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Fibrous and composite materials for civil engineering applications

Edited by R. Fangueiro

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The use of fibrous materials in civil engineering, both as structural reinforcement and in non-structural applications such as geotextiles, is an important and interesting development. *Fibrous and composite materials for civil engineering applications* analyses the types and properties of fibrous materials and structures and their applications in several fields such as concrete reinforcement and acoustic and thermal insulation.

Part I introduces different types of fibrous materials and structures. Chapters cover the properties of natural and man-made fibres and of yarns, as well as an overview of textile structures. Part II focuses on fibrous material use in concrete reinforcement, with chapters on the properties and applications of steel fibre reinforced concrete, natural fibre reinforced concrete and the role of fibre reinforcement in mitigating shrinkage cracks. In Part III, the applications of fibrous material-based composites in civil engineering are covered. Chapters concentrate on production techniques and applications such as reinforcement of internal structures and structural health monitoring. Concluding chapters focus on fibrous materials for acoustic and thermal insulation and for architectural membranes.

With its distinguished editor and international team of contributors, *Fibrous and composite materials for civil engineering applications* will be a standard reference book for fabric and composite manufacturers, civil engineers and professionals, as well as academics with a research interest in this area.

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5 Natural fiber reinforced concrete

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Abstract: The construction industry is responsible for the depletion of large amounts of non-renewable resources. This activity generates not only millions of tons of mineral wastes but also carbon dioxide gas emissions. More building materials based on renewable resources such as vegetable fibers are needed. This chapter discusses the utilization of natural fibers for concrete reinforcement. It includes fiber characteristics, properties and the description of the treatments that improve their performance; it covers the compatibility between the fibers and the cement matrix and also how the fibers influence cement properties. It also includes the properties and durability performance of concrete reinforced with natural fibers.

Key words: reinforced concrete, natural fibers, properties, durability.

5.1 Introduction

The construction industry is one of the major and most active sectors in Europe. It represents 28% and 7% of the employment, respectively, in the industry and in all the European economy. Unfortunately, this industry is also responsible for the depletion of large amounts of non-renewable resources and for 30% of carbon dioxide gas emissions. This is particularly serious in the current context of climate change caused by carbon dioxide emissions worldwide, causing a rise in sea level (IPCC, 2007), and being responsible for a meltdown in the world economy (Stern, 2006). In order to achieve a more sustainable construction, the European Union recently established that, in the medium term, raw materials consumption must be reduced by 30% and also that waste production in this sector must be cut by 40%. The use of renewable resources by the construction industry will help to achieve a more sustainable pattern of consumption of building materials. Concrete is the most-used material on Earth and it is known for a high compressive strength and a low tensile strength. The combined use of regular concrete and steel-reinforcing 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 enter, leading to carbonation and chloride ion attack resulting in corrosion problems (Glasser *et al.*, 2008; Bentur, 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 mentioned that 40% of the 600 000 bridges in the U.S. were affected by corrosion problems, resulting in an estimated US$50 billion for repair operations (Ferreira, 2009). Since world population is expected to grow more than 2000 million by the year 2030, more reinforced-concrete structures will be built and many more deterioration problems are expected to take place. Concrete durability is environment related, because if we were able to increase the life time of a concrete from 50 to 500 years, its environmental impact decreases 10 times (Mora, 2007). Since an average of 200kg of steel rebar are used for each cubic metre of concrete structure, it is clear that the replacement of reinforced steel rebar by vegetable fibers is a major step to achieving a more sustainable construction. On the other hand, reinforced steel is a high-cost material, has high energy consumption and comes from non-renewable resources. As for synthetic fibers like polyvinyl alcohol (PVA) and polypropylene, their production requires phenol compounds as antioxidants and amines as ultraviolet stabilizers and flame retardants, which is not the path to more sustainable materials (Berge, 2007). Therefore, to promote the use of concrete reinforced with vegetable fibers could be a way to improve concrete durability and also sustainable construction. This chapter is divided into six sections: 5.1 Introduction, 5.2 Fiber characteristics and properties, 5.3 Matrix characteristics, 5.4 Properties, 5.5 Durability and 5.6 Future trends.

5.2 Fiber characteristics and properties

Vegetable fibers are natural composites with a cellular structure. Different proportions of cellulose, hemicellulose and lignin constitute the different layers. Cellulose is a polymer containing glucose units, and hemicellulose 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). Different fibers possess different compositions (Table 5.1), therefore it is expected that their behavior inside a cement matrix could differ.

Natural fibers possess a high tensile strength and they have a low modulus of elasticity (Table 5.2). Even so, their tensile performance compares favourably to synthetic fibers.

Table 5.1 Composition of vegetable fibers

Fiber	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

Source: Arsene *et al.*, 2003

Table 5.2 Properties of natural and synthetic fibers

Properties	Specific gravity (kg/m^3)	Water absorption (%)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Sisal	1370	110	347–378	15.2
Coconut	1177	93.8	95–118	2.8
Bamboo	1158	145	73–505	10–40
Hemp	1500	85–105	900	34
Caesar weed	1409	182	300–500	10–40
Banana	1031	407	384	20–51
Piassava palm	1054	34–108	143	5.6
Date palm (Kriker *et al.*, 2005)	1300–1450	60–84	70–170	2.5–4
Polypropylene	913	–	250	2.0
PVA F45 (Passuello *et al.*, 2009)	1300	–	900	23

Source: Arsene *et al.*, 2003

One of the disadvantages of using natural fibers is that they have a high variation in their properties that could lead to unpredictable concrete properties (Swamy, 1990; Li *et al.*, 2006). Pre-treatment of natural fibers was found to increase concrete performance. Pulping is one of the fiber treatments that improves fiber adhesion to the cement matrix and also resistance to alkaline attack (Savastano *et al.*, 2003). It can be obtained either chemically (kraft) or mechanically. The latter has a lower cost (around half) and does not require effluent treatments (Savastano *et al.*, 2001a). Table 5.3 presents some pulping conditions for sisal and banana fibers.

Some chemical treatments lead to a higher mechanical performance than others (Peanich, 2004). Some authors suggest the use of organofunctional silane coupling agents to reduce the hydrophilic of vegetable fibers (Castellano *et al.*, 2004; Abdelmouleh, 2004). But recently, Joaquim *et al.* (2009) compared the performance of cementitious composites reinforced by kraft pulp sisal fibers, and by sisal fibers modified by the organosolv process. They found that the best mechanical performance was achieved by the composites with kraft pulp fibers.

Table 5.3 Sisal and banana kraft pulping conditions

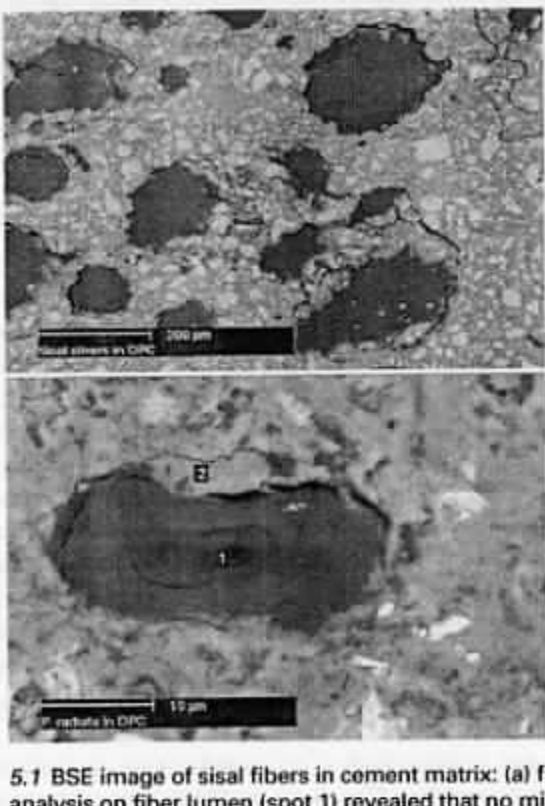
Parameter	Sisal	Banana
Active alkali (as Na_2O) (%)	9	10
Sulphidity (as Na_2O) (%)	25	25
Liquor/fiber ratio	5:1	7:1
Temperature (°C)	170	170
Digestion time	~75 minutes to temperature 120 minutes cook	~85 minutes to temperature 120 minutes cook
Total yield (%w/w)	55.4	45.9
Screened yield (%w/w)	45.5	45.3

Source: Savastano *et al.*, 2003

Arsene *et al.* (2007) suggest that using a pyrolisis process can increase the fiber strength by a factor of three.

5.3 Matrix characteristics

Savastano (2000) mentioned that acid compounds released from natural fibers reduce the setting time of cement matrices. Some authors reported that fiber sugar components, hemicellulose and lignin can contribute to preventing cement hydration (Bilba *et al.* 2003; Stancato *et al.*, 2005). According to Sedan *et al.* (2008), fiber inclusion can reduce the delay of setting by 45 minutes. The explanation relies on the fact that pectin (a fiber component) can fix calcium, thus preventing the formation of calcium silicate hydrate (CSH) structures. According to Savastano and Agopyan (1999), the interfacial transition zone between concrete and natural fibers is porous, cracked and rich in calcium hydroxide crystals. Those authors reported a 200 μm thickness at 180 days. On the contrary, Savastano *et al.* (2005) reported that using vacuum dewatering and high pressure applied after molding led to a dense ITZ (Fig. 5.1(a)), also reporting fibers without hydration products (Fig. 5.1(b)).



5.1 BSE image of sisal fibers in cement matrix: (a) fibers with ITZ; (b) EDS analysis on fiber lumen (spot 1) revealed that no mineralization due to the presence of hydration products has detected (Savastano *et al.*, 2005).

The use of water-repellents leads to a good bond between natural fibers and concrete (Ghavami, 1995). The mechanical treatment of the fibers also improves the bonding between the fiber and the cement (Coutts, 2005). According to some authors, alkaline treatment of fibers improves their strength and also fiber-matrix adhesion (Sedan *et al.*, 2008). Tonoli *et al.* (2009) compared cement composites with vegetable fibers previously submitted to surface modification with Methacryloxypropyltri-methoxysilane (MPTS) and Aminopropyltri-ethoxysilane (APTS). The results of composites with fibers modified by MPTS show fibers free from cement hydration products, while APTS-based fibers presented accelerated mineralization that leads to a higher embrittlement behavior of cement composites.

5.4 Properties

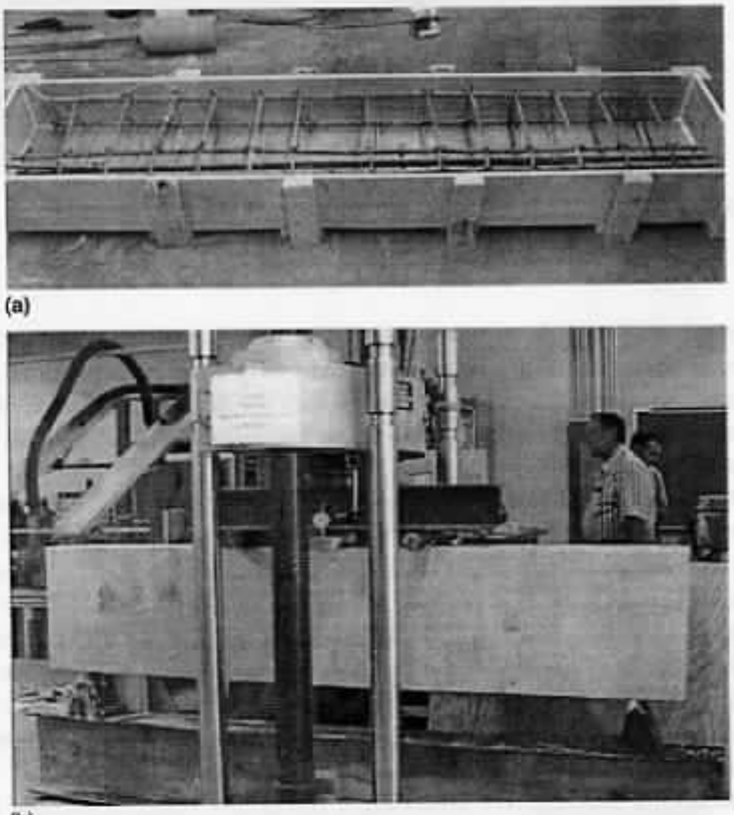
5.4.1 Using small vegetable fibers

Some authors found out that the use of a 0.2% volume fraction of 25 mm sisal fibers leads to free plastic shrinkage reduction. The combined use of coconut and sisal short fibers seem to have delayed restrained plastic shrinkage and controlling crack development at early ages (Filho *et al.*, 2005). As for the mechanical performance of natural fiber concrete, Al-Oraimi and Seibi (1995) reported that using a low percentage of natural fibers improved the mechanical properties and the impact resistance of concrete, and had similar performance when compared to synthetic fiber concrete. Other authors reported that fiber inclusion increases impact resistance by 3–18 times higher than when no fibers were used (Ramakrishna and Sundararajan, 2005). The use of small volumes (0.6–0.8%) of *Arenga Pinata* fibers shows that the capacity increases the toughness characteristics of cement-based composites (Raza *et al.*, 2005). As for Reis (2006), studies showed that the mechanical performance of fiber concrete depends on the type of fiber. He found that coconut and sugar cane bagasse fiber increases concrete fracture toughness, but banana pseudostem fiber does not. The use of coconut fibers shows even better flexural than does synthetic fiber (glass and carbon) concrete. Silva *et al.* (2007) studied the addition of sisal fibers to concrete and reported that the compressive strength was lower than concrete samples without the fibers. 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 fibers. Sisal and banana fibers with higher lengths (1.65 mm and 1.95 mm) than eucalyptus (0.66 mm) showed a more stable fracture behavior, which confirms that fiber length influences the process by which load transfers from the matrix to the fibers. Silva *et al.* (2010) tested cement composites reinforced by long sisal fibers placed at the full length of a steel mold in 5 layers (mortar/fibers/mortar). These composites reach ultimate strengths of 12 and 25 MPa under tension and bending loads. The vegetable type also influences the performance of cement composites (Tonoli *et al.*, 2010), being that eucalyptus-based ones present improved mechanical performance after 200 ageing cycles than pinus based. The explanation related to a better distribution of vegetable particles in the cement matrix.

5.4.2 Using long 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. 5.2).

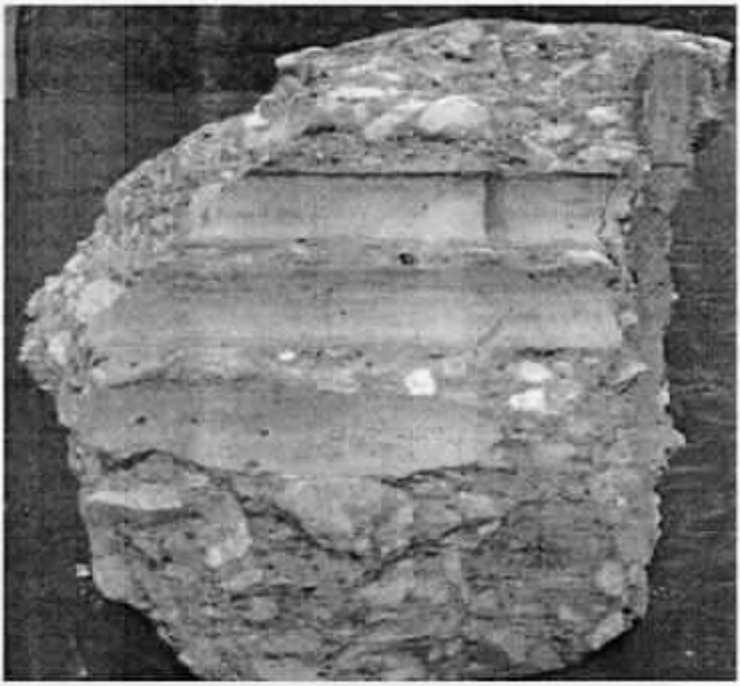
This author reported that the ultimate load capacity of bamboo was about 35% of the equivalent reinforced-steel concrete beams. Fig. 5.3 shows a concrete sample where fiber imprints are visible as an example for low adhesion between cement matrix and bamboo.



(a)

(b)

5.2 Concrete beam reinforced with bamboo rebars: (a) finished bamboo reinforcement; (b) test set-up (Khare, 2005).

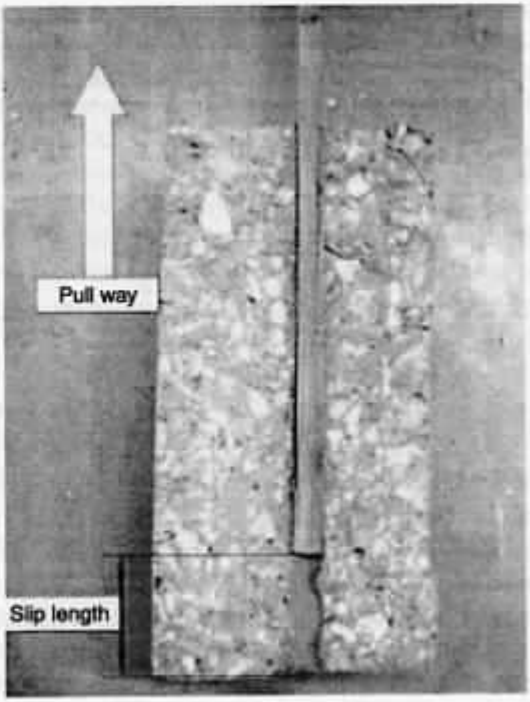


5.3 Imprints of fiber reinforcement (Khare, 2005)

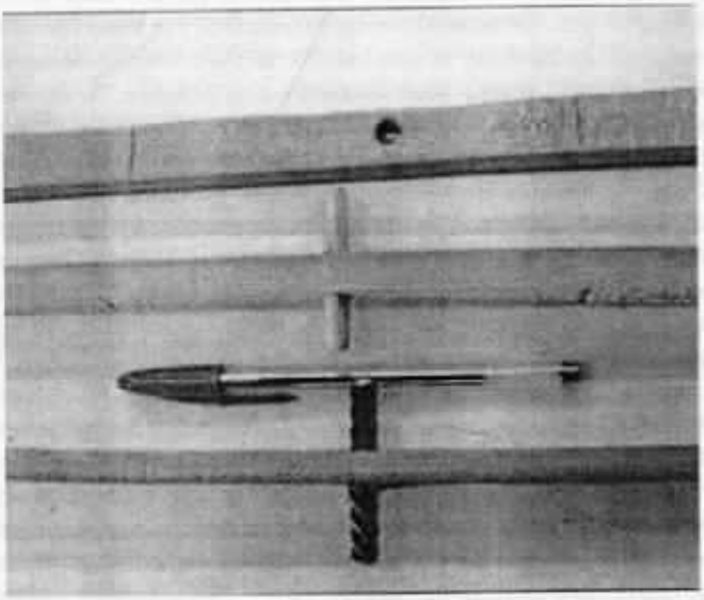
Junior *et al.* (2005) mentioned just 25% of the equivalent reinforced-steel concrete beams' ultimate load capacity. Analysis of adhesion between cement and bamboo by pull-off tests (Fig. 5.4) shows that bamboo/cement have much lower adhesion than steel rebar/cement and that adhesion results are influence by node presence (Jung, 2006).

These authors suggest that bamboo rebar should previously be submitted to 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 artificial 2 pins (2 of bamboo and 2 of steel) studding 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. 5.5) in the bond strength of bamboo rebar using pull-out tests.

The results show that the use of just 1 pin is insufficient to increase bamboo bond strength (Table 5.4). In the same work this author studied several 20 MPa concrete beams reinforced with bamboo rebars ($2 \times 1\ cm^2$) and steel stirrups, which exhibited an acceptable structural behavior.



5.4 Pull-out test of concrete with bamboo reinforcement (Jung, 2006).



5.5 Bamboo rebars bamboo and steel pins (Ferreira, 2007).

Table 5.4 Bond strength using pull-out tests

Rebar type	Bond strength (MPa)
Bamboo	0.81
Bamboo with epoxy resin	0.32
Bamboo with 1 bamboo pin	0.82
Bamboo with 1 steel pin	0.69
Bamboo with hole	1.10
Rough steel	6.87
Smooth steel	1.33

Source: Ferreira, 2007

5.5 Durability

Durability of natural fiber reinforced concrete is related to the ability to resist both external (temperature and humidity variations, sulfate or chloride attack, etc.) and internal damage (compatibility between fibers and cement matrix, volumetric changes, etc). The degradation of natural fibers immersed in Portland cement is due to the high alkaline environment that dissolves the lignin and hemicellulose phases, thus weakening the fiber structure (Gram, 1983). Gram was the first author to study the durability of sisal and coir fiber reinforced concrete. The fiber 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 fiber degradation. He also stated that fibers were able to preserve their flexibility and strength in areas with carbonated concrete with a pH of 9 or less. Filho *et al.* (2000) also investigated the durability of sisal and coconut fibers when immersed in alkaline solutions. Sisal and coconut fibers 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 fibers 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 fibers' pores. Ramakrishna and Sundararajan (2005a) also reported degradation of natural fiber when exposed to alkaline media. Other authors studied date palm reinforced concrete, reporting low durability performance that is related to fiber degradation when immersed in alkaline solutions (Kriker *et al.*, 2008). Ghavami (2005) reported the case of a bamboo-reinforced concrete beam which was 15 years old and without deterioration signs. Lima *et al.* (2008) studied the variations of tensile strength and Young's modulus of bamboo fiber reinforced concrete exposed to wetting and drying cycles, reporting insignificant changes, thus confirming its durability. The capacity of natural fibers to absorb water is another path to decreasing the durability of fiber 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 fiber reinforced concrete, the two following paths could be used:

5.5.1 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 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 others that used artificial carbonation in order to obtain $CaCO_3$ from $Ca(OH)_2$ leading to increased strength and reduced water absorption (Tonoli, 2010a). The use of cement-based polymers can contribute to increased durability (Pimentel, 2006). D'Almeida (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 fiber lumen, middle lamella and cell walls and thus avoid embrittlement behavior.

5.5.2 Fiber modification

Coating natural fibers to avoid water absorption and free alkalis. Use water-repellent agents or fiber impregnation with sodium silicate, sodium sulphite, or magnesium sulphate. Ghavami (1995) reported that using a water-repellent in bamboo fibers 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 fibers is a good way to improve the durability of natural-fiber reinforced concrete (Bilba and Arsene, 2008). Other authors mentioned that using pulped fibers may improve durability performance (Savastano *et al.*, 2001). Some even reported that a fiber extraction process can prevent durability reductions (Juárez *et al.*, 2007). The use of compression and temperature (120, 160 and 200°C) leads to an increase of fiber stiffness and a decrease of fiber moisture absorption (Motta, 2009).

5.6 Future trends

Further investigations about natural 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 natural-fiber reinforced concrete. For instance, only recently has the delaying effect of fiber inclusion received the proper attention. Since the main reason for fiber degradation relates to alkaline degradation, much more research is needed about the chemical interactions between the cement matrix and the natural fibers. The right treatments to improve fiber- and cement-matrix compatibility are still to be found. The same could be said about the variation on fiber properties, thus control quality methods are needed in order to ensure minimal variations on the properties of natural fibers. Durability related issues also deserve more research efforts.

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