

Article

Hygrothermal and Mechanical Behaviors of Fiber Mortar: Comparative Study between Palm and Hemp Fibers

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Abstract: This paper presents an experimental investigation of the hygrothermal and mechanical properties of innovative mortar mixtures reinforced with natural fibers. Fibers extracted from palm stems (PS) and hemp (HF) were evaluated at different percentages. Scanning electron microscope (SEM) observations showed that the PS fibers have rough surfaces and very complex microstructures. Prior to their incorporation into the mortar, the fibers were subjected to different treatments to reduce their hydrophilic character. The employed treatments showed good efficiency in reducing the water absorption of both PS and HF fiber types. Furthermore, the mortar mixtures incorporating these fibers exhibited low thermal conductivity and excellent moisture buffering capacity. Indeed, the moisture buffer value (MBV) of the investigated mixtures ranged between 2.7 [g/(%HR·m²)] and 3.1 [g/(%HR·m²)], hence providing them excellent moisture regulator character. As expected, the fiber mortar mixtures showed very high porosity and low compressive strength ranging between 0.6 and 0.9 MPa after 28 days of age. The low-environmental footprint materials developed in this study are intended for thermal insulation and building filling.

Keywords: natural fibers; morphology; chemical treatments; fiber mortar; moisture buffer value; hygrothermal properties



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1. Introduction

The building industry is a large materials and energy consumer, highly polluting (emission of CO₂), and a residues generator. Therefore, the new global research policy is focused on the development of new innovative bio-based materials with low environmental impact [1]. Nowadays, the demand for bio-based materials is greatly increasing due to their abundance and regenerative capacity. Natural materials are known to develop comparable performance to the standard building ones [2]. Indeed, the date palm wood is shown to be an efficient insulating green material compared to the other materials [3–6], hence becoming attractive in developing good thermal-insulation and low-cost materials. In this context, several types of vegetable fibers, including hemp, flax, bamboo, coir, animal hairs, and cork have been combined with different materials, including Portland cement, clay, sand, and gypsum to produce composite materials [7,8]. The properties of composite materials reinforced by natural fibers are influenced by the shape and size of the fibers, distribution and orientation of fibers in the matrix, bond between the fibers and matrix, mixture design, and the mixing efficiency and processing methods [9]. The various investigations carried out on the composites considered only content, length, and type of fiber to evaluate their performance [10]. Cork–gypsum composites are shown to exhibit good thermal and acoustic insulators and can be used as partitioning materials [11]. Other research has

shown that the incorporation of cork fibers improves the thermal resistance of concrete but reduces its mechanical properties [12]. On the other hand, the use of wood chips (3–8 mm) influenced the water sorption of cement–clay matrix, and macro porous wood aggregates reduced capillary absorption within the material [13]. This composite material also showed a low thermal conductivity. Other researchers [14] have investigated the use of corncob as a sustainable building material for thermal insulation and concluded that corncob can improve thermal properties of construction materials. The authors revealed that the corn's cobs have adequate thermal properties for building purpose. The thermal and acoustic behaviors of sheep wool have been tested under different conditions [15]. The reported results showed that sheep wool is an excellent acoustic and thermal insulator. The mechanical behavior of other natural fibers has also been studied [16–19]. The obtained results revealed that the presence of vegetable fibers improves the flexural strength of fiber-reinforced concrete. Moreover, the presence of certain vegetable fibers has a pozzolanic effect. The presence of cellulose filaments considerably reduced the thermal conductivity of conventional concrete [20]. For example, the thermal conductivity of hemp concrete is about 0.15 W/(m·K) compared to 2 W/(m·K) of conventional concrete [21–25]. In the case of hemp concrete with dry densities of 200–840 kg/m³, thermal conductivity varying between 0.06 and 0.19 W/(m·K) has been reported [26]. In addition to hemp concrete, several other vegetable aggregates were used to develop sustainable building materials from recycled natural wastes to protect the environment and reduce the energy consumption of buildings. Among these vegetable particles, flax shives present a low thermal conductivity [19,27–29]. Indeed, flax concrete, composed of flax shives, binder (mainly lime) and water, has a high water absorption capacity of approximately two to three times its weight within 48 h. This is due to its pores which are organized in parallel capillaries and high cellulose content of about 48% [30–32]. Flax concrete is widely developed and used in the Grow2 Build project at Brunel University because of its energy and environmental performances [33]. Flax concrete exhibited a low thermal conductivity between 0.082 and 0.127 W/(m·K). The thermal conductivity is inversely proportional to the percentage of fibers [34]. Furthermore, the flax concrete is shown to be an excellent moisture regulator with a moisture buffer value (MBV) of about 2.8 [g/(%HR·m²)]. On the other hand, the use of vegetable fibers (flax) considerably increases the water and mechanical performance of composites. Furthermore, the treatment of flax shives improves their physico-chemical properties and the mechanical properties of the composites [35]. The treatment of flax shives with raw and emulsified linseed oil improved the vegetal/matrix compatibility. The coating of these fibers by linseed oil reduces the water absorption capacity and improves the workability of the mortar [36]. However, a large specific surface area of the flax fibers can negatively influence the workability. Additionally, none of the investigated treatments improved the mechanical properties of the composite. Other researchers revealed that flax and hemp concrete exhibited high hygric performance and 'excellent' moisture buffer capacity [37,38]. Moreover, the use of 2 and 16% hemp fibers, by volume, increased mechanical performance of the composites, but reduced the bond stress by 20–50% [39].

In the present study, the hygrothermal performance of a novel date palm fiber in mortar composite is evaluated. It is worth mentioning that the extracted fibers are different from the oil palm broom fibers (OPBF) [40] which are extracted from the petiole of the palm leaf, unlike the palm stems (PS) fibers which are extracted from the stems of the date palm cluster. The extraction and valorization of palm fibers, which are incineration instead of being used in agriculture, have both ecological and economic benefits, from an ecological point of view, the recovery of these materials helps to protect the environment by reducing the emission of CO₂ due to their incineration. From an economic point of view, the extraction of vegetable fibers with low costs and enhanced mechanical properties compared to conventional fibers can have an added value to construction materials. A hemp fiber (HF) is also investigated for comparison purposes. The morphology of PS fibers was analyzed using a scanning electron microscope (SEM). The vegetable fibers

are composed of cellulose, hemicellulose, lignin, and pectin. The presence of amorphous and hydrophobic lignin provides rigidity, impermeability, and durability resistance to fibers in alkaline medium. On the other hand, the presence of pectin (polysaccharides) can provide high flexibility and hydrophilicity of PS fibers. However, the presence of pectin can considerably affect durability of the composites due to their hygroscopic and thermolabile natures. On the other hand, within the fiber, hemicellulose acts as a binder between the cellulose microfibrils [41]. In this study, different treatments have been applied to reduce the hydrophilic characteristics of PS fibers. The adsorption/desorption isotherms of vegetable fibers were then measured to assess the efficiency of treatments. Subsequently, both PS and HF fibers were mixed in their raw state with air lime to proportion different composite fiber–mortar mixtures. The hygrothermal and mechanical behaviors of the investigated mortar composites were then evaluated.

2. Materials and Methods

The experimental program carried out in this study is divided into two different phases. The Phase 1 is devoted to extracting and characterizing a novel natural fiber. In the Phase 2, the hygrothermal and mechanical behaviors of fiber mortar mixtures are investigated. The fibers were subject to different treatments before their incorporation in mortar mixtures. In addition to the morphological characteristics, the adsorption/desorption isotherm curves of the investigated fibers were determined. The extraction processes and the tests performed on fibers are presented in Section 2.1. Fiber mortar mixtures investigated in Phase 2 were proportioned using different fiber contents and investigated. Two different fiber types, including PS and HF types, were investigated. The length of the fibers was 2 cm, and the diameter varied between 0.2 and 0.4 mm. The length of the fiber was chosen to facilitate the casting process of the mortars. The physical, hygrothermal, and mechanical properties of the composite mortar mixtures were investigated. The binder used to proportion the composite mortar mixtures is the Tradical® PF70 lime according to the NF 459 [42] specifications. This binder was composed of 75% air lime, 15% hydraulic binder, and 10% pozzolanic binder. The investigated mixtures were proportioned with a water-to-powder ratio (w/p) of 1.0. Two different percentages of fibers corresponding to 2.5% and 5%, by volume, were evaluated. Prior to the preparation of the fibers-reinforced mortar mixtures, the vegetable fibers (PS and HF) were soaked for 24 h in water. Afterwards, the fibers were filtered and added to the lime and water to make the mortar. A Collomix XM 2-650 vertical axis rotary mixer was used to prepare the mixtures. The mixing sequence is as follows: (i) introduction of water and fibers and kneading for 30 s; (ii) addition of half of the air lime and kneading for 60 s; (iii) addition of the second half of the binder (air lime) and kneading for 60 s; (iiii) cleaning the mixer tank and rest for 60 s, followed by a final kneading for 60 s.

For each mixture, various $15 \times 15 \times 15 \text{ cm}^3$ and $10 \times 10 \times 40 \text{ cm}^3$ prisms were sampled to determine the mechanical properties. After 7 days of mixing, the samples were stored in a climate room with regulated temperature and relative humidity ($T = 20 \text{ }^\circ\text{C}$ and $\text{RH} = 50\%$). The investigated mixtures are summarized in Table 1.

Table 1. Identification of the investigated mixtures.

ID	Type of Fibers	Fiber Content (%, by Volume)
Reference	/	0
PS 2.5	Palm Fibers	2.5
HF 2.5	Hemp Fibers	2.5
PS 5.0	Palm Fibers	5.0
HF 5.0	Hemp Fibers	5.0

The hygrothermal behavior, porosity, sorption/desorption isotherms, specific heat, moisture buffer value (MBV), and compressive strength of the investigated mixtures were determined. The experimental program carried out in this study is shown in Figure 1.

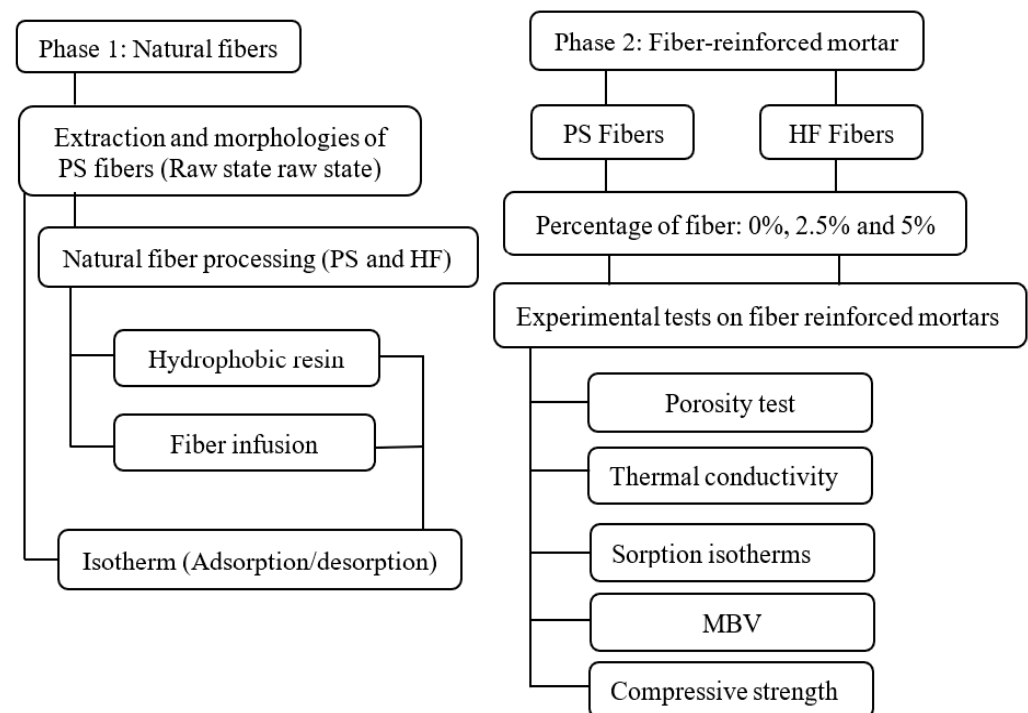


Figure 1. Summary of the experimental program.

2.1. Phase 1—Extraction and Treatment of Natural Fibers

2.1.1. Extraction and Morphology of PS Fibers

First, the stems were collected and cut to different lengths to extract date palm fibers. The stems were then stored in a controlled room temperature for 48 h before the extraction process. The stems were placed in a disk mill (Figure 2) and subjected to different preparation processes to optimize their geometry. After several trial-and-error tests, the best quality of fibers was obtained by using 30 g of PS and grinding for 60 s. The morphological characteristics of fibers were assessed evaluated using a scanning electron microscope (SEM) equipped with an Oxford Energy Dispersive Spectroscopy (EDS).

2.1.2. Fibers Treatment

Natural fibers are known to have high hydrophilic character. The absorption and desorption cycles influence the fiber-matrix bonding [43]. Indeed, under repetitive absorption and desorption cycles (swelling/deflation), the fibers undergo volume changes, which causes loss of adhesion between fibers and matrix. Furthermore, natural fibers are made of cellulose, hemicellulose, lignin, and pectin [41]. Some of these constituents, including hemicellulose and pectin, are hydrophilic, and their extraction reduces the hydrophilicity of the fibers and, consequently, limits their dimensional variation. In addition to the hydrophilic character, the observed delayed setting [39] is probably due to the polysaccharides present on the fibers that fix the calcium (Ca^{2+}) and delay the formation of hydrated calcium silicate gel (C-S-H). Two different treatments were evaluated in this study. The first treatment is based on the impregnation of the PS and HF fibers in a hydrophobic resin varathane type for 10 min, then dried at laboratory room temperature (22 °C). At the end of this treatment, the adsorption–desorption isotherms of the fibers were determined. The second treatment consisted of immersing a representative quantity of the fibers (20 g) (PS and HF) in 1.5 L of water and boiling for 45 min. A filtration process was performed to collect the filtered liquid. The infused fibers were kept at room temperature for 48 h and then used for a

second infusion. This was done to validate the efficiency of the first infusion process. The adsorption–desorption isotherms of the treated fibers were measured using the Belsorp Aqua 3 [44]. The test consists of measuring the change in volume of water vapor adsorbed or desorbed by a sample at a fixed temperature. The measurement process is based on defining the volume of gas adsorbed by the system using the number of moles of gas after helium injection at atmospheric pressure [45]. Prior to testing, the fibers were previously dried at 40 °C under vacuum until mass stabilization using the VacPrep 061 [45].



Figure 2. Different extraction steps of palm fibers. (a) Salvaged date stems; (b) cut palm stalk; (c) mill components; (d) palm stem fibers.

2.2. Phase 2—Fibers-Reinforced Mortar Mixtures

The investigated fiber mortar mixtures were made by mixing water with PS and HF fibers. The HF and PS fibers were used at two different percentages of 2.5% and 5%, by volume. The porosity of mortar mixtures was determined according to the AFPC—AFREM specifications [46] using $5 \times 5 \times 5 \text{ cm}^3$ cubic samples. This method is based on vacuum saturation using bench and then three separate weighings. The first is the hydrostatic weighing of a saturated sample immersed in water. The sample is weighed in air after extracting it from the water. Finally, the third measurement is taken to weigh the sample in its dry state. The porosity was calculated using Equation (1), as follows:

$$\varepsilon_p = \frac{M_{\text{air}} - M_{\text{dry}}}{M_{\text{air}} - M_{\text{water}}} * 100 (\%) \quad (1)$$

where M_{air} is the weight sample after removal from the water, M_{dry} is the weight dry sample, and M_{water} corresponds to the hydrostatic weight of the sample saturated in water.

Furthermore, the thermal conductivity was measured for three different temperatures of 10, 23, and 40 °C using the λ -meter Ep500 e which is based on the guarded hot plate method [47,48]. The samples of dimensions $15 \times 15 \times 5 \text{ cm}^3$ were placed between two plates of different temperatures. The thermal conductivity was deduced from the electrical power (U.I) and the temperature gradient between the two plates (DT), as shown in Equation (2):

$$\lambda = \frac{U \cdot I \cdot e}{\Delta T \cdot A} \left(\frac{W}{m \cdot K} \right) \quad (2)$$

where 'e' is the thickness of the sample and 'A' is the exchange surface.

The sorption–desorption isotherms of the fiber mortar mixtures were measured using the ProUmid SPS apparatus, which is based on the gravimetric method principle [34]. Fiber mortar samples of 1 cm^3 were placed in the climatic chamber of the device and exposed to different levels of relative humidity at a temperature of 23 °C. The adsorption/desorption isotherms were obtained from the mass variation (gain/loss) of the samples at equilibrium. The tested samples were first dried at 40 °C under a vacuum until mass stabilization.

The moisture buffering (MBV) capacity was measured according to the Nordtest project [38]. This defines the ability of the material to moderate changes in the relative humidity of the ambient air. The principle of the MBV test is to expose the samples to daily relative humidity cycles in order to be representative of the cycles encountered in buildings. The relative humidity used was 75% and 33%, with an exposure time of 8 and 16 h, respectively, using $10 \times 10 \times 5 \text{ cm}^3$ samples. In addition, the samples were previously conditioned at 23 °C and 50% RH to reach the equilibrium. Generally, materials are considered to be excellent moisture regulators if they have an MBV of 2 [g/(%HR·m²)].

The Moisture Buffer Value of the material can be calculated using Equation (3), as follows:

$$\text{MBV} = \frac{\Delta m}{A(\text{HR}_{\text{max}} - \text{HR}_{\text{min}})} \quad (3)$$

where MBV [g/(%HR·m²)] is the Moisture Buffer Value, Δm [g] is the mass variation during the absorption/desorption phase, A [m²] is the exposed sample surface area and HR_{max}; HR_{min} (%) is the maximum and minimum relative humidity applied during the humidification and drying cycle, respectively. Finally, the compressive strength of the investigated mortar mixture was performed according to the ASTM C109 specifications [49] using $5 \times 5 \times 5 \text{ cm}^3$ samples. The measurements were carried out using a Zwick Roell[®] hydraulic press. Each reported value is a mean value determined on three different samples.

3. Test Results and Discussion

The obtained results are first discussed in terms of the morphological characteristics of the investigated fibers, then the hygrothermal and mechanical behaviors of the fiber mortar mixtures are discussed.

3.1. Morphological Characteristics of the Fibers

The microscopic evaluation (Figure 3) revealed a rough and porous structure with the presence of lignin, hemicellulose, and pectin on the fiber's surface. As can be observed in the SEM image (Figure 3c), lignin, hemicellulose, and pectin are deposited on the surface of the cellulose fibers. Furthermore, the image shown in Figure 3d reflects the presence of cavities in the cellulose fibers. According to literature [34], the pores of the flax shives are organized in parallel capillaries and oriented in the direction of vegetable growth. Additionally, these capillaries are connected to each other by small cavities. This porous and complex structure allows the damping of heat transmission in the flax shives, which consequently gives it a low thermal conductivity, but higher water absorption and transfer capacities. It is expected that the incorporation of these vegetable particles in hydraulic matrix can therefore improve the hydrothermal behavior of the composite and increase its porosity. The cross-section of PS fibers shown in Figure 4 comprises many elementary fibers. The observed cross-section of PS fibers is almost similar to the coir fibers [50].

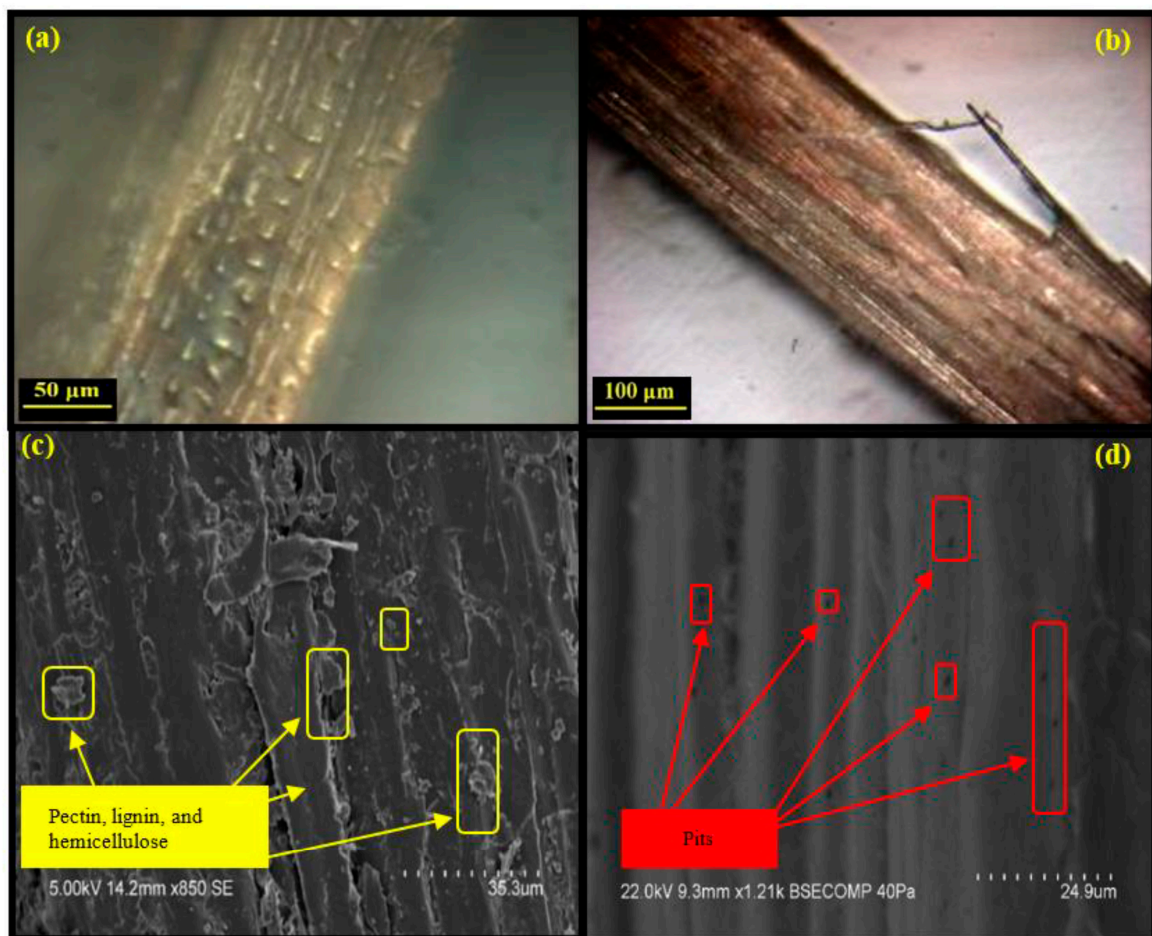


Figure 3. SEM images of PS fibers, including (a) rough surface of the fiber; (b) longitudinal section of unit fibers; (c) presence of lignin, pectin, and hemicellulose particles; (d) presence of cavities on the surface of the fibers.

As can be observed in Figure 4, natural fibers are composites reinforced by cellulose fibers in an amorphous matrix of lignin and hemicellulose with a very complicated cellular structure. An opening is observed on each elementary fiber, which is commonly referred to the lumen. Additionally, each individual fiber consists of a few fibrils [50] and each cell consists of 2 main cell walls: primary and secondary. The secondary wall being composed of 3 layers, corresponding to S1, S2, and S3. Each cell wall contains a matrix of lignin and hemicellulose, surrounded by cellulose microfibrils. From the literature, these layers are

arranged in different directions with respect to the longitudinal axis of the fiber with a constant angle in each layer.

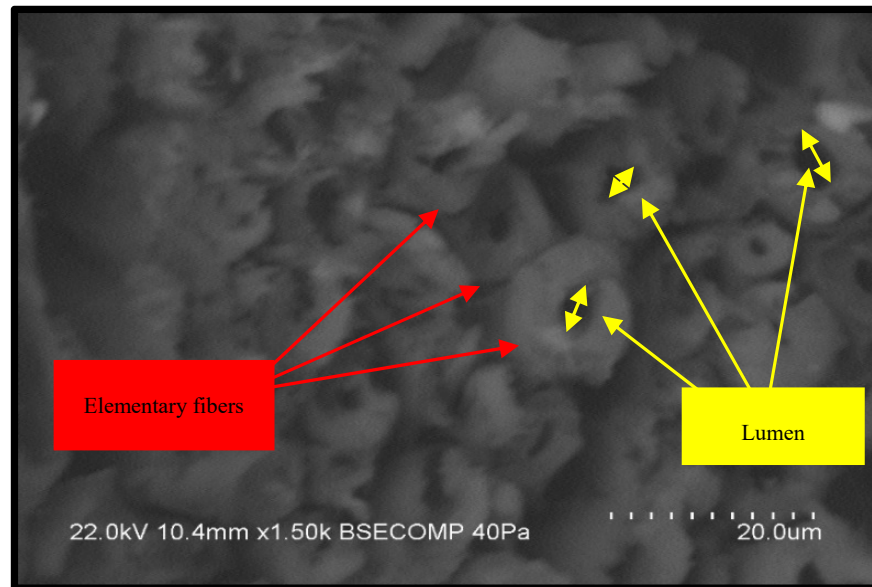


Figure 4. SEM cross-section of PS fibers.

3.2. Sorption Isotherms of the Investigated Fibers

The sorption/desorption isotherms of the investigated raw and treated fibers are presented in Figures 5 and 6, respectively. Isotherm measurements were made using the Belsorp Aqua3 apparatus.

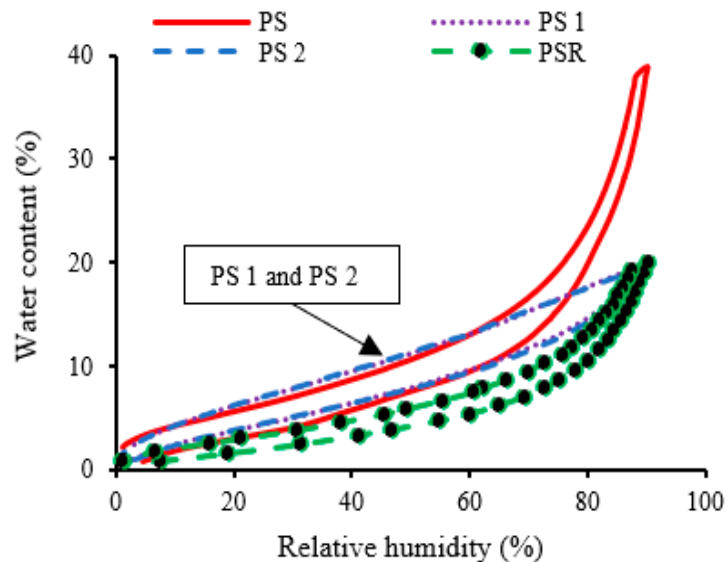


Figure 5. Sorption isotherms of PS fibers.

As can be observed, the PS fibers exhibited higher adsorption rate than HF fibers. For example, at 90% of relative humidity, the PS fibers showed an absorption of 39% compared to 22% obtained with HF fibers. This may be due to the presence of pectin and hemicellulose in fibers which are responsible for their hydrophilic character. On the other hand, the treatment of fibers resulted in a reduction in adsorption by 50%. This is probably due to the extraction of the hydrophilic constituents. In the case of HF fibers, the treatment results in 17% absorption reduction. The sorption after the first (PS 1 and HF 1) and second (PS 2 and HF 2) infusions are very similar. This confirms that the first infusion was enough

to extract the most hydrophilic constituents. Moreover, the impregnation of fibers in the hydrophobic resin considerably reduced the rate of adsorption for both PS and HF fibers. Indeed, an important reduction of the order of 48% and 52% was recorded for PSR and HFR compared to PS and HF, respectively. This is mainly due to the reduction of the hydrophilic character of fibers by means of creating a hydrophobic resin coating on the surface of fibers.

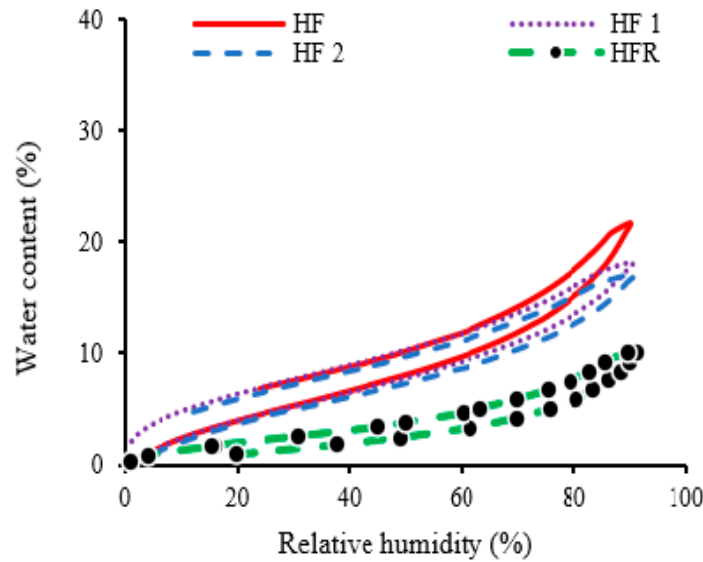


Figure 6. Sorption isotherms of HF fibers. It is worthy to mention the fiber’s abbreviations, as follows: PS/HF corresponds to the raw fibers (i.e., without treatment), PS1/HF1 corresponds to the treated fibers after the first infusion and PS2/HF2 after the second infusion, and PSR/HFR are those impregnated in resin.

3.3. Porosity of the Fibers-Reinforced Mortar Mixtures

For each of the investigated fiber mortar mixtures, the total porosity was determined using three different samples for better repeatability. The density of the reference mixture was in the order of 748.48 kg/m³, while that of the fiber mortars was 652.29, 644.61, 614.72, and 610.83 kg/m³ for PS 2.5, PS 5, HF 2.5, and HF 5 mixtures, respectively. The mean porosity value and the corresponding standard deviation are shown in Figure 7. The water porosity test is based on Archimedes’ principle and allows a global characterization of the total porosity of the matrix.

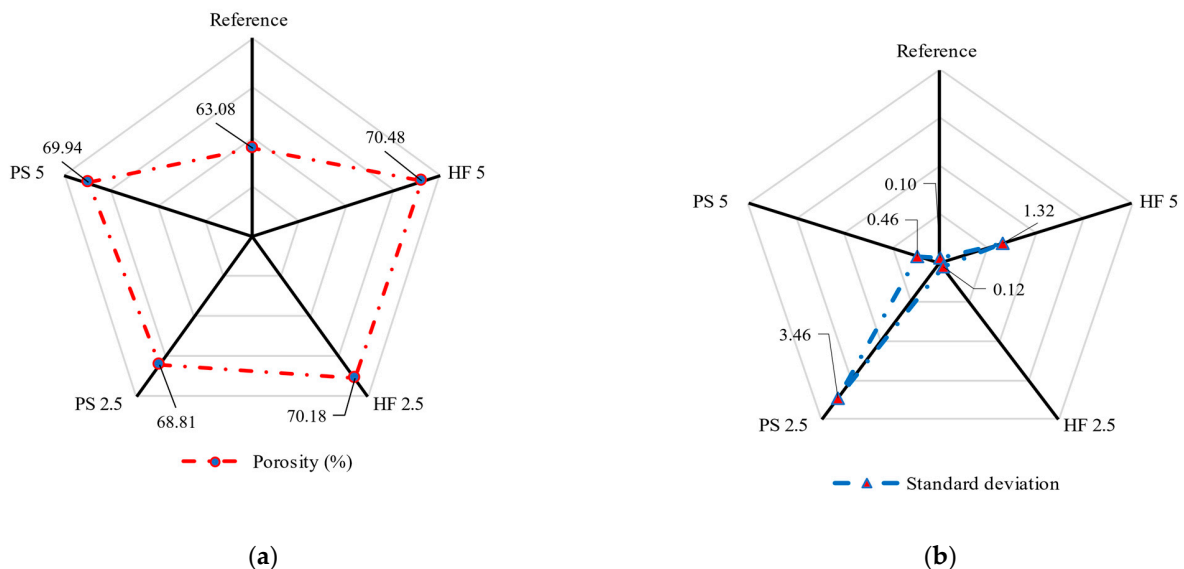


Figure 7. (a) Porosity of fiber mortar and (b) standard deviation.

As can be observed, the investigated mortar mixtures showed a high porosity between 68% and 71%. These values are in good agreement with those reported in literature on the hemp (71%) and flax (74%) concrete mixtures [34,51,52]. The fiber mortar mixtures incorporating 5% of PS and HF showed slightly higher porosity than those containing only 2.5% of fibers and the reference mortar mixtures. The incorporation of natural fibers with lime increases the surface area and heterogeneity of the mixture, thus leading to the appearance of pores. This is advantageous in improving the insulating capacity of the materials, because the porosity is inversely proportional to thermal conductivity [34,53]. The porosity tests showed a low standard deviation, hence indicating that the porosity values obtained from the mixtures are close and, therefore, reflecting the good repeatability of the mixtures (Figure 7b).

3.4. Thermal Conductivity of the Investigated Fiber Mortars

The thermal conductivity of the investigated fibers-reinforced mortar mixtures was measured at three different temperatures of 10, 23, and 40 °C. For each mixture, an average of three measurements was determined. The evolution of the thermal conductivity of dry and wet fiber mortars is presented in Figure 8.

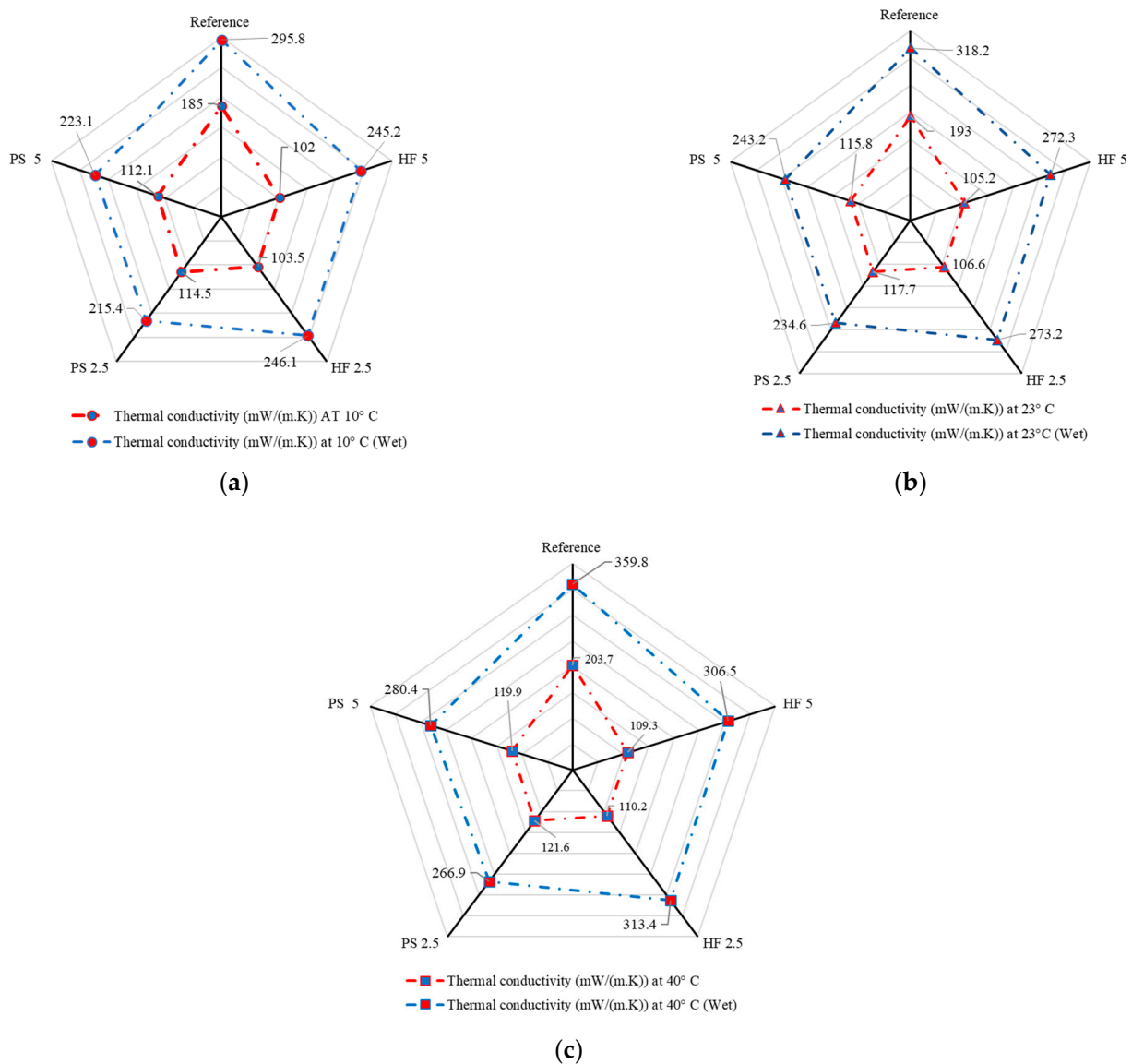


Figure 8. Evolution of the thermal conductivity of fiber mortar at different temperatures, including (a) 10, (b) 23, and (c) 40 °C.

As expected, the fiber mortar mixtures exhibited low thermal conductivity compared to the control mixtures (without fibers), regardless of the fiber types. In the dry state and in the case of the lowest temperature of 10 °C, the thermal conductivity of the mortar is around 185 mW/(m·K), while that of the PS and HF fiber mortar mixtures varies between 102 and 114 mW/(m·K), respectively. This represents a reduction in the thermal conductivity by 38% and 45%, respectively. This significant reduction is due to the low thermal conductivity of the incorporated fibers and the increase in the porosity of the matrix incorporating PS and HF fibers. This porosity contributes in damping the transmission of heat. This trend is also observed at higher temperatures of 23 and 40 °C. As expected, the thermal conductivity increases linearly with temperature. This is consistent with reported literature [54]. The average thermal conductivities of the investigated hemp and palm fibers mortar mixtures are ranging between 102 and 114 mW/(m·K), respectively, which is much lower than that of the conventional materials used in construction, including polystyrene concrete [44,45]. It is worth mentioning that the increase in fiber dosage from 2.5% to 5.0% did not significantly affect the thermal conductivity. However, the use of a higher percentage can reduce the thermal conductivity of the mixtures. In addition, the mortar mixtures containing HF fibers showed better thermal conductivity behavior. This is probably due to a better distribution of HF fibers compared to PS fibers.

The thermal conductivity of wet fiber mortar mixtures was determined on samples that were first saturated in water to constant mass. Thereafter, the saturated samples were wrapped in a stretch film to avoid evaporation of water from the sample during the measurement. Although the temperature gradient imposed by the equipment (15 K) is likely to induce diffusion inside the sample, the water remains trapped inside because of the stretch film where the material is enclosed. The thermal conductivity of the wet samples was measured at different temperatures of 10, 23, and 40 °C. As can be observed in Figure 8, wet mixtures exhibited a higher thermal conductivity than dry ones at all temperatures. For example, at 10 °C, the thermal conductivity increased from 102 to 245 mW/(m·K), corresponding to 240%, for fiber mortar mixtures containing 5% HF fiber content. At a temperature of 23 °C, this increase corresponds to 260% (i.e., increase from 105 to 272 mW/(m·K)). The same trend is also observed at 40 °C, where the thermal conductivity increases from 109 to 306 mW/(m·K). This trend was also observed in the case of mixtures containing 2.5% of fibers and reference composites, which is also reported in literature [51]. This behavior is due to the presence of water, for which the thermal conductivity is 24 times higher than that of air (λ_{water} of 600 mW/(m·K vs. λ_{air} of 25 mW/(m·K at a temperature of 25 °C)). As expected, the investigated mixtures are insulating materials in their dry state, and conductive in their wet state.

3.5. Sorption/Desorption Isotherms of the Investigated Mixtures

For each mixture, sorption/desorption isotherms were measured on two different samples. The sorption/desorption isotherm curves for the investigated mortar mixtures containing 2.5% and 5% PS and HF fibers are shown in Figure 9. It can be stated that the incorporation of fibers significantly affects the maximum absorbed water content. For example, at 94% of relative humidity, an increase in water content of 2.5% and 7.0% was observed for PS2.5 and HF2.5 mixtures compared to the reference mortar, respectively. The same trend was also observed for the fiber mortar made with 5% of fibers. This is due to the presence of highly hygroscopic materials which can absorb two to three times their weight at saturation. However, the increase in fiber dosage from 2.5% to 5.0% did not result in a significant difference. This may be due to the high heterogeneity of the materials and poor distribution of the fibers in the matrix. Moreover, the adsorption capacity of fiber reinforced mortars does not only depend on the fiber content. For example, porosity is a parameter that affects the adsorption of the mortar. In the case where the pores of the materials are emptied of air and filled with water, this results in a higher adsorption rate.

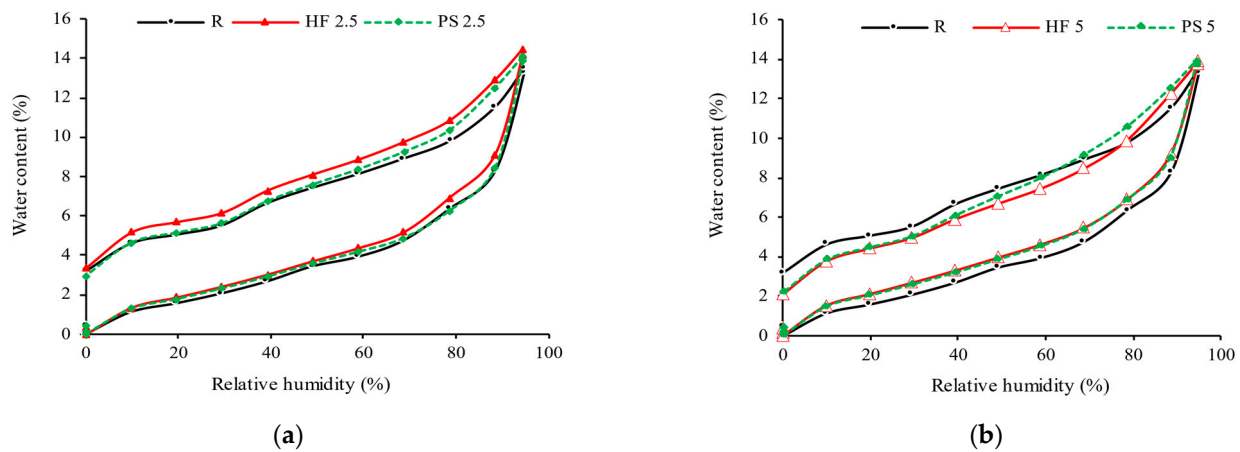


Figure 9. Sorption isotherms of fiber mortar with different contents of fibers, including (a) 2.5%; (b) 5%.

As can be observed in Figure 9, the area of the sorption hysteresis loop differs in a random way from a formulation to another. The same behavior has been observed in flax concrete mixtures [34]. This behavior is probably due to the complexity of the microstructure of these materials, which governs the hysteresis phenomenon. Indeed, natural fibers increase the intergranular porosity of the materials, which changes their microstructure and pore-size distribution. Due to the “ink bottle” effect, water can be trapped inside the small pores where their emptying can be achieved only under relatively high capillary pressures, hence resulting in larger hysteresis loop. Moreover, during desorption, the emptying process of the large pores starts only after that of the small ones, which explains the difference between the observed hysteresis curves.

3.6. Moisture Buffer Value (MBV)

The moisture buffering capacity of the investigated mortar mixtures was measured according to the Nordtest protocol [38]. The average MBV values and their standard deviations are presented in Figure 10.

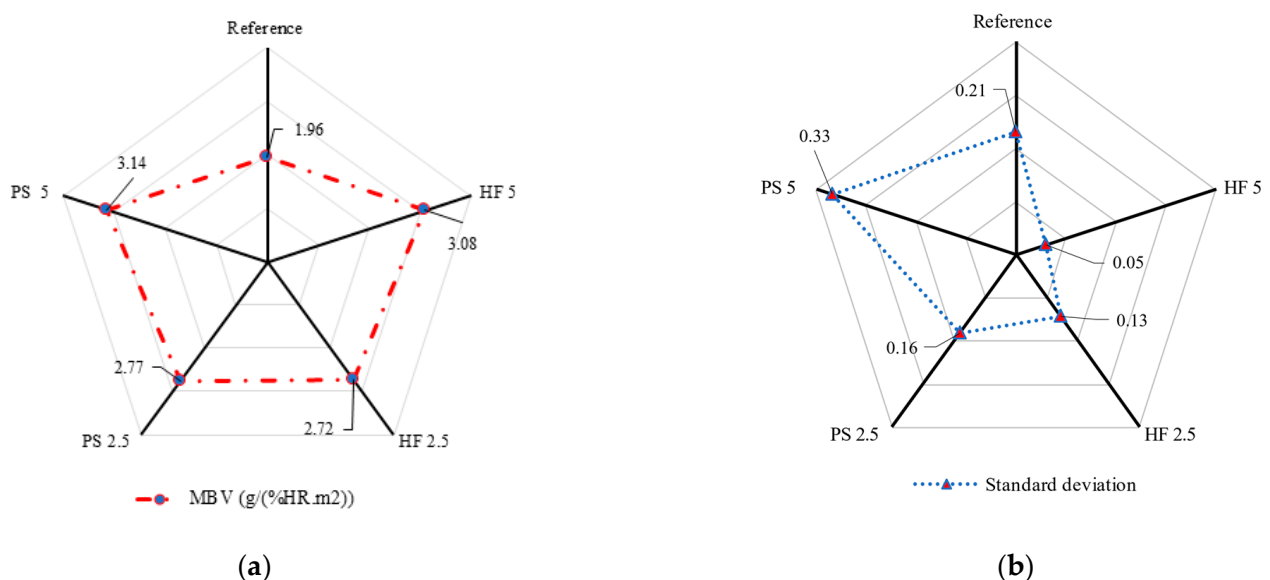


Figure 10. (a) Moisture buffer value (MBV) of fiber mortar; (b) standard deviations.

The obtained results revealed the good behavior of the investigated fiber mortar mixtures to the moisture variation. Indeed, MBV greater than 2 [g/(%HR·m²)] corresponds to excellent moisture regulator materials according to the Nordtest classification. These

results are in good agreement with those reported in literature [34,51,52]. Bio-based materials, including flax and hemp concrete, are shown to be excellent moisture regulators. The fiber content (PS and HF) considerably increased the MBV of the investigated fiber mortar mixtures. Indeed, the use of 5% of PS and HF fibers increased the MBV from 1.96 to 3.14 and 3.08 [g/(%HR·m²)], respectively. This suggests the ability of fiber mortar to regulate humidity variations in living environments. Furthermore, the different mixtures investigated in this study showed a low standard deviation (Figure 10b) and, therefore, good repeatability.

3.7. Compressive Strength Development of the Investigated Mortar Mixtures

For lightweight filling and insulating materials, a minimum compressive strength is required to support their own weight during installation and service life. The compressive strength of the investigated fiber mortar mixtures was determined according to the ASTM C109 specifications [49]. The obtained results are summarized in Figure 11.

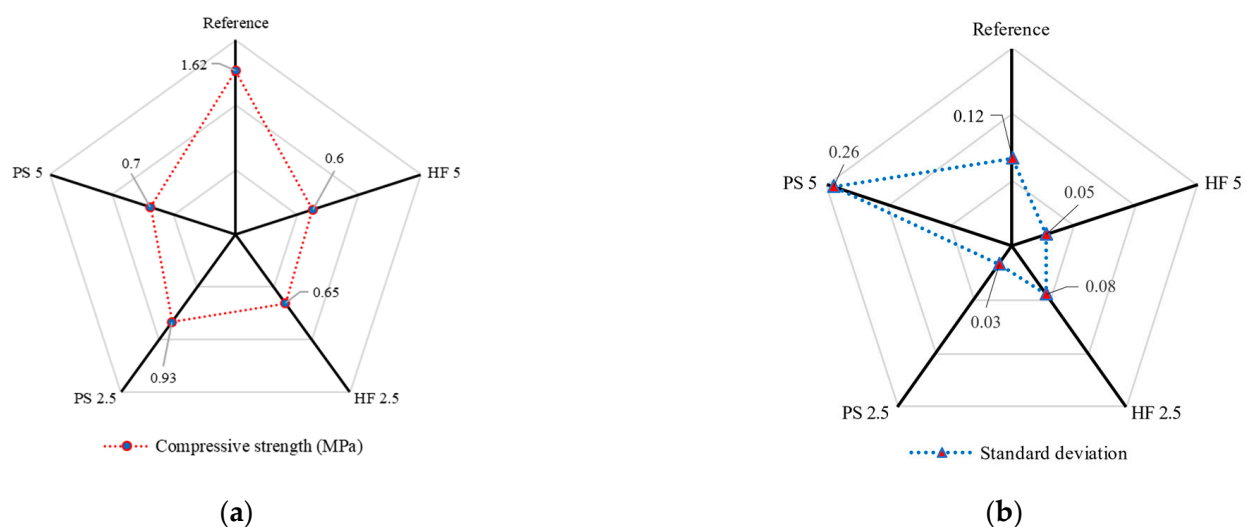


Figure 11. (a) Compressive strength of fiber mortar; (b) standard deviation.

The compressive strength of the fiber mortar mixtures varies between 0.60 and 0.93 MPa, compared to 1.62 MPa of the control mixture. The obtained results revealed that the compressive strength is inversely proportional to the percentage of fibers. For example, the compressive strength decreased from 1.62 to 0.93 MPa (reduction of 43%) when 2.5% of PS fiber is used. In the case of 5% dosage, this reduction was 57% (decrease from 1.62 to 0.70 MPa). The same behavior was also observed for the mortar mixtures made with hemp fiber. Indeed, the presence of fibers in the material reduces its compactness due to the dependence between the intergranular porosity and the volume of vegetable particles in the material [34]. The increase in the void volume causes the embrittlement of the mechanical behavior and, consequently, reduces the compressive strength of the composite. In addition, the increase in the vegetable particles content results in higher specific area and weak binder/fiber bond [55], thus resulting in low compressive strength of the material [53].

4. Conclusions

The experimental investigation presented in this study contributed to a novel natural fiber. The fiber was successfully extracted from date palm and characterized, then incorporated in mortar mixtures at different dosages. The effect of this fiber on the hydrothermal properties of the mortar was investigated. Based on the results presented in this paper, the following conclusions can be pointed out:

- The palm stem fibers (PS) have a rough and porous surface with a clear deposition of lignin, hemicellulose, and pectin on their surface. The microscopic observations revealed that PS fibers have a morphology similar to that of coir fibers and a complex microstructure of an assembly of elementary fibers having opened on their surfaces.
- The novel PS fibers are hygroscopic materials with high capillary condensation. The infusion of fibers significantly reduced their water absorption by up of 50%. In addition, their impregnation in hydrophobic resin reduced their hydrophilic character.
- The dry mortar mixtures incorporating 5% of PS and HF fibers exhibited low thermal conductivity in the order of 102 and 112 mW/(m·K), respectively, compared to 185 mW/(m·K) of the control mixture. In the case of wet mixture, this represents an increase of 245% and 200% compared to the control mortar (245 mW/(m·K) and 223 mW/(m·K)).
- The thermal conductivity of the mixture is affected not only by the percentage of fibers and their orientation in the matrix, but also by the water content of the material.
- The fiber mortar mixtures exhibited higher porosity and water absorption compared to the control mixture, regardless of the fiber content. Higher fiber content resulted in higher porosity and water absorption. This resulted in better moisture buffer capacity and lower thermal conductivity and compressive strength.
- The investigated fiber mortar mixtures exhibited an MBV greater than 2 [g/(%HR·m²)], regardless of the fiber content. The use of 5% of fibers resulted in the best moisture regulating behavior.
- The compressive strength of fiber mortar mixtures is inversely proportional to the percentage of fibers. The higher the percentage of natural fibers, the lower the compressive strength of the investigated mortar mixtures. This is mainly due to the reduction of compactness of the lime matrix and increase in porosity.

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