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## Chapter

# Recycling of Tropical Natural Fibers in Building Materials

*Huyen Bui, Mazhar Hussain and Daniel Levacher*

## Abstract

This chapter deals with the reuse and recycling of tropical natural fibers and their potential valorization in construction materials in a context of circular economy and sustainable development. These fibers constitute large volumes of fibrous waste resulting from various agro-food industries worldwide. Depending on their intrinsic qualities and properties (physical and mechanical), they can be reused as reinforcing material in cementitious mixes (hardened mixes) or mixes with soils (raw mixes) and molded into a prismatic brick-like shape. These bricks constitute construction materials that have mechanical and other characteristics. A whole methodology specific to the development of such materials and their optimization is presented. It includes the preparation, characterization, cutting of the fibers to the desired length and the making of the mixtures. This is followed by optimization (fibers distribution), control and quality of the fiber-reinforced material. Two examples illustrate the application of this methodology: a reinforced mortar based on coconut fibers (hardened cementitious mix) and a green brick based on sediment and oil palm fibers.

**Keywords:** natural fibers, recycling, sustainability, waste management, building materials

## 1. Introduction

Natural fibers, whether of plant, animal or mineral origin, are widely available throughout the world. The diversity and abundance of plant fibers make them a highly renewable resource. And while some plant resources need to be preserved to ensure a sustainable global food supply, a very large quantity of plant fibers remains available. This concerns invasive plants that disrupt natural ecosystems and threaten biodiversity in the long term, as well as waste fibers. Waste fibers are mostly agricultural by-products or residues from industrial manufacturing processes. They constitute a renewable resource that amounts to millions of tons per year, of which only a small part is presently recovered.

The recycling of waste fibers is a part of an environmental strategy for sustainable waste management and implements the three Rs – reduce, reuse and recycle. It aims to reduce waste, preserve natural resources, save space for disposal and/or landfill and prevent the burning and incineration commonly applied to these waste fibers thus limiting CO<sub>2</sub> emissions. In many cases, the voluntary incineration of waste fibers results in the production of ash which, due to its chemical properties, can be used

as a binding material as an addition to the components of cement or as a substitute for it [1]. However, the ecological impact of this disposal process is quite negative. It has been observed that for some fibers, waste or not, it is possible to design innovative products with high added value. However, their recovery has a cost and requires energy and the use of other raw materials: bio-based composite materials for the automobile and other modes of transport, furniture, packaging, nanofibers, building materials [2]. However, it is the most basic building materials, i.e., bricks, blocks and tiles, that appear to be best suited to recycle natural fibers, whether short or long, intact or crushed. The incorporation of waste fibers in the manufacturing of these basic materials has little effect on the production process while improving some of the properties and eliminating the waste without additional greenhouse gas emissions. Furthermore, if the brick is unfired, as is the case with fiber-reinforced bricks or blocks made from cementitious products, it is important to minimize the use of ordinary Portland cement with a high clinker content, i.e., OPC CEM I cement. The use of cement made from industrial by-products up to low-carbon binders allows to limit or even drop the carbon footprint. And for these bricks and binders, the economic cost can be reduced by eliminating one or more waste products, fibers and industrial byproducts. This is how the concept of co-valorization was developed [3, 4], which is both economic and ecological: eliminating waste, saving natural resources and limiting the carbon footprint. The crude brick reinforced with waste fibers makes it a perfectly ecological construction element without firing and without the use of binders. It is based on the principle of eco-valorization, which is founded on the integration of the circular economy, sustainable development, the conservation and the renewability of natural resources, and ultimately the limitation of greenhouse gas emissions. This is illustrated in **Figure 1**. Eco-valorization is intended to be more environmentally friendly. The soft material of these crude bricks that bind the fibers most often comes from clay-loam soils, but the introduction of waste soils is preferable, such as sediments or dredged sludge.

The waste fibers that can be recycled into eco-friendly building materials are numerous and diversified. Their quantity is closely linked to the world production of agricultural plants. Some of the fibers are consumed almost entirely by livestock (food such as straw and flour) and industry (textiles such as flax), but the rest are considered as waste, such as palm oil or coconut fibers. In the last decade, there has



**Figure 1.** Circular economy, eco-valorization, sediment and fiber waste, earth reinforced bricks [5].

been a disproportionate growth in the agro-industry, which has resulted in an expansion of crops and consequently the production of waste fibers, as shown in **Table 1** for oil palm fibers. In the same **Table 1**, it can be seen that natural fibers of tropical origin alone constitute a huge potential of fibrous materials for recycling.

The recycling of waste fibers into building materials implies an industrial process to use a sufficient quantity of fibers over time i.e., renewability of the resource, which is why natural tropical fibers are of great interest. To ensure and maintain a quality manufacturing process, a methodology must be followed. It can be simply illustrated as in **Figure 2**.

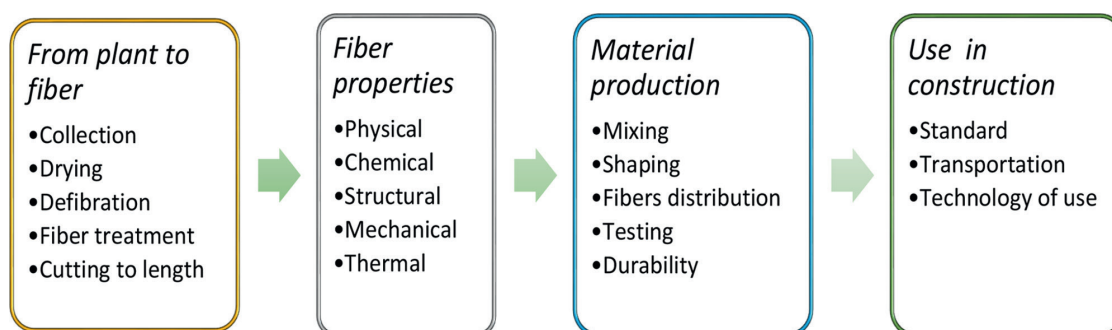
This chapter demonstrates the importance of natural fibers in renewable and environmentally friendly building materials and also, the availability of fibers (introduction). Section 2 discusses the variability of shape, i.e., aggregates or fibers, structure (internal and external), intrinsic properties and applications of natural fibers. Section 3 gives background information on the process of fiber extraction, processing and methodologies for determining the main characteristics of fibers useful for use in building materials. Two applications are thoroughly described, one for a fiber-reinforced mortar (Section 4) and the other for fiber-reinforced raw earth, a truly ecological material (Section 5). The chapter concludes with a discussion on the advantages and shortcomings of tropical natural fibers as reinforcement materials.

In detail and accordance with **Figure 2**, the identification of the resource is necessary before any action of recycling waste fibers, this is the focus of Section 2 of the chapter “natural fibers and tropical fibers”. This identification must be more complete with the knowledge of the properties of the waste fiber and its intrinsic characteristics useful for its future material recovery. These characteristics are obtained from specific tests carried out on these fibers and in particular, on natural tropical fibers such as oil palm and coconut fibers, see Section 3. The material recovery considered for these tropical waste fibers concerns the production of eco-materials for applications that are primarily local, i.e.,

Year	Tropical natural fibers				Other natural fibers*		
	Banana	Coconut	Palm oil fruit	Sugar cane	Flax	Hemp	Wheat
2009	103	61	216	1673	0.661	0.485	683
2019	116	62.4	411	1950	1.085	0.174	765

\* *subtropical and temperate climate zones.*

**Table 1.**  
 Production of main agricultural products as a potential natural fiber resource in Mt. [6].



**Figure 2.**  
 A certain methodology for recycling waste natural fibers in building materials.

close to the sources of waste fiber collected. A case study of a mortar based on coconut fibers is reported in Section 4. In particular, this mortar uses calcium sulfoaluminate cement with a 37% smaller carbon footprint than Portland cement. The development of mud bricks based on oil palm waste fibers incorporated into dredged river sediment is an example of a possible eco-valorization in Section 5. These two studies demonstrate that the recycling of waste fibers into building components is potentially possible and beneficial for sustainable development.

## 2. Natural fibers and tropical fibers

### 2.1 The use of natural and tropical fibers in building materials

The use of these fibers has been temporarily set aside in preference to so-called modern cementitious materials (concretes, mortars, plasters). The usage of fibers, due to their renewability and their eco-friendly nature, is raising new interest among builders because they have interesting properties for construction. A new category of fiber-based construction materials is emerging in the field of construction and restoration: these are bio-sourced materials. Natural fibers are diverse and available in

Type of fibers	Density (g/cm <sup>3</sup> )	Absorption coefficient (%)	Elasticity modulus (GPa)	Tensile strength (MPa)	References
Temperate climate and subtropical fibers					
Bamboo	0.45–1.3	40–145	2.82–54	39.5–1000	[7–9]
Cotton	1.21–1.6	—	1.1–13	265–800	[10]
Flax	1.19–1.55	63–330	4.4–110	93–2000	[2, 11–13]
Hemp	1.07–1.50	85–415	10–90	159–1264	[2, 10, 14]
Jute	1.23–1.50	84–281	2.5–78	300–800	[2, 10, 15]
Palm date	0.92	133–140	1.9–85	58–678	[16]
Ramie	1–1.58	—	23–128	400–1620	[10]
Reed	0.54–0.94	—	35.9	112–503	[17]
Rice straw	0.86–1.11	52–84	3.3–26.3	435–450	[18]
Sisal	1.2–1.50	110–230	1.46–38	80–1002.3	[2, 10, 14]
Wheat straw	1.14–2.05	96–320	1.4–4.8	3.45–140	[19]
Tropical fibers					
Banana spine	0.31–1.36	134–282	3–32	49.3–914	[2, 10, 17]
Coconut-coir	0.67–1.52	63–180	0.628–28	15–593	[2, 14, 20]
Palm oil <sup>†</sup>	0.1–1.55	54–120	0.5–25	147–400	[2, 5, 21]
Sugar cane	0.31–1.31	102–219	15–271	20–290.5	[2, 10]

<sup>†</sup>Palm oil flower and fruit are all considered.

**Table 2.**  
A review of physical and mechanical properties of natural fibers.

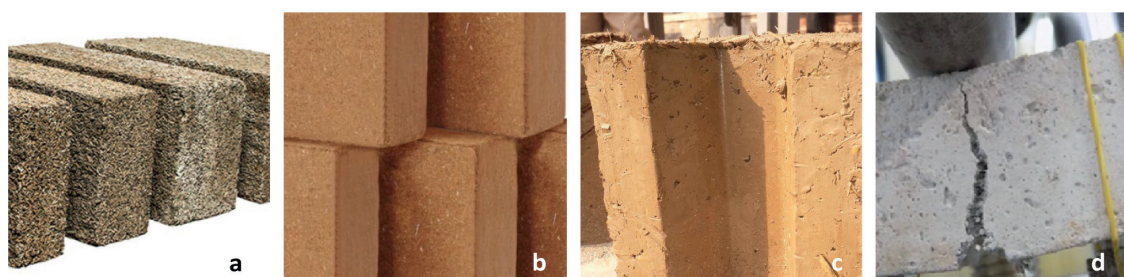
large quantities, mainly from the residues of large-scale agricultural production. The most commonly used natural fibers in building materials are, whether tropical or not, are straw (wheat, rice), flax, hemp, reed, sugar cane, jute, sisal, coconut and bamboo, as listed in **Table 2**.

The natural fibers considered in this chapter come from plants and trees and are therefore of plant origin. They are essentially so-called cultivated plants and trees, i.e., they are a renewable resource whatever their periodicity, annual for plants and several years for trees. These natural fibers are composed of cellulose, hemicellulose, lignin and pectin and impurities. While cellulose is the highest constituent in mass fraction for some plant fibers, it is much lower for woody plants where the lignin content increases or even exceeds the cellulose content (coconut, wood). The stem of the plant provides the main part of the plant fibers, whereas the leaves, fruits, seeds, bark and inter-fiber impurities are considered as plant aggregates.

Plant fibers are widely used as a building material. Over the centuries, long, flexible fibers have been used in their raw state as roofing material for rural habitats. These include wheat straw, rice straw, rushes and reeds, bamboo ... and not included in the use of plant leaves such as palm leaves, banana leaves ... But it is by combining soils and short fibers (a few centimeters) that building materials have been developed at a regional scale. They are made up of raw short fibers mixed with soils that are sometimes clayey and silty with the presence of coarse grains. These are filling materials such as cob and wooden beams; raw earth materials for the construction of load-bearing walls such as cob and prefabricated materials in the form of raw earth bricks such as adobe, see **Figure 3**. In recent decades, these plant fibers have given rise to investigations leading to more efficient construction materials, especially in terms of thermal insulation (plant fiber panels and blocks) and strength by reinforcing fibers in composite materials with a soil or cement matrix. **Figure 4** shows these different materials, noting that rice husk is a plant aggregate.



**Figure 3.** Raw plant fibers in building materials: a-roofing, b-cob and wood, c-cob wall and d-adobe bricks.



**Figure 4.** Ready-to-use fiber-based insulating blocks (a-lime and hemp shiv and b-compressed coconut fibers), rice husk-based raw earth (c-rice husk) and composite mortar undergoing flexural testing (d-jute fiber [22]).

Fiber-based materials are now available in various types and shapes for construction. They are natural fibers alone, matrices of ready-to-use materials (cob), so-called efficient materials depending on the properties developed (bricks, panels, blocks), as illustrated in **Figures 3** and **4**.

Generally, plant fibers have intrinsic properties such as those related to their internal structure which gives them a high absorption capacity and hygroscopic properties. These properties are sometimes in conflict with the desired performance of the composite material being made, especially the strong performance. To achieve this, the fibers undergo a more or less chemical treatment to make them hydrophobic and improve their adhesion properties. Indeed, the external structure of the fibers plays a role in the adhesion of the fibers to the binding matrix (soils, hydraulic and similar binders, geopolymers, biopolymers, etc.). This treatment can take place at the time of the defibration process, i.e., the shaping of the fibers. In certain cases, it would delay the degradability of the fibers, and thus, improving the durability of the material.

## 2.2 The use of natural and tropical fibers in building materials

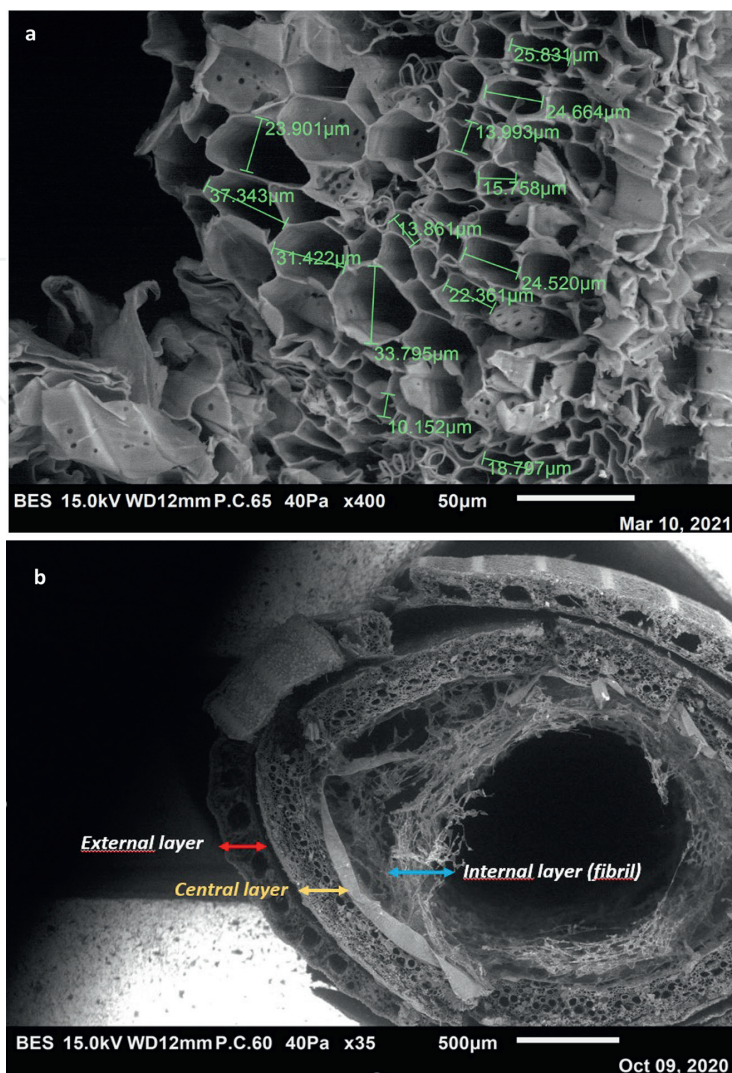
The selection and performance of building elements from among bio-based materials depend on the intrinsic characteristics of the fibers incorporated and the matrix containing them. These properties are thermal, acoustic, mechanical and hygroscopic. The hygroscopic character is related to both the fibers and the binding material (cob). The microstructure and biochemical composition of the fibers affect their properties as well as the treatment applied to them before their incorporation (destruction of the structure), see **Figures 5** and **6**. These fibers as mechanical reinforcement (density, length, interfacial adhesion) improve strength and performance of building materials.

Plant fibers have interesting physical properties for building materials. Due to the structure observed in **Figure 5**, these fibers have a relatively low specific density compared to metal reinforcement fibers. This is an advantage for their use, as they can produce lightweight composite materials. The bulk density is difficult to estimate due to the nature of the fiber itself as well as the geometry of the fibers, i.e., diametral dimension, cross-sectional shape. This difficulty also affects the determination of mechanical properties. The interest in plant fibers comes from their good mechanical properties, in particular a very high tensile uniaxial strength. As noted above, the determination of the ultimate strength of a fiber depends on its geometry, morphology, test operating mode (free length of the fiber, installation, loading rate), the variety of fiber plant and the unit character of the fiber (extraction mode).

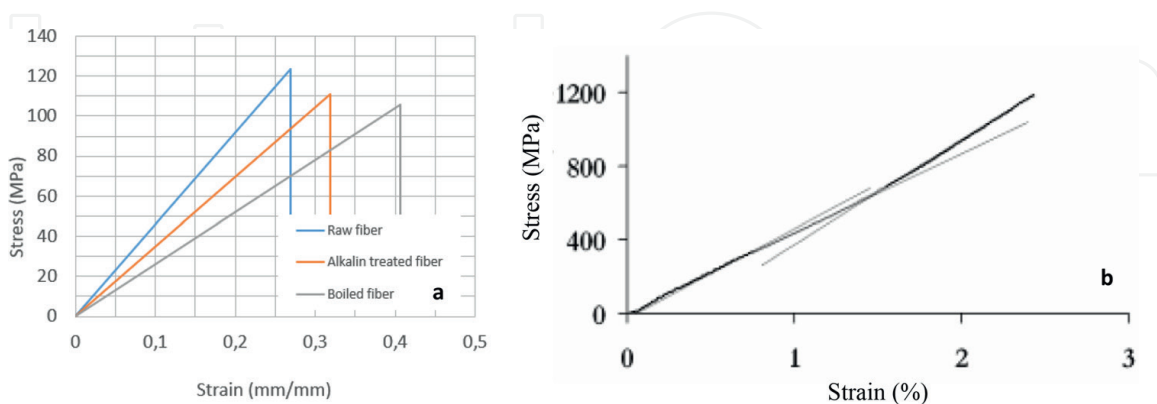
The behavior of the fibers in uniaxial tension can differ depending on the fiber structure as shown in **Figure 6** where a linear behavior is observed for treated and untreated coir fibers and an elasto-visco-plastic behavior for flax fiber. The determination of the deformation modulus in the case of **Figure 6b** is problematic. Depending on the behavior, the moduli of deformation may correspond to either the initial or final slope or a linear fit over the whole curve. Both the modulus of elasticity and the ultimate tensile stress is expressed as a range of data for a fiber type due to the natural variability of fibers.

**Table 2** gives an overview of these data ranges for density, absorption coefficient, modulus of elasticity in tension and tensile stress at failure for different natural and tropical fibers. Fibers in building materials are widely used as the main component either as a protective covering (braided, woven fibers) or as an insulating material





**Figure 5.**  
 SEM images of a flax straw (a) and a reed fiber (b).



**Figure 6.**  
 Typical stress-strain relationships for (a) coconut raw and treated fibers (length 10 mm, speed rate test 0.5 mm/min, [20]) and for (b) flax fiber (length free of fiber 10.9 mm, speed test 1 mm/min [11]).

(pressed, heat-bonded, impregnated fibers). But they are also used in smaller quantities in the composition of building materials as reinforcing material. They are then randomly mixed into a binding matrix (soils, mortars or concretes).

### 3. Characterization and properties of tropical natural fibers

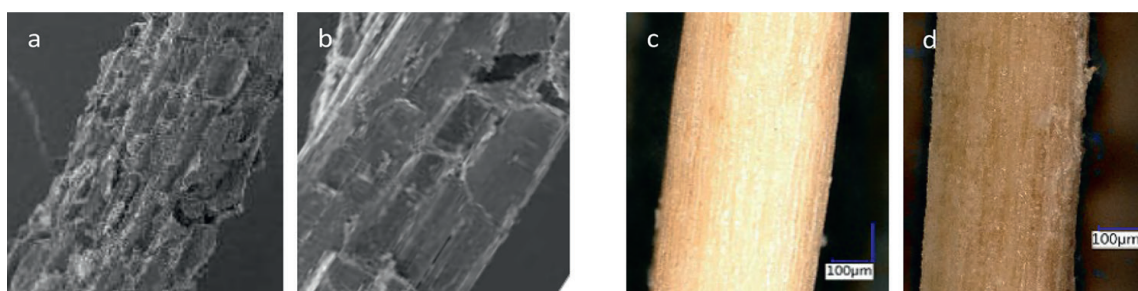
#### 3.1 Useful properties of natural fibers in building materials

This section includes the discussion on the physical and mechanical characteristics of natural fibers which are important for their recycling in construction materials. Water absorption of fibers has a significant influence on the strength of building composites as swelling and shrinkage of fibers with their interaction with water introduce cracks in building composites. There is also a competition between the water required for hydration in the case of cementitious matrices reinforced with natural fibers and the water absorption-desorption of the incorporated fibers. Natural fibers have a low density which makes them suitable additives in lightweight building composites. Geometrical characteristics of fibers include length, diameter, surface roughness and cross-section. Increasing fibers length has a positive impact on the tensile strength of building composites however their compressive strength decreases with long fibers. Diameter of technical fiber increases with increasing elementary fibers which increases the tensile strength of technical fibers. Alignment of elementary fibers at different microfibrillar angles is also important for tensile strength of fibers. Higher tensile strength of fibers increases the tensile strength and toughness of composite materials. Surface roughness of fibers is essential for bonding between matrix and fibers in composites. The pull-out strength of the fibers shows how the interfacial bonding of the fibers with the matrix behaves. Failure and sliding of fibers at different loads and depths change the resistance and failure mechanism of building composites. Life and performance of fibers decrease with time. This is rapid in an alkaline environment associated with concrete structures. Treatment of fibers improves the shelf life and resistance.

Natural plant fibers are used or recycled with or without treatment. Whatever their future use, they are subject to biochemical and physical, morphological and mechanical characterisations. The biochemical characterization concerns the evaluation of the quantities of cellulose, hemicellulose, pectin, lignin, impurities and water. The physical parameters investigated include density, dimensional aspect, geometry, microfibrillar angle and water absorption capacity. The analysis of the morphology of the fibers focuses on the microstructure, the dimensional variations (diameter, length and section). The mechanical parameters sought are most often related to the traction of the fibers (isolated or anchored in a matrix). In this section, only a few procedures (treatment) or characterization tests intended for the use or recycling of fibers in construction materials are mentioned.

#### 3.2 Treatment of fibers

The treatment of natural fibers is part of the preparation process. It takes place at the level of defibrillation (fiber separation), removal of impurities (fiber cleaning), reduction of absorption capacity (fiber hydrophobicity) and improvement of fiber adhesion to the matrix of a composite material (surface roughness and fiber bonding). Immersion in an alkaline solution (NaOH) reveals well the cleaning of the fibers which can be observed on a bamboo fiber as well as the change in roughness for a coir fiber as shown in **Figure 7**. Fiber treatments with water, boiling water, water with organic solvents or acidic agents such as ethylene diamine tetra acetic acid (EDTA) are the most eco-responsible treatments [8, 10, 14, 20]. Physical treatments are to a lesser degree environmentally acceptable but energy consuming (autoclave treatment,



**Figure 7.** Aspect of treated fibers: (a) raw bamboo fiber and (b) bamboo fiber treated for 3 days in 1% NaOH solution [23]—(c) raw coir fiber and (d) coir fiber immersed for 30 minutes in a 5% NaOH solution [20].

steam explosion, plasmas, Corona technique ...). But chemical treatments based on  $\text{Na}_2\text{S}$ ,  $\text{Na}_2\text{CO}_3$ ,  $\text{NaOH}$  solutions pose the problem of wastewater treatment. Some other treatments include impregnation, coupling, grafting, acetylation, benzylation, esterification, etherification, liming ... In the most applications, alkaline solutions (**Figure 7**) and coupling techniques are the most applied. A promising technique based on enzymatic transformations would allow a more ecological treatment. These biological treatments are naturally focused on the development of biocomposites.

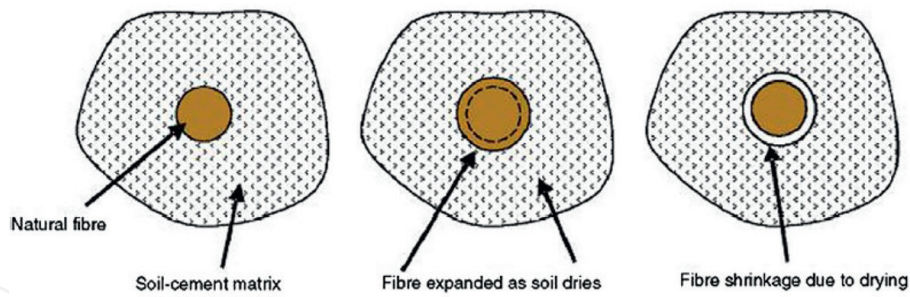
The benefits of these treatments are hydrophobicity, modification of the external surface of the fibers for better adhesion and improvement of the durability. The geometry of the fibers changes (decrease of diameter), they lose their flexibility but the mechanical characteristics are more or less similar.

### 3.3 Water absorption of fibers

Natural fibers have a very high-water absorption capacity, due to their microstructure. This absorbed water poses a problem in the elaboration of fiber-reinforced composite materials with a cementitious matrix (mortar, concrete) or raw fiber earth (adobe, cob). For the former, the water in a mixture must participate in the hydration and in the raw earth, the percentage of water is necessary for the kneading and the preparation for optimal compaction. But in the drying phase, whatever the type of material, the water contained in the fibers will be extracted and the fibers will shrink with a risk of loss of adhesion between the fiber and the matrix as shown in **Figure 8**. This amount of water absorbed must be known when making the material-fiber mixtures and the parameter to be determined is the water absorption capacity  $W_a$  expressed in %, defined by:

$$W_a (\%) = \frac{\text{Mass of saturated fiber} - \text{Mass of dry fiber}}{\text{Mass of dry fiber}} \times 100\% \quad (1)$$

The methods of water absorption determination are not always standardized. They consist of immersion in water and then measuring the mass of the fibers as a function of time. Each time the mass of the fibers is measured as a function of a time step, it is necessary to wipe them out (**Figure 9**). Various procedures are used such as the use of filter paper, fine synthetic fabric as a bag, tweezers or tea balls or manual wiping of the fibers. However, one protocol can be recommended for bio-based materials: RILEM TC 236-BBM (immersion and then dewatering for 15 seconds at 500 rpm, by means of the centrifuge). Some ranges of  $W_a$  values are given in **Figure 9**.



**Figure 8.** Behavior of a fiber at the interface of a matrix, from the mixing phase to the curing and/or drying: illustration in the case of a cementitious material [24].



**Figure 9.** Fabric bags and clips (a) for plant aggregates, tea baskets (b) for plant fibers, fiber bags (c) for centrifugal spinning and  $Wa$  ranges for different fibers [20, 25].

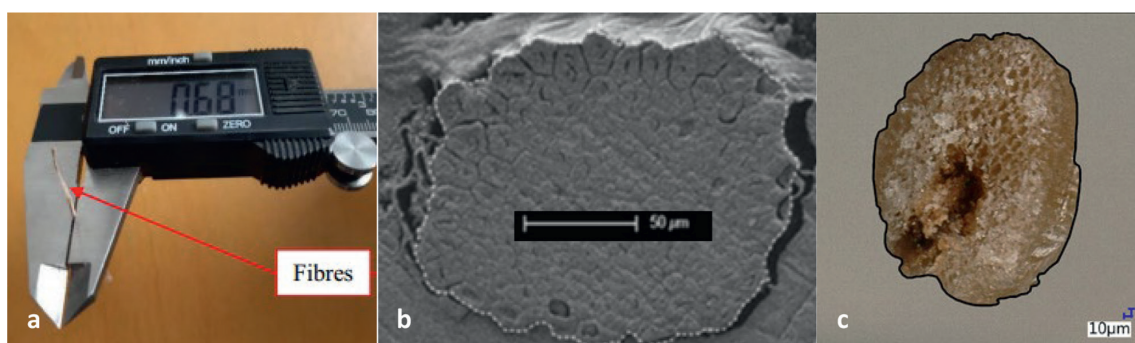
Alfa fiber	Banana	Coir	Date palm	Flax	Hemp	Jute	Hay	Kelp	Kenaf	Rice husk	Sisal	Straw
460-640	134-282	63-180	133-140	63-330	85-415	84-281	78-90	80	285	52-84	110-230	96-320

### 3.4 Specific gravity of fibers

The measurement of the absolute density or the material constituting the fiber is normally done using a helium pycnometer. But some authors still use the water pycnometer. The problem is that water, depending on the structure of the fiber, does not penetrate all the pores (underestimated density) and the absorption capacity of the fibers may overestimate the density. To avoid these phenomena, gas pycnometer (helium) is more realistic. Specific gravities differ from each type of fibers as reported in **Table 2** from the literature.

### 3.5 Geometry of fibers

The dimensions useful for defining the geometric parameters of a fiber are its length and diameter. The length is measured after the fibers have been cut to length by a manual (laboratory scale) or mechanical (industrial scale) process. It can be measured directly on a number of selected fibers (manual procedure) or in a more representative way, the distribution of the fibers is analyzed from a volume or a large number of fibers. This distribution gives rise to a statistical analysis (histograms, distribution law, median length...). The measurement of the diameter is more problematic because of its micro-structure (compressibility, porosity) and morphology (shape). The shape of the fibers



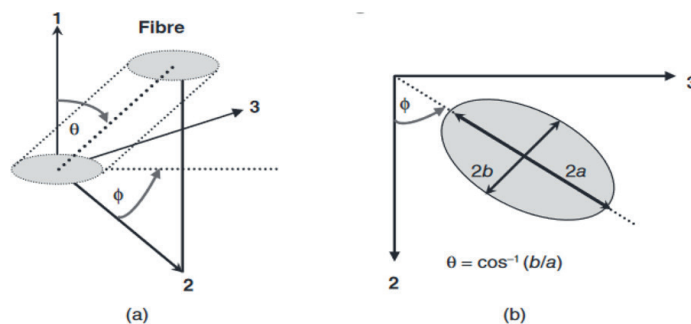
**Figure 10.** Dimensions measurements: fiber diameters with digital caliper [18] (a), fiber areas with digital optical microscope (b) for a bamboo fiber [26] and a coir fiber [20] (c).

can be circular, an ellipse, an oblong shape ... depending on the type of fiber but also on the mechanical treatment: separated, crushed, shredded fiber, .... The measurement of diameters, of orthogonal axes allows to define the cross-sectional area of a fiber. But if the shape is arbitrary, the most suitable means of measurement is image analysis using a digital optical microscope associated with image processing software. From microscope images, several geometric quantities can be defined: the largest and smallest dimension (flattening coefficient), the perimeter, the area of the fiber. A more advanced exploitation allows to approach the porosity at the level of the cross-section observed. The length and the diameter of the fibers can be measured with the help of a steel rule and digital caliper respectively for diameters of the fibers as shown in **Figure 10a**. With these measurements, the fiber aspect ratio, i.e., ratio of the length to the diameter of the fiber can be determined and it is useful in the implementation of fiber composites materials.

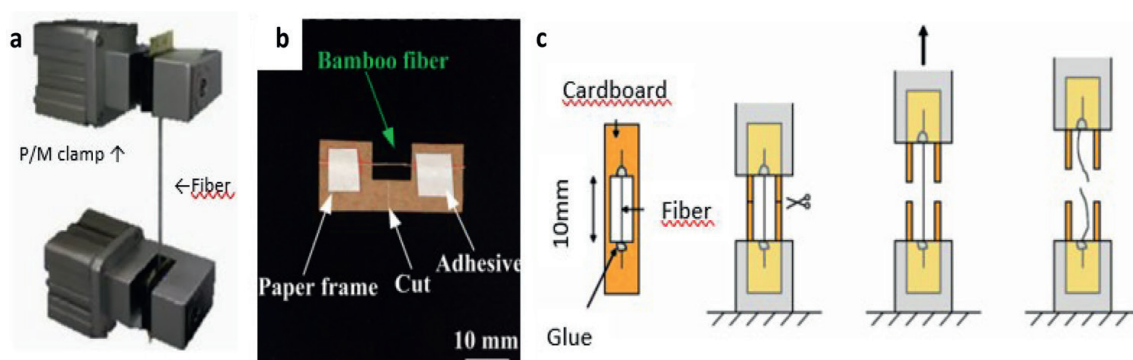
Also, to determine the ultimate tensile stress at failure, it is necessary to know the fiber cross-section. Two methods are proposed depending on the type and shape of fibers. The first consists of taking two measurements using a caliper with a usual accuracy of  $\pm 0.01$  mm that makes it possible to obtain the dimensions of the two axes of a disk or an ellipse (assumed cross-sections). The second method more representative of the shape of fibers, is essentially based on microscope image observation. Indeed, once the fiber is broken, an optical microscope is used to obtain an image of the cross-section. This image is then processed by computer-aided drawing software to determine the area of the fiber cross-section as shown in **Figures 10b** and **c**. This second method is applied in studies of the distribution and orientation of fibers within fiber-reinforced cementitious matrices or crude earth. Fiber counting in a cross-section of the composite material allows the counting of fibers in the cross-section but also the study of the observed shapes gives the orientation of fibers in the matrix. The measurement of fiber orientation by the image analysis technique requires the preparation of a material sample cross-section depending on the technique used according to Fu et al. [27]. The spatial position of a fiber can be defined by the two Euler angles  $\theta$  and  $\varphi$  as shown in **Figures 11a** and **b**, where  $\theta$  is the angle that the fiber makes with the normal direction 1 of a plane on which the fiber orientation will be observed.  $\varphi$  is the angle of the fiber projected in the 2–3 direction plane.  $\theta$  is given by the inverse cosine of the ratio  $b/a$  (ellipse axes) and  $\varphi$  by the orientation of ellipse axis  $a$  to the 2-axis.

### 3.6 Tensile strength of fibers

One of the mechanical properties of interest is the ultimate tensile strength of the fibers. This strength value is useful in the development of composite materials. But



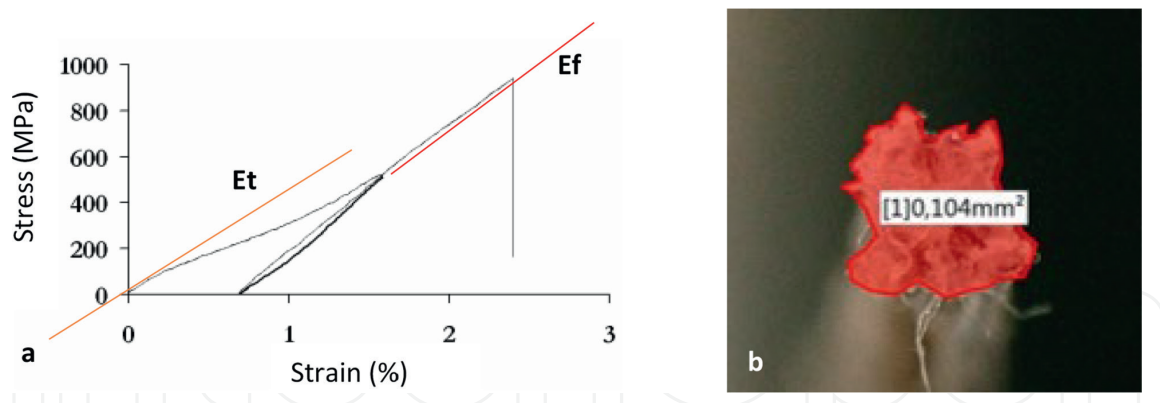
**Figure 11.** An example of definitions and determination of the fiber orientation  $\theta$  and  $\phi$  angles according to Hine [28] and Fu et al. [27].



**Figure 12.** Tensile strength test: possible elementary fiber installation [(a) [29], (b) [9], (c) [11]].

knowing the tensile behavior law of a free fiber (or gauge fiber) is needed for any development of numerical modeling for these materials. This behavior law is often defined by the stress-strain relationship. It is obtained from the tensile force-displacement relationship recorded during a tensile test on a fiber. To carry out the tensile tests, it is necessary to install the fiber on specific support if the fiber flexibility is limited and becomes too brittle. If the fiber is sufficiently flexible, the fiber can be clamped directly in the jaws of the testing machine. The clamping system is mechanical (M) or pneumatic (P) as shown on **Figure 12a**. But usually, for short fibers, a cardboard is used to hold the fiber before testing (**Figures 12b** and **c**). To install fiber on a cardboard frame, squares or rectangles of card stock are cut and prepared with internal dimensions depending on the free length of fiber testing. The test procedure is presented in **Figure 12c** and is as follows: installation of fiber on cardboard, clamping the cardboard on the machine, cutting the cardboard, putting the fiber under tensile loading till failure. The data recorded concerns load versus axial displacement and mainly the ultimate tensile strength as well as the maximum elongation at failure. Usually, tensile tests are carried out on different machines using different sensors. The test is performed at various constant speed rates ranging from 0.5 mm/min to 5 mm/min. Also, the machines are equipped with different more or less accurate sensors. Tests are conducted in constant room thermo-hygrometric conditions (temperature around 20–25°C). For short fibers (total length  $\leq 50$  mm), the free length varies from 10 to 20 mm.

Once the test is validated (failure in the part of free fiber) the stress-strain curve is analyzed and another parameter is determined: the modulus of elasticity if the fiber has an elastic or pseudo-elastic behavior. Depending on the behavior of the fiber, a linear part exists or not. It can be defined then an initial tangent modulus  $E_t$  (**Figure 13a**), or the modulus of deformation can be defined on the linear part just before the failure



**Figure 13.** (a) Flax fiber behavior under tension cycle [11], (b) determination of coconut fiber cross-section after a tensile strength test [20].

as shown in the same **Figure 13a** (modulus  $E_f$ ). And this choice can be justified by the fact that a cyclic test can demonstrate elastic behavior as for a flax fiber, see **Figure 13a**. Furthermore, the determination of the ultimate stress in a fiber under traction requires the knowledge of the cross-section at the moment of rupture, although there is a constriction of the cross-section as shown in **Figure 13b**, for which the determination of the cross-section is made by using microscope image and image analysis software.

### 3.7 Pull-out resistance of fibers

The pull-out strength of the fibers in the matrices in which they are incorporated is another mechanical parameter necessary for the formulation of composite materials. In particular the shear stress at the fiber/matrix interface. It plays a major role in the case of short fibers [27]. It is also used to evaluate the critical fiber length. The critical fiber length ( $L_c$ ) is the minimum length required to effectively strengthen and stiffen the material. It is defined by:

$$L_c = \frac{1}{4} \sigma_{ff} D / \tau \quad (2)$$

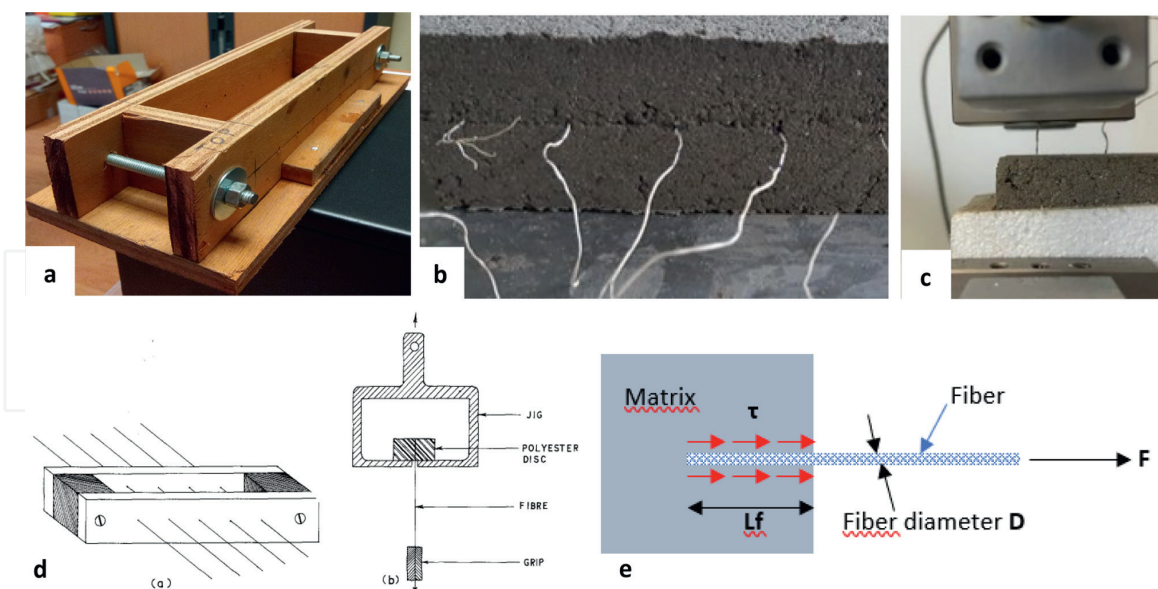
where  $\sigma_{ff}$  is the ultimate tensile strength of the fiber,  $D$  is the fiber diameter, and  $\tau$  is the interfacial shear strength at the fiber/matrix interface, see **Figure 14e**.

The critical fiber length can be estimated using the measured fiber diameter  $D$  and the values of  $\sigma_{ff}$  and  $\tau$  issued from experimental tests or literature. The isolated (single) fiber pull out test requires a particular molding of anchored unit fibers of length  $L_f$  as shown in **Figure 14e**. The unit fibers are distributed along with a cast matrix (in the case of a cementitious or polyester resin-based material, **Figure 14d**) or crude earth (**Figures 14a** and **b**). The samples thus produced (**Figures 14c** and **d**) are submitted to a tensile test until the fiber is pulled out ( $L_f < L_c$ ) or the fiber breaks ( $L_f > L_c$ ). The test machines are the same as those used for the fiber tensile tests (Section 3.6).

### 3.8 Some properties of natural tropical fibers

#### 3.8.1 Useful properties of natural tropical fibers in building materials

Natural fibers from the Tropics for use in building materials are relatively abundant, as the data in **Table 2** show. But among the fibers incorporated in building materials are



**Figure 14.** (a) Crude earth specific wooden mold for pull out a test of hemp fiber, (b) crude earth sample with different hemp fibers before pull out testing, (c) pull out test of hemp fiber, (d) coir polyester composite specific mold for pull out test [30], and (e) simple mechanism of shear stress and pull-out force in the case of elementary fiber in a matrix.

coconut, sugarcane, sisal, palm fibers and to a lesser degree banana spine fiber. These are also the most widely investigated fibers in building materials at present. More recent interest has focused on the recycling of natural fibers considered as waste, such as oil palm fibers after the production of oil from the fruit. The characteristics of tropical fibers detailed below have been the focus of studies conducted by the authors. They are the most widely used fibers in building materials and in particular, the use of palm fibers constitutes an innovation in eco-friendly building materials.

### 3.8.2 Bio-physical properties of natural tropical fibers

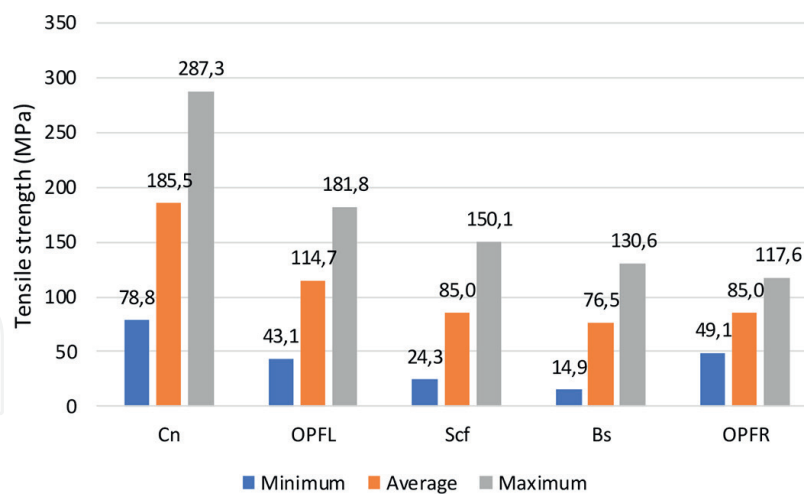
**Table 2** shows great variability in the data related to natural fibers, which is explained by the morphology and composition of each fiber, whether treated or not. Five types of tropical natural fibers were specifically investigated which are palm oil flower (POFl), palm oil fruit (POFr), coconut from the outer shell (Cn), sugar cane bagasse (Sc) and banana stem (Bs) fibers. These fibers are taken from the state of Tabasco in Mexico. Sugarcane fibers are separated into coarse (Scg) and fine (Scf) fibers for the study. Palm oil flower and fruit fibers are also separately considered even if some of their properties are closely related, see **Table 3**. They were not processed but extracted manually. Only the banana rachis required soaking in water and then drying of the isolated fibers.

Fibers	Density (g/cm <sup>3</sup> )	W <sub>a</sub> (%)	K (W/mK)	Cellulose (%)	Avg. area (mm <sup>2</sup> )
POFL	1.37	235	0.058	48.84	0.070
POFR	1.36	258	0.055	37.36	0.027

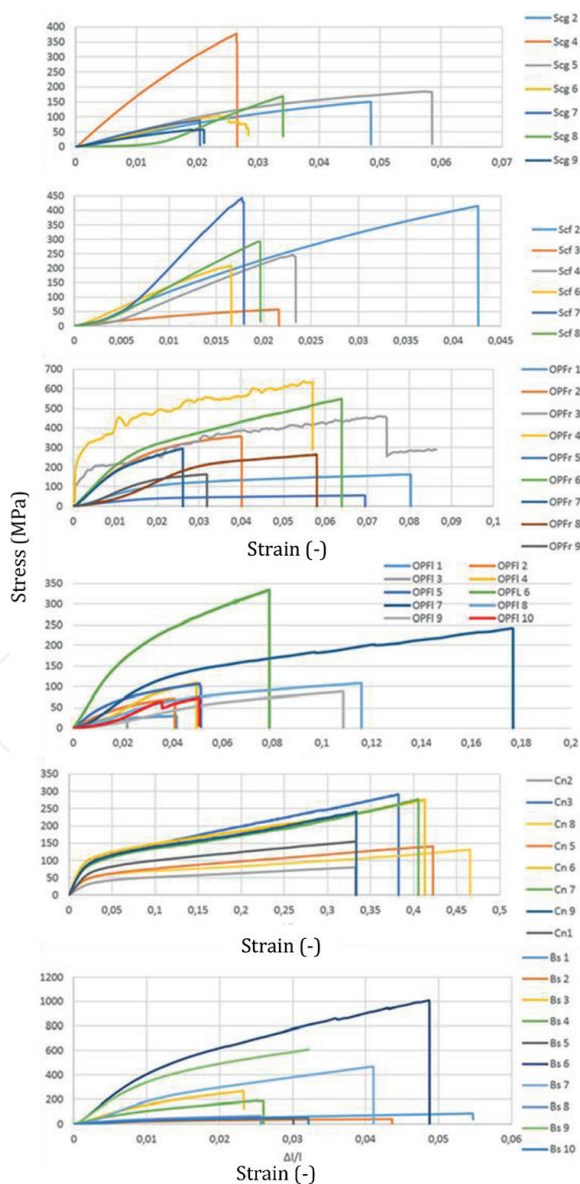
Note: W<sub>a</sub> = water absorption, K = thermal conductivity, and Avg. = average.

**Table 3.** Some bio-physical properties of palm oil flower and fruit fibers.





**Figure 15.**  
 Tensile strengths observed on typical tropical fibers from Mexico.



**Figure 16.**  
 Typical stress-strain relationships for different tropical fibers.

**Table 3** shows the bio-physical properties of palm oil fibers such as density, water absorption, thermal conductivity, cellulose content and area. The low density of fibers makes them a suitable additive in manufacturing lightweight building composites. Natural fibers are hydrophilic materials and higher water absorption of fibers in composite leads to micro-cracks growth in composites. Natural fibers have a low thermal conductivity which has a positive influence on the thermal behavior of building materials. Higher cellulose content of fibers contributes significantly to the tensile strength of fibers. The area of fibers is important to study the mechanical characteristics of fibers such as tensile strength. Tensile strength of fibers is heavily influenced by the area of fibers as technical fibers tested in this study are consist of the number of elementary fibers.

### 3.8.3 Bio-physical properties of natural tropical fibers

The five types of fibers were subjected to a tensile test. The length of the fiber chosen is 20 mm (free or gauge length) for a total length of 30 mm. The constant test speed was 0.5 mm/min at a room temperature of  $22 \pm 2^\circ\text{C}$  and relative humidity of 40–50%. A minimum of 10 fibers were tested for each series. The minimum, average and maximum tensile strength of Mexican tropical fibers is presented in **Figure 15**. The tensile and strain loading curves reveal different mechanical behaviors depending on the fiber. Pseudo-elastic, visco-elastic or elasto-plastic behavior with a strain-hardening effect can be observed in **Figure 16**.

The tensile strength of fibers discussed in **Figures 15** and **16** is one of the most important parameters for their use in bricks as fibers act as reinforcement. The higher tensile strength of fibers increases the tensile strength of building composites.

## 4. Application in reinforced mortars by natural fibers as cementitious material

An innovative solution to reduce the negative impact on the environment is the production of structural reinforced composites from these natural fibers. Section 4 introduced an alternative binder to improve the durability of these plant fibers in an alkaline environment of cementitious composite. CSA cement was used in coconut fiber-reinforced mortar to totally replace the traditional cement. This section is divided into 2 parts including the *mechanical properties of fiber-reinforced mortar*, and *carbonation resistance of fiber-reinforced mortar*. In each part, the comparison between unreinforced- and reinforced mortars is presented.

Among the natural fibers, coconut fiber is considered is a potential candidate for reinforcement in cement matrix due to its most ductile and energy absorbent properties compared to other plant fibers. Incorporation of natural fibers into cementitious composite could, therefore, constitute an alternative solution to waste management and contribute to the development of reinforced mortars by improving comfort performance in buildings. Besides, it is necessary to use alternative binders to improve the durability of these plant fibers into composites and reduce the negative impacts on the environment. In this section, the new formulations of mortar are proposed, in which the Portland cement is totally replaced by calcium sulfoaluminate cement (CSA cement). CSA cement, consisting of nearly 55% of calcium sulfoaluminate, could be considered as a clean, green and alternative binder due to its environmentally-friendly features [31]. Additionally, CSA cement contains a lower alkali content compared to

PC, i.e., the pH ranges of CSA cement and PC are 10–11 and 12–13, respectively. As a consequence, the lower pH value of CSA cement can also lead to the less natural degradation rate of the fibers in the alkaline environment of the cementitious matrix.

#### 4.1 Mechanical properties of fibers-reinforced mortars

The mechanical properties of fibers-reinforced mortars depend on various parameters such as intrinsic properties of fibers, fiber contents, fiber distribution, fiber orientation, interfacial transition zone (ITZ), i.e., fibers and cementitious matrix adhesion. The decrease in the compressive strength of mortars with increasing fiber content is observed. A part of the explanation is that the pectin, ash, and other impurities are included in the fiber component, inducing the reduction of the bond between fibers and cementitious matrix. Additionally, the higher air content and porosity, relative to the increase in fiber content, involve a decrease in compressive strength. The combination method of coconut fibers and CSA cement in mortar significantly increased flexural strength of mortar, up to approximately 17%, which meets the desired mechanical performance since fibers are used as reinforcement. However, at the higher content of fibers ( $\geq 3\%$  by mass of cement), the flexural strength starts suffering a slight decrease due to much more fibers being in the restricted area of the brittle cementitious phase, which leads to the significant cumulative effects on the strength of the material. In addition, frictional energy losses considerably in the wake of pulling out of fibers due to the debonding at the interface, which is partly responsible for the failure.

Figure 17 shows the typical evolution graphs of the force applied as a function of the displacement at mid-span of the specimen for unreinforced and 2% fiber-reinforced mortars. To clarify the understanding of the different periods of crack initiation and propagation in bending, five particular points corresponding to five load steps are noticed for reinforced mortar. Point A is at the end of the non-linear elasticity period (so A is also at the first of the linear period). This point shows how the normal displacement evolves in the elastic period during the flexural test. Crack has not occurred in this step, although the load reaches 55% of the maximum load. In the next step, point B represents the displacement in the linear part of the curve and corresponds to the point where crack starts appearing at the load of 85% the maximum. It should be noted that the formation and development of cracks also depend on the characteristics of supporting

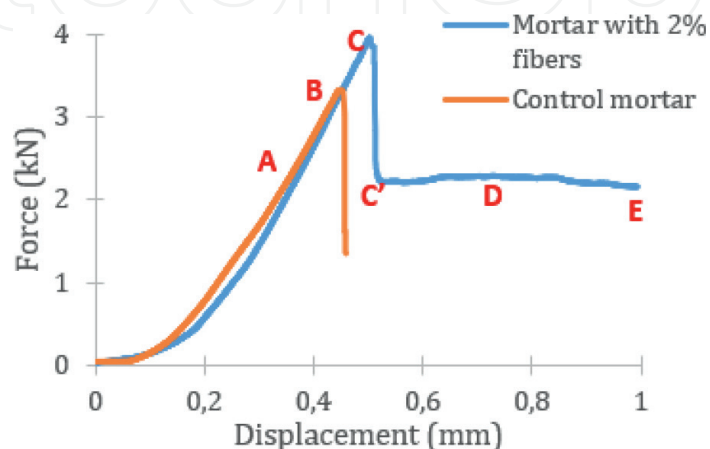


Figure 17.  
Typical curves of behavior in 3 points bending of mortars [32].

(two) and loading (one) rollers of the flexural test. If one of them is capable of tilting or sliding slightly, a uniform distribution of the load over the width of the specimen is well applied. And thus, this induces the appearance of a single crack. Otherwise, multi-cracks would have occurred, and flexural behavior will be affected if all supporting rollers cannot freely rotate. Therefore, the scatter of cracks is observed on the cross-section of the sample in this case [33]. In the third step, point C corresponds to the peak of the force-displacement curve, i.e., the maximum of the flexural load. As the sample partly suddenly fails, point C' is reached to introduce the residual force. The load reaches the maximum load, and some fibers begin pulling out from the cementitious matrix and then slip inside the mortar, as clearly shown by the drop from point C to point C'. The period from point D to point E is along the residual force step which mobilizes the shear resistance of fibers. This step describes a nearly constant load period while the bending displacement continues increasing due to the remaining fibers. The crack initiates at the base, i.e., an opposite plane to the applied load, of the sample and propagates toward the direction of loading in the wake of the appearance of the initial crack. In this stage, the contribution of fiber to preventing brittle fracture suddenly is shown clearly. Additionally, resisting fragmentation is observed as there is no spalling at the surface of the specimen due to the bridging effect of the fiber distribution. For control mortar, the bridging effect could not be observed. The sample shows a sudden drop at about 80% of the maximum applied force. The strain development of the control mortar is characterized by a non-linear elastic part followed by a nearly linear behavior before sudden failure occurs (fragile behavior). The single crack appears at the base of the samples on which it is believed to have the maximum bending moment and no shear load. The reinforced mortars show that a progressive load decrease is likely associated with a progressive rupture of the fiber-matrix interface and then limits a brittle fracture. The addition of fibers into mortar has remarkable effects on the cracking behavior of mortar. Fiber acts as a crack-arrester since the presence of fibers could contribute to preventing brittle fracture suddenly after the first crack appears. Also, the bridging effect of the fiber distribution induces a decrease in the crack width and length compared to the control sample at the same level of loading. The enhancement of toughness and preventing the development of cracks inside reinforced mortars are the most important contributions of fibers.

#### 4.2 Carbonation resistance of fibers-reinforced mortars

In terms of durability, the usage of CSA cement with low alkali content could lead to a significant decrease in carbonation resistance owing to the lower content of CaO compared to conventional cement. Additionally, several previous studies [34, 35] also pointed out the negative effects of the Ca/Si ratio on the carbonation resistance performance. They believed that a rapid carbonation degree was acquired in consequence of the rapid decalcification of calcium silicate hydrate gel (CSH) at the higher ratio of Ca/Si. Additionally, the formation of carbonation products that result from the decomposition of ettringite, which is the principal phase of CSA cement, and contributes to boosting the carbonation depth in mortar specimens. This observation also proves that the dense microstructure formed by ettringite has negligible effects on the carbonation resistance of the CSA cement-based matrix. Besides, incorporating fibers could improve the carbonation rate due to the high air content (the fibers act as channels and entrain air), encouraging CO<sub>2</sub> penetration happened could be easier [36].

The various effects of carbonation on the performances of mortar were obtained. In detail, the compressive strength increased by approximately 9 and 33% for

conventional cement-based mortars incorporating and no fibers, respectively. In contrast, the carbonation process could induce a slight decrease by 1–3% in compressive strength of CSA specimens with and without fibers, respectively. The pore structure of composite, which acquires significant changes after accelerated carbonation, is partly responsible for these results. It should be noted that a higher carbonation depth is found in CSA specimens. Therefore, the relationship between carbonation resistance and mechanical strength seems to be significantly dependent on the binder type used in composite [37]. Carbonation-induced strengths of mortar are various due to the cumulated effect of fibers incorporated. Mechanical behavior, hence, could not be a substantial factor in deciding the carbonation resistance of the cementitious composite.

The process of carbonation also induces a slight decrease in the thermal resistance ability of the matrix. For instance, non-carbonated zones have a strong ability to resist temperature than others in carbonation. In detail, at elevated temperature ( $\sim 900^{\circ}\text{C}$ ), the carbonated area lost up to 14% of its mass. Meanwhile, the mass loss value of the non-carbonated area is below 10%. This observation is the result of  $\text{CaCO}_3$  formation during the carbonation process. This compound is thermally decomposed at a temperature higher than  $650^{\circ}\text{C}$ . Otherwise, the calcium-carbonated filler, which is generated in conventional cement production, is the main phase decomposed at this temperature.

Mechanical properties of composite materials need to be assured considering the environmental vulnerability. Generally, exposure in wetting and drying cycles has strong effects on the mechanical properties of samples due to the repetition of the negative environment on the interfacial bonding between fibers and cementitious matrix. After the sample is exposed to wetting and drying cycles, compressive strength is the most critical factor in assessing the performance of composite materials [38]. The wetting and drying repetition has adverse effects on the mechanical performance of mortar, regardless of the number of fibers, and reduces both compressive and flexural strengths. Generally, losses in mechanical properties of CSA-based mortars were higher than that of PC-based mortars. However, it should be noted that the maximum compressive strength was observed after one cycle since complete hydration of cement was reached due to the addition of water during the wetting process. In the next cycles, due to the formation of crystallized hydrate products [39], more micro-cracks appeared gradually inside the mortar structure and induced a decrease in compressive strength. Both strength and deformation of mortar samples decreased at the higher level of porosity and the higher number of cycles. The loss of strength was observed when fibers were incorporated into the mortar. More pores in fine aggregate mortar appear due to adding coconut fibers, which creates a convenient environment for the deep penetration of ambient air and water. The change in mechanical strength with predicted tendency was governed by the porosity, the number of cycles and fiber content as well, i.e., the higher fiber content, the higher porosity, the higher number of wetting and drying cycles, the lower mechanical strength.

In conclusion, for natural fibers reinforced composite to become widely used construction materials, consistent and predictable results need to be obtained. To achieve these outcomes, further studies are required on these composite performances by testing and modeling, which are necessary to help the application of this material for the building materials widely. These outcomes might contribute to environmental benefits and sustainable development of the construction industries in the future.

## 5. Application in reinforced crude bricks by natural fibers as an eco-friendly material

The emission of greenhouse gases, global warming and environmental concerns associated with modern construction materials have forced us to look for environmentally friendly construction materials. Construction materials such as concrete, cement and fired bricks manufacturing consume a higher amount of energy and are responsible for a considerable amount of CO<sub>2</sub> emission. Moreover, these materials have higher thermal conductivity. On other hand, adobe bricks are environment-friendly building materials manufactured with sediments and waste natural fibers. Dredged sediments and natural fibers are renewable waste materials, easily available in most regions of the world. Disposal of waste fibers and dredged sediments have negative impacts on the environment as they are the source of air, water and land pollution. Dredged sediments and natural fibers valorisation in adobe bricks generates sustainable and green construction material as adobe bricks manufacturing does not consume energy. Adobe bricks are sun-dried and they have a low thermal conductivity which reduces the energy consumption for heating and cooling.

Adobe bricks are the cheap and oldest construction materials, used in historical buildings. Adobe bricks are manufactured with soil and natural fibers. Soil suitability for adobe bricks is observed with standards such as AFNOR and MOPT [40, 41]. Sediment's mineralogy, molding moisture content, compaction energy, clay and sand content have a significant influence on the characteristics of adobe bricks. The strength and durability limitations of adobe bricks are the obstacles to their large-scale use. The addition of natural fibers and the use of stabilization techniques reduce these drawbacks to some extent.

Natural fibers are agricultural waste generated by food industries such as sugar cane, palm oil, etc. Natural fibers act as reinforcement in adobe bricks and increase their tensile strength. The low thermal conductivity and density of natural fibers make them suitable additives for adobe bricks and composite materials. Distribution, orientation, quantity and length of fibers are some important parameters that affect the quality and performance of adobe bricks. Fibers are randomly distributed in crude bricks, and it is difficult to control their orientation. The longitudinal distribution of fibers parallel to the bricks axis increases the tensile strength of bricks while their distribution perpendicular to the bricks cross-section does not contribute to the tensile strength of bricks. The quantity of fibers has also a significant impact on the performance of composite materials. The quantity of fibers used in adobe bricks usually varies from 1–5% by mass. The length of fibers is another factor that influences the tensile and compressive strength of bricks. Length of fibers varies with the choice of fibers and available fibers cutting mechanism. The distribution of fibers in bricks is homogenous with fibers of short length. The tensile strength of bricks increases with increasing fibers length however, longer fibers harm the compressive strength of bricks. The presence of knots and weak bond in long fibers affects their performance. Therefore, the use of appropriate length fibers is suggested. The common length range of natural fibers for crude bricks varies from 2 cm to 10 cm in literature studies.

The stabilization of bricks is achieved either by compaction or by using binding materials such as lime, cement and gypsum. As the use of binders involves the cost and contributes to global CO<sub>2</sub> emissions. Therefore, bricks stabilization with compaction is a reasonable option. Compaction of bricks can be achieved by static loading, dynamic compaction, and tamping. The compaction of bricks removes the voids inside the bricks and improves their mechanical characteristics along with durability [42].

However, compaction of bricks with dynamic loading and tamping causes the upward movement of fibers along with water which may perturb the distribution of fibers. The durability of adobe bricks is also a challenge as the performance of fibers decreases with time due to degradation. Treatment of fibers improves their characteristics but it has environmental concerns.

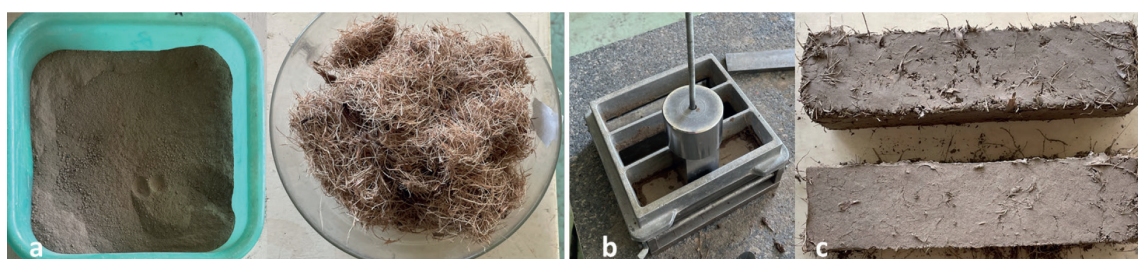
Adobe bricks are manufactured by mixing sediments, fibers and water. Molding moisture content varies with the type of sediments and natural fibers. It is important to respect the water absorption coefficient of natural fibers. As water absorption of natural fibers is not instantaneous, prior fibers saturation helps to make homogenous sediments and fibers mixture.

### 5.1 Manufacturing of crude bricks

Dredged sediments from the Usumacinta River and palm oil flower fibers (POFL) from the Tabasco State of Mexico were investigated to use them in adobe bricks. Usumacinta River sediments (USU) are shown in **Figure 18a**. Sediment's characteristics such as granulometry, density, Atterberg limits, optimum moisture content, carbonate content, pH, XRF and organic matter were analyzed. Sediment characteristics are summarized in **Table 4**.

Palm oil flower fibers were used as reinforcement in adobe bricks. POFL fibers are obtained from palm oil empty fruit bunches which are waste material from the palm industry. Empty fruit bunches were cut with a knife mill by using a grid of 3 cm. POFL fibers are shown in **Figure 18a**. Due to the grinding of fibers in the knife mill, there is length variation for grid-3 cm long fibers. The average length of fibers is 11.54 mm.

Fiber's characteristics such as length, cross-section, tensile strength, water absorption, chemical composition and thermal conductivity are important for their use in crude bricks. Cellulose is the main component of POFL fibers which play a key role in the tensile strength of fibers. The tensile load behavior of POFL fibers is elastoplastic behavior. Characteristics of POFL fibers are shown in **Table 3**.



**Figure 18.** Adobe bricks manufacturing, (a) dry sediment and fibers, (b) miniature proctor for prismatic sample, and (c) molded crude bricks.

Sediments	LL (%)	$\rho_{sed}$ (g/cm <sup>3</sup> )	Clay (%)	Sand (%)	pH (-)	OM (%)	MBV (g/100 g)	CaCO <sub>3</sub> (%)	W <sub>opt</sub> (%)	SSA (m <sup>2</sup> /g)
J3-9C	37.74	2.63	5.9	52.8	7.5	4.48	2.73	7.84	19.3	28.20

Note: LL = liquid limit, OM = organic matter, MBV = methylene blue value, and SSA = specific surface area.

**Table 4.** Usumacinta sediments characteristics.

Crude bricks were manufactured with POFL fibers and Usumacinta River sediments. Manufacturing of fired bricks consists of mixing sediments and fibers, molding, compaction and drying. USU sediments were crushed, grinded and passed through a 2 mm sieve. Sediments were mixed with 0, 1, 2, 3, 4 and 5% saturated POFL fibers. 450 g sediments are recommended for prismatic bricks of size 4\*4\*16 cm<sup>3</sup>. The quantity of fibers for each brick can be calculated by Eq. (3).

$$m_{\text{fibers}} = (m_{\text{sed}} \times \% \text{ of fibers}) / 100 \quad (3)$$

where  $m_{\text{sed}}$  is the mass of dry sediments,  $m_{\text{fibers}}$  the mass of fibers and % of fibers, the percentage of fibers used. The optimum moisture content of sediments was found by the Proctor test and its value is 19.3%. It was used as molding moisture content. The quantity of water for the mixture can be calculated by Eq. (4).

$$m_{\text{water}} = (m_{\text{sed}} \times \% \text{ of water}) / 100 \quad (4)$$

where  $m_{\text{sed}}$  is the mass of dry sediments,  $m_{\text{water}}$  the mass of water and % of water, the optimum water content.

USU sediments and POFL fibers were poured into a mixing bowl followed by the addition of water. Sediments and fibers were mixed with an electric mixer for 10 minutes. Sediment mixing was followed by molding. Sediment's mixture was molded into prismatic bricks of size 4\*4\*16 cm<sup>3</sup> which is commonly used for manufacturing composite materials at laboratory scale [11]. Bricks were compacted with dynamic compaction. Compaction energy used is similar to the Proctor test energy, i.e., 600 kN.m/m<sup>3</sup>. The compaction of adobe bricks is shown in **Figure 18b**. After compaction bricks were unmolded and oven-dried at 40°C and sun-dried. Bricks were kept in the oven until their mass variation was below 1%. It was observed that sun-drying of bricks at room temperature (20°C ± 2°C) takes 2–3 weeks while oven drying can be achieved in 3–4 days. **Figure 18c** shows oven drying of adobe bricks.

## 5.2 Characteristics of bricks

Adobe bricks characteristics include tensile strength, fibers distribution, thermal conductivity, shrinkage and density, etc. Characteristics of bricks are strongly influenced by fiber content. Tensile strength and toughness of bricks increase with fiber content up to optimum moisture content. Fibers contribute to the tensile strength of bricks and transform the brittle failure into ductile failure by increasing the post-peak load-bearing capacity of bricks. The higher quantity of fibers produces fibers clusters in the matrix and reduces the bonding between fibers and sediments which decreases the tensile strength and toughness of bricks. The indirect tensile strength of bricks is determined with a three-point bending test according to ASTM standard [43]. The toughness index of bricks is also be determined with a tensile strength test. The tensile strength and toughness index of Usumacinta sediments bricks at different fiber content are shown in **Table 5**.

**Table 5** shows that the tensile strength and toughness of Usumacinta sediments bricks increases with fiber content up to the optimum fiber content. Tensile strength of fiber-reinforced crude bricks, i.e., adobe bricks, reported in the literature and different standards vary from 0.04 to 2.05 MPa [44].



DCi%	DC0%	DC1%	DC2%	DC3%	DC%	DC5%
$\sigma_t$ (MPa)	1.79	1.79	2.56	3.19	2.02	2.59
Toughness	1	2.58	4.18	4.42	2.83	3.89

Note: DCi% = dynamic compaction of crude brick with i (%) of fiber content, and  $\sigma_t$  = tensile strength at failure.

**Table 5.**  
Mechanical characteristics of bricks.

Bricks	Mass (g)	Density (kg/m <sup>3</sup> )	Shrinkage (%)	K (W/mK)	UPV (m/s)
USU	370	1524	2.25	0.23	924

Note: K = thermal conductivity, and UPV = ultrasonic pulse velocity.

**Table 6.**  
Physical characteristics of adobe bricks.

Physical characteristics of bricks include mass, density, shrinkage, ultrasonic pulse velocity (UPV) and thermal conductivity. The addition of fibers decreases the density of bricks and makes them lightweight construction material. On the other hand, Ultrasonic pulse velocity of bricks also decreases with increasing fibers content due to the presence of voids as saturated fibers swell initially and shrink after drying the bricks which produce small cracks. Shrinkage is another important property of bricks which increases with higher molding moisture content and higher clay content of sediments.

Physical characteristics of adobe bricks made with USU sediments at optimum fiber content are summarized in **Table 6**.

Uniform distribution of fibers inside the bricks is important. The distribution of fibers inside bricks can be observed with ImageJ software [5]. Crude bricks are divided into 4 parts with 6 cross-sections. A microscopic image of each brick cross-section is analyzed with ImageJ software to find the number of fibers, their area and orientation in bricks. Upward movement of fibers in composite materials with dynamic compaction can be observed with image analysis.

This section includes a detailed analysis of the physical and mechanical characteristics of natural fibers especially tropical fibers for their recycling in construction materials such as crude bricks. Crude bricks specimens were manufactured at different fibers content and their characteristics were analyzed. The Addition of natural fibers in construction material has a positive impact on the tensile strength, density and thermal properties of these materials.

## 6. Conclusions

This chapter focuses on the recycling of waste natural fibers in composite materials used for construction. Fiber's recycling eliminates agriculture waste and contributes to conserving natural resources used in building materials and sustainable development.

For fibers recycling, the study of their biochemical, physical, morphological, microstructural and mechanical characteristics is essential. In addition, durability analysis of fibers helps to determine the long-term evolution of these characteristics. This chapter reviews the characteristics of natural fibers suitable for building composites such as tensile strength, water absorption, modulus of elasticity and density.

Moreover, characteristics of tropical fibers are also discussed for their reuse in earth bricks.

Analysis of natural fibers characteristics used in building materials shows the great variability in their intrinsic properties. The development of composite materials such as reinforced cementitious mortars or fiber-reinforced raw earth must consider this variability.

Natural fibers addition in building composites improves the tensile strength of these materials. Moreover, natural fibers improve the thermal and acoustic performance of composite materials.

Case studies for the recycling of natural fibers in mortar and earth bricks are also discussed. Natural fibers addition reduces the density of earth bricks and mortar. The tensile strength of earth bricks increases significantly with the addition of natural fibers. Natural fibers act as reinforcement and transform the brittle behavior of mortar and earth bricks into ductile behavior.

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