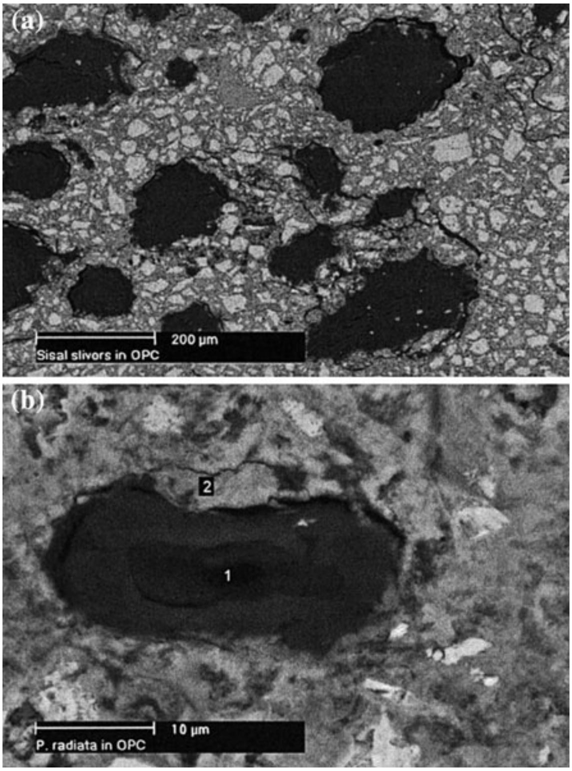

Fig. 7.3 **a** BSE image of sisal fibres in cement matrix with dense ITZ, **b** EDS analysis on *Pinus radiata* fibre lumen (*spot 1*) revealed that no mineralization due to the presence of hydration products was detected (Savastano et al. 2005a)

7.4 Properties of Cement Composites

7.4.1 Using Small Vegetable Fibres

Some authors found out that the use of a 0.2% volume fraction of 25 mm sisal fibres leads to free plastic shrinkage reduction. The combined use of coconut and sisal short fibres seem to have delayed the restrained plastic shrinkage, thus controlling shrinkage and controlling crack development at early ages (Filho et al. 2005). As for the mechanical performance of natural fibre concrete, Al-Oraimi and Seibi (1995) reported that using a low percentage of natural fibres improved the mechanical properties and the impact resistance of concrete, having similar performance when compared to synthetic fibre concrete. Other authors reported that fibre inclusion increases impact resistance by 3 to 18 times higher than when no fibres were used (Ramakrishna and Sundararajan 2005). The use of small volumes (0.6 to 0.8%) of *Arenga Pinata* fibres show an increase in the toughness characteristics of cement-based composites (Razak and Ferdiansyah 2005). As for Reis (2006), their studies showed that the mechanical performance of fibre concrete depends on the type of the fibre. He found that coconut and sugar cane bagasse fibre increases concrete fracture toughness, but banana pseudo stem fibre does not. The use of coconut fibres showed even better flexural strength than does synthetic fibre (glass and carbon) concrete. Silva and Rodrigues (2007) studied the addition of sisal fibres to concrete and reported that the compressive strength was lower than concrete samples without the fibres. The explanation for that behavior seems to be related to concrete workability. Savastano et al. (2009) compared the mechanical performance of cement composites reinforced with sisal, banana and eucalyptus fibres. Sisal and banana fibres with higher lengths (1.65 mm and 1.95 mm) than eucalyptus (0.66 mm) showed a more stable fracture behavior which confirms that fibre length influences the process by which the load transfers from the matrix to the fibres. Silva et al. (2010) tested cement composites reinforced by long sisal fibres placed at the full length of a steel mold in five layers (mortar/fibres/mortar). These composites reach ultimate strengths of 12 and 25 MPa under tension and bending loads. The vegetable type also influences the performance of fibre reinforced cement composites (Tonoli et al. 2010a), being that eucalyptus-based ones present improved mechanical performance after 200 ageing cycles when compared to pinus based ones. The explanation relates to a better distribution of vegetable particles in the cement matrix.

7.4.2 Using Bamboo Rebars

Khare (2005) tested several concrete beams made with stirrups and rebar bamboo and reported that this material has the potential to be used as a substitute for steel reinforcement (Fig. 7.4).

This author reported that the ultimate load capacity of bamboo reinforced concrete beams was about 35% of the equivalent reinforced-steel concrete beams. The strength reduction was due to the low adhesion between the cement matrix and the bamboo rebars. Júnior et al. (2005) mentioned just 25% of the equivalent reinforced-steel concrete beams ultimate load capacity. Analysis of adhesion between cement and bamboo by pull-off tests shows that bamboo/cement have much lower adhesion than steel rebar/cement and that adhesion results are influence by node presence (Jung 2006).

These authors suggest that bamboo rebar should previously be submitted to a thermal treatment to improve bond strength. According to Mesquita et al. (2006), the bond strength of bamboo is 70% of smooth steel bond strength when a 35 MPa concrete is used. However the bond strength of bamboo is almost 90% of smooth steel bond strength when a 15 MPa concrete is used. These authors analyzed the effect of using artificial pins (two of bamboo and two of steel) in bamboo splints, noticing they led to a bond strength of bamboo higher than smooth steel. Ferreira (2007) also studied the effect of artificial pins (Fig. 7.5) in the bond strength of bamboo rebar using pull-out tests.

The results show that the use of just one pin is insufficient to increase bamboo bond strength (Table 7.4). In the same work this author study several 20 MPa concrete beams reinforced with bamboo rebar's (2×1 cm^2), and steel stirrups mentioning an acceptable structural behavior.

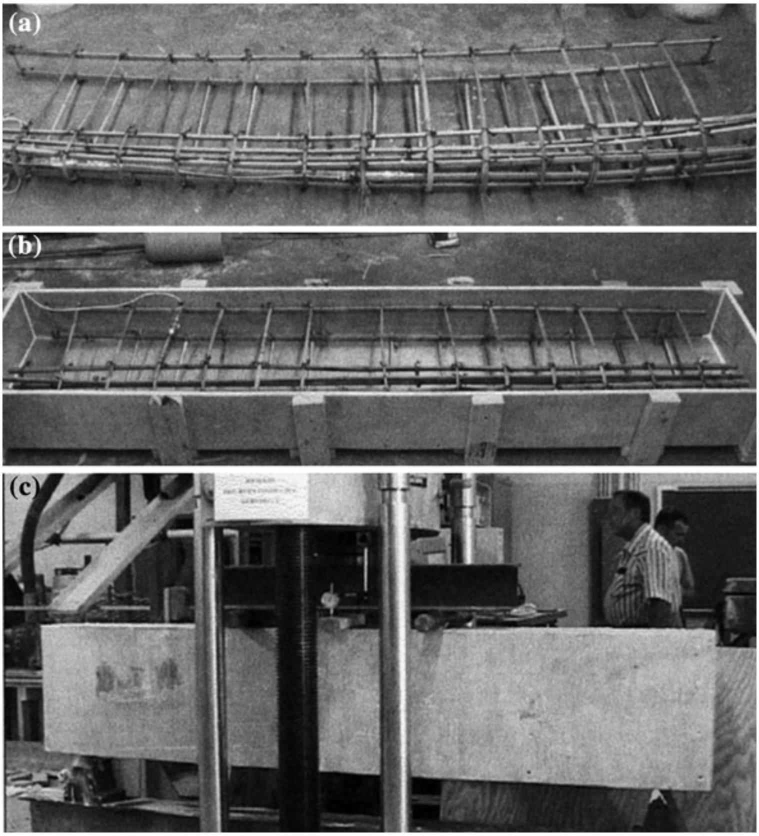

Fig. 7.4 Concrete beam reinforced with bamboo rebars and bamboo stirrups: **a** finished bamboo reinforcement, **b** finished reinforcement in the form, **c** test set-up (Khare 2005)

Fig. 7.5 Several bamboo rebars: The first with hole, the second with bamboo pin and the third with steel pin (Ferreira 2007)

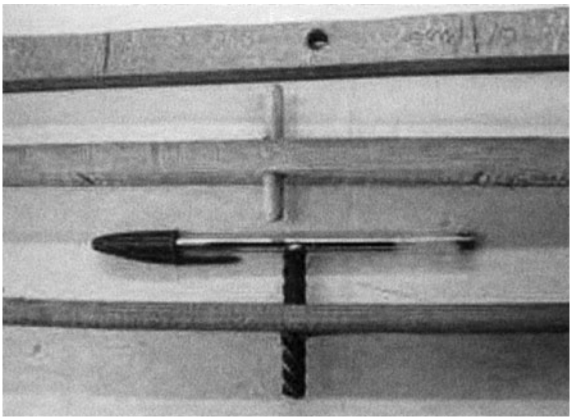

Table 7.4 Bond strength using pull-out tests (Ferreira 2007)

Rebar type	Bond strength (MPa)
Bamboo	0.81
Bamboo with epoxy resin	0.32
Bamboo with one bamboo pin	0.82
Bamboo with one steel pin	0.69
Bamboo with hole	1.10
Rough steel	6.87
Smooth steel	1.33

7.5 Durability

Durability of natural fibre reinforced concrete is related to the ability to resist both external (temperature and humidity variations, sulfate or chloride attack, etc.) and internal damages (compatibility between fibres and cement matrix, volumetric changes, etc.). The degradation of natural fibres immersed in Portland cement is due to the high alkaline environment that dissolves the lignin and hemicellulose phases, thus weakening the fibre structure (Gram 1983). Gram was the first author to study the durability of sisal and coir fibre reinforced concrete. The fibre degradation was evaluated by exposing them to alkaline solutions and then measuring the variations in tensile strength. This author reported a deleterious effect of Ca^{2+} elements on fibre degradation. He also stated that fibres were able to preserve their flexibility and strength in areas with carbonated concrete with a pH of nine or less. Filho et al. (2000) also investigated the durability of sisal and coconut fibres when immersed in alkaline solutions. Sisal and coconut fibres conditioned in a sodium hydroxide solution retained respectively, 72.7% and 60.9% of their initial strength after 420 days. As for the immersion of the fibres in a calcium hydroxide solution, it was noticed that the original strength was completely lost after 300 days. According to those authors, the explanation for the higher attack by $Ca(OH)_2$ can be related to a crystallization of lime in the fibres' pores. Ramakrishna and Sundararajan (2005a) also reported the degradation of vegetable fibres when exposed to alkaline media. Other authors studied date palm-reinforced concrete, reporting low durability performance that is related to fibre degradation when immersed in alkaline solutions (Kriker et al. 2008). Ghavami (2005) reported the case of a 15-years-old bamboo-reinforced concrete beam without any deterioration signs. Lima et al. (2008) studied the variations of tensile strength, and Young's modulus of bamboo reinforced concrete exposed to wetting and drying cycles, reporting insignificant changes, thus confirming its durability. The capacity of vegetable fibres to absorb water is another path to decreasing the durability of fibre reinforced concrete. Water absorption leads to volume changes that can induce concrete cracks (Ghavami 2005; Agopyan et al. 2005). In order to improve the durability of fibre reinforced concrete, the two following paths could be used.

7.5.1 Matrix Modification

Using low alkaline concrete and adding pozzolanic by-products such as rice husk ash, blast furnace slag, or fly ashes to Portland cement (Gutiérrez et al. 2005; Agopyan et al. 2005; Savastano et al. 2005a). Results show that the use of ternary blends containing slag/metakaolin and silica fume are effective in preventing fibre degradation (Mohr et al. 2007). But in some cases the low alkalinity is not enough to prevent lignin from being decomposed (John et al. 2005). Other authors reported that fast carbonation can induce lower alkalinity (Agopyan et al. 2005). These results are confirmed by other authors that used artificial carbonation in order to obtain $CaCO_3$ from $Ca(OH)_2$ leading to increased strength and reduced water absorption (Tonoli et al. 2010b). The use of cement-based polymers can also contribute to an increased durability (Pimentel et al. 2006). D'Almeida et al. (2009) used blends where 50% of Portland cement was replaced by metakaolin to produce a matrix totally free of calcium hydroxide in order to prevent migration of calcium hydroxide to the fibre lumen, middle lamella and cell walls, thus avoiding an embrittlement behavior.

7.5.2 Fibre Modification

Coating natural fibres to avoid water absorption and free alkalis. Use waterrepellent agents or fibre impregnation with sodium silicate, sodium sulphite, or magnesium sulphate. Ghavami (1995) reported that using a water-repellent in bamboo fibres allowed only 4% water absorption. The use of organic compounds such as vegetable oils reduced the embrittlement process, but not completely (Filho et al. 2003). Recent findings report that silane coating of fibres is a good way to improve the durability of vegetable fibre reinforced concrete (Bilba and Arsene 2008). Other authors mentioned that using pulped fibres may improve the durability performance (Savastano et al. 2001b). Some authors even reported that the fibre extraction process can prevent durability reductions (Juárez et al. 2007). The use of compression and temperature (120°C, 160°C and 200°C) leads to an increase of fibre stiffness and a decrease on the fibre water absorption (Motta et al. 2009).

7.6 Conclusions

The replacement of asbestos and synthetic fibres by vegetable fibres in the manufacture of cementitious composites could contribute to a higher eco-efficiency of the construction industry. The same happens with the replacement of steel bars by bamboo rebars. Further investigations about vegetable fibre reinforced concrete are needed in order to clarify several aspects that current knowledge does not.

The available literature data is mostly related to the mechanical behavior of vegetable fibre reinforced concrete. For instance, only recently has the delaying effect of vegetable fibre inclusion received the proper attention. Since the main reason for vegetable fibre degradation relates to alkaline attack, much more research is needed about the chemical interactions between the cement matrix and the vegetable fibres. The right treatments to improve fibre and cement matrix compatibility are still to be found. The same could be said about the variation on the fibre properties, therefore control quality methods are needed in order to ensure minimal variations on the properties of vegetable fibres. Durability related issues also deserve more research efforts. For concrete with bamboo rebars investigations to improve the adhesion to the cement paste are still needed.

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