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Review Article

Physical, Thermal and Mechanical Characterization of Raffia Palm and Composite Materials with Cement Matrix Reinforced with Raffia Fibers and Other Similar Species

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Abstract

The accentuation of climate variations is an additional constraint that challenges almost all countries in the world and for which urgent actions are required to counter the harmful effects caused by these phenomena such as floods, excessive heat, acute drought, late and violent rains, etc. Among these urgent measures, we can cite, among others, the protection of the environment for sustainable development in all sectors of human activity. In the construction or building sub-sector, it is urgent to use environmentally friendly materials capable of reducing the carbon footprint compared to the conventional construction materials. The work entitled " Physical, thermal, mechanical characterization of the raffia palm and composite materials with cement matrix reinforced with raffia fibers as well as other similar species: state of the art", fits well within this framework and aims to summarize the work related to natural fibers in particular cement matrix composites, a local resource available in Africa. In this review of scientific literature, our attention is focused on the potential use of natural fibers as reinforcement in the cement matrix. The work of several researchers has demonstrated that the orientation of the fibers has only a negligible effect on thermal conductivity. On the other hand, certain varieties of palm trees, such as the date palm, influence this thermal conductivity, with an average value measured at 0.083W.m-1.K-1 under atmospheric pressure. Regarding mechanical properties, palm fibers have a tensile strength ranging from 97 to 197 MPa, a Young's modulus ranging from 2.5 to 5.4 GPa, and an elongation at break ranging from 2.0 to 4.5%. In addition, further research has determined for raffia palm fibers a Young's modulus of approximately 30 GPa and a breaking stress of around 0.50 GPa. These properties are determined using scanning electron microscope examinations, which reveal a layered structure, as well as X-ray diffraction measurements.

Keywords

Composite Material, Raffia Palm, Cement Matrix, Local Resources, Physical, Thermal and Mechanical Characterization

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1. Introduction

In recent years, the use of composite materials has undergone considerable evaluation in various fields including construction, aeronautics, automotive, packaging, etc. A composite material can be defined as an assembly of several materials of different natures. Composites are most often made up of a matrix containing dispersed reinforcements (fibers) in either controlled or uncontrolled manner. The matrix maintains the reinforcements and ensures load transfer, while the reinforcements mainly enhance their high mechanical characteristics (moduli and elastic limits, mechanical resistance, etc.) and allow better control of concrete cracking by limiting the opening of cracks, transforming the brittle behaviour of concrete into ductile behavior [1]. This association aims to obtain a material whose specific properties are superior to those of its components taken individually. The concept of composite material, through the choice of constituents and their respective proportions, as well as the choice of the shape, the dimensions and arrangement of the reinforcements, enables the design of a material with the specific characteristics sought [2]. Several classes of composite materials can be cited depending on the nature of their matrix: organic matrix composite materials (OMCs), ceramic matrix composite (CMCs) and metallic matrix composite (MMCs). The most developed are the OMCs, 92% of the world market, then come the CMCs, 7%, and far behind the MMCs, 1%. [3]. In recent decades, due to global warming and increasing environmental toxicity, the scientific community has reoriented its interests towards natural, eco-friendly materials, focusing their research themes on recyclable, renewable and sustainable materials, that minimise environmental impact [4]. Accordingly, the international community has set the goal to halve greenhouse gas emissions by 2050 [5]. Industrialized countries will have to make a special effort and divide their emissions by four in less than fifty years. The conservation of natural resources and the environment is among the major concerns of the international community, as evidenced by holding several international conferences on the environment [6-9], the creation of the United Nations Environment Program (UNEP) and the signing of several international conventions. The management of forest areas holds a prominent place in these concerns, given the functions of the forest [10, 11], particularly at the level of soils, hydrological regimes, climates, global biological diversity and the economies of the countries concerned, as well as the particularities and precariousness of the tropical environment [12]. However, the use of these composites as an engineering product in construction is limited by their performances which require further improvements to optimally address [13] the problem of demographic pressure, urban explosion, etc. Indeed, the energy efficiency of buildings based on natural fibers is a reliable means to combat global warming [14].

To this end, the valorisation of plant fibers and their integration into the development of sustainable composites, within the framework of green technologies, for various applications, currently constitutes one of the most considered solutions. This approach, already widely adopted and promising, encourages researchers working in the construction and manufacturing sectors to incorporate plant fibers as reinforcing elements into construction materials.

Such integration not only contributes to improving their strength, durability and thermal insulation properties, but also promotes the valorization of local materials while reducing construction costs and energy consumption required for heating or air conditioning [15]. The depletion of natural aggregate deposits and the difficulties in setting up new quarries require the search for new sources of supply. Given the growing need for material resources and the requirements of environmental preservation in a vision of sustainable development, it has become necessary to explore and study all possibilities for the reuse and recovery of industrial waste and by-products, particularly in the field of civil engineering [16].

Based on the Government Action Program (PAG) of the Republic of Benin (located between the equator and the Tropic of Cancer between the parallels 6°30' and 12°30' north latitude and the meridians 1° and 30°40' east longitude. In Africa, Benin is located in West Africa and is bordered by Burkina Faso and Niger to the north, by Nigeria to the east, by Togo to the west and by the Atlantic Ocean to the south), which aims to promote arts, culture and crafts. The instruction of an energy efficiency and electrical safety protocol in buildings and public installations, with the aim of promoting local materials and increasing the country's tourism sector. The PAG has implemented the reconstruction or structuring of the museums of the epic of the Amazons, the Kings of Danhomè and the rehabilitation of the surrounding palatial site. The rehabilitation of tourist infrastructure in Allada, construction of the Vodun Orisha Museum in Porto-Novo and rehabilitation of the Adandé and Honmé museums using local materials aims to mitigate the phenomenon of excessive heat in these buildings [17].

Despite the measures adopted to combat climate change, particularly through the use of natural fibers, global warming and excessive heat in buildings persists. This study is of crucial importance, as it aims to reduce the rate of use of endangered materials such as (rolled and crushed gravel) and to anticipate, in the coming years, the exhaustion of quarries as well as gravel mining areas.

The use of these composites in the construction industry as raw materials is a very interesting alternative, which has a dual objective. On the one hand, it allows us to meet the needs for new materials, with specific or improved properties compared to conventional materials. On the other hand, it helps to overcome the problems of disappearance of conventional traditional materials (rolled gravel, etc.).

This article is based on an in-depth review, structured in two distinct parts. The first part is devoted to a review of the bibliographic literature relating to the raffia palm, including the description of the palm, its exploitation, as well as its physical, mechanical and chemical characteristics. The second part is dedicated to composite materials with a cement matrix reinforced with natural fibers.

2. Review on the Raffia Palm

2.1. Raffia Palm Description

Palm trees are among the most well-known and popular plants. Worldwide, they are considered a "symbol of the tropics" [18]. The sites richest in biodiversity are often those most affected by the species extinction crisis. This is the case in particular of Congo Brazzaville, Gabon, Cameroon, Benin, Madagascar constitutes a concrete example. Having lost a large majority of its diversity in fauna and flora since the arrival of Man on the island [19], the decline in specific diversity results in the dysfunction of ecosystems which results in various environmental, biological and ecological problems and sometimes the accentuation of the effects of climate change. The greatest specific diversity of palm trees (90%) is found in tropical rainforests [20]. They constitute one of the most remarkable and most important members of this biome. Through their diversity and abundance, they play major ecological roles, among other things, in the structuring and composition of soils or interactions plant-animal [21]. During its vegetative growth, the raffia palm can reach a height of 20 meters. Covered by the remains of old palms, the stipe of 1 to 3 meters in diameter is straight and very slender. Pinnate, the evergreen green leaves have a length of up to 20 meters, with a width of 3 meters. This palm produces a large ovoid fruit, similar to pears in shape, characterized by a size similar to that of a hen's egg. Reddish-brown in color, this fruit is 5 to 15 cm long, scaly and pointed. Inside this fruit, there is a yellow pulp that envelops a large hard seed. The raffia palm produces a large inflorescence with light green flowers, fruits only once and dies: the trunk dries up but the roots survive and emit new suckers [22].

2.1.1. Different Parts of a Raffia Palm

Figure 1, is composed of the base of the palms, stipe, of the raffia palm which is made up of (basalt sheath, petiole or bamboo, rachis and leaflet), allowing the production of a large ovoid fruit of various granular sizes, known as raffia farinifera. This palm appears like the date palm due to their morphological and anatomical similarities. This has prompted several researchers to study the recent advances in the manufacturing methods of composite materials has led to a notable increase in their use in various sectors, especially in the production of composite materials for insulation elements [23, 24]. Various types of plant fibers used as reinforcement in cementitious or organic matrix composite materials have captured the attention of many researchers due to their remarkable mechanical and physical properties despite their low density, as well as their economic and environmental advantages. These fibers include, for example, hemp [25, 26], sisal [27-29], bamboo [30], and flax [31, 32]. Wood [33, 34], and cork [35], which are used as natural materials for the rubrication of ecological insulation elements. In the same context, fibrous wood such as vibrae extracted from various parts of the palm tree have attracted the interest of researchers, because of their technically acceptable mechanical properties at low density [36, 37]. It is interesting to note that the renewable parts of the palm tree (petiole and cluster) are the most insulating and lightest [28]. In this field, several studies have been conducted in recent years on the properties of date palm fibers. Among them, we can cite a study on the liffe [39], the cluster arm [28], the spadix stem [29], and another on the rachis [30]. However, date palm fibers have good tensile strength despite a low modulus of elasticity as well as a low specific weight, which results in higher specific strength and stiffness [31-34]. Despite these characteristics of fiber wood and fibers extracted from a date palm, studies of polymers reinforced by these fibers remain insufficient at the current state [35-37]. The idea of using fibrous wood and fibers extracted from the date palm in the materials industry is recent, compared to the use of other varieties of wood and plant fibers [38, 39].

This plant is generally composed of a single, unbranched trunk with a crown of leaves at the top. In what follows, we will identify the different types of wood constituting the palm tree [40]. The palm or " Palm " in English, is a pinnate leaf furnished with leaflets regularly arranged in an oblique position along the upper part of the rachis. The lower segments are transformed into thorns, more or less numerous, and more or less long. The number of palms varies between 30 and 150 palms, arranged in a spiral with a length which reaches 350 to 450 mm. The palm tree produces 10 to 20 palms per year depending on the varieties and the cultivation method. These last live and remain green for 3 to 7 years before they become dry and inclined and then they would be removed by pruning [41, 42].

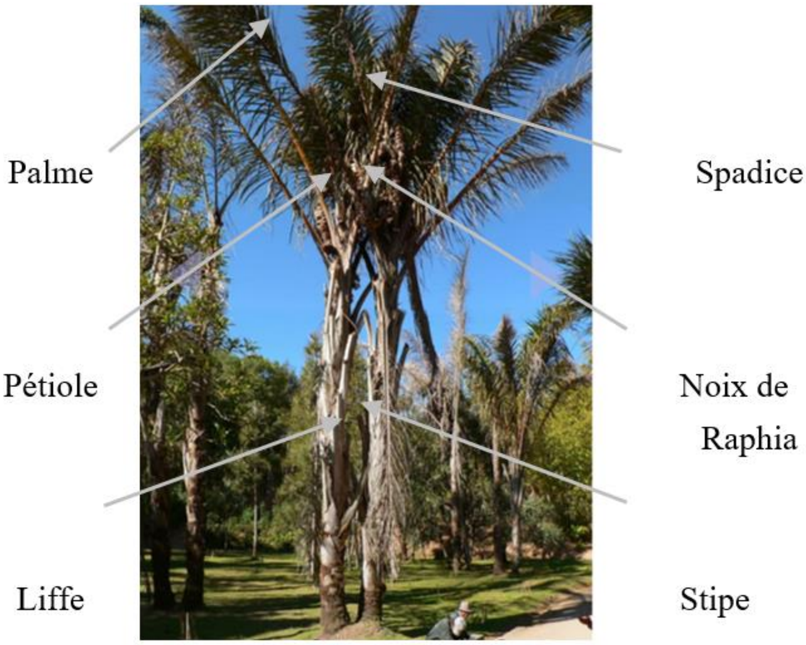

Figure 1. *Different parts of a raffia palm tree.*

2.1.2. Exploitation of the Raffia Palm

Figure 2. *Raffia palm exploitation in Africa, a - roofing made with raffia palms, b - light framework with bamboo, c - basket made from the internal part of the spine, d - semi-modern furniture [13].*

The raffia palm is distinguished by the functional versatility of its trunk (Raffia hookeri), from which raffia wine is extracted [43]. The stipes, which can reach considerable heights, maintain an erect support by producing abundant lignified fibers, associated or not with the conducting vessels. These fibers are also found in the leaves, thus conferring a particular resistance to the latter. The vascular system and the fibers occupy the entire stipe in large vertical bundles. During the growth of the young palm, the stipe initially increases in diameter until reaching a mature circumference, then in height. The diameter therefore freezes early. However, in some species, the stipe can subsequently show an increase in diameter thanks to the increase in the size and number of fibers [44]. The longevity of the stipe cells and the mechanisms ensuring their functional and metabolic maintenance over a prolonged period remain little known, constituting a vast area of research for the future. The absence of secondary growth confers advantages to palms by allowing them to avoid several ecological limitations faced by trees with a cambium. This makes them more resistant to fire, pathogens and wind. However, the continuous activity of the primary tissues prevents them from entering dormancy, which explains their vulnerability to frost and their mainly tropical and subtropical distribution. Modifications of the stipe are also noted in a category of palms adopting a distinct lifestyle, the climbing or rattan palms (e.g. Calamus). These species are characterized by a considerably elongated stipe (which can reach several hundred meters) adorned with thorns and structures favoring the attachment to other trees [45], of great versatility, this palm, through its stipe (Raffia hookeri), produces a renowned wine [46]. The nuts of this palm allow the extraction of an oil prized for food and cosmetics, while the raw rachis and leaves are useful in construction. The fiber from the leaf epidermis is also exploited. Indeed, raw fibers, of significant economic value, are obtained from the upper part of the leaf rachis. Traditionally, these fibers are used in the manufacture of various objects such as ceremonial attire, carpets, blankets, artistic articles, as well as utilitarian objects such as hats, baskets, brooms, ropes and traps; in Europe in particular, they are used as ties for grafting [47]. Raphia fibers are attracting great interest for their various applications, particularly in the textile and construction fields [48]. In Benin, like the different wood species used in various sectors, raffia is used in various fields such as food, pharmacopoeia, firewood, timber, and handicrafts. The rachis of R. hookeri serves as structural components for the manufacture of traditional or semi-modern furniture (Figure 2c, 2d), as well as for lightweight constructions (Figure 2a, 2b). In other local applications, such as the creation of birdcages, the internal part of the rachis is prized for its lightness and mechanical robustness, thus serving as a reinforced frame with the laminated epidermis to fill the structure.

2.1.3. Morphological Properties of the Palm Tree

Cross-sections of the wood of different parts of date palm reported in the literature [49], show that there is a difference between the lumen diameters of the studied wood parts (Figure 3a). Nevertheless, they represent the same texture and the same internal structure. Indeed, the structure is porous forming vessels conducting water and other liquids [49, 50]. These are long tubes, whose inner wall has thickenings that will lead to the formation of discs or grooves of various arrangements (Figure 3b). These tubes are supposed to be responsible for the hydrophilic power of plant fibers [50], fibrillium fibers has been studied by several authors [31, 50]. Its length varies between 100 and 500 mm while its diameter varies between 0.1 and 1 mm these are wide fibers compared to other plant fibers. They are made up of several multicellular fibers, each multicellular fiber contains a central lumen of diameter 2-5 μm [49]. This justifies the important role played by this type of fiber to protect the trunk from external heat [39]. Comparing the average length of trunk, rachis and petiole fibers, trunk fibers are the longest and petiole fibers are the shortest, taking into consideration the diagram of structural parameters of fibers (Figure 3) [51]. Similarly, the diameter of the trunk fibers is wider than that of the petiole fibers (four times wider), [52, 51]. In another place, when compared with the diameter of the leaflet fibers, it is found to be more than 4 times wider [51, 53]. This difference in size certainly comes down to the nature of function of each organ in the date palm.

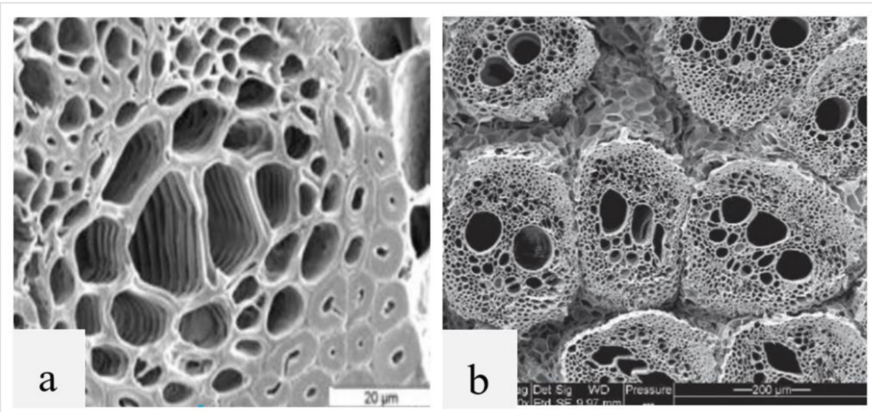

Figure 3. *Micrograph of a cross-section of the wood of different parts of date palm: a- leaflet wood, b - rachis wood [53].*

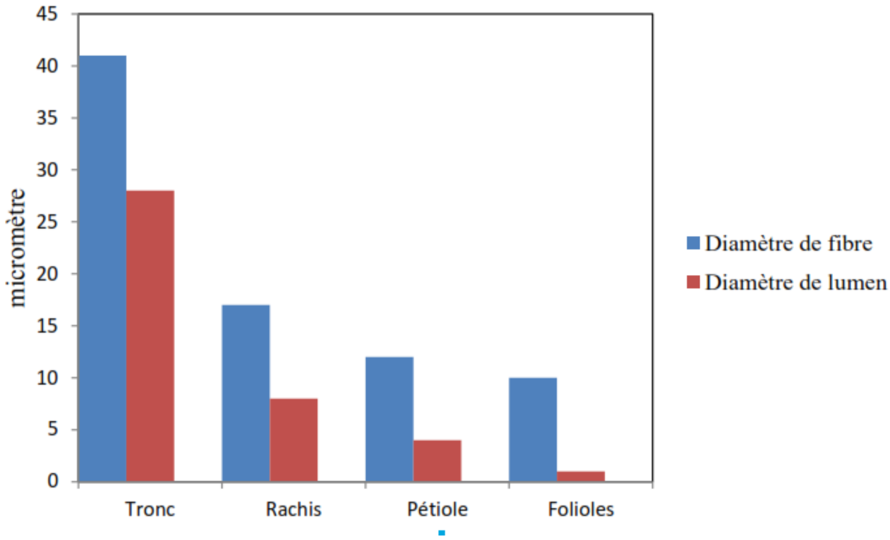

Figure 4. *Comparison of structural parameters of date palm fibers [53].*

2.1.4. Chemical Properties

Date palm wood, like other plant fibers, is made up of three main components: cellulose, hemicelluloses and lignin. The rest of the composition includes extractives, water-solubles and ash mineral matter [49, 53]. The cellulose, hemicellulose and lignin contents of date palm wood vary from one variety to another and within the same variety they depend on the organ, age and growth environment of the date palm [53-55]. However, the proportions of each constituent reported in most studies concerning the same organ are not too different. Palm wood is very rich in lignin. The average rate is around 27%, that of cellulose is around 37% and that of hemicellulose is around 28% [54, 55]. In this way [52], studied the thermodynamic, chemical and dielectric properties of three varieties of date palm wood (Phoenix dactylifera L), from the oases of Biskra in Algeria, in order to use this natural material in the thermal insulation of buildings. A simultaneous determination of thermal conductivity and diffusion coefficient was determined and showed that the date palm is a good thermal insulator for the development of efficient insulating materials. It is in this same perspective that [50], studied the durability of palm fibers treated with different alkaline solutions: calcium hydroxide, sodium hydroxide and Laurent solution with a pH between 12.5 and 12.95. Then, the durability of concrete beams reinforced with treated fibers was evaluated by tensile tests and scanning electron microscopy observations. The results of this study show that date palm fibers are easily attacked by an alkaline solution under the conditions of concrete curing and consequently, the durability of concrete reinforced with these fibers is poor. The average chemical composition of some types of date palm fibers is given in (Table 1).

Table 1. *Chemical composition of some types of date palm wood [50, 56].*

Date palm wood type / Authors	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Others (%)
Leaflets / D. Sibihi et al., 2011	35	28	27	10
Leaflets / P. Khristova et al., 2005	30.3	Nd	31.2	Nd
Leaflets / A. Bendahou et al., 2009	33.5	26	27	13.5
Spine / H. Ammar et al., 2012	41.2	28.5	27.3	3
Spine / R. Khiari et al., 2010	45	29.8	27.2	5
Spine / MMS El Morsy et al., 1980	44	28	14	2.5
Spine / P. Khristova et al., 2005	43.1	Nd	23.8	5.6
Fibrillium / A. Kriker et al., 2005	43	8	35	14
Fibrillium / A. Hammami et al., 2005	46	18	20	16

Date palm wood type / Authors	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Others (%)
Petiole / SI Salih, 2013	75.6		16.8	7.6
Trunk / FF Bassat	45	23	Nd	Nd

A characteristic of natural fibers is the variation in mechanical and chemical properties due to the variation in their composition. The origin of this variation in composition is on the one hand the fact that there are several varieties of plants [56].

2.1.5. Physical and Mechanical Characteristics of Raffia Palms and Other Similar Species

The physical and mechanical properties of raffia palms are almost non-existent. In this work, we present preliminary results on the physico-mechanical properties of raffia fiber. Scanning electron microscopy reveals a layered structure: an outer layer with scales, and an inner alveolar layer of the "honeycomb" type. FTIR-ATR spectra and X-ray diffraction measurements reveal the presence of a crystalline phase of cellulose. Mechanical tests have determined a Young's modulus of around 30 GPa and a breaking stress of about 0.5 GPa for a total deformation of about 2% [47].

We present these characteristics by considering the specificities of other similar palms. The physical and mechanical characteristics of palms are of paramount importance for their adaptation and prosperity in diverse environments, giving them the ability to withstand sometimes hostile climatic conditions while preserving their unique structure and vital functions. Several researchers have devoted their efforts to the in-depth analysis of these physical and mechanical characteristics specific to palms.

The integration of plant fibers in the manufacture of bio-composite materials is experiencing significant growth in various industrial sectors, due to their natural availability and ease of extraction. The research conducted by [57], focused on a natural material, namely the cluster wood of the date palm. Microscopic observations clearly identified two distinct layers, designated as the "skin" and the "core". Measurement of the fiber concentration in these two layers revealed an average fiber content of 29% in the skin and 25% in the core, as well as an average moisture content of 228% when both layers are intact, with values of 204% and 286% for the skin and the core, respectively. The mechanical analysis of these different wood layers was carried out using the tensile test, highlighting a Young's modulus of 9124 MPa in the linear part of the stress-strain curve, for a maximum deformation not exceeding 0.6%. The core layer showed a maximum stress of σmax = 54MPa, while the skin displayed a Young's modulus of 10538MPa for a limit deformation not exceeding 1%, with a maximum stress of σmax = 84MPa.

Physical and mechanical properties according to [58], The following curve represents the average moisture content of different layers of the cluster wood (Figure 5a). Determining the value of Young's modulus from the curve (Figure 5b), the value of Young's modulus corresponds to the slope of the linear part of the curve.

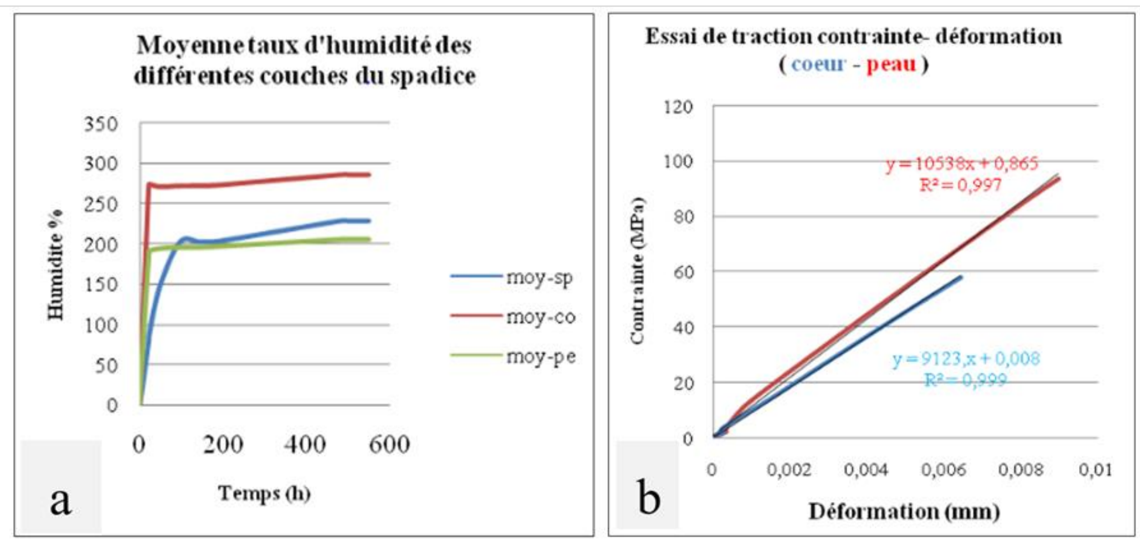

__Figure 5.__ a - Average moisture content of different layers of spadix wood, b - Stress-strain tensile curve of different layers of spadix wood [58].

The development of new composite materials mainly adapted to thermal insulation in different sectors, particularly in the field of sustainable buildings, constitutes the main objective of the Materials and Thermal Habitat (MTH) theme. In this context, an approach based on the use of natural and renewable by-products of the date palm for the thermal insulation of housing is adopted by the PHC Tassili 16MDU976 project entitled Development of new bio-sourced materials based on PHC Tassili 16MDU976 entitled Development of new bio-sourced materials based on The originality of this approach will consist in valorizing and reducing waste by integrating them into more efficient materials in order to reduce the energy consumption of buildings. The thermo-physical properties of date palm wood was studied using samples in parallelepiped form (kornaf). The results of the thermophysical study revealed that [59], the effect of fiber orientation on thermal conductivity is negligible, date palm varieties have a low effect on thermal conductivity with an average value of 0.083$Wm^{-1}.K^{-1}$ measured at atmospheric pressure.

The thermal conductivity of date palm wood is close to the range of many natural insulation materials. The density of date palm wood is slightly higher than that of cork and hemp (276 $kg.m^{-3}$ for the petiole part of Deglet-Noor type date palm). The results of thermogravimetric analysis (mass loss vs. temperature) on the fibers surrounding the date palm stem revealed that the degradation temperature is about 250℃. These results are comparable to those obtained with other types of natural fibers such as sisal [49]. The mechanical properties of date palm fibers were determined and compared with other natural fibers (Table 2).

Table 2. *Mechanical properties of some natural fibers [60].*

Fiber	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Date palm	97-196	2.5-5.4	2.0-4.5
Hemp	690	70	1.6
Sisial	511-635	9.4-22	2.0-2.5

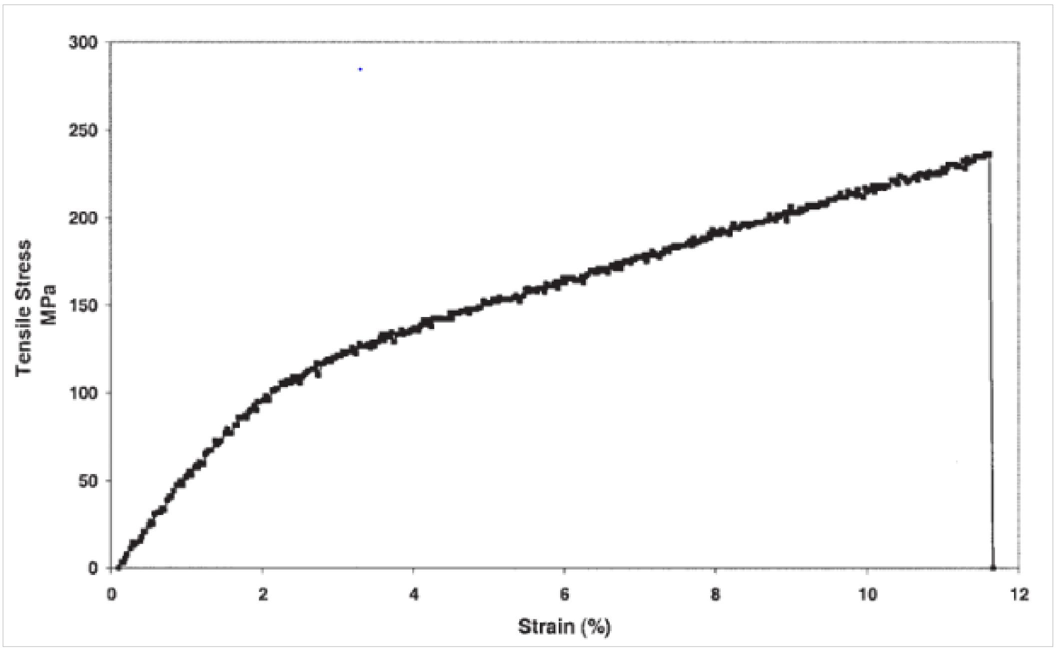

Figure 6. *Typical stress-strain curve of date palm fibers with 10 mm length [49, 59].*

The stress-strain curve of date palm fibers with 10 mm length [59], is characterized by an initial linear region followed by a curvature indicating the increase in strain rate with stress. This behavior is similar to other types of natural fibers [49]. Typical values of tensile strength of date palm fibers were between 97 and 196 MPa, while values for Young's modulus were between 2.5 and 5.4 GPa. In addition, the elongation at break was between 5 and 10%.

According to the comparison made in Table 1, the tensile strength of date palm fibers is low compared to other natural fibers. Furthermore, a similar observation can be made on Young's modulus. These low mechanical properties of date palm fibers can be attributed to their large diameters which were between 100 and 1000 µm [49]. This diameter range is larger in general than other natural fibers.

It is in this same logic that researchers have deepened other aspects relating to the physical and mechanical characteristics of palm trees [47], several fibers were deformed in uniaxial traction at a constant strain rate of the order of 3x10 -4 s -1 and at room temperature (25 ℃). Figure 4 illustrates the resulting macroscopic mechanical behavior. This curve has the typical appearance of that of ductile semi-crystalline polymer materials above the Tg. After an elastic domain (Fe = 10.5 N), the material "plasticizes" and presents a maximum, followed by softening, then a very short plateau. Then the load increases up to the breaking point. Classically, the increase in load is linked to the alignment-elongation of amorphous chains along the direction of stress [61], experimentally determined the mechanical properties of date palm stems (rachis). The test results show that the tensile strength of the stem wall is between 116 to 208N/mm^2, while the core properties of the spine are close to half of these values. The elastic modulus of the stems is between 10 to 30KN/mm^2 [62], studied the effect of chemical treatment with different concentrations of alkali (0.5%, 1%, 1.5%, 2.5% and 5%) and acid treatment with 0.3, 0.9 and 1.6 N on the trunk surface fiber (Lif). All treatments were carried out at 100 ℃ for 1 h. Different experimental techniques such as surface morphology, thermal gravimetric analysis (TGA), Fourier transform infrared spectroscopy (FTIR), mechanical tests and chemical analysis of Lif, showed that the sample treated with 1% alkali has optimum mechanical property. Hydrochloric acid treatment resulted in deterioration of mechanical properties [31], examined date palm surface fibers (Lif) extracted from four varieties of date palm. Their mechanical and physical properties are determined based on curing in water and in a hot and dry climate. The results found are represented in (Table 3).

Table 3. *Mechanical properties of some varieties of palm tree [31].*

Dry				**Wet**		
Variety	**Breaking strength (MPa)**	**Elongation at break (%)**	**Modulus of elasticity (GPa)**	**Breaking strength (MPa)**	**Elongation at break (%)**	**Modulus of elasticity (GPa)**
Dokar	290 ±20	11 ±2	5.2 ±3	300 ±20	12 ±2	3.55 ±2
Elgers	88.75 ±20	11.1 ±2.5	3.5 ±1.2	90.10 ±18	12 ±3	3.10 ±1.5
Deglet-Nour	72.34 ±18	8.7 ±2.2	3.15 ±1.5	74.34 ±1.5	9.5 ±2.5	2.3 ±2
Degla - Bida	71, 15 ±16	7.5 ±2.3	2.5 ±1	73, 19 ±13	8.5 ±2.7	2.10 ±1

According to Table 3, Dokhar fibers are the strongest and most elongable. In addition, humidity slightly increases the strength and elongation at break of the fibers. However, in the dry state, the fibers have a slightly higher modulus of elasticity than in the wet state. Adil Sbiai [35], applied a cellulose modification method by TEMPO oxidation to lignocellulosic fibers of the date palm leaflet. The results of the chemical composition revealed that the date palm leaflet fibers are mainly composed of cellulose, lignin and hemicelluloses. This same analysis revealed that the distribution of the fiber constituents after TEMPO oxidation is significantly modified compared to the distribution of the constituents of the initial non-oxidized fiber. This results from the strong degradation of lignin in the strongly alkaline oxidation environment and a slight decrease in the hemicellulose content. On the other hand, this study showed a positive effect of oxidation on the progress of RTM (resin transfer molding) injection. Better wettability of the resin-oxidized fiber mat is the reason for the improvement of the process.

Several researchers have elaborated the crucial variables that determine the overall properties of fibers are: structure, microfibrillar angle, cell dimensions, chemical composition [63]. In addition, the mode of fiber extraction and independent and variable characteristics (natural defects, growth environment, climate and age of the plant, location of the fiber in the plant, etc.).

Generally, the tensile strength and Young's modulus of plant fibers increase with increasing cellulose content. Fiber failure occurs when a matrix element loses its bonding with the reinforcing fibrils and the hydrogen bond in the cellulose microfibrils is broken. Therefore, the lower the cellulose content, the lower the tensile strength [64].

Mechanical properties are affected by the presence of the lumen, which is most often neglected considering the full cross-section. Indeed, when the lumen diameter is large compared to that of the fiber, the actual section of the fiber walls is smaller, which leads to an underestimation of the mechanical properties. Similarly, water absorbed by plant fibers infiltrates into the pores and amorphous regions of the fibers, reducing the cohesion between microfibrils and acts as a plasticizer [65, 66], transforming the pectic matrix into an almost fluid gel [67]. On the other hand, water absorption has little effect on cellulose and hemicellulose; the rigidity of the crystalline regions is not affected by increased humidity [68]. Humidity causes the formation of fungi on the fiber surface after 3 days of exposure, which degrades the fiber and decreases its mechanical properties [69].

The hierarchical structure of natural plant fibers gives the fibrous material excellent property performance. Hemicellulose molecules are linked with hydrogen bonding to cellulose and act as a cementing matrix between cellulose microfibrils, forming the cellulose/hemicellulose network, which is considered the main structural component of the fiber cell [70]. Some important physical elements must be known about each plant fiber before it is used to achieve the maximum potential [71], such as shape, size, fibrillar angle, cell wall thickness, crystallinity rate. The presence of the lumen decreases the bulk density of the fiber and acts as an acoustic and thermal insulator. The dimensions of individual cells of lignocellulosic fibers depend on the species, maturity and location of the fibers in the plant and also on the fiber extraction conditions [72].

2.2. Review of the Literature on Cement Matrix Composite Materials

General Concepts on Cement Matrix Composite Materials

Definition and different types of composite materials

A composite material is a material made up of two or more distinct substances, combined in such a way as to obtain properties superior to those of the individual materials. Typically, these materials are composed of a framework called reinforcement, which provides the mechanical strength of the composite material. Reinforcement allows composite materials to have isotropic, anisotropic, or orthotropic properties (which improves strength and rigidity), and a matrix, which binds the components together.

Table 4. *Specific stiffness of some materials [73].*

Material	Density (t/m3)	Young's modulus (GPa)	Specific stiffness
Aluminum	2.7	71	26.3
Boron	2.63	400	152
Beryllium	1.8	315	175
Magnesium	1.74	42	24.1
Titanium	4.51	120	26.6
Steel	7.8	210	26.9
Tungsten	19.3	411	21.3
Zirconium	6.49	94	14.5
Polyethylene Polycarbonate Polyepoxide Polyester	0.93	0.2	0.2
	1.3	2.4	1.8
	1.3	2.4	1.8
	1.35	5	3.7
Al2O3	4	500	125
AlN	3.3	350	106
SiC	3.2	700	218.8
Si3N4	3.1	380	122.6
BeO	3	357	119
Wood (spica pine)	0.39	13	33.3

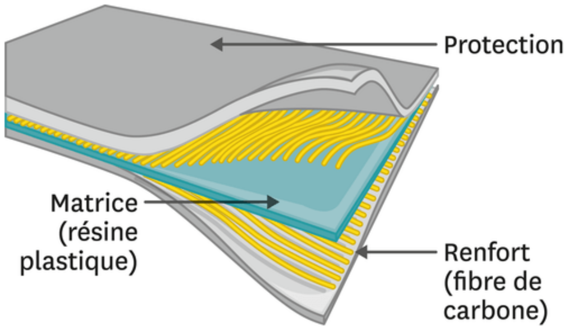

Figure 7. *Composite material diagram [73].*

Today there are a large number of composite materials that can be classified either according to the shape of the components or according to the nature of the components [74].

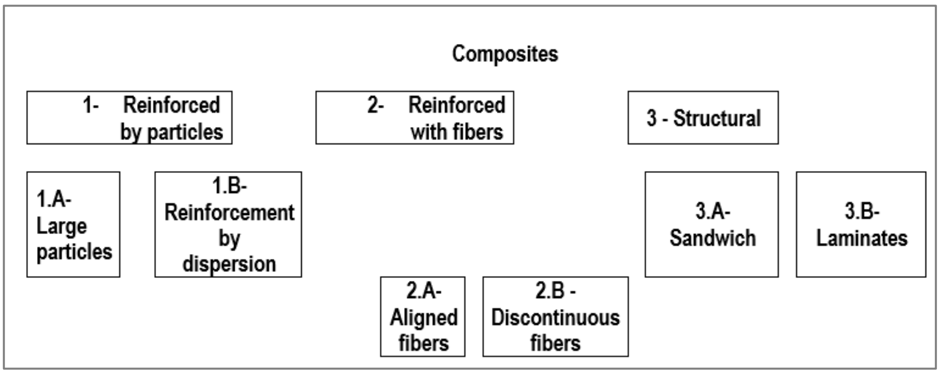

Figure 8. *Schematic classification of different types of composites [74].*

2.3. According to Geometry

2.3.1. Fiber Composites

A composite material is a fiber composite if the reinforcement is in the form of fibers. The fibers used are either in the form of continuous fibers or in the form of discontinuous fibers: chopped fibers, short fibers. The arrangement of the fibers and their orientation make it possible to modulate the mechanical properties of composite materials, to obtain materials ranging from highly anisotropic materials to isotropic materials in a plane.

2.3.2. Structural Composites

Reinforcement can be produced using randomly dispersed fibers or fibers oriented in one or more directions. Reinforcement axes can be defined by crossing threads (weaving). 3D structures have also been developed to improve material reinforcement and address delamination issues.

Laminates consist of a stack of monolayers, each with a specific orientation in a common frame of reference for the different layers and referred to as the laminate frame of reference. By manipulating the order and orientation of these layers, it is possible to carefully customize the mechanical characteristics of the laminate according to external constraints, thus achieving a high level of optimization by optimally allocating material.

The structures of woven composites are characterized by an arrangement of fibers braided or arranged in "cables" called strands or simply threads, each grouping several hundred or even thousands of fibers. These threads are then interwoven in more or less complex patterns, these fabric patterns can present a significant diversity in order to meet the specific properties required of the material.

Sandwich material, the ASTM C393 standard (ASTM, 2008) defines the sandwich structure as follows: "A sandwich structure is a special form of laminated composites composed of different materials glued together whose purpose is to compensate the properties of each component thus improving the behavior of the entire structure." Thus, a sandwich panel is a structure made up of 3 main layers: two outer layers called skins (or soles) and a central, inner layer, sandwiched and called the core. The skins are often made of rigid and tensile materials, and capable of being formed into layers, such as metals, wood, or composites [75]. The choice of skins is made mainly according to the mechanical performance requirements for the sandwich. It has great lightness in flexion and is an excellent thermal insulator.

2.3.3. Nature of the Constituents

Depending on the nature of the matrix, composite materials are classified and various reinforcements are associated with these matrices. Only certain combinations between matrices and fibers are possible and currently have industrial use, while others are being developed in research laboratories.

Organic matrix composites (OMCs) which constitute, by far, the largest volumes today on an industrial scale. Ceramic matrix composites (CMCs) are reserved for very high-tech applications and working at high temperatures such as in the fields space, nuclear and military. Matrix composites metallic (CMM) is a material combining two elements, a metallic matrix, for example aluminum, magnesium, zinc; a metallic or ceramic reinforcement, such as steel wires, silicon carbide (SiC) particles, carbon fibers, alumina (Figure 9).

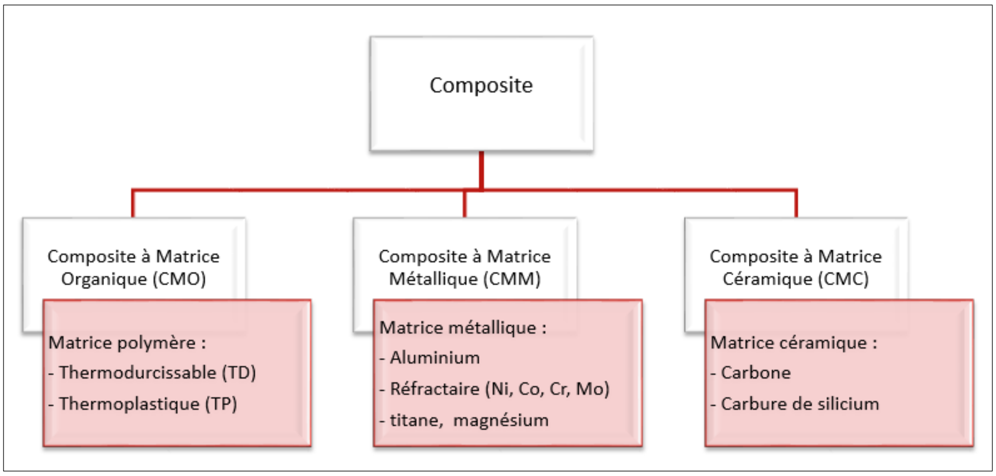

Figure 9. *Type of Composites [76, 77].*

2.3.4. Matrices

In many cases, the matrix constituting the composite material is a polymer resin. Polymer resins exist in large numbers and each has a particular area of use [78]. The matrices essentially have the role of transferring the stresses applied to the material to the fibers, protecting them against external aggressions and giving the shape of the material. They must also be sufficiently deformable and present a certain compatibility with the reinforcement in order to be able to provide composite materials with sufficiently high mechanical properties. The classification of the types of matrices commonly encountered is given in (Figure 10).

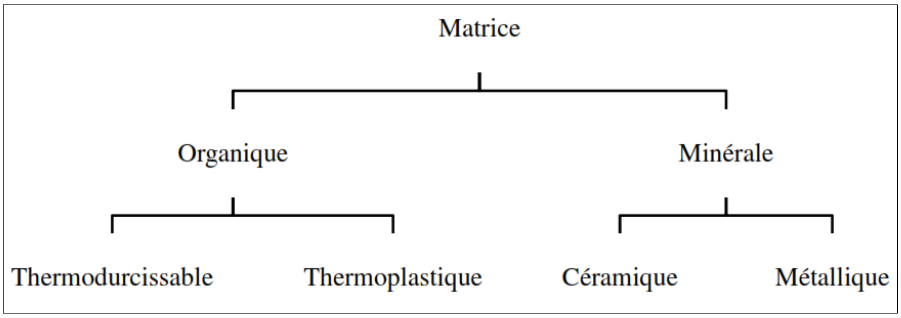

Figure 10. *Matrix Types [76, 78].*

The cementitious matrix is a product obtained from the mixture of granular skeletons, cement binder and additive materials with a reasonable amount of water. Its purpose, after being hardened, is to generate the load transfer between the reinforcing textiles in the textile reinforced concrete (TRCs). Therefore, it must have satisfactory physical properties in the fresh state to adequately penetrate towards reinforcing textiles to ensure good adhesion at the matrix/textile interface. The maximum grain diameter in the cementitious matrix is generally less than 2 mm, as well as it must be compatible with the geometry of the reinforcing textile used, and the thickness of the TRC composites. In particular, the cementitious matrix must have chemical compatibility with the reinforcing textile to ensure long-term durability of TRC resistance. Sometimes, the cementitious matrix plays a significant role as a protective layer in specific environments such as corrosion or high temperature. The cement matrix can be classified into main groups based on the nature of the binder product (cement) as recently reported in the work of [79-81]. This matrix (cement) is obtained in the following way: Limestone and clay rocks are recovered from quarries and crushed; they are then mixed (approximately 80% limestone and 20% clay); Then they are ground and fired at very high temperatures (1450 ℃), the material obtained after sudden cooling is called Clinker. The Clinker is then ground and heated and cement is obtained in powder form (Figure 11) [82].

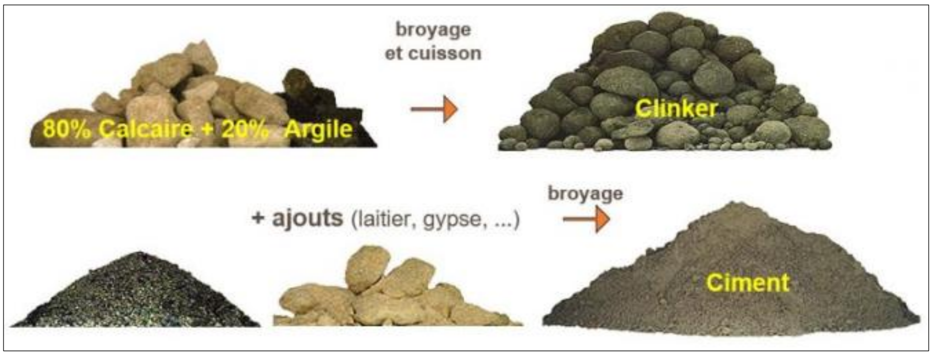

Figure 11. *The main stages of cement manufacturing [82].*

The chemical composition guarantees the qualities of the cement in the long term, that is to say during its manufacture, it is composed of 65% of Clinker (CaCO3) and 35% of other constituents, including blast furnace slag (This is a mixture composed essentially of silicates , aluminates Al2SiO5 and lime CaO with various metal oxides , except iron oxides . Its roles in the metallurgy of molten ferrous metals are multiple), silica fume (Silica fume, also called fumed silica, has the chemical formula SiO2 . It is a form of silicon dioxide, or silica, which is a colorless solid found abundantly in the natural environment and in various living beings), pozzolan (Pozzolan is mainly composed of silica (SIO2) at a rate of 42 to 55%, alumina (AL 2 O 3) at a rate of 12 to 24%, and iron sesquioxide (FE 2 O 3) at a rate of 8 to 20%), fly ash, limestone and 5% gypsum (CaSO42H2O) to regulate the setting [82].

2.3.5. Reinforcements

Often in the form of fibers, the purpose of reinforcements in composite materials is essentially to increase their mechanical properties (rigidity, breaking strength, hardness, etc.) and to improve physical properties, such as fire and abrasion behavior, temperature resistance or electrical properties. The characteristics sought in reinforcements are low density, compatibility with matrices and ease of processing [83]. Reinforcements made of fibers come in the following forms: linear (threads, wicks), surface fabrics (fabrics, mats), multidirectional (braid, complex fabrics, tri-directional weaving) [84]. The classification of commonly encountered reinforcement types is shown in (Figure 12).

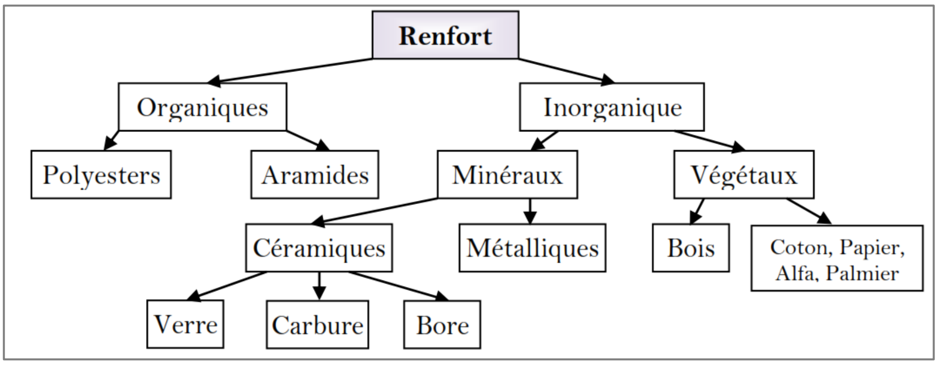

Figure 12. *Types of reinforcement [78, 73].*

Table 5. *Properties of some reinforcements [73].*

Fiber	Density	Rr_traction (GPa)	Ar (%)	E (GPa)
Glass E	2.54	3.4	4.8	73
Glass R	2.48	4.4	5.4	86
Low modulus aramid	1.45	3.1	2	70
Low modulus aramid	1.45	3.1	1	130
High toughness carbon	1.78	2.8	0.5	200
High modulus carbon	1.8	2.2	-	4 00
Boron	2.	3.5	0.8	4 00
C10 steel	7.85	1	-	210
Aluminum	2.63	0.358	-	69.8

2.3.6. Advantages and Disadvantages of Composites

Natural fibers (NF) have attracted increasing interest as a reinforcing element for matrix systems (polymeric, inorganic or combination of both), which has given rise to extensive research in several disciplines (civil, military, industrial, space and biomedical sectors, etc.) and which seek to develop and integrate new ecological and biodegradable materials, due to their interesting mechanical properties [35, 85]: (i) cost and weight reduction (ii) reduction of the environmental impacts of industrial products and (iii) renewable (Table 6). Therefore, the application has long been limited to non-structural assemblies, the reason for which lies in the traditional defects of composites, including low strength (mechanical and impact), degradation by wet process and formal fiber/matrix incompatibility, etc. Recent research [86-89], adapted for natural fibers, allows to improve the mechanical properties as well as the adhesion of the fibers to the matrix and to limit moisture absorption.

Plant fibers also have a number of disadvantages that result mainly from their natural character. Therefore, the high variability of structural properties, climate, plant age and chemical composition lead to a change in their mechanical and thermo-physical properties. For example, the cellulose content, which is the main component of a plant fiber, the amount of which directly influences the mechanical properties of the fiber, varies depending on the age of the plant.

Table 6. *Advantages and disadvantages of natural fibers [90].*

Benefits	Disadvantages
Significant and renewable availability	Poor dimensional stability
Lower cost	Low moisture resistance
Remarkable biodegradability	Low interfacial adhesion
No CO2 emissions (absorption)	Hydrophilic/hydrophobic interaction
Rigidity and soundproofing	Incompatible with thermoplastics
Good energy behavior	Limited temperature conditions of use
High breaking strength	Water absorption
Excellent specific module	Dispersion of properties
Reduced tool abrasion	

2.3.7. Thermo-physical and Mechanical Behavior of Cementitious Bio-composites with FPD

Ordinary Portland cement (OPC) mortars are the most widely used construction materials worldwide, recognized for their low cost and wide applicability and availability [91]. Their quasi-brittle characteristics, high compressive strength, low tensile strength, and low crack opening resistance are the main disadvantages of conventional concrete and OPC cementitious materials.

To overcome the low flexural strength and crack opening resistance of CPO-based concrete and mortars, as well as to improve the tensile strength and enhance the durability properties, i.e., thermal shock and fatigue resistance, vegetable fiber (VF) reinforcement is implemented [92-94]. Various VFs and synthetics have been used to limit crack growth in concrete and CPO cementitious materials. Among them, much effort has been devoted to the study of date palm fibers (FPD) as reinforcement for CPO concrete and mortars [38], investigated the thermo-physical behavior of an FPD-reinforced bio-mortar for three different lengths (3mm, 6mm and mix). It is reported that the addition of FPD in the mortar matrix produces a significant increase in water absorption (Figure 13b), as well as a significant reduction in the thermal conductivity of the composite (Figure 13a). This reduction is expected because date palm fibers have a lower thermal conductivity than the mortar matrix, and the thermal conductivity of porous materials is governed by the pores (voids) and grain size in the sample that are created by the addition of the fibers. The results obtained in this axis revolve around a reduction in thermal conductivity with an increase in the water absorption rate with the addition of FPD.

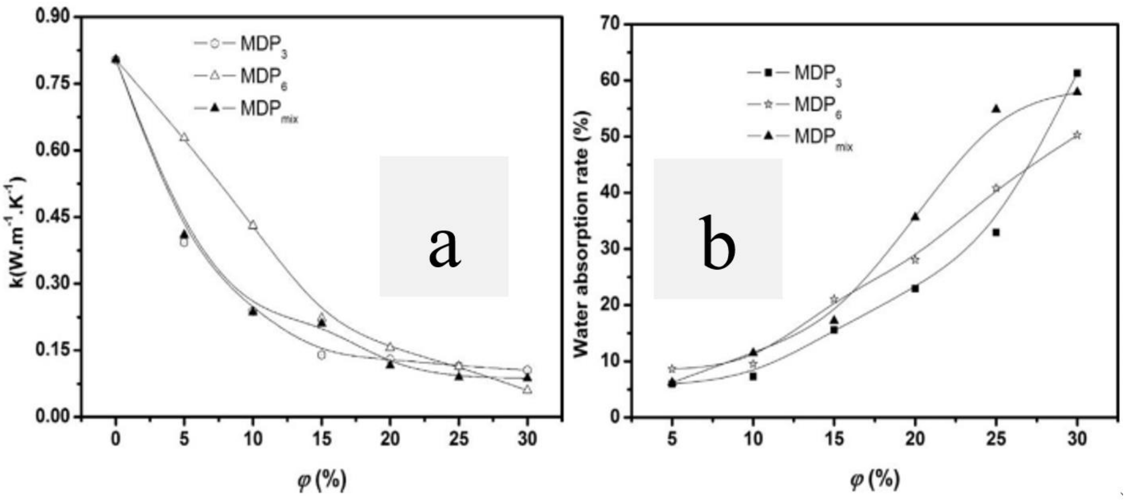

Figure 13. *Evolution of: a - Thermal conductivity, b - Water absorption of mortar/FPD composites as a function of fiber content [38].*

In addition, the identification of the mechanical behavior of construction materials and more precisely the mortar is governed by the compressive strength and flexural strength, which are evaluated by [95]. In (Figure 14c-d), the variation of the flexural strength of mortars reinforced with different plant fibers, namely: MT: Control Mortar, MPP: Mortar with Polypropylene fiber, MAF: Mortar with Alfa fiber, MDS: Mortar with Dis fiber, MPD: Mortar with date palm fiber and MCV: Mortar with hemp fiber, and those according to the deformation, have been shown. From the curves in this figure, the authors found that mortars reinforced with FPDs (MPD) and those reinforced with hemp fibers (MCV) have better flexural strength compared to other fibers including mortar without fiber (MT).

It is reported in (Figure 14) presented by [60], that the flexural strength of different mortars (without or with fibers) is continuously increasing according to the curing time (7, 14, 21 and 28 days), and that the mortars reinforced with 10% of FPD (MCDS10) presented the best flexural strength. In conclusion, the date palm fiber reinforced construction composites (DPFCs) offer very impressive advantages in all their levels.

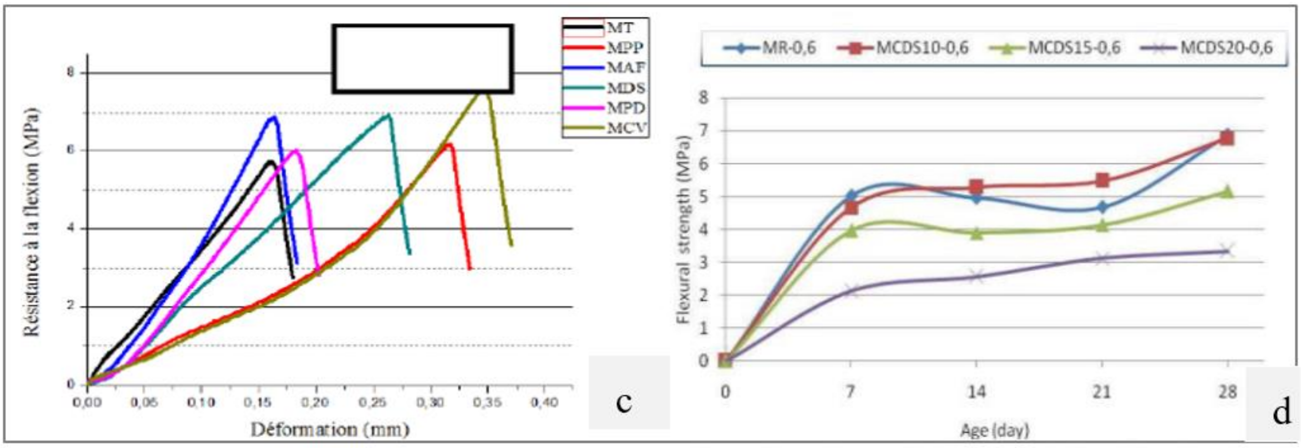

Figure 14. 3-point flexural strength of: c - Varieties of bio-composites; MT, MPP, MAF, MDS, MPD, MCV and. d - Palm fiber reinforced bio-mortar with different fiber% (10%, 20%, and 30%) [95].

2.3.8. Hygrothermal Properties

Based on the work of [96], the concrete formulation incorporating 15% date palm wood fibers was then developed by [97]. First, an experimental study was conducted to analyze the water properties and thermal conductivity of date palm fiber concrete (DPC). The experimental results highlighted that DPC is a water vapor permeable material, due to its microstructure. Its water vapor diffusion resistance was estimated at 4.4, a value considerably lower than that of conventional construction materials such as conventional concrete and autoclaved aerated concrete, which have values of 130 and 10, respectively. (Table 7).

Table 7. Water diffusivity results [97-99].

Mass concentration%	Resistance to water vapor diffusion
CPD	4.4
LHM-wall	4.8
Solid concrete	130
Autoclaved cellular concrete	10

The water diffusivity of date palm fiber concrete (DPC) was estimated based on its water vapor permeability and the sorption isotherm. The shape of the curve thus obtained is consistent with De Vries' theory. The average value determined in the hygroscopic range revealed significant water diffusion for DPC. The thermal conductivity in dry conditions is lower than 0.3 W. $m^{-1}K^{-1}$, similar to the "LHM-wall" hemp concrete. According to the RILEM classification, lightweight aggregate concretes with a thermal conductivity lower than 0.3 W. $m^{-1}K^{-1}$ meet the thermal insulation requirements. However, the impact of humidity (80% RH) on thermal conductivity remains limited, with the results remaining within a range compatible with the thermal insulation criteria. Numerous studies on the thermo-physical properties of bio-sourced materials confirm the dependence of thermal conductivity on humidity, due to the high hygroscopy of these materials [100−102]. The presence of humidity in the sample reduces the proportion of air in the pores, thus decreasing its insulation capabilities and thermal capacity, [100, 29]. For example, the apparent thermal conductivity can increase by a third when the water content of the sample increases from 2% to 11% at an ambient temperature of 30 ℃ (Figure 15).

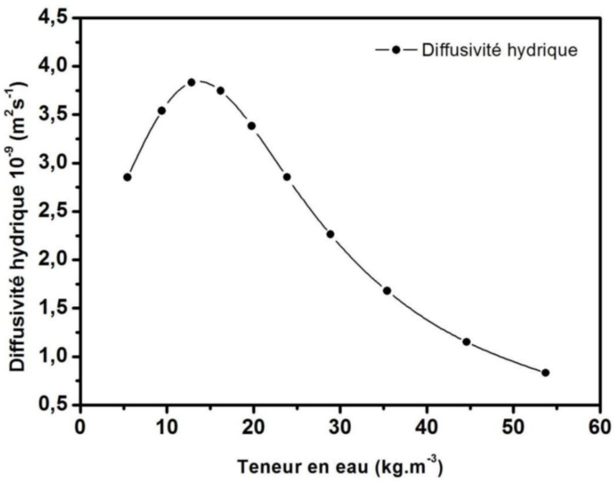

Figure 15. Evolution of water diffusivity for DPC [26].

2.3.9. Mechanical Properties of Composites

Mechanical testing is an essential step in accessing the characteristic quantities of materials, from Young's modulus to the elastic limit, including toughness or fatigue resistance, and this under variable conditions, for example temperature or stress speed.

They are therefore experiments whose aim is to characterize the behavior laws of materials that establish a relationship between constraints (pressure = force/surface) and deformations (dimensionless unit elongation). A deformation should not be confused with a displacement or an expansion.

However, the deformation of a part depends on the geometry of the part and the way in which external forces are exerted on this part. It is therefore necessary to standardize the tests. These standards therefore define:

1) the shape of the test piece whose material is being tested; we then speak of a standardized test piece;
2) How the forces are exerted on the test piece, we then speak of a standardized test.

The mechanical behavior study of Date Palm Wood Gypsum composites showed that the compressive and flexural strength of gypsum-fiber composites decreases with increasing fiber concentration. The authors also revealed that the values of flexural and compressive strength of composites filled with fine fibers are higher than those of composites prepared with coarse fibers and for concentrations above 2% (Figure 16).

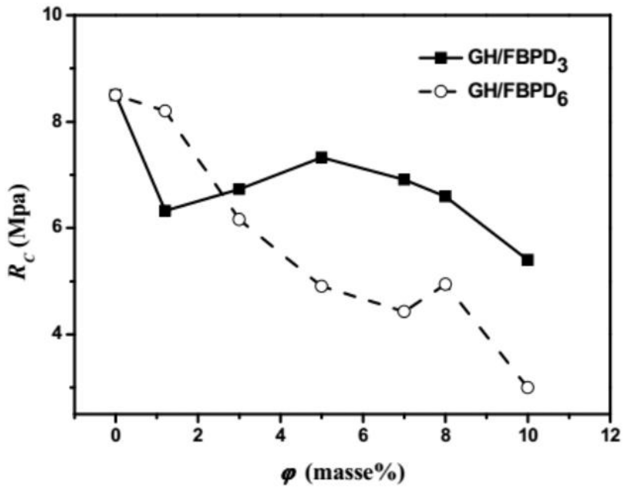

Figure 16. *Compressive strength of gypsum-fiber composites at the 28th day (20) [26].*

3. Conclusion

This article is dedicated to the description of the raffia palm, its nuts, as well as other similar species. It aims to identify the physical, thermal, and mechanical properties of raffia palms. These properties are analyzed using scanning electron microscopy (SEM), which reveal a layered structure, as well as measurements made by X-ray diffraction (XPD). Based on the most extensive results obtained by the experimental method, mechanical tests have determined a Young's modulus of approximately 30 GPa and a stress of 0.5 GPa for raffia palms, for a total deformation of 2%. Without omitting some varieties of the palm Lif, which have established the breaking strength, elongation at break, and modulus of elasticity in dry and wet states. The chemical properties of some types of date palm wood which is a similar species of raffia farinifera are illustrated in (Table 1), then the morphological, anatomical and technological properties of these related species. farinifera nuts into the cement matrix, despite the limitations of the results obtained concerning palm trees, which still require improvements. Several researchers have conducted studies on the variation of mechanical properties of natural fibers, particularly Young's modulus and Poisson's ratio. Similarly, the physical properties of Raphia farinifera nuts have been investigated, including the Los Angeles and Micro-Deval tests, which are used to measure the combined resistance to impact and wear due to friction between aggregate elements. These parameters will enable us to incorporate these nuts into a cement matrix, which will be the subject of future publications.

Abbreviations

CMO	Organic Matrix Composites
CMC	Ceramic Matrix Composites
CMM	Matrix Composites Metallic
PAG	Based on the Government Action Program
UNEP	United Nations Environment Program
TRC	Textile Reinforced Concrete
FPD	Date Palm Fibers

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Lobouaka Mokandzi Owen Paverl: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software Writing,-original draft

Fannou Jean-Louis Comlan: Formal Analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing-review & editing

Adamon Gildas David Farid: Methodology, Project administration, Resources, Supervision, Validation, Writing-review & editing

Doko Valery Kouandété: Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing-review & editing

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Research Field

Lobouaka Mokandzi Owen Paverl: Materials Engineering, Test Instrumentation, Modeling, Building Energy Efficiency, composite Materials.