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ORIGINAL PAPER

Investigation of Fiber Surface Treatment Effect on Thermal, Mechanical and Acoustical Properties of Date Palm Fiber-Reinforced Cementitious Composites

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Abstract
High energy consumption in the building sector appeals for the implementation and the improvement of innovative approaches with low-environmental impact. The development of eco-friendly composites as insulating materials in buildings provides practical solutions for reducing energy consumption. Different mass proportions (2.5%, 10%, and 20%) of untreated and chemically treated palm fibers were mixed with (cement, water and sand) so as to prepare novel composites. Composites were characterized by measuring water absorption, thermal conductivity, compressive strength and acoustic transmission. The results reveal that the incorporation of untreated and chemically treated date palm fibers reduces novel composites' thermal conductivity and the mechanical resistance. Thermal measurements have proved that the loading of fibers in composites decreases the thermal conductivity from 1.38 W m^{-1} K^{-1} for the reference material to 0.31 W m^{-1} K^{-1} for composites with 5% of treated and untreated fibers. The acoustical insulation capacity of untreated palm fiber-reinforced composites (DPF) was the highest at 20% fiber content, whereas treated palm fiber-reinforced composites (TPF) had the highest sound insulation coefficient for fiber content lower than 10%. Compressive strength, thermal conductivity and density correlation showed that only chemically treated fiber-reinforced composites (TPF) are good candidates for thermal and acoustic building insulations.

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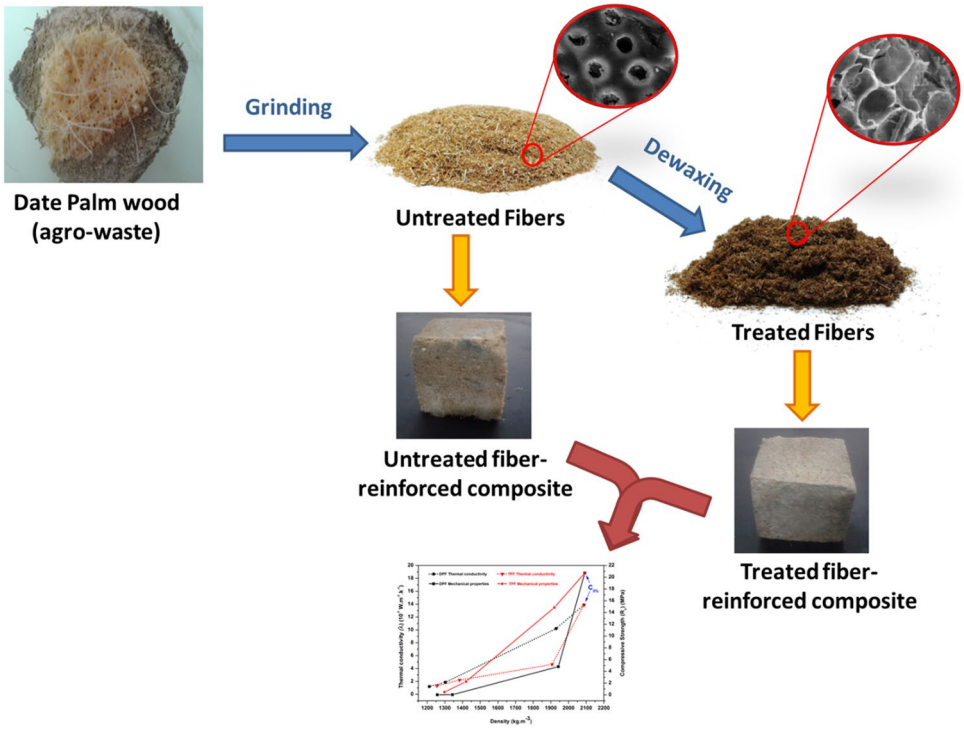
Graphic Abstract



Keywords Agro-waste · Composites · Thermal insulation · Mechanical strength · Water absorption · Acoustic transmission

Statement of Novelty

Even though lignocellulosic fibers are regarded as promising materials for thermal and acoustic insulating composites fabrication raw fibers (without further treatment) suffer from low interfacial interactions with the composite matrix. This work demonstrated the benefit of date palm fiber dewaxing using ethanol–acetone mixture for improvement of cementitious composites thermal and acoustic performances owing to fiber-matrix adhesion enhancement. Additionally, treated fiber-reinforced composites have physical, thermal and mechanical properties comparable with commercial lightweight aggregates concretes. The sustainable nature of this economic, easy, and efficient approach is notable.

Introduction

Thermal insulation products that are available in construction materials market tend to be manufactured from fiber glass, mineral wool or polyurethane foams. Even though these (composites) have low thermal conductivity, good moisture protection and fire resistance they can be hazardous to human health and the environment.

The exposure to small particles from fiberglass and glass wool insulation can, indeed, cause respiratory problems or skin and eyes irritation [1–4]. In addition, these composites cannot be always found in third world countries, and they usually need to be imported from overseas. The new approaches to energy-efficient design are the development and use of natural and local building materials [5].

Thermal insulating materials industry increasingly used renewable resources such as natural fibers. Fiber reinforcement of cement materials still remains an exciting and innovative technology [6, 7]. Because of serious environmental pollution problems, the development of green composite materials has become increasingly important [8, 9].

Several studies were carried out with natural materials and have shown that they are not only comparable with standard building materials but they also cause little concern in terms of health and safety during handling [1, 10]. The need to optimize buildings' energy behavior has been imposed by climatic and economic motives. Indeed, it is well-known that energy efficient buildings could reduce the consumed fossil fuels quantities and thereby reduce CO_2 and SO_2 emissions into the atmosphere. Additionally,

agricultural countries produce considerable amounts of waste [11]. The exploitation of this agro-waste in insulating materials production could help in agricultural processing industry diversification and provides a source of income to farmers. Moreover, by adopting local materials such as available lignocellulosic materials, the impact of transportation decreases by up to 400% compared to building materials imported from overseas [12]. The date palm (*Phoenix dactylifera*) wood is abundant in North African and Golf countries. Tunisia has more than 4 million date palms which occupy nearly 41 thousand hectares [13].

After the date fruit harvesting, important quantities of date palm rachis and leaflet wastes are accumulated every year. In this context, some published works have focused on new eco-friendly materials reinforced by natural fibers such as palm fibers [14], corn cob [15, 16], rice straw [17] and sisal fibers [9–11]. The potential of this raw material is based on its sustainability, low cost, availability, low density, high quantity and low environmental impacts [18].

Interfacial interactions between fibers and the cement matrix play a significant role in mechanical properties of fabricated composites [19]. However, it is well-known that the hydrophilic property of lignocellulosic fibers decreases the bonding strength between fibers and matrices and consequently reduces composites mechanical properties [20].

As already reported in the literature, the incorporation of raw lignocellulosic materials without any treatment improves thermal conductivity but reduces mechanical properties [15, 16]. For these reasons, many scientists have dealt with the chemical pre-treatment of fibers to improve the interfacial bending as well as mechanical characteristics of composites [21, 22]. The treatment of the Alfa fiber has, for instance, enhanced the mechanical properties and has lessened the effect of water aging [23]. El-Abbassi et al. [24] showed that the use of alkali treatment enhances tensile properties when compared to the untreated materials. These recent works show that fiber treatment plays a crucial role in improving thermal and mechanical properties of composites.

The use of the date palm wood as a component of thermal insulating materials has been investigated by [25–27]. They concluded that palm wood is a promising candidate for developing efficient and safe insulating materials [28]. The evaluation of thermal and mechanical properties of date palm fiber-reinforced mortar allowed concluding that this composite has interesting thermal and mechanical characteristics. A good thermal insulating material must have better sound absorbing properties compared to conventional concrete and acceptable mechanical properties (> 0.5 MPa) [29, 30].

Due to noise pollution in the world, there is a big need to find new sound absorbing materials that are capable of reducing noise level at various frequency ranges [31]. In general, porous materials hold promise for use as raw material for sound absorbing [32]. Fibrous and cellular materials such as rice husk [33], corn cob and palm fiber [28], and hemp [34] have shown good thermal and sound absorption properties. It is well known that porous materials and composites with internal pores have good acoustic absorption properties in high frequency range [35]. Many researchers reported that natural fiber-cement composites can be used for thermal insulation and sound reflecting purposes, however, only a limited number of studies focused on their chemical, thermo-physical, mechanical, water absorption and acoustic characteristics.

This work is aimed at investigating the impact of palm fiber treatment on the thermo-physical and sound properties of new composites composed of cement, sand, and untreated and chemically treated date palm fibers. Palm fiber chemical treatment effect on thermo-physical properties of composites was tested.

Materials and Methods

To prepare the bio composite, raw (untreated) and treated palm fibers were utilized. Palm fibers were collected from the only coastal oasis in the world (Gabes-Tunisia). After having been dried under natural conditions, the petiole rods were crushed into small fibers. The obtained powder was then chemically treated.

Chemical Treatment

The protocol of material's dewaxing used in this work was prepared according to methods of Hamza et al. [13]. In brief, date palm fibers were washed with distilled water to eliminate any adhered impurities. Fibers were then dried in hot air oven at 70 °C until constant weight. 10.00 g ± 0.05 g of dried fibers was mixed with 100 mL of acetone–ethanol (2:1) in a Soxhlet at 80 °C for 4 h under mechanical stirring. The residue was afterwards filtered, washed several times with distilled water and dried at 70 °C until constant weight and then used for further characterization and composite preparation.

Composite Preparation

Cement/palm fiber composites were performed by mixing Portland cement—CEM I (composed of ≥ 95% Clinker and ≤ 5% of minor additional constituents according to the NF EN 197-1), CEN-standard sand according to EN 196-1, palm fibers and enough water was added to give correct workability. Table 1 lists the compositions of DPF and TPF composites.

For thermal analyses, the mixture was placed into rectangular molds (44 × 44 × 10) mm^3. For compressive strength

testing, composite specimens were prepared in accordance with ASTM C109, in cubic molds ($5 \times 5 \times 5$) cm^3.

Other specimens were prepared in cylindrical molds (D: 9 cm, H: 1 cm) with a central hole (D: 2 mm) so as to evaluate the acoustic performances.

Scanning Electron Microscopy

The morphology of natural and treated fibers were observed using a scanning electron microscope from JEOL (model JSM 6301 F, Japan). The untreated and treated fibers were sputter coated for 200 s with colloidal gold/palladium under vacuum with a JSC1100 (JEOL, Japan) Ion Sputter-Coater. The samples were then mounted on aluminum holders using double-sided electrically conducting carbon adhesive tabs prior to the analysis. The untreated and treated date palm fibers were randomly scanned at magnifications from 100× to 1500× under 5 kV accelerating voltage.

Particle Size Analysis

Raw and treated palm particles size distributions, specific surface area (SSA), volume moment mean (D [4;3]—De Brouckere mean), and surface area moment mean (D [3;2]—Sauter mean diameter) were determined by a laser diffraction apparatus (Malvern Panalytical, Mastersizer 3000, UK) equipped with a dry powder disperser (Aero S). Measurements were performed in triplicate, at 25 °C.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectra were obtained using a Spectrum Two PerkinElmer spectrometer, in the attenuated total reflection (ATR) mode. ATR-FTIR measurements were carried out at room temperature and samples were scanned 32 times in the range of 450–4000 cm^{-1}. The technique of Ledvik et al. [36] was used to calculate the mean strength of hydrogen bonds (MSHB).

Chemical composition of petioles

The chemical composition of petiole palm fibers was measured with reference to Technical Association of Pulp and Paper Industry (TAPPI) methods. The holocellulose (cellulose + hemicelluloses) content was analyzed in accordance with the titration method (TAPPI T19m-54). The α-Cellulose was removed from the holocellulose by alkali extraction using the T203 om-88 TAPPI standard method. In addition, Almond shells lignin content was determined by a reaction with sulfuric acid using the TAPPI T222 om-88 standard method [37]. Measurements were performed in sextuplicate.

Water Absorption

Measurements were carried out in accordance with ASTM C642-97. After drying the composite at 50 °C until constant weight, specimens were completely submerged under deionized water maintained at 25 °C [24]. Both of mass and time variations were being subsequently recorded through a balance placed above the water bath. The absorption coefficient, the sorption as well as the permeability were calculated.

The weight percent uptake W_t for water by 100 g of materials was plotted against the square root of time ($min^{0.5}$). The W_t value is calculated using

$$W_t\% = \frac{m_t - m_0}{m_0} \times 100 \quad (1)$$

where m_t is the moist weight at time (t), m_0 is the dry weight (g).

Thermal Properties

The thermal conductivity and diffusivity of the prepared composites were determined using a Hot Disk TPS 2500. The thermal conductivity (λ) and the thermal diffusivity (a), of composites were determined using the measurement device DICO. This technique was developed in the laboratory of CERTES-university of Paris-Est.

The principle of measurement is based on the periodic thermal excitation of a block by comprising a sample between two metal plates. The temperature measurement was performed on the front and rear plates using thermocouples. On the basis of these two measurements, we can calculate the thermal transfer function of the material.

To determine the samples' thermo-physical parameters, the simultaneous identification of the thermal diffusivity and

Table 1 Composition of DPF and TPF composites

Composition (percentage by mass)	$C_{0\%}$	$DPF_{2.5\%}$	$DPF_{10\%}$	$DPF_{20\%}$	$TPF_{2.5\%}$	$TPF_{10\%}$	$TPF_{20\%}$
Portland cement—CEM I	22.26	22.22	20.56	17.72	22.26	22.22	20.56
CEN-standard sand	66.77	64.69	56.34	39.32	66.77	64.69	56.34
Untreated date palm fibers	0.00	2.13	6.20	13.83	0.00	0.00	0.00
Treated date palm fibers	0.00	0.00	0.00	0.00	2.13	6.20	13.83
Water	10.98	10.96	16.90	29.13	10.96	16.90	29.13

conductivity was carried out. This was done through the minimization of the squared difference between the experimental and theoretical heat transfer functions using Levenberg–Marquardt method [38]. This device is well described in literature [39].

Compressive Strength

The compressive strength of specimens was determined using Automatic Compression Test Plant Toni (Model 1540) with a maximum test load 300 kN.

Acoustic Transmission

The composites acoustic absorption was evaluated in accordance with ASTM E1050 using a modified impedance tube. In fact, the composite was placed at one end of the tube, and a microphone was located on the other end, which detected the sound wave pressure transmitted to the sample. A speaker generates an acoustic excitation from 200 to 2000 Hz.

When a sample receives a wave, a portion of the sound energy will be absorbed and the other portion will be reflected and transmitted [40]. To evaluate how the composite absorbed the sound, the absorption coefficient (α) was calculated with the following formula

$$\alpha = 1 - |R|^2 \quad (2)$$

where R is the complex sound reflection coefficient.

Result and Discussions

Petioles chemical composition, on dry basis, is tabulated in Table 2. It can be observed that petioles are rich in lignin (~35%) and waxes (~16%) compared to other natural fibers.

Particle Size Analysis

Both materials exhibited a modal distribution. Table 3 shows that the specific surface area (SSA) of untreated fibers is higher compared with treated ones. This SSA difference could be attributed to an agglomeration effect due to the dewaxing treatment. This assumption is confirmed by the fact that treated palm fibers Sauter and De Brouckere mean diameters are higher than that of untreated materials.

ATR-FTIR

ATR-FTIR spectra of untreated and treated palm fibers are shown in Fig. 1. The broad band of stretching vibrations of C–H and O–H groups within 3650–3000 cm^{-1} region observed in both spectra showed principal functional groups found in lignocellulosic materials. The absorbance band within 1740–1700 cm^{-1} is attributed to the C=O stretching of methyl ester and carboxylate groups in pectin, ester linkage of lignin and hemicelluloses carboxylic groups or to hemicelluloses acetyl group and uronic ester. Moreover, lignin showed characteristic peaks at 2850 cm^{-1} and 1505 cm^{-1} originating from C–H stretching and aromatic skeletal vibration of C=C, respectively.

The untreated and treated palm fibers mean strength of hydrogen bonds (MSHB) were estimated from (3330 cm^{-1}/2916 cm^{-1}) and (3335 cm^{-1}/2919 cm^{-1}) transmittance intensities ratios, and were found to be 2.15 and 3.19, respectively.

This MSHB increase after treatment can be ascribed to the wax removal, which leads to enhancing the intermolecular hydrogen bonds between particles. This result is in good agreement with the particle size analysis, where particles agglomeration was attributed to fiber chemical treatment.

Table 3 Particle size distribution of treated and untreated palm fibers

	Untreated palm fiber	Treated palm fiber
Specific surface area ($m^2\ kg^{-1}$)	119	74
Sauter mean diameter (μm)	134	215
De Brouckere mean diameter (μm)	274	288

Table 2 Comparative chemical composition (wt%) of palm fibers with some other natural fibers

Sample	Cellulose	Hemicellulose	Lignin	Waxes	References
Date palm fiber	34.36 ± 0.08	22.9 ± 0.1	34.8 ± 0.1	15.9 ± 0.8	This study
Sisal	45	14.2	20.2	2	[52]
Sugar palm fiber	43.80	7.24	33.24	2.73	[53]
Alfa	44.86	28.90	19.54	–	[13]
Palm leaf	39.23	28.41	20.05	–	[13]
Kenaf bast fiber	43.7 ± 1.2	34.7 ± 1.2	11.05 ± 0.5	–	[54]
Abaca	56-63	20-25	7-9	3	[55]

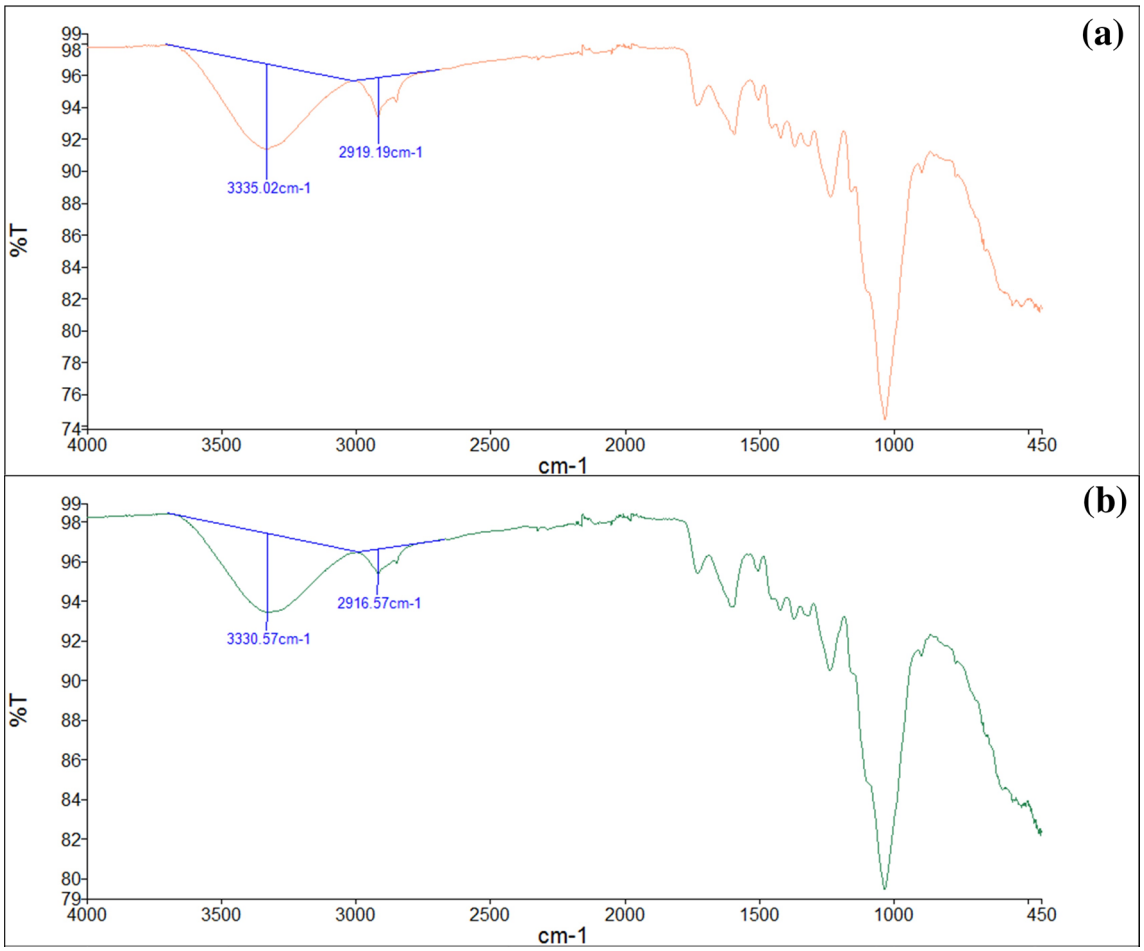


Fig. 1 FTIR spectra of untreated (**a**) and treated (**b**) palm fibers

Morphology

Figure 2 depicts the morphology of untreated and treated palm fibers. SEM images show that materials surface morphology is affected by the dewaxing treatment. Indeed, Fig. 2a reveals that untreated fibers surface was smooth and covered with a complex film with dispersed hollows (Fig. 2b), indicating the surface coverage by waxes and impurities. Treated palm fibers SEM micrographs (Fig. 2c, d) demonstrate that the surface was rough and arranged in a honeycomb-like pattern. It is well known that the bond between fibers and cements is insured by a mechanical interlocking (anchorage), chemical bonds (principally hydrogen bonds), or a combination of both [41]. Therefore, the rise of surface roughness, due to the dewaxing process, can lead to fiber-matrix adhesion enhancement. In addition, Fig. 2d displays numerous pores, cavities and cracks, confirming the low density of petiole.

Composites Water Absorption

For cellulosic fibers-reinforced composites, the water absorption capacity is strongly influenced by the fiber percentage because of their hydrophilic nature. Figure 3 shows the water uptake of $C_{0\%}$ and composites reinforced by 2.5, 10 and 20 wt% of untreated and treated palm fibers, as a function of the square root of time. After saturation, the water absorption capacities were more significant in an order of $C_{0\%}$ (~ 12%) < [$TPF_{2.5\%}$ (~ 18%) = $DPF_{2.5\%}$ (~ 18%)] < $TPF_{10\%}$ (~ 79%) < $TPF_{20\%}$ (~ 163%) < $DPF_{10\%}$ (~ 177%) < $DPF_{20\%}$ (~ 259%).

Thus, water absorption increases with fiber content for DPF and TPF. Indeed, the water uptake increases owing to lignocellulosic materials highly hydrophilic nature compared to composite matrices. In addition, fiber swelling can promote water absorption by causing micro-cracks inside composite structures.

DPF composites also show higher moisture absorption capacity, which can be attributed to lower interfacial interactions between fibers and composite matrices caused by lower

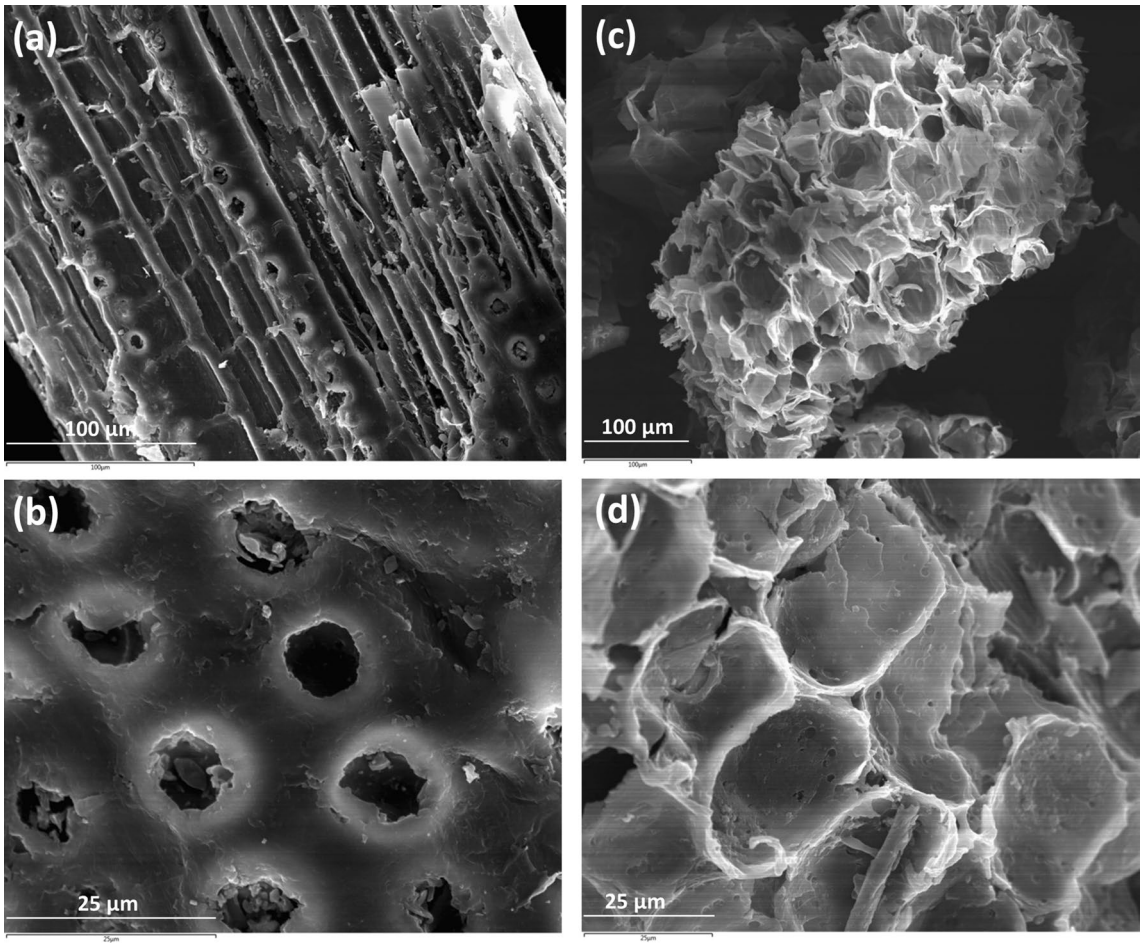


Fig. 2 SEM micrographs of untreated (**a**, **b**) and treated (**c**, **d**) palm fibers

amount of exposed hydroxyl groups and smoother surfaces. Indeed, the feeble adhesion between untreated fibers and the matrix increases the diffusion velocity of water molecules and consequently results in significant water absorption improvement.

Kinetics of Water Absorption

Water molecules penetration in composites is governed by three mechanisms:

- Water molecules diffusion into the structure of lignocellulosic fibers and composite matrices;
- Water molecules migration into fiber-matrix interfacial gaps and flaws;
- Capillary transport into micro-damages and micro-cracks in composite matrices.

It was proven, though, that the most accurate method to model water absorption is to only consider the diffusion mechanism; even if all mechanisms occur simultaneously when composites are exposed to water.

The mechanism at the origin of the diffusion can be determined by the equation

$$\frac{M_t}{M_f} = k.t^n \tag{3}$$

where M_t is the water uptake percentage at time t, M_f is the water uptake percentage at the equilibrium, k is a constant characteristic of the composite and n indicates the diffusion mechanism. Indeed, when n is equal to 0.5 the diffusion is Fickian. However, when n is comprised within the range from 0.5 to 1 the diffusion is non-Fickian (or anomalous).

k and n were determined using the linearized form of Eq. (4) given by

$$\log\left(\frac{M_t}{M_f}\right) = \log k + n \log t \tag{4}$$

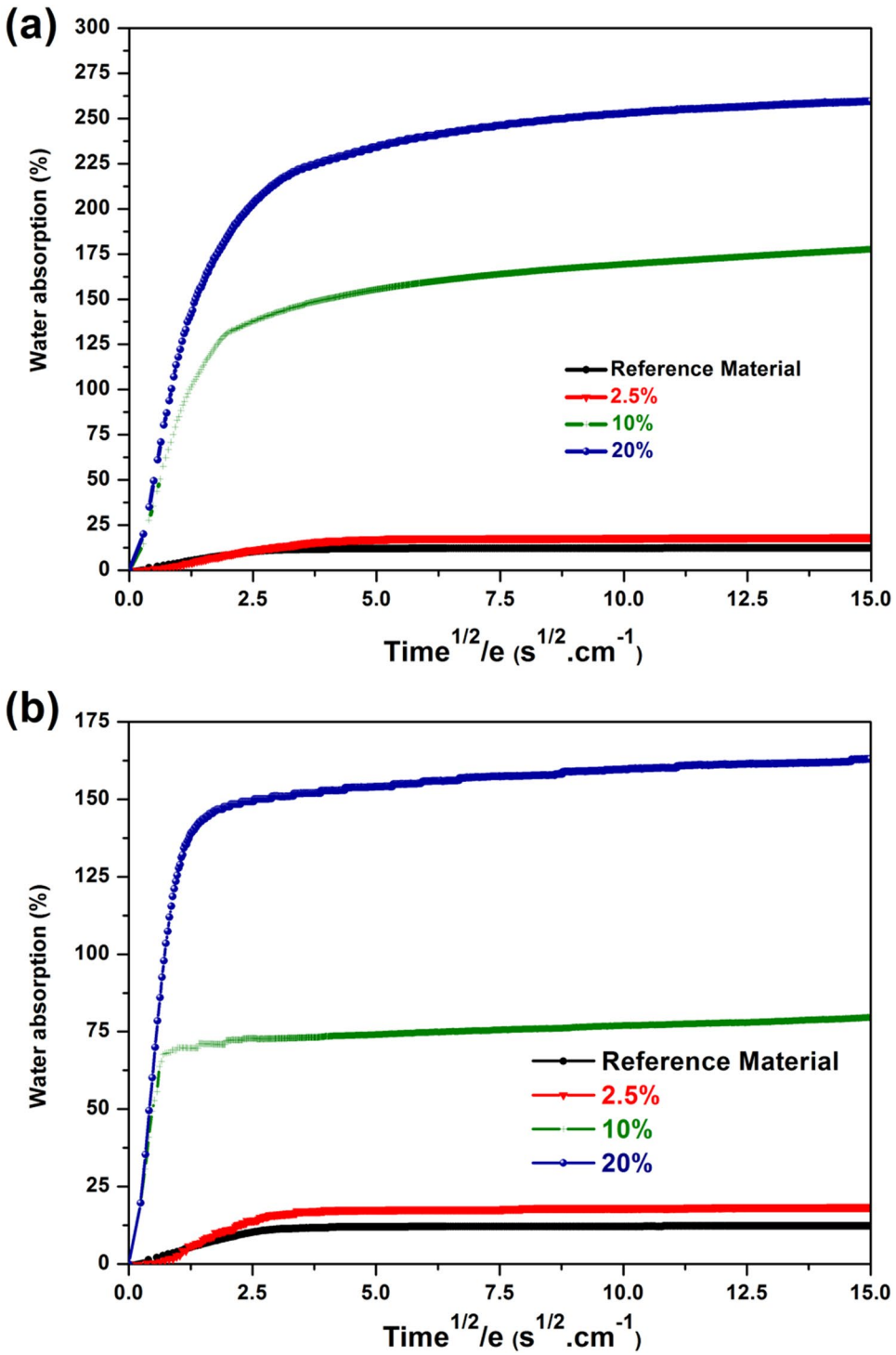


Fig. 3 Water absorption (%) of DPF (**a**) and TPF (**b**) composites

The n and k values of treated and untreated fiber-reinforced composites are listed in Table 4.

We notice that all composites have n values lower than 0.5. Hence, the Fickian diffusion model does not fit DPF and TPF composites water uptake data. Similar behaviors have been reported in previous works dealing with other natural fiber-reinforced composites [42].

Transport Coefficients

It is well known that materials permeability to water is dependent on liquid molecules sorption and diffusion. The diffusion coefficient (D) implies the aptitude of liquid molecules to diffuse into materials structure. This coefficient can be computed using the formula

Table 4 DPF and TPF composites water uptake parameters

Sample	D ($cm^2\ s^{-1}$)	n	k	wt%
$C_{0\%}$	0.15	0.22	0.71	12.2
$DPF_{2.5\%}$	0.71	0.38	0.55	18.4
$TPF_{2.5\%}$	0.90	0.33	0.60	18.4
$DPF_{10\%}$	0.01	0.46	1.59	182
$TPF_{10\%}$	$9.84E^{-3}$	0.30	0.08	80
$DPF_{20\%}$	0.018	0.27	0.67	265
$TPF_{20\%}$	$1.44E^{-2}$	0.15	0.78	163

$$D = \pi\left(\frac{\theta}{4M_f}\right)^2 \tag{5}$$

where θ is the slope of the linear portion of water absorption curves, and M_f is the water uptake percentage at the equilibrium.

We remark that lowest diffusion coefficients were obtained with $TPF_{10\%}$ and $TPF_{20\%}$. This can be attributed to lower fiber-matrix interfacial gaps and flaws in TPF composites due to stronger interactions between treated fibers and matrices as compared to DPF composites. In addition, treated fibers have higher affinity to water molecules, which can limit the liquid diffusion in the composite structure. These results connote a better impermeability of TPF compared to DPF composites.

Thermal Conductivity and Diffusivity

Figure 4a shows thermal conductivity (λ) evolution as a function of treated and untreated fiber loading. It is clear that the addition of both fibers into the composites matrices reduces the thermal conductivity and the thermal diffusivity of DPF and TPF. Indeed, as soon as fibers content reach 5%, thermal conductivity values drop from 1.38 W m^{-1} K^{-1} for the reference material ($C_{0\%}$) to 0.31 W m^{-1} K^{-1} for DPF and TPF composites, which corresponds to a reduction of 92%. In fact, this decrease is expected because natural fibers have lower thermal conductivity compared to reference material ($C_{0\%}$), as shown in Fig. 4. Similar behaviors have been reported by other authors who worked on vegetal fiber-reinforced composites [29, 43, 44]. The composites thermal conductivity decrease can be caused by the rise in the number of voids due to fibers addition [45]. In comparison with other composites such as some new hemp-lime composites (λ ≈ 0.55 W m^{-1} K^{-1}) [46] and mortar-date palm fibers mesh composites (λ ≈ 0.4 W m^{-1} K^{-1}) [29], the thermal insulating properties of composites developed in this study are significantly better. Moreover, Fig. 4b displays that thermal diffusivity (*a*) values fell from 8.33×10^{-7} m^2 s^{-1} for the reference material ($C_{0\%}$) to 3.16×10^{-7} m^2 s^{-1} and 3.22×10^{-7} m^2 s^{-1} for DPF and TPF composites, which corresponds to a reduction of 62%. It seems clear that DPF and TPF thermal behavior is governed by the materials fiber nature as well as air inclusions and voids induced by fibers addition.

Considering low thermal conductivity and diffusivity of DPF and TPF, these composites can be regarded as considerably interesting thermal insulation materials.

Compressive Strength

The effect of treated and untreated fibers content on the compressive strength (R_c) of DPF and TPF composites was also studied (Fig. 5). Figure 5 shows that the compressive strength decreases with the rise of fibers content in composites. Compared to $C_{0\%}$, the compressive strength went down by 76% and 28% for $DPF_{2.5\%}$ and $TPF_{2.5\%}$, respectively. The compressive strength of $DPF_{10\%}$ and $TPF_{10\%}$ were found to decrease by 98% and 65%, respectively. However, the compressive strength fell by 99% and 97% for $DPF_{20\%}$ and $TPF_{20\%}$, respectively.

This behavior can be induced by air inclusions and voids between fibers and matrices, which led to a lower strength in reinforced composites compared to the reference material ($C_{0\%}$). It was also already reported that when the fiber content rises, mechanical properties of composites drop [25, 26].

We also notice that treated fiber-reinforced composites compressive strength was higher compared to the untreated fiber-reinforced composites. This improvement in treated fiber-reinforced composites mechanical properties can be attributed to better interfacial interactions between fibers and matrices caused by waxes removal [44, 47, 48].

Compressive Strength, Thermal Conductivity and Density Correlation

After having been dried at 50 °C until constant weight, specimens were immersed in water; composites bulk density was determined by the triple weighing method [29].

$$\rho = \frac{m_d}{m_d - m_w} \times \rho_w \tag{6}$$

where m_d is the mass of dry samples (kg), m_w is the mass of water (kg) and ρ_w is the density of water (1000 kg m^{-3}) [15]. Palm fiber-reinforced composites density falls when fibers content grows. For instance, the increase in fibers content in composites lead to a decrease in density by 41% and 39% for $DPF_{10\%}$ and of $TPF_{10\%}$, respectively.

Thermal conductivity and compressive strength were highly dependent on the density of composite which is a key parameter for the optimal point determination (top material determination). Figure 6 shows the relationship between

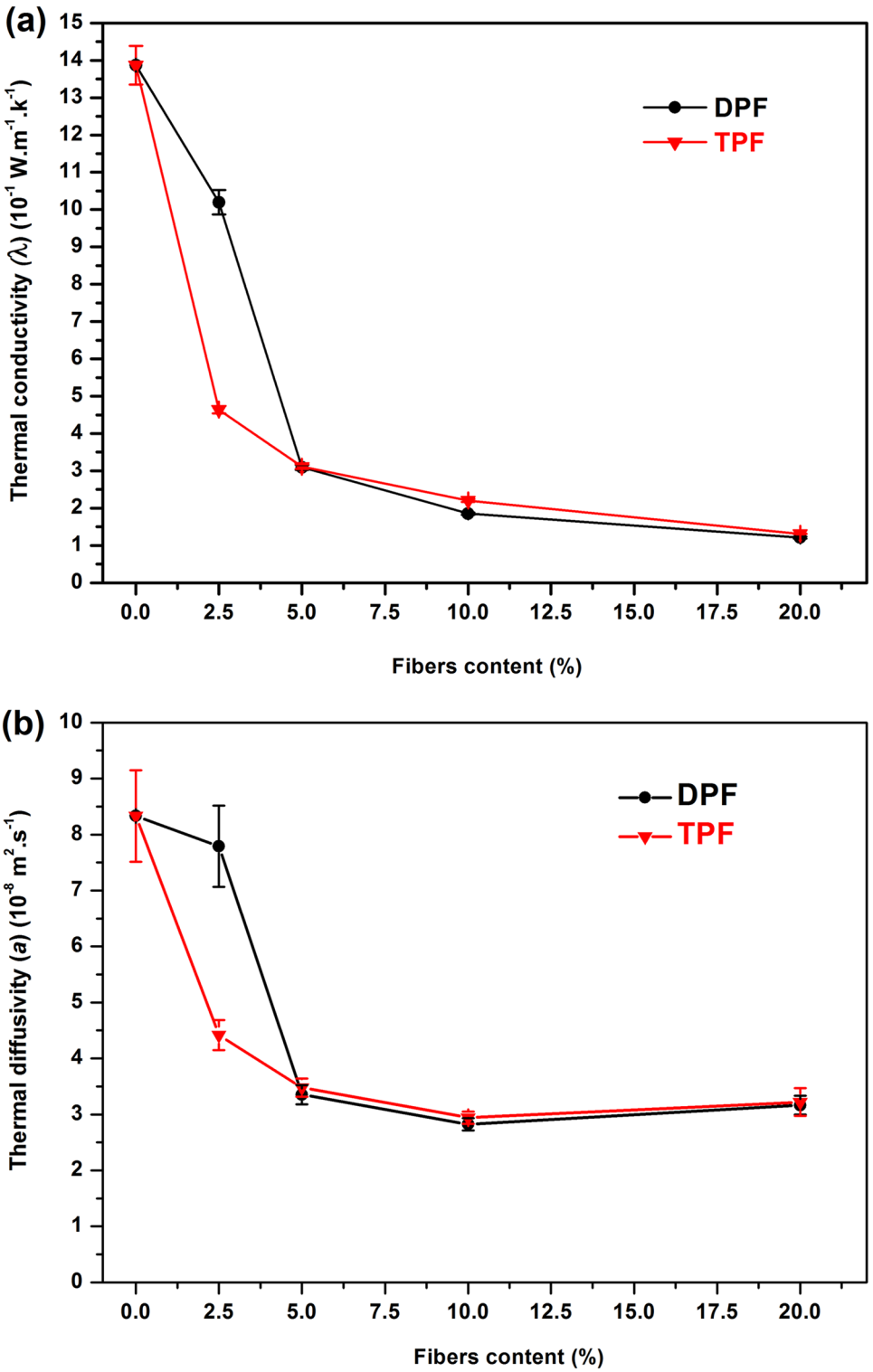


Fig. 4 Thermal conductivity (**a**) and diffusivity (**b**) of DPF and TPF composites

three parameters (conductivity, compressive strength and density). Indeed, fiber content augmentation is accompanied by a diminution in composites thermal conductivity, density and mechanical strength.

Based on data presented in Figs. 4, 5 and 6, it appears that DPF composites cannot be used as structural and insulating materials. Indeed, $DPF_{5\%}$, $DPF_{10\%}$, and $DPF_{20\%}$ mechanical strengths (< 0.05 MPa) are much lower than those of building insulating materials (> 0.5 MPa), whereas $DPF_{2.5\%}$ thermal conductivity (> 1 W m^{-1} K^{-1}) is higher compared with structural and insulating materials (< 0.75 W m^{-1} K^{-1}). These results show therefore that for all DPF fibers content,

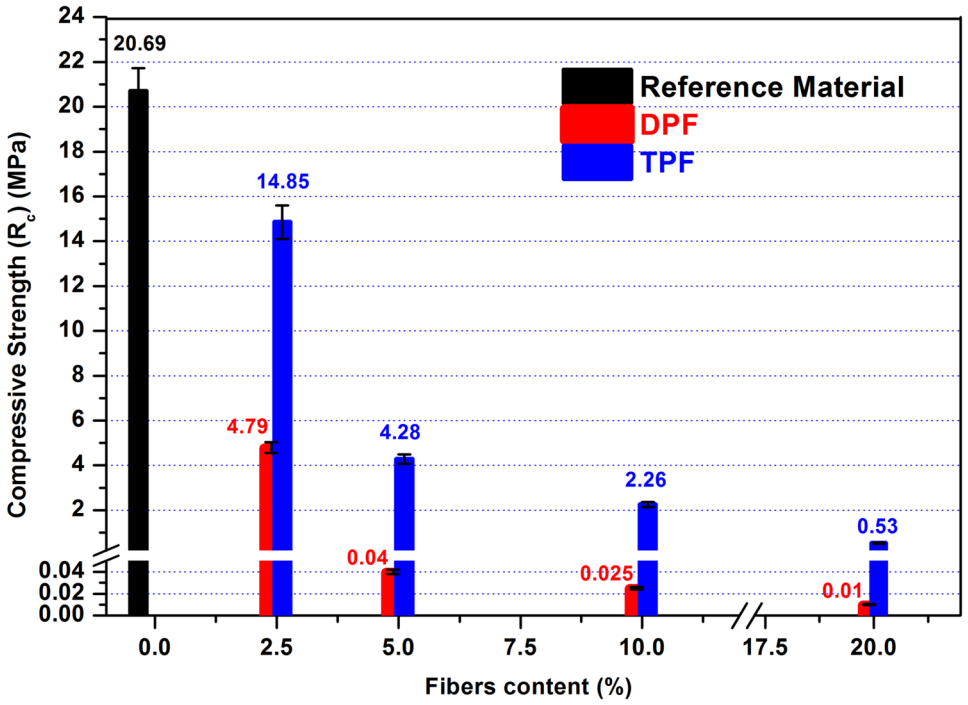


Fig. 5 Compressive strength (R_c) of reference material and (DPF and TPF) composites

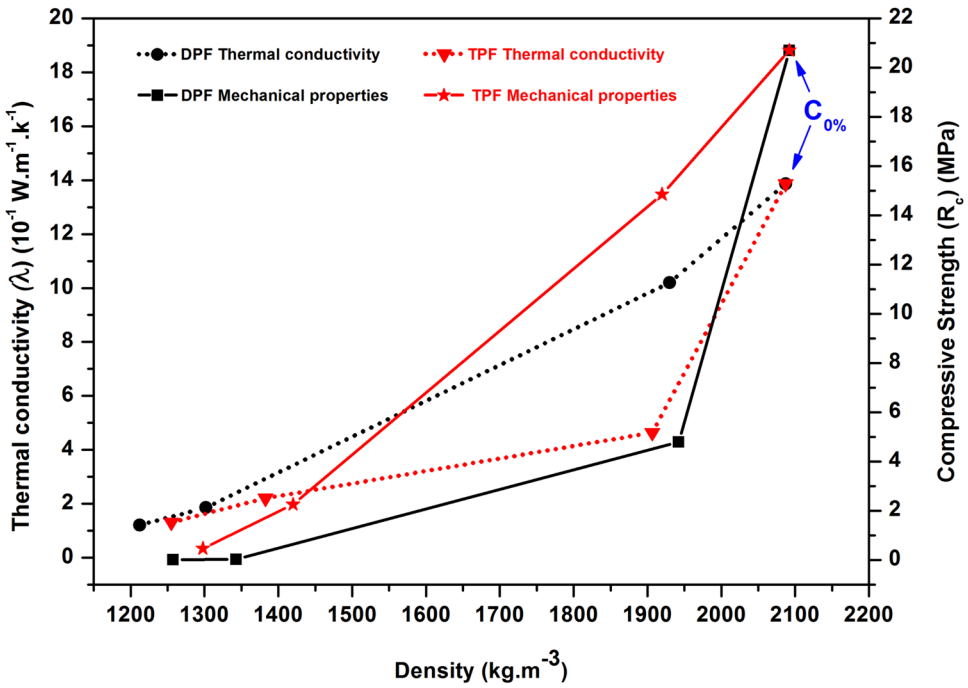


Fig. 6 Correlation between density, λ and R_c

mechanical strength and/or thermal conductivity are not consistent with those of building thermal insulation materials.

However, the range of compressive strength (R_c) and the thermal conductivity (λ) of $TPF_{2.5\%}$, $TPF_{5\%}$, $TPF_{10\%}$, and $TPF_{20\%}$ were found to be about (14.85, 4.28, 2.26, and 0.53 MPa) and (0.46, 0.31, 0.22, and 0.13 W m^{-1} K^{-1}), respectively. Then, $TPF_{2.5\%}$ and $TPF_{5\%}$ composites can be categorized as structural and insulating materials ($R_c > 3.5$ MPa, $k < 0.75$ W m^{-1} K^{-1}), whereas $TPF_{10\%}$ and $TPF_{20\%}$ are considered as insulating materials ($R_c > 0.5$ MPa, $k < 0.30$ W m^{-1} K^{-1}). Moreover, Fig. 6 illustrates that $TPF_{10\%}$ and $TPF_{20\%}$ densities are in the

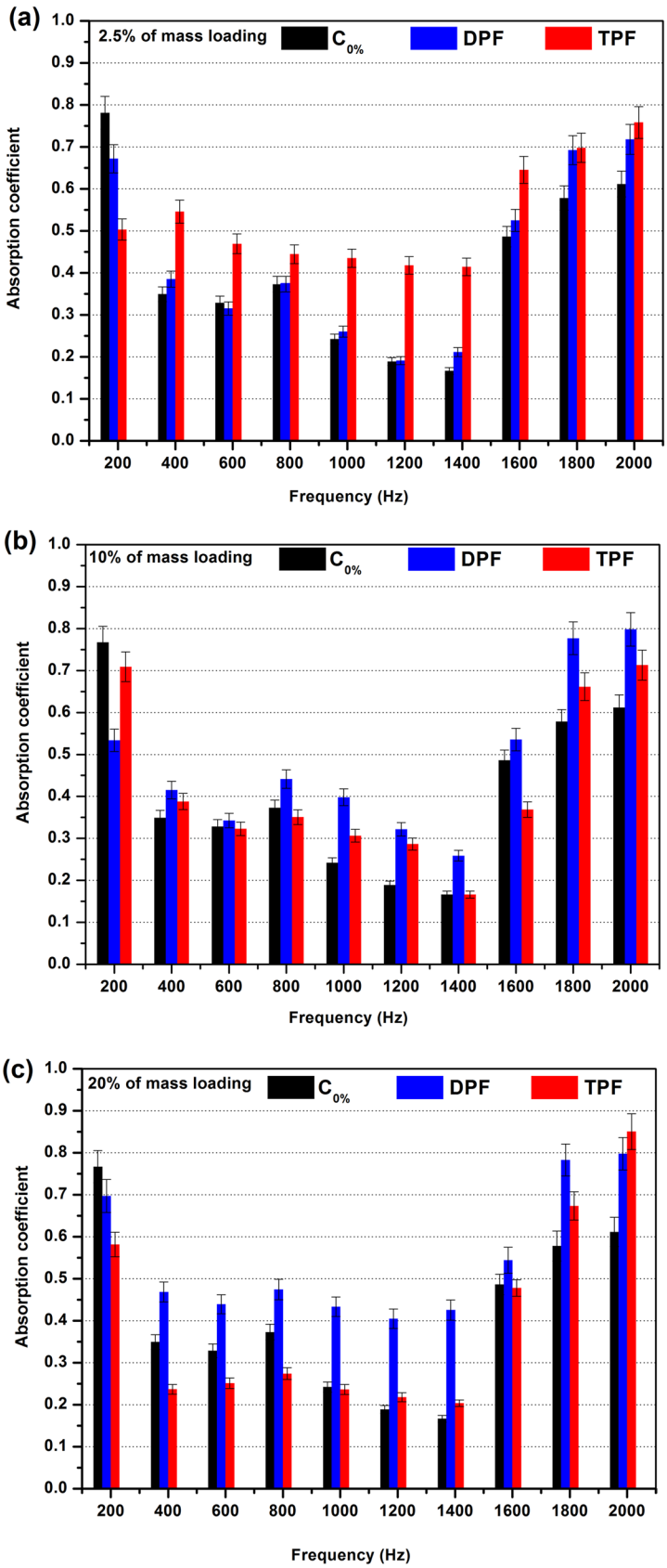


Fig. 7 Sound absorption coefficient of DPF and TPF composites for 2.5% (**a**), 10% (**b**), and 20% (**c**) palm fibers mass proportions

(400–1850 kg m^{-3}) range. These results clearly show that $TPF_{10\%}$ and $TPF_{20\%}$ have physical, thermal and mechanical properties comparable with lightweight aggregates concretes [25, 49].

Acoustical Properties

In the case of fiber-reinforced composites, it is difficult to foresee visco-inertial [50] and thermal phenomena governing acoustical dissipation, as these phenomena depend on pore size distribution and connectivity between various pores [28]. Figure 7 shows the sound absorption coefficient (α) as function of frequency for the reference material, and DPF and TPF composites with different mass contents.

For all samples, sound absorption coefficient values were lower at medium frequencies (400–1400 Hz) than that at low (200 Hz) and high (1400 Hz<) frequencies.

The reference material $C_{0\%}$ shows lower absorption coefficient values than DPF and TPF composites except at 200 Hz. This behavior could be attributed to the fact that fibrous materials behave as porous composites with interconnected cavities. Hence, the number of connected porous channels in composites rises with the fiber content and leads to an increase in the sound absorption capacity [40].

At low fiber content (2.5%), the TPF composite displays the highest sound absorption coefficients at medium ($\alpha_{DPF} < 0.4 < \alpha_{TPF}$ in the 400–1400 Hz range) and high frequencies ($\alpha_{DPF} < 0.6 < \alpha_{TPF}$ in the 1600–2000 Hz range) compared to DPF. In fact, due to high interfacial interactions between the matrix and fibers, energy losses are caused by scattering phenomena and consequent fibers mechanical vibrations [18]. This trend is inverted at higher fiber content (10% and 20%), where the DPF composite shows a better sound absorption capacity. This behavior can be attributed to voids between fibers and DPF matrices which lead to significant adiabatic energy losses at medium and high frequencies [51].

These results show that $\alpha_{DPF} < \alpha_{TPF}$ at low fiber content (2.5%), however the tendency is inverted at high fiber content ($\alpha_{TPF} < \alpha_{DPF}$) in the 400–1800 Hz range.

Conclusion

The development of new insulating materials plays an important role in reducing buildings power requirement and therefore gas emissions. This work focused on the development of novel thermal and acoustical insulating composites using locally available waste materials (date palm wood) for sustainable development.

Two types of composites were produced using treated and untreated palm fibers. Water absorption capacity, thermal conductivity and diffusivity, compressive strength, and acoustical properties were compared with the reference material ($C_{0\%}$).

Our findings based on quantitative and qualitative analyses are as follows:

- Untreated palm fibers composites showed higher water absorption increase with fibers content, which can cause micro-cracks inside composite structures. Thus, treated palm fibers composites (TPF) are expected to be more durable than untreated palm fibers composites (DPF) in a humid environment.
- The augmentation of treated and untreated fibers content lightens both composites by decreasing their density. In this work, treated and untreated palm fibers composites showed similar densities.
- The increase in palm fiber content reduces the mechanical strength of both composites. However, TPF composites showed higher mechanical strength values.
- Treated and untreated palm fibers composites thermal conductivity values demonstrated that an increase in fiber content improved their resistivity. In addition, the thermal diffusivity of both composites (for fiber content higher than 2.5%) was about 60% lower than that for the reference material ($C_{0\%}$).
- Compressive strength, thermal conductivity and density correlation showed that only treated palm fibers composites are good candidates for building insulation.
- Untreated palm fibers composites (DPF) acoustical insulation capacity was higher for 20% fiber content, however, treated palm fibers composites (TPF) showed better acoustical insulation efficiency for fiber content lower than 10%.

Through the results reported in this study, treated and untreated palm fibers composites showed a remarkable improvement of the thermal and acoustical properties as compared with the reference mortar. Besides, it must be kept in mind that only treated palm fibers composites (TPF) allow obtaining materials with thermophysical, mechanical and acoustical properties compatible with the building energy efficiency sector needs.

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