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Experimental Study of the Reinforcement of Unstabilized and Stabilized Local Clay Materials with Date Palm Fibers

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Abstract. The aim of this study is to experimentally test the stabilization of unexploited clay from the Errachidia region (south-east Morocco) with date palm spathes, with a view to its potential use in construction. The main objective of the present work is to evaluate the thermophysical and mechanical behavior of fiber-stabilized clay blocks. Several samples of spathe-reinforced clay at six different grades (0%, 1%, 2%, 3%, 4%, and 5%) were prepared and tested. Thermal characterization was carried out using the PHYWE House thermal insulation method to determine thermal conductivity and resistance. Mechanical performance was measured in terms of compressive and flexural strength. In addition, the chemical identification of Errachidia clay was studied using the X-ray fluorescence method. The results of the clay identification showed that Errachidia clay meets the minimum requirements for the manufacture of compressed earth bricks and adobe. The results of the thermophysical tests showed that the addition of date palm spathes had a positive influence on the lightness and thermophysical properties of the clay samples stabilized by the spathes. In terms of mechanical test results, the flexural and compressive strengths of clay blocks stabilized with date palm fibers continue to increase up to a fiber content of 3%. After this content, mechanical performance decreases with the addition of spathes and no improvement is detected. Consequently, a fiber content of 3% represents the optimum content for stabilizing Errachidia clay. At this content, stabilized clay blocks show optimal mechanical performance and improved thermal properties compared to reference samples. However, increasing the percentage of fiber mass leads to an increase in water absorption and a decrease in density. Clay compounds reinforced with date palm spathe can be considered as environmentally friendly building materials.

1. Introduction

Owing to the swift urbanization and population expansion, the substantial energy requirements in the foreseeable future pose a looming crisis globally. This escalating demand for energy is driven not only by large-scale development projects but also by routine daily activities. The construction industry, responsible for approximately a quarter of Morocco's yearly energy consumption, is a major contributor to 30% of energy-related CO_2 emissions and roughly a third of black carbon emissions [1]. Hence, there is an urgent need for substantial advancements in the realm of sustainable construction, with the objective of achieving a 30% reduction in the energy intensity of buildings by 2030 in comparison to the 2015 baseline [2]. One of the strategies employed by Moroccan authorities to curtail energy consumption in building air-conditioning systems involves enhancing the thermal performance of the building envelope. This is crucial because conventional building materials, primarily constructed using standard mortar, often lack the requisite thermal insulation properties. This holds particularly true for regions in the Mediterranean, with Morocco being no exception, where conventional building materials are known for their high environmental impact. They contribute significantly to pollution due to their CO2 emissions during manufacturing and create disposal-related ecological challenges. The adoption of locally sourced materials in the construction sector has emerged as a vital solution to address the economic challenges faced by developing nations [3,4]. Given that the building industry is a substantial consumer of both materials and energy resources, as well as a major contributor to pollution and waste generation, the pursuit of sustainable construction has increasingly shifted focus toward the judicious use of industrial and agro-industrial materials [5]. These materials offer numerous benefits, including ready availability, recyclability, cost-effectiveness, non-toxicity, resistance to wear and tear, biodegradability, and favorable thermo-mechanical performance. Consequently, leveraging waste and renewable resources as alternative construction materials has gained traction as an effective means to address environmental concerns in most developing countries, with researchers now emphasizing environmental preservation as a prerequisite before implementing new technologies. Soil serves as a robust, eco-friendly, and highly thermally retentive building material. In the construction of traditional dwellings and ksars in the cold winters and hot summers of southern Morocco, soil is extensively employed. Enhancing the thermal and mechanical properties of clay can be achieved by integrating natural additives, leading to a more effective insulating composite material. Ongoing research has been dedicated to investigating the impact of stabilization on the mechanical and thermal characteristics, as well as the longevity, of clay-based materials. Therefore, the primary goal of reinforcing soil masses is to enhance structural stability, increase load-bearing capacity, and diminish settlement and lateral deformation [6]. Furthermore, reinforcement encompasses the integration of specific materials possessing desired attributes into other materials that may lack these characteristics. Consequently, soil reinforcement can be described as a method directed at enhancing the technical properties of soil with the intention of refining parameters such as shear strength, compressibility, density, and thermal conductivity [7]. In a study conducted by Ben Mansour and al [8], it was deduced that optimizing the bulk density of compressed earth blocks can effectively achieve the dual purpose of reducing thermal conductivity while providing sufficient compressive strength. Recently, researchers have increasingly directed their attention toward fiber-soil composites as a subject of heightened interest. The Drâa-Tafilalet region in the southeast of Morocco boasts a vast expanse dedicated to date palm cultivation. Among the provinces in this region, Ouarzazate, situated in the Drâa Valley, and Errachidia, covering Tafilalet and Ziz Valley, stand out as the principal hubs for date palm cultivation, collectively constituting the largest regions for date palm cultivation. Ouarzazate province leads the way with 40% of the total date palm trees, followed by Errachidia with 28.24%. In light of this, our study centers on the development and characterization of novel eco-friendly building materials. These materials are derived from soil and reinforced with waste from date palms, which are abundantly available in the Drâa-Tafilalet region. The intention is to employ these materials in housing construction. Several researchers have explored the utilization of palm by-products in building materials due to their exceptional thermal and mechanical properties. Palm fibers exhibit filamentous textures and possess unique attributes, including affordability, local abundance, durability, and lightweight properties [9]. Fibers obtained from deteriorated palm material exhibit brittleness, possess low tensile strength, a low modulus of elasticity, and a high capacity for water absorption [10]. Research conducted by Salehan and Yaacob [11] demonstrated that water absorption levels slightly rise as the palm fiber content increases. Synthetic fibers are a commonly employed resource in the field of soil reinforcement, facilitating the augmentation of both compressive and shear strength [12,13]. In a study by Namango, a substantial boost in strength was observed with escalating proportions of sisal fibers, cassava powder, cement, and cement fiber, albeit within specific limits. The findings indicate that exceeding these thresholds for sisal fiber content has an adverse effect on the strength attributes of compressed earth blocks [14]. Minke highlighted the potential of incorporating fibers such as human or animal hair, coir, sisal, agave, bamboo, and straw to mitigate shrinkage by reducing clay content and allowing for some water absorption through the fiber's pores [15]. Similarly, Villamizar and al [16] observed that the utilization of cassava peels notably enhanced the dry strength of mixtures, a property beneficial in addressing challenges associated with handling block-earth construction waste. Nevertheless, Rigassi argued, without presenting specific research data, that while fibers are frequently employed to reinforce adobe, they may not be compatible with the compaction pressures associated with compressed earth blocks (BTC) due to their potential elasticity-inducing properties [17]. It is noteworthy, however, that in the pursuit of environmental conservation, investigations have been conducted on compressed earth blocks infused with recycled synthetic fibers, as exemplified by the work of Eko and al [18]. In their work, Ouakarrouch and al [19] conducted both experimental and numerical analyses to evaluate the thermal comfort of "Ksar Lamaadid" in the Erfoud region, which is constructed using an innovative biocomposite material comprising clay and sisal fibers. Their research demonstrated that incorporating 4% sisal fibers can lead to an approximate 11.2% reduction in the material's thermal conductivity. This reduction has the potential to enhance thermal comfort and reduce greenhouse gas emissions by roughly 62442 kg CO2 per year. Liuzzi et al. [20] investigated the impact of adding plant fibers on the thermophysical characteristics of clay mixtures, while Calatan and al [21] found that the utilization of hemp fibers positively influenced both thermal and mechanical properties. The study conducted by Ismail and Yaacob [22] revealed that incorporating 3% palm fiber resulted in an improvement in the compressive strength of composite bricks. Additionally, the authors noted a slight uptick in water absorption as the fiber content increased. The incorporation of date palm as a natural additive in construction materials is not a novel concept, as multiple studies have already demonstrated the manifold benefits of utilizing natural fibers in brick production. Taallah and Guettala, in their extensive research [23,24], delved into various compositional factors, including the addition of date palm, and their influence on reducing the thermal conductivity of bricks. In addition to floor bricks, a separate investigation concluded that the inclusion of palm fibers in mortar specimens generally enhances post-crack performance and ductility when compared to specimens lacking palm fibers, thus extending the composite material's resistance to failure [25]. More recently, a study introduced the combination of palm fibers and lime in the development of an eco-friendly insulation material, revealing its advantages in terms of thermo-acoustic properties [26]. Furthermore, Oskouei and al reported a noteworthy enhancement in compressive strength, measuring at 15.6%, resulting from the inclusion of palm fibers within the composition of gravel, sand, and clay [27]. This compositional adjustment also led to a significant 62.5% reduction in final deformation and an extended duration of resistance to water exposure, surpassing the properties of materials consisting solely of gravel, sand, and clay by 23%. In Biskra, Algeria, D. Khoudja et al. conducted a thermomechanical study on raw earth bricks stabilized with lime and fortified with aggregates derived from a blend of waste components from date palm materials. Their research exhibited improved thermal insulation, with a thermal conductivity rating of 0.342 W/(m·K) for bricks containing 10% aggregates, while still meeting the minimum performance standards required for earth construction [28]. Our experimental research centers on the creation of a novel composite material using a blend of date palm fibers and clay. This composite serves as the fundamental component for adobe and brick construction in the southeastern region of Morocco, with the aim of enhancing their thermal and mechanical attributes, as well as their hygroscopic behavior. The primary objective of this study is to investigate the impact of integrating date palm waste into the composition of mud bricks concerning their thermal, physical, and mechanical properties. The ultimate goal is to develop bricks with robust mechanical characteristics and improved thermal insulation properties, allowing for the construction of housing with highly insulating walls.

2. Experimental methods

2.1 Materials

2.1.1 Date palm spathe

The date palm spathes used in this study were sourced from the Draa Tafilalt oasis in Morocco. These date palm fibers had been exposed to the natural environment, leading to contamination by significant amounts of sand and dust. The fibers underwent a rigorous cleaning process, which involved washing them with fresh water and manually separating them into fiber bundles. Prior to their use, a high-pressure water wash was performed to eliminate any pollutants. Subsequently, the fibers were left to air-dry for a duration of three days. After the drying process, the fibers were cut to the desired length. For this study, we utilized individual fiber samples, each measuring 5 mm in length, as described below and depicted in Figure 1.

Fig.1 Element of the date palm used in the study.

2.1.2 Sol

The earth used (figure 2) comes from the Errachidia region in south-east Morocco, and is a very high-quality material. It is often used in construction projects because of its properties, which are well suited to certain types of structure.

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Fig.2 Soil studied.

Table 1 Soil mineralogical composition (%).

Minerals	Chemical formula	Mineralogical composition (%)
Calcite	Ca(CO3)	43.33
Quartz	SiO2	36.51
Dolomite	CaMg(CO3)2	16.18
Muscovite	H2KAl3Si3O12	3.98

X-ray fluorescence spectrometry (XRF) was used to determine the chemical composition of the soil. Table 2 shows the data obtained from this analysis.

Table 2 Soil chemical composition.

Components	Percentage %
SiO2	33.91
CaO	22.15
P.a.F	20.81
Al2O3	11.96
MgO	3.98
Fe2O3	3.57
K2O	1.74
Na2O	0.55
TiO2	0.49
CI	0.25
SO3	0.20
P2O5	0.11

2.2 Sample preparation

The material studied was obtained by mixing clay with date palm spathe fibers (Fig. 3). Five mass fractions (1%, 2%, 3%, 4% and 5%) of these fibers were selected. To obtain homogeneous composites prepared by hand, we followed the following steps: (1) immerse the fibers in water for five minutes before use, (2) mix the dry fibers with the soil, (3) then add the water solution in the required proportions. After demolding, the molds were placed in the laboratory to undergo a hardening process under controlled conditions. Pure samples (100% clay) of the same size were prepared to follow the evolution of thermal, mechanical and hydric properties. Samples were made in 250x250x30 mm^3 molds for thermal characterization. To assess flexural strength, we used prismatic molds with dimensions of 40x40x100 mm^3. For compressive strength, we used cubic molds measuring 40x40x40 mm^3. Cylindrical samples measuring 100x100 mm^2 were molded to determine the water absorption rate (Figure 3). After 3 days air-drying, the samples were dried at 50°C to remove moisture.

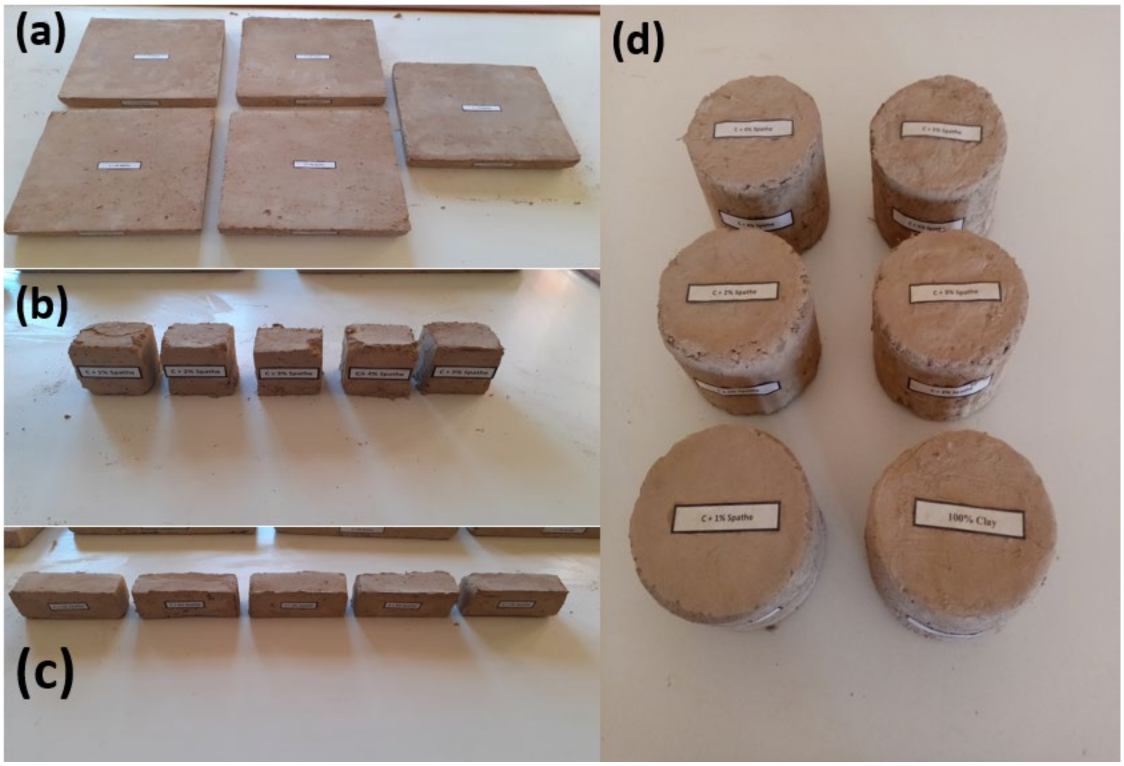

Fig.3 The various samples tested include (a) measurement of thermal conductivity, (b) evaluation of compressive strength, (c) measurement of flexural strength (d) determination of water absorption.

Table 3. Characteristics of the various samples studied.

Samples	Percentage of Fiber Spathe (%)	Number of samples	Average Density (Kg / m^3)
E1 : 100 %Clay	0	4	2985,18
E2 :1% Spathe	1	4	2827,56
E3 :2% Spathe	2	4	2758,85
E4 :3% Spathe	3	4	2613,59
E5 :4% Spathe	4	4	2540,70
E6 :5% Spathe	5	4	2319,25

3. Measurement methods

3.1 Thermal characterization method

The experimental tests were conducted within a highly insulated thermal house featuring interchangeable walls, as depicted in Figure 4. This approach has been employed by several researchers in previous studies [29,30]. The thermal house comprises four vertical walls, each equipped with a well-insulated square polystyrene opening measuring 210x210 mm^2. To provide controlled heating, a 100 W incandescent bulb was utilized as the heat source and connected to an internal thermal controller, allowing for the regulation of the desired temperature. During steady-state operation, the heat source maintained an internal temperature of approximately 50°C. Thermocouples were affixed to both the interior and exterior of the wall to capture the T_{int} and T_{ext} temperatures of the sample. The ambient temperature was rigorously controlled in a laboratory environment, maintained consistently at 20°C through the use of an air-conditioning unit. Following 8 hours of heating and the attainment of thermal equilibrium, the acquisition system recorded the three temperature values, T_{loc}, T_{int}, and T_{ext}, with an estimated error margin of 10% for this method [30].

Fig.4 PHYWE thermal insulation house.

To determine thermal conductivity, we take into account the conservation of heat flux that occurs by convection between the inner air and the inner wall surface, as well as by convection between the outer air and the outer wall surface, and by conduction through the sample is given by:

$$\varphi = h_{int}\left(T_{loc} - T_{int}\right)\, S = S \times \lambda \frac{T_{int} - T_{ext}}{e} = h_{ext}\left(T_{ext} - T_{amb}\right)\, S \qquad \text{Eq.1}$$

With:
h_{int}: internal convection coefficient.
h_{ext}: external convection coefficient.
T_{int}: temperature of the inside of walls.
T_{ext}: temperature of the outside of the wall.
T_{loc}: air temperature inside thermal house.
T_{amb}: ambient temperature.
e: wall thickness.

We determined the thermal conductivity value (λ) by applying equation (3) along with a coefficient value of 8.1 $W/m^2 \cdot K$, as indicated in prior references [31, 32]. In assessing the thermal conductivity of our construction materials, we followed the manufacturer's recommended protocol, utilizing a PHYWE thermal control stand and a set of thermocouples to monitor temperature fluctuations both inside and outside the thermal house [33]. Readings were recorded when the thermocouples stabilized at a consistent value, ensuring that the system had reached thermal equilibrium, typically 8 hours after initiating the measurement.

$$h_{int}\left(T_{loc}-T_{int}\right)=\frac{\lambda}{e}\left(T_{int}-T_{ext}\right) \quad \text{Eq.2}$$

$$\lambda=\frac{\left(T_{loc}-T_{int}\right)}{\left(T_{int}-T_{ext}\right)}\times h_{int}\times e \quad \text{Eq.3}$$

Thermal resistance can be calculated according to the following equation:

$$R=\frac{e}{\lambda} \quad \text{Eq.4}$$

3.2 Mechanical performance tests

3.2.1 Dry and wet compressive strength test

Compressive strength tests are carried out on cubic specimens composed of a mixture of soil and fibers, at 28 days of age. Compression tests are carried out using a 30 KN capacity machine, in accordance with the requirements of Moroccan standard NM 10.1.538. Compressive strength can be calculated according to the following relationship:

$$R_C=\frac{F}{A_c} \quad \text{Eq.5}$$

With;

R_C: compressive strength, expressed in MPa (N/mm^2);

F: is the maximum breaking load, expressed in N;

A_C: is the cross-sectional area of the specimen to which the compressive force is applied, calculated from the specimen's nominal size, expressed in mm^2.

Compressive strength should be expressed to the nearest 0.1 MPa (N/mm^2).

3.2.2 Dry bending strength test

Flexural strength was measured on prismatic samples of soil mixture and spathe fibers. Figure 5 below shows the set-up for the three-point bending experiment. Bending tests were carried out using a 30 KN capacity machine in accordance with the requirements of Moroccan standard NM 10.1.538. According to the bending relationship and knowing the load obtained at break, the bending strength can be calculated as shown in the relationship:

$$R_f=1.5\times\frac{F\times L}{b\times d^2} \quad \text{Eq.6}$$

With;

R_F: is the compressive strength, expressed in MPa (N/mm^2);

F: is the maximum load applied to the sample, in newtons (N);

L: is the distance between the axes of the support rollers, in millimeters (mm);

b: is the width of the specimen, in millimeters (mm) ;

d: is specimen thickness, in millimeters (mm).

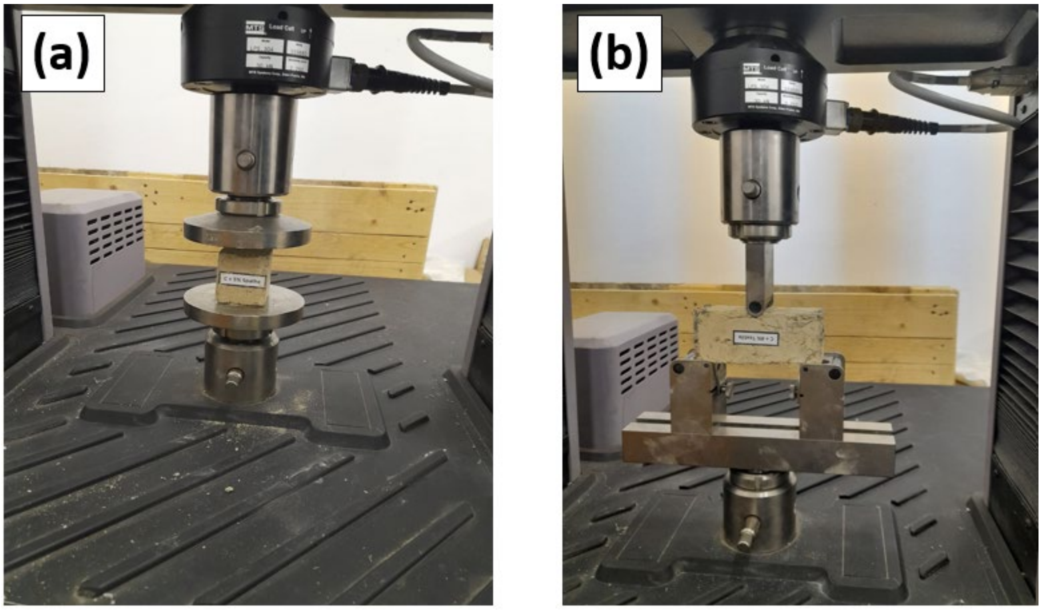

Fig.5 (a) Soil and fiber sample tested for strength; (b) C+5% spathe sample tested for flexural strength.

3.3 Immersion water absorption test

Immersion absorption was carried out in accordance with ASTM D570. Samples were immersed in distilled water at 27°C and sample weight changes were recorded every 0.5 h, 1.0 h, 2.0 h, 24 h, 48 h and 72 h respectively using a 0.01 mg resolution digital balance. The weighing process was carried out within 30 s, removing surface water from the sample using filter paper to avoid any errors. The water absorbed by the samples was determined using equation (7).

$$W(\%) = \frac{W_t - W_0}{W_0} \times 100 \qquad \text{Eq.7}$$

Where, W (%) is the average percentage of water absorption, W_0 and W_t are the initial and final sample weights after time t, respectively.

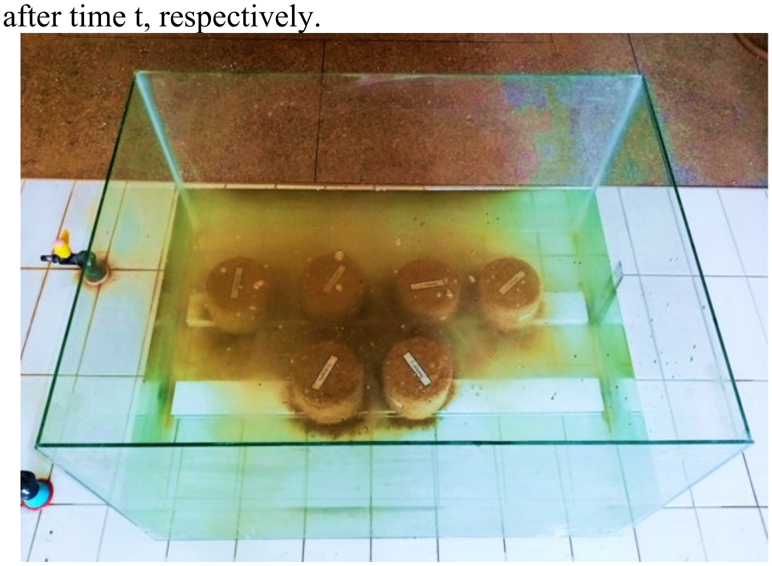

Fig.6 Measuring the degree of water absorption in the sample.

4. Results and discussion

4.1 Conductivity and thermal resistance of the samples studied

Thermal conductivity and thermal resistance are key parameters for assessing a building material's ability to conduct heat. Figure 7 illustrates the changes in thermal conductivity and thermal resistance concerning the incorporation of different fiber content in the various biocomposites developed. Notably, as fiber content increases, thermal conductivity decreases, and thermal resistance increases. Furthermore, it is evident that the sample enriched with 5% date palm spathe fibers exhibits superior insulation properties compared to the other samples. This enhancement is attributed to the reduction in thermal conductivity, which decreased from 0.514 W/(m·K) for the sample devoid of fibers to 0.274 W/(m·K) for the sample containing 5% of these fibers. This remarkable reduction amounts to an estimated 47% improvement in thermal insulation performanceThe results obtained for the 5% fiber content scenario can be rationalized in two ways. First, the gradual increase in the fiber quantity, characterized by their inherently low thermal conductivity, plays a significant role. Secondly, the heightened fiber content within the composites leads to a decrease in sample density, potentially generating air-filled pores within the material [34]. The latter can be attributed to the substantial cellulose content present in the fibers, which is associated with their insulating properties, evident through the high air permeability seen in the fibers as observed in SEM micrographs [35]. However, it is essential to acknowledge that the latter explanation is contingent on other factors such as fiber fragmentation and the uniformity of cellulose distribution within the fibers. In this context, date palm spathe fibers stand out due to their notably high cellulose content, which aligns with the observed lower thermal conductivity in samples containing these fibers.

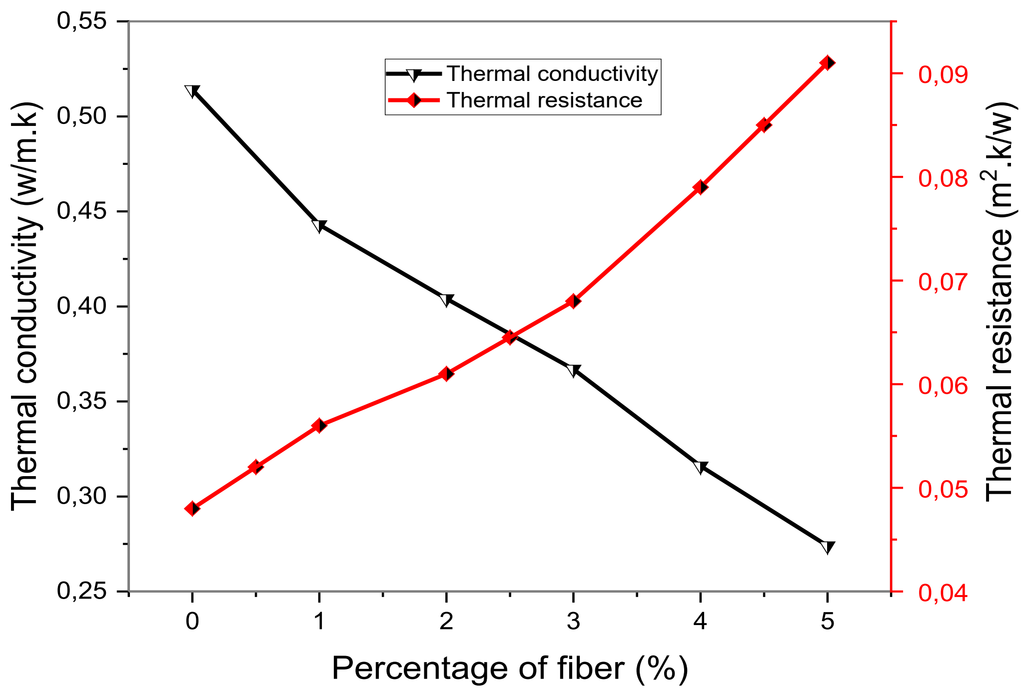

Fig.7 Conductivity and thermal resistance as a function of sample fiber content.

4.2 Compressive strength

Figure 8 presents the outcomes of the compression tests. Notably, the compressive strength values of the stabilized soil samples remained within the specified range, with a maximum increase of 40% recorded at the optimal fiber content of 3%. These values did not surpass the upper limit of 5.6 MPa specified by the fiber or fall below the lower limit of 3.4 MPa set by the clay. Beyond this optimal threshold, the compressive strengths displayed a decline at higher fiber content levels, indicating that further increases in fiber content do not yield significant benefits in terms of enhancing block strength.

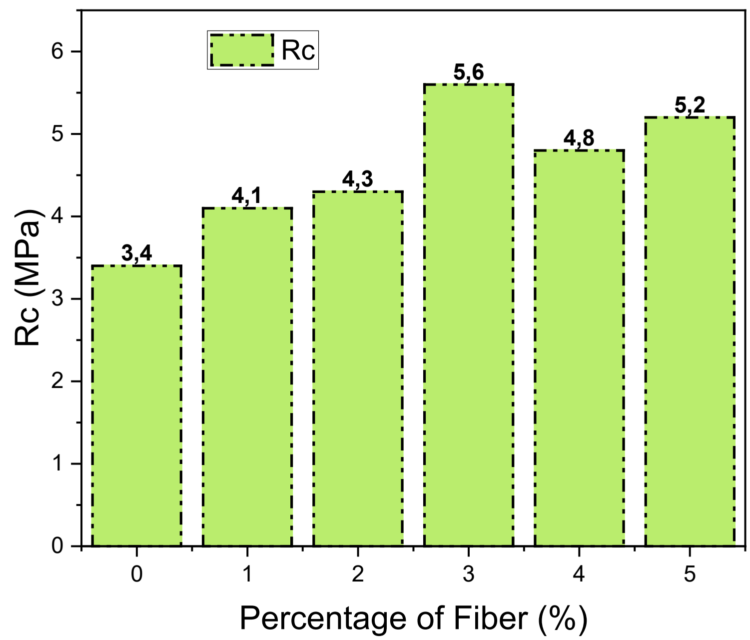

Fig.8 The effect of incorporating fibers into the mortar mix on compressive strength.

4.3 Flexural strength

In Figure 9, the outcomes of the flexural strength tests are depicted. The behavior of flexural strength in the stabilized soil blocks closely mirrored that of the compressive strength. The maximum enhancement, approximately 17% in comparison to the control samples, was observed at the optimal fiber content of 3%. Subsequently, the strength exhibited a reduction, which was then recuperated with higher fiber content, up to 3%.

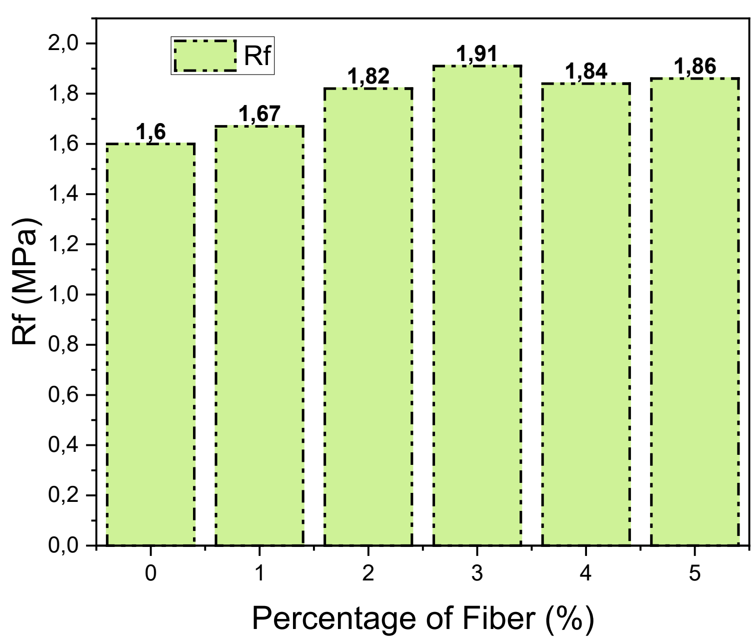

Fig.9 The effect of incorporating fibers into the mortar mix on flexural strength.

4.4 Analysis of hydric results

Figure 10 shows the evolution of water incorporation in a soil mixture reinforced with date palm spathe fibers. The increase in water incorporation is clearly perceptible and observable in correlation with the proportion of plant fibers. This observation is attributable to the presence of a large volume of voids produced by the addition of the fibers, as well as to the intrinsic nature of the latter.

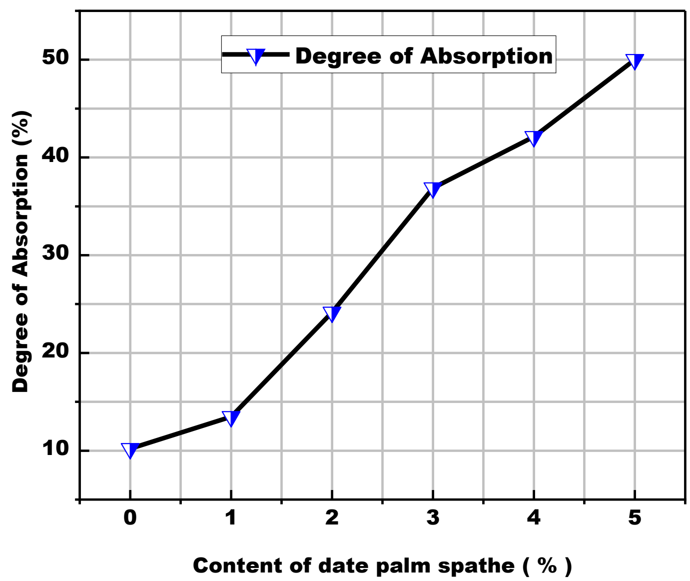

Fig.10 Variation in water absorption of a date palm soil and spathe mortar as a function of fiber mass percentage.

Conclusion

In this article, we present the findings of an experimental investigation focused on examining the thermo-physical and mechanical characteristics of soil that has been enhanced with date palm fibers. The primary objective of this study is to explore the viability of incorporating this enhanced material into construction practices, with the intention of reinforcing soil and mitigating heat loss within building structures. Our comprehensive analysis, encompassing both quantitative and qualitative assessments, has yielded the subsequent outcomes:

- Soil composites augmented with date palm spathe exhibit a noteworthy increase in water absorption as the fiber content rises. This heightened water absorption has the potential to result in microcracks within lateral composite structures.
- Empirical studies have revealed that elevating the fiber content contributes to an enhancement in the mortar's insulation capabilities. This improvement is attributed to a reduction in thermal conductivity as a direct consequence of the increased fiber content.
- Fiber-reinforced mortars increase compressive and flexural strength at low fiber percentages.

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