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Journal of Natural Fibers

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/wjnf20

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To cite this article: Mazhar Hussain, Daniel Levacher, Nathalie Leblanc, Hafida Zmamou, Irini Djeran-Maigre, Andry Razakamanantsoa & Léo Saouti (2023) Analysis of physical and mechanical characteristics of tropical natural fibers for their use in civil engineering applications, Journal of Natural Fibers, 20:1, 2164104, DOI: 10.1080/15440478.2022.2164104

To link to this article: https://doi.org/10.1080/15440478.2022.2164104

JOURNAL OF NATURAL FIBERS
2023, VOL. 20, NO. 1, 2164104
https://doi.org/10.1080/15440478.2022.2164104

Analysis of physical and mechanical characteristics of tropical natural fibers for their use in civil engineering applications

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ABSTRACT
Natural fibers investigated in this study are mainly waste from agro industry. The importance of natural fibers in building composites is increasing, as they partially replace nonrenewable natural resources acting as reinforcement in composite materials such as concrete, mortar and earth bricks. Their recycling requires a detailed analysis of the physical, chemical, and mechanical characteristics of the fibers. In this study, tropical natural fibers *i.e.*, palm oil flower fibers (POFL), palm oil fruit fibers (POFR), sugarcane bagasse (Sc), coconut coir (Cn), and banana spine (Bs) were investigated, and their characteristics such as cross-section, density, water absorption, thermogravimetry, chemical composition, and tensile strength of fibers were determined. The area of these fibers ranges from 0.03 mm^2 to 0.07 mm^2. POFL fibers have highest density (1.36 g/cm^3), while Cn fibers have lowest density (0.79 g/cm^3). Chemical composition of fibers shows that cellulose content of tropical fibers ranges from 37–54%, followed by hemicellulose 5–27%, and lignin and cutins content 5–25%. Mechanical characteristics of tropical fibers show that tensile strength of these fibers fluctuates between 119–347 MPa. Tensile load-deflection behavior of Cn, Bs, POFL, and POFR fibers is elastoplastic with hardening, while the behavior of Sc fibers is pseudo elastic.

KEYWORDS
Tropical fibers; fiber's characteristics; mechanical behavior; waste material; recycling

关键词
热带纤维; 纤维的特性; 机械性能; 废料; 回收

摘要
本研究中研究的天然纤维主要是农业工业的废弃物. 天然纤维在建筑复合材料中的重要性正在增加, 因为它们部分取代了不可再生的自然资源, 在混凝土、砂浆和土砖等复合材料中起到加固作用. 它们的回收需要对纤维的物理、化学和机械特性进行详细分析. 在本研究中, 研究了热带天然纤维, 即棕榈油花纤维（POFL）、棕榈油果纤维（POFR）、甘蔗渣（Sc）、椰子椰壳（Cn）和香蕉脊（Bs）, 并测定了它们的横截面、密度、吸水率、热重、化学成分和拉伸强度等特性。这些纤维的面积范围为0.03 mm2至0.07 mm2. POFL纤维的密度最高（1.36 g/cm3）, 而Cn纤维的密度最低（0.79 g/cm3）. 纤维的化学成分表明, 热带纤维的纤维素含量在37%至54%之间, 其次是半纤维素5-27%, 木质素和角质含量5-25%. 热带纤维的机械特性表明, 这些纤维的拉伸强度在119至347MPa之间波动. Cn、Bs、POFL和POFR纤维的拉伸载荷-挠度行为是硬化弹塑性的, 而Sc纤维的行为是伪弹性的.

Introduction

Natural fibers can be obtained from plants such as jute, palm oil, sugar cane bagasse, banana spines, flax, etc. Traditionally, waste fibers are thrown in fields to decay or burnt. However, burning of fibers

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/15440478.2022.2164104

Table 1. Worldwide tropical natural fibers production in million tons (FAO, 2021).

Year	Tropical natural fibers			
	Palm oil fruit	Sugarcane	Coconut	Banana
2009	216	1673	61	103
2019	411	1950	62.4	116

results in air pollution due to the emission of CO_2 and smog. Therefore, recycling natural fibers is essential to avoid air pollution. Natural fibers are sustainable materials with large-scale industrial production. As environmental challenges have forced the building sector to look for green and environmentally friendly products, natural fibers replace a portion of nonrenewable natural resources and improve their mechanical characteristics. The low density and thermal conductivity of natural fibers make them attractive for their use in composite materials as reinforcement (Hussain et al. 2021). Fiber-reinforced building composites show ductile behavior under tensile loading. After the initial crack, the fibers shift the load to the matrix with bond stresses and cracking continues. Failure of composite material takes place when there is no further crack propagation due to failure of fiber (Mehta and Monteiro 2001).

The efficiency of fibers in composites depends on their tensile strength, percentage added, morphology, geometry, orientation, and distribution in the matrix (Kesikidou and Stefanidou 2019). Natural fibers usually have higher tensile strength, which increases strength and durability of composite materials. Geometry of fibers is another important parameter. Natural fibers usually have circular or elliptical shapes. The length of fibers is controlled by extraction method. For concrete composite, fiber length of 2.5 cm is recommended in ASTM standard (ASTM D7357–07, 2012), while for adobe bricks, length of fibers ranges from 1–10 cm (Araya-Letelier et al. 2018; Bakhaled et al. 2019; Kumar and Barbato 2022). The percentage of natural fibers in composite material has a significant influence on the strength of composites. For adobe bricks, natural fiber addition ranges from 1–POFLP15% by mass (Salih, Osofero, and Imbabi 2020).

Common Mexican tropical fibers include POFL, POFR, Cn, and Sc fibers. Information on reuse of Mexican tropical fibers in different sectors is limited. The worldwide production of a few tropical natural fibers is shown in Table 1.

Tropical natural fibers in Mexico are treated as waste. Recycling of fibers in building materials can help make sustainable building materials and reduce environmental impacts associated with fibers disposal.

The objective of this study is to find the physicochemical and mechanical characteristics of Mexican tropical natural fibers for their recycling in civil engineering applications such as building composites, geotextiles, and soil reinforcement in embankments. These fibers include Cn, Sc, Bs, POFL, and POFR.

Materials and methods

A few tropical natural fibers having significant volume in the form of waste from agro industry in Tabasco state of Mexico were investigated in this study for their prospective recycling in composite materials. These fibers include POFR, POFL, Cn, Bs, and Sc fibers .

Palm fibers from species *Elaeis oleifera* were further divided into POFL and POFR fibers. POFL fibers are obtained from palm oil empty fruit bunches. POFR fibers are obtained from pressed palm oil fruits. Fibers were extracted with knife mill of model Retsch-SM100 with grids of different sizes. Extracted POFL and POFR fibers are shown in Figure 1.

Sugarcane bagasse is waste material from sugarcane. Sugarcane bagasse fibers are obtained by pressing the sugarcane to get sugar juice. Sugarcane bagasse fibers are divided into coarse sugarcane fibers (Scc) and fine sugarcane fibers (Scf). Sc fibers are shown in Figure 1.

Coconut fibers (Cn) were manually extracted from coconut shells and are shown in Figure 1.

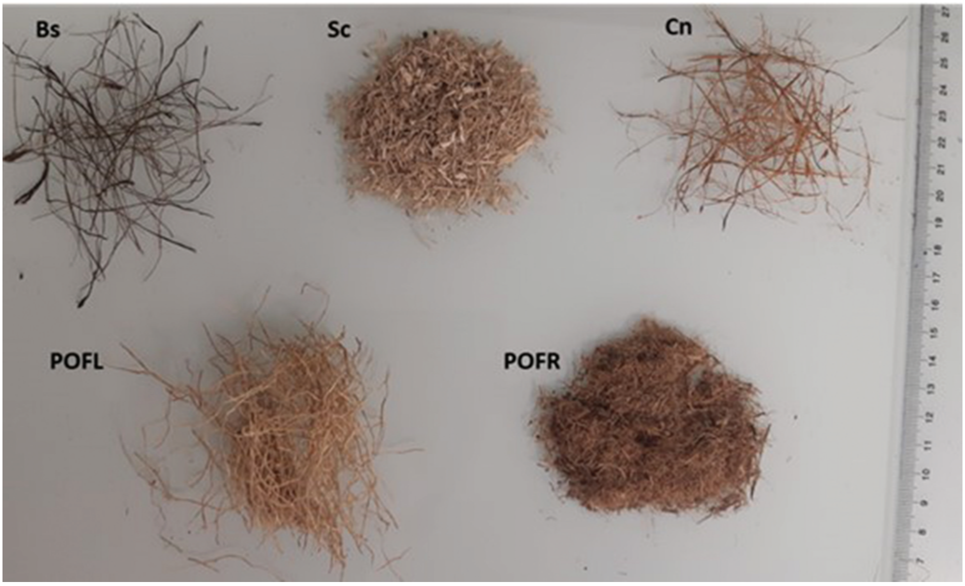

Figure 1. POFL, POFR, Cn, Sc, and Bs fibers.

Bs were manually extracted and are shown in Figure 1. The physical and mechanical characteristics of these fibers were investigated for their use in recycling for different applications.

Fibers extraction and preparation

Natural fibers need to be extracted for their testing. Tropical fibers were extracted manually and with knife mill. The source materials of a few tropical fibers are palm oil fruit, palm oil empty fruit bunch, Bs, Sc, and Cn. As large-scale extraction of fibers is not possible manually, machine extraction of fibers was done with a knife mill. The length of the fiber is not uniform after milling action due to crushing of fibers. However, the maximum fiber length is usually controlled with grids. Extracted tropical fibers were cleaned with water and air-dried to perform different tests. Fiber samples after manual and machine extraction for different tests are shown in Figure 1.

Testing of fibers

Different tests were performed on tropical fibers to observe their physical, chemical, and mechanical characteristics.

Physical and chemical characteristics of fibers

Physical and chemical characteristics of tropical fibers such as cross-section, absolute density, thermogravimetry, water absorption, and chemical composition were studied to observe their behavior and suitability for construction applications.

Microscopic images of fibers with digital microscope of model Keyence VHX 6000 were processed using computer-assisted drawing software to estimate the area of Mexican tropical fibers (Bui et al. 2020). Microscopic analysis of fibers helps see the fiber's internal structure, voids, presence of elementary fibers, and their alignment in a fiber bundle.

The absolute density of fibers is another useful characteristic of natural fibers. Lower density of natural fibers make them suitable for lightweight composite materials. The absolute density of tropical fibers was determined after measuring the fibers volume with argon gas displacement with gas pycnometer model AccuPyc. Gas is introduced into a chamber of 21.42 cm^3, which contains the fiber sample at a temperature of 20°C and pressure was set as 1 bar (100 kPa). Finally, density was calculated with the mass of fiber sample and their volume. The test was repeated three times on each sample to get an average value.

Water absorption of natural fibers was found by immersing the fibers for 48 h after the protocol recommended by Amziane and Collet (2017), in which fibers were dried at 40 °C and immersed in water for 48 h. After immersion, water from the surface of fibers was removed by vacuum filtration. Finally, mass of fibers after immersion was measured to determine the water absorption coefficient.

Thermal characteristics of fibers help observe their behavior at extreme temperatures and degradation with temperature. Thermogravimetric analysis of tropical fibers was performed with TGA 295 F1 Libra thermogravimetric analyzer (Netzsch) to observe their thermal stability at a temperature range of 25 °C–800° C and a heating rate of 10°C/min. Mass loss of fibers with decomposition was observed with increasing temperature (Khennache et al. 2019).

Chemical composition of fibers has a significant influence on their mechanical characteristics. Chemical composition of tropical fibers was found by Van Soest method (Van Soest, Robertson, and Lewis 1991) by using Fibertec TM 8000 semiautomatic machine. Van Soest method is based on a series of chemical attacks that contributes to the mass loss of material in order to identify the percentage of cellulose, hemicellulose, lignins, and cutins. A few tropical fibers used in this study were crushed to 1 mm size and dried at 40 °C. Successive reactions of fibers with neutral detergent fiber, acid detergent fiber, and sulfuric acid helps identify the proportion of soluble compounds, hemicellulose, and cellulose, respectively.

Mechanical characteristics of fibers

Mechanical characteristics of natural fibers play an essential role in the reinforcement of construction materials. Mechanical characteristics of fibers include tensile strength, specific strength, modulus of elasticity, elongation to break, etc.

Tensile strength of different fibers was found by using the ASTM standard (ASTM C1557–2003). Universal testing machine of Shimadzu AGS-X model was used for this test with sensors of 200 N and a displacement rate of 0.5 mm/min.

Fibers of length 4 cm were used for tensile strength test and glued to a cardboard framework of length 4 cm × 4 cm. Cardboard is used to protect fibers as machine clip damages the fibers at the corners. Gauge length of fiber on which tensile strength acts is 2 cm (Bui et al. 2020). Figure 2a shows the fibers glued to cardboard. Figure 2b explains the fiber and cardboard dimensions. Figure 2c shows the testing of fibers.

Results and discussion

In building materials, the addition of natural fibers improves the mechanical, thermal, and acoustic characteristics of composites. Physicochemical and mechanical characteristics of natural fibers are key factors that determine their reuse in different applications.

Analysis of physical and chemical properties of fibers

It is difficult to control the intrinsic characteristics of natural fibers such as diameter, fineness, and number of elementary fibers.

Area of fibers is important in analyzing the tensile strength of fibers. The area of tropical fibers is shown in Table 2. The average area of POFL and Cn fibers is higher than other fibers, which shows the presence of higher number of elementary fibers in the fibers bundle.

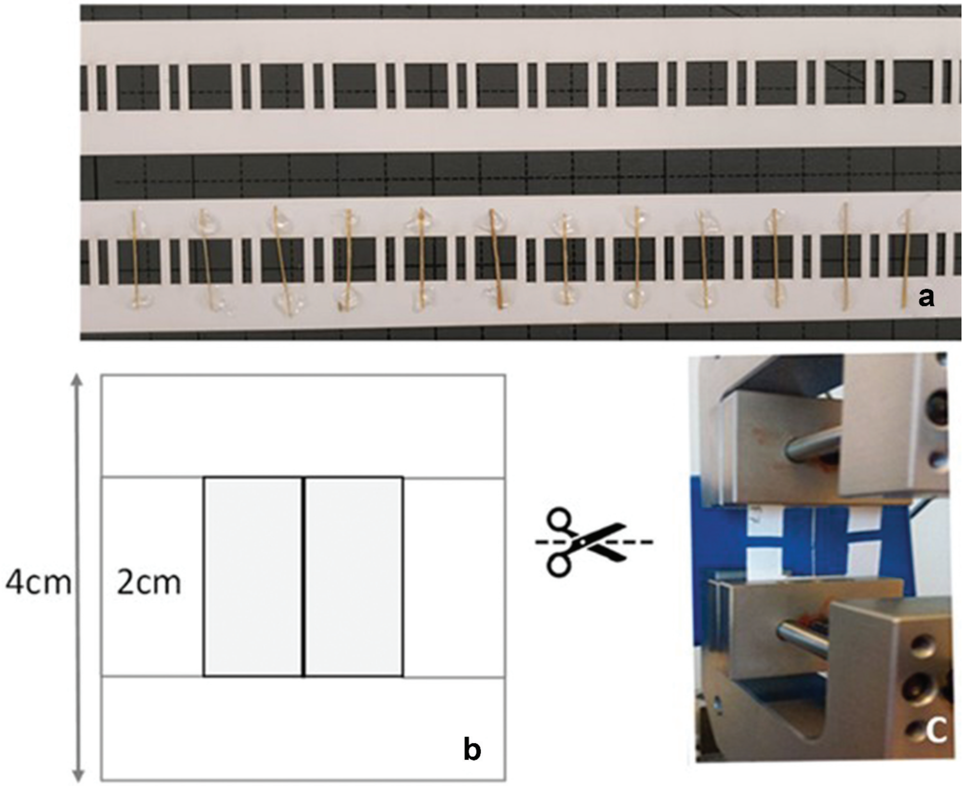

Figure 2. Fiber sample and tensile testing.

Table 2. Area of tropical natural fibers.

Fibers	POFL	POFR	Scf	Cn	Bs
Area (mm^2)	0.07 ± 0.04	0.03 ± 0.01	0.06 ± 0.04	0.07 ± 0.02	0.05 ± 0.03

The area of technical natural fibers has high variation and ranges from 0.03–0.07 mm^2. As technical fiber is the sum of elementary fibers, the area of technical fibers increases with the increasing number of elementary fibers. The actual area of fibers is less than the measured area due to the presence of lumen (empty tubular structures). Tubular structures increase surface roughness of fibers and increase their adhesion in composite materials.

Microscopic images of technical fibers of POFL, POFR, Sc, Cn, and Bs fibers are shown in Figures 5a, 5b, 5c, 5d, and 5e, respectively, for observing the morphology of fibers. Morphology of fibers has significant influence on the strength of fibers, as strength varies with number of elementary fibers and their alignment. Morphology is also important for adhesion of fibers with matrix in composite materials. In the case of POFR fibers, white spots in Figure 3b show the presence of silica bodies, which harm the blades of the mill during mechanical extraction of fibers Presence of voids, peaks, and troughs on surface of fiber bundles in Cn and Bs fibers, as shown in Figures 3d and 3e, make their surface rough, which increases their adhesion and bonding with the matrix. The surface of Sc fibers is relatively smooth. In Figure 3d, elementary fibers can be observed. The length of fibers plays a significant role in controlling the growth of cracks during the drying of building composites (Laborel-Préneron et al. 2016).

The density of natural fibers influences the density of composite materials. In this study, absolute density of tropical fibers was determined with gas pycnometer. The average density values of three tests are summarized in Table 3.

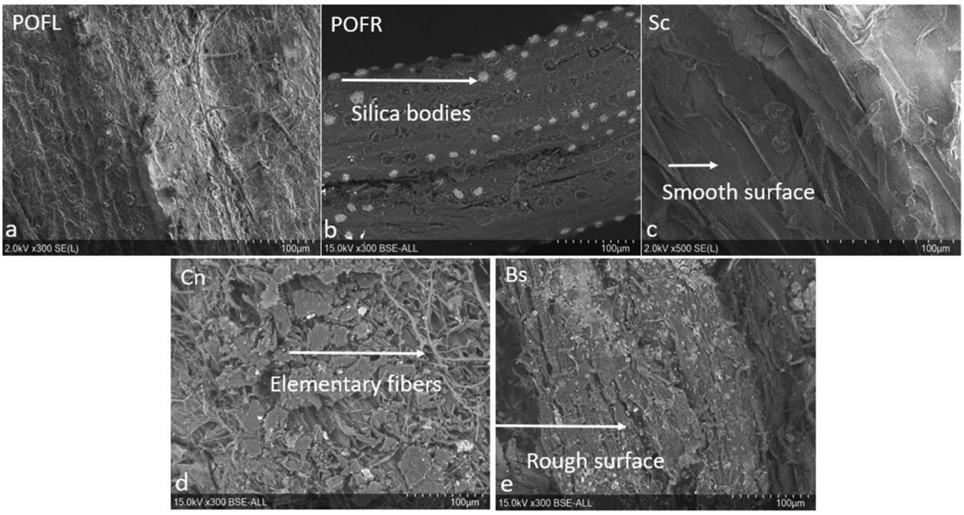

Figure 3. SEM images of external aspects of POFL (a), POFR (b), Sc (c), Cn (d), and Bs (e).

Table 3. Absolute density of tropical natural fibers.

Fibers	POFL	POFR	Sc	Cn	Bs
Density (g/cm^3)	1.36 ± 0.006	1.37 ± 0.021	0.91 ± 0.0001	0.79 ± 0.001	1.49 ± 0.0028

Density values of tropical fibers ranges from 0.79–1.36 g/cm^3 and is influenced by lumen and its diameter. As the density of fibers is considerably lower than the density of soil, their addition in earth bricks and concrete helps design lightweight building composites (Khedari, Watsanasathaporn, and Hirunlabh 2005). Density values for different tropical and natural fibers observed in literature are shown in **Table 8**. Values of density for tropical fibers are within the range of density values observed in the literature and are shown in**Table 8**.

Water absorption of fibers helps regulate humidity and improve thermal and hygroscopic characteristics of buildings (Laborel-Préneron et al. 2016). The average of water absorption coefficients of five samples of a few tropical natural fibers are shown in Table 4.

The water absorption of tropical fibers ranges from 1–2 times of their mass. Natural fibers are hydrophilic and they increase the water absorption capacity of composite materials (Salih, Osofero, and Imbabi 2020). Swelling and shrinkage of fibers occur during the interaction of fibers with water and drying, which induces the voids in composites and affects their strength and performance. Fiber treatment is sometimes used to decrease its affinity for water. The water absorption coefficients of natural and tropical fibers observed in literature are presented in Table 7.

Thermogravimetric analysis of tropical fibers for POFL fibers at a temperature range of 25– 850°C is shown in Figure 4. Figure 4 shows that significant degradation of POFL fibers takes place between 200–500°C. Nearly 70% mass loss of fibers takes place at this temperature. In this temperature range, evaporation of inherent moisture content, oxidation, and burning of organic matter take place.

Table 4. Water absorption of tropical natural fibers.

Fibers	POFL	POFR	Sc	Cn	Bs
*WA (%)	181.1 ± 10.1	117.2 ± 16.05	232.7 ± 6.2	239.5 ± 44.5	218.8 ± 6.1

*WA = water absorption.

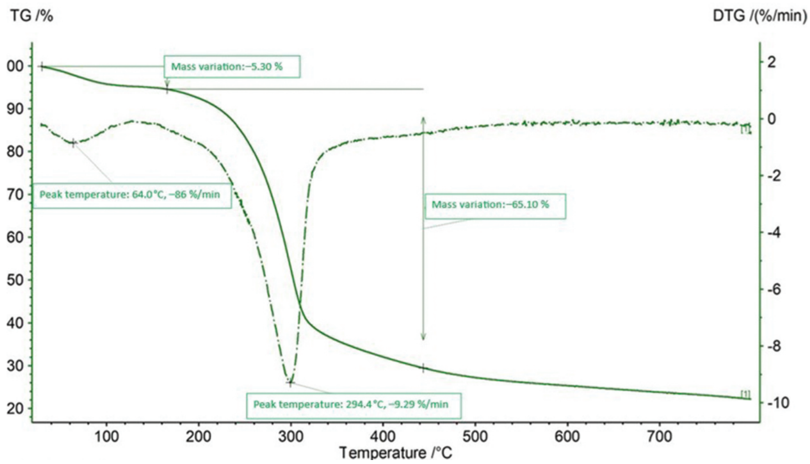

Figure 4. TGA curve for POFL fibers.

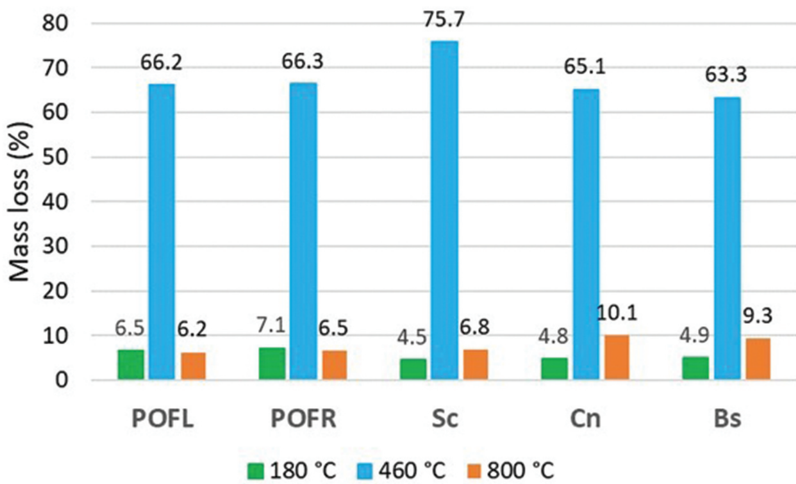

Figure 5. Mass loss of fibers with heat.

Degradation of tropical fibers with temperature is shown in Figure 5.

It can be observed from Figure 7 that at 180°C, mass loss ranges from 4.5–7.1%. This degradation is associated with evaporation of inherent moisture, which occurs at a temperature between 100 °C and 200 °C (Pillai, Manimaran, and Vignesh 2020). At 460 °C, mass loss is 63.3– 75.7%, which is linked with thermal decomposition of organic matter such as lignin and cellulose that takes place at a temperature from 300–500 °C. From 460–600 °C, there is mass loss around 6.2–10.1%. After 600 °C, there is no further degradation up to 850 °C, due to remaining impurities and ash.

Chemical composition of fibers

Chemical composition of fibers has a significant influence on the strength of composite materials. Natural fibers are mainly composed of cellulose, hemicellulose, lignin, cutins, and water-soluble compounds . The higher cellulose content of natural fibers increases the tensile strength and stiffness of fibers (Pillai, Manimaran, and Vignesh 2020). Table 5 shows the chemical composition of a few investigated tropical fibers and a few literature values.

Table 5. Chemical composition of tropical fibers.

Fibers	Cellulose (%)	Hemicelluloses (%)	Lignin and cutins (%)	Water soluble extractives (%)
POFL	48.84	23.32	11.61	16.2
POFR	37.36	23.62	23.73	15.3
Sc	46.71	27.08	11.22	14.99
Cn	54.09	5.27	25.34	18.15
Bs	42.43	11.99	5.84	39.74

Literature values of a few fibers chemical composition.

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	References
Straw	40.8	31.7	10	-	[6]
Banana	60-65	6-19	5-10	1-3	[10]
Bagasse	42	28	20	2.4	[9]
POFL	59	2.1	25	3.2	[13]

Table 5 shows that the cellulose content of tropical fibers ranges from 37–54%, followed by hemicellulose (5–27%), lignin and cutins content (5–25%). Cellulose is responsible for bilinear behavior of fibers under tensile load. The strength of fibers is influenced by chemical composition of fibers, which play an important role in the reinforcement of composites (Millogo et al. 2015).

Analysis of mechanical characteristics of fibers

Tensile load deflection curves of POFL are shown in Figure 6a. Tensile load deflection behavior of POFL fibers is elastoplastic with hardening. The slope of the elastic part is steeper than the plastic part, which shows that the fibers resist the load in the plastic part more than in the elastic part. The maximum tensile strength, strain at failure, and initial elastic modulus for POFL fibers are described in Table 7. The average tensile strength of POFL fibers is 119 MPa. Figure 6a shows the tensile load behavior of POFL fibers. The tensile load deflection curves of palm oil fruit fibers are shown in Figure 6b. The behavior of POFR fibers is elastoplastic. Table 7 shows that the average tensile strength of POFR fibers is around 327 MPa. The tensile load deflection behaviors of sugarcane bagasse fine fibers (Scf) and coarse fibers (Scc) are shown in Figures 6c and 6d, respectively. The behavior of Sc fibers is pseudo elastic. The average tensile strength of Scf fibers is 277 MPa, while the average tensile strength of Scc fibers is 161 MPa.

The tensile load deflection behavior of Cn fibers is shown Figure 6e. The behavior of Cn fibers is elastoplastic. The average tensile strength of Cn fibers is 187 MPa. The tensile load behavior of Bs fibers is shown in Figure 6Ff. The tensile strength behavior of Bs fibers is elastoplastic. The average tensile strength of Bs fibers is 288.50 MPa.

The tensile strengths of 10 fibers of POFL, POFR, Scf, Scc, Cn, and Bs were determined. The average tensile strength observed for each type of fiber is summarized in Table 6. The tensile strain at failure for tropical fibers is also shown in Table 6. The tensile strain for Cn fibers is higher than other fibers, which shows that these fibers are flexible and exhibit higher elongation before failure.

Most of the natural fibers have an elastoplastic behavior. It can be observed in Figures 6a, 6b, and 6e that POFL, POFR, and Cn that fibers show elastoplastic behavior. However, the behavior of Sc fibers (Scc and Scf) is considered pseudo elastic. The initial elastic modulus of elasticity of fibers is determined from the elastic part of the slope. The modulus of slope in the plastic part was also determined. The load deflection behavior of fibers is mainly controlled by fibers morphology and chemical composition. Figure 7 shows the mechanism used to determine the modulus for different parts of the slopes.

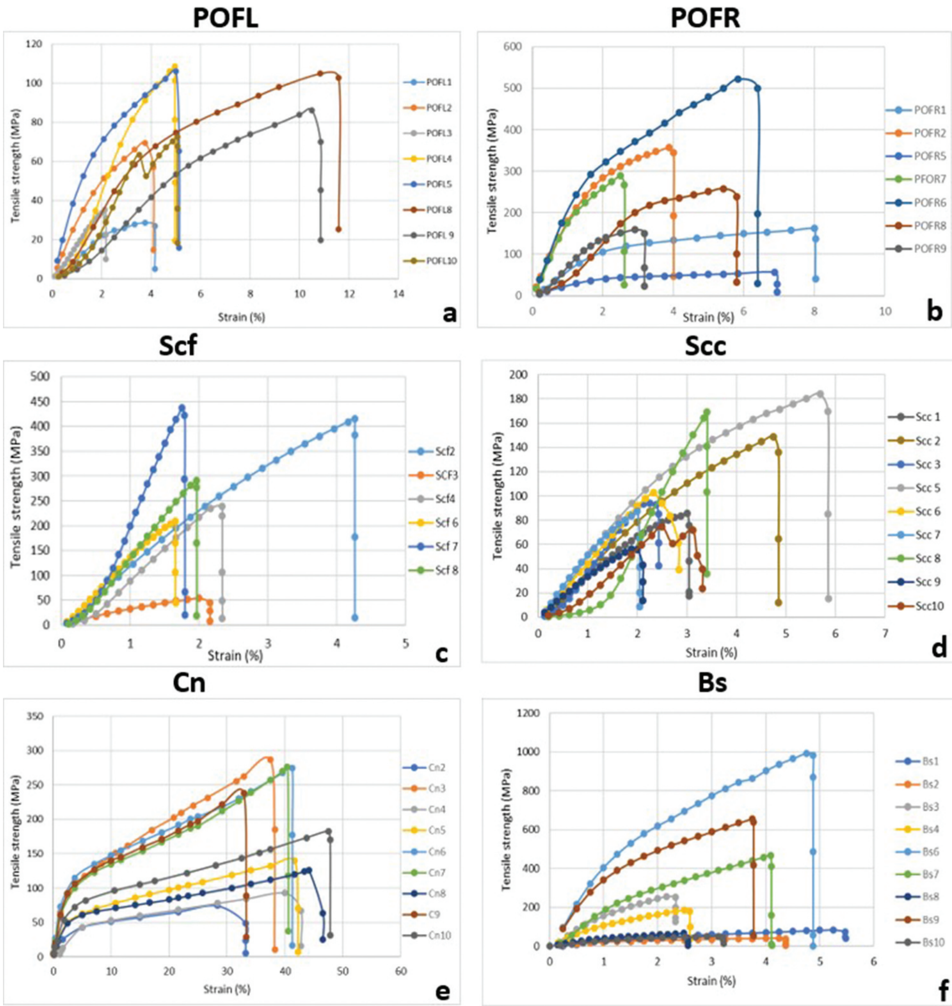

Figure 6. Typical tensile load deflection curves for tropical fibers.

Average values of modulus of elasticity are summarized in Table 6. Table 6 shows that Bs and Scf fibers have higher modulus of elasticity. This is because these fibers exhibit higher tensile strength, and the modulus of elasticity is directly proportional to the tensile strength. The modulus for the plastic part of the slope is smaller and in plastic deformation zone, the ultimate tensile strength continues to increase with large deformation.

Mechanical characteristics of fibers such as tensile strength, specific strength, strain at failure, elastic modulus (Et_1), and final modulus for plastic deformation zone (Et_2) are shown in Table 6.

It can be observed from Table 6 that POFR, Bs, and Scf fibers have maximum tensile strength. Fibers of higher tensile strength increase the tensile strength of the composite material as they act as reinforcement. The distribution of fibers parallel to the axis of earth bricks contributes significantly to tensile strength and toughness (Bui, Hussain, and Levacher 2022).

Tensile strength of technical fibers shows high variation. The inherent irregular morphology of natural fibers is one of the reasons behind this variation. Moreover, the number of elementary fibers, their orientation, and alignments also have significant influence on tensile strength. A perfect micro-fibers inclination angle and orientation in which elementary fibers completely overlap leads to high strength of technical fibers.

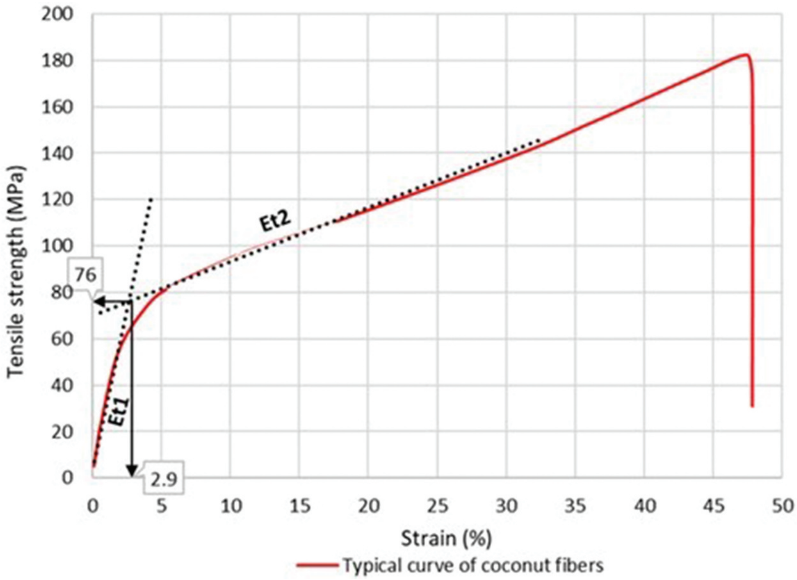

Figure 7. Modulus of elasticity of fibers.

Table 6. Mechanical characteristics of tropical natural fibers.

Fibers	POFL	POFR	Scf	Scg	Cn	Bs
Tensile strength (MPa)	119 ± 95	327 ± 192	277 ± 142	161 ± 105	187 ± 78	288 ± 326
Specific strength (KN.m/kg)	80.27	414.42	304.51	177.50	136.72	212.13
Strain at failure (%)	7.36	5.70	2.36	3.39	40.66	3.63
Et_1 (GPa)	2.91 ± 2.79	12.28 ± 7.70	15.01 ± 8.35	6.04 ± 4.98	3.22 ± 1.97	16.71 ± 15.90
Et_2 (GPa)	1.63	4.39	-	-	0.67	5.52
Et_1/Et_2	2.18	3.52	-	-	7.18	0.50

Table 7. A review of physical and mechanical properties of natural fibers.

Type of fiber	Density (g/cm^3)	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	[37, 41, 47]
Cotton	1.21–1.6	-	1.1-13	265-800	[44]
Flax	1.19–1.55	63-330	4.4-110	93-2000	[8, 14, 16, 17]
Hemp	1.07–1.50	85-415	10-90	159-1264	[14, 42, 44]
Jute	1.23–1.50	84-281	2.5-78	300-800	[17, 43, 44]
Palm date	0.902	133-140	1.9-85	58-678	[28]
Ramine	1–1.58	-	23-128	400-1620	[44]
Reed	0.54–0.94	-	35.9	112-503	[45]
Rice straw	0.86–1.11	52-84	3.3–26.3	435-450	[15]
Sisal	1.2–1.50	110-230	1.46-38	80–1002.3	[17, 42, 44]
Wheat straw	1.14–2.05	96-320	1.4–4.8	3.45-140	[34]
Tropical fibers					
Banana spine	0.31–1.36	134-282	3-32	49.3-914	[17, 44, 45]
Coconut coir	0.67–0.52	63-180	0.628-28	15-593	[12, 42, 44]
Palm oil*	0.1–1.55	54-120	0.5-25	147-400	[17, 20, 21]
Sugarcane	0.31–1.31	102-219	15–27.1	20–290.5	[17, 44]

*Palm oil flowers and fruit are all considered.

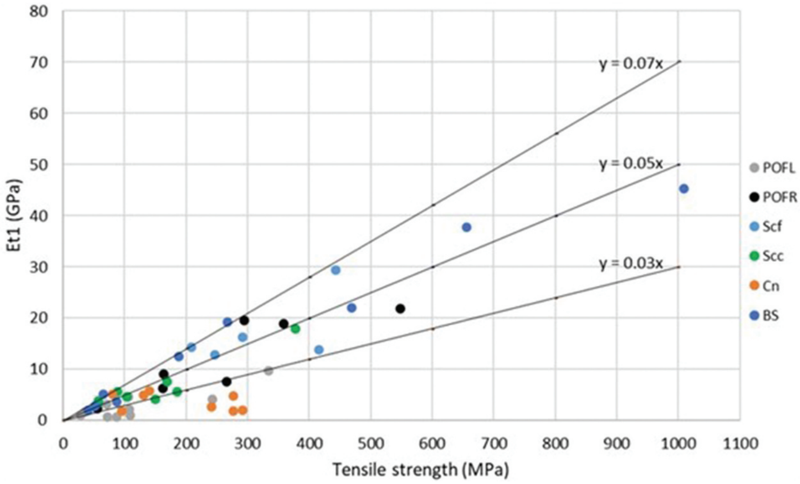

Figure 8. Modulus of elasticity vs tensile strength.

The modulus of elasticity for the plastic zone for Sc fibers is zero, as tensile load deflection behavior of sugarcane bagasse fibers is pseudo elastic or nonlinear, as shown in Figure 8(e,f). The tensile strength and modulus of the elasticity graph in Figure 8 explain the variation of elasticity modulus (Et_1) with tensile strength.

Figure 10 shows that most of the modulus of elasticity values (in GPa) are between 0.03–0.07 times of tensile strength (in MPa).

Table 7 presents the review of physicochemical and mechanical characteristics of a few tropical fibers and a few other natural fibers.

Conclusion

In this study, physical and mechanical characteristics of tropical natural fibers were studied for their valorization in construction industry. Fiber characteristics such as density, diameter, length, thermal degradation, and tensile strength were determined. The mechanical characteristics of tropical fibers indicates that tensile strength of POFR fibers and Sc fibers is maximum, while POFR fibers have minimum strength. The tensile load deflection curves show that tropical fibers show elastoplastic deformation with hardening.

A review of different natural fibers from plants used in construction composites shows that tensile strength and physical properties of tropical fibers are similar to the characteristics of the natural fibers used in civil engineering applications and their reuse in these applications is realistic. However, further testing and analysis are recommended according to norms and standards recommended in different applications.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by the Agence Nationale de la Recherche of France and Consejo Nacional de Ciencia y Tecnología of Mexico [ANR-17-CE03-0012-01 and FONCICYT-290792].

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