Civil Engineering and Architecture 12(5): 3615-3625, 2024 http://www.hrpub.org
DOI: 10.13189/cea.2024.120535

Experimental Study of Hemp Fibers Effect on Thermal Properties of Clay Matrix

Oussama Jarachi[1,*], Mohamed Lamrani[2], Najma Laaroussi[2], Khaoula Doghmi[2]

[1]Mohammadia School of Engineers, Mohammed V University in Rabat, Morocco
[2]Higher School of Technology of Salé, Mohammed V University in Rabat, Morocco

Received April 24, 2024; Revised July 30, 2024; Accepted August 23, 2024

Cite This Paper in the Following Citation Styles

(a): *[1] Oussama Jarachi, Mohamed Lamrani, Najma Laaroussi, Khaoula Doghmi , "Experimental Study of Hemp Fibers Effect on Thermal Properties of Clay Matrix," Civil Engineering and Architecture, Vol. 12, No. 5, pp. 3615 - 3625, 2024. DOI: 10.13189/cea.2024.120535.*

(b): *Oussama Jarachi, Mohamed Lamrani, Najma Laaroussi, Khaoula Doghmi (2024). Experimental Study of Hemp Fibers Effect on Thermal Properties of Clay Matrix. Civil Engineering and Architecture, 12(5), 3615 - 3625. DOI: 10.13189/cea.2024.120535.*

Abstract As a natural building material, clay provides excellent thermal mass, which helps regulate indoor temperature. In addition, hemp fibers are characterized by good mechanical resistance and excellent thermal insulation qualities. To promote these abundant materials in Moroccan rural areas, the impact of hemp fibers on the thermal insulation of clay was studied. Six mortars were made from local clay and varying proportions of Moroccan hemp fibers. Mass fractions of 0%, 1%, 2%, 3%, 4% and 5% clay were systematically replaced by hemp fiber and then, for each fiber content, three samples were prepared to ensure the reproducibility of the results. The thermal conductivity and volumetric heat capacity of the composite materials were then evaluated using the Hot Disk method, along with other derived properties. Experimental findings indicate that a minor reduction in density occurs with the incorporation of hemp fibers, while the thermal insulation capabilities of clay are notably improved, particularly when the fiber mass fraction ranges between 4 and 5%. Hence, with 5% fiber replacement, thermal conductivity is decreased by 53%, and heat capacity is increased by 55%. Additionally, thermal diffusivity and effusivity are decreased by 68% and 17%, respectively. Furthermore, it has been established that for a 20 cm thick wall, the thermal resistance and the diffusivity characteristic time are increased by 67% and 208%, respectively. This highlights the potential for integrating hemp fibers as a partial substitute for clay, thereby enhancing the thermal comfort and energy efficiency of prevalent constructions, particularly in rural regions.

Keywords Thermal Properties, Insulation Materials, Ecological Materials, Clay, Hemp Fibers

1. Introduction

Improving energy efficiency in the building sector involves a multifaceted approach that encompasses design, technology and behavior. In this sense, architects and engineers have integrated passive design strategies such as maximizing natural light, optimizing insulation and using energy-efficient materials [1]. The choice of building materials can significantly minimize environmental impact and improve building performance [2-4]. Opting for insulation using recycled or sustainable materials can significantly reduce heating and cooling needs. Additionally, selecting locally sourced materials [5-7] reduces transportation-related emissions and supports the local economy.

Incorporating renewable materials like rammed earth, bamboo, wood, cork, hemp, straw etc. not only reduces the environmental impact but also contributes to the overall energy efficiency and sustainability of the built environment. Many studies have been carried out in this direction [5-7] and the thermal performances of constructions, using ecological materials, were carried out. The use of local and unexploited materials as thermal insulation is, currently, considered a sustainable approach.

Furthermore, to improve the thermal properties of matrices such as mortar, clay, plaster etc., the common approach is to incorporate natural fibers.

Petcu et al. [8] explore the thermophysical properties of 12 compacted clay soil samples, focusing on their suitability for rammed earth wall construction. The results emphasize the importance of understanding clay's properties for sustainable building practices, aiming to enhance indoor comfort, energy efficiency, and overall sustainability in construction. El Azhary et al. [9] studied the use of unfired clay straw subjected to the harsh climatic conditions of the southern region of Morocco. Experimental assessment of the thermal characteristics of this composite involved employing both the flash method and the hot plate method to estimate its thermal conductivity and thermal capacity. Alternatively, a building simulation was conducted utilizing a raw clay-straw envelope to assess its thermal inertia and its potential to offer comfortable conditions by mitigating summer overheating and preserving internal warmth during winter. In particular, the clay-straw composite exhibits commendable thermal characteristics for heat retention and temperature regulation, effectively moderating fluctuations between daytime and nighttime temperatures in winter. It demonstrates resilience against warm and dry climates without the need for a cooling or heating system. On their side, Lamrani et al. [10] showed the good thermal efficiency of clay reinforced by date palm fibers. These palm fibers were valorized in developing sustainable high performance materials. In addition, they were interested in the thermophysical properties of the composite based on peanut shells and clay [11]. They studied the influence of peanut shells percentage and their size on this composite and concluded that the composite became a good insulating material. They proved the possibility of using the composite as an appreciable ceiling or wall coating. The research presented by Arena et al. [12] provided insights into the use of local materials and affirmed that the introduction of esparto added two positive points, and the composite became a sound-absorbing medium, and airflow-resistant. The study performed by Parlato et al. [13], introduces the utilization of sheep wool fibers. They noted that it augments their earthen tensile strength, ductility, impact resistance, and toughness and diminishes drying shrinkage. Mounir et al. [14] investigated the thermal inertia and carbon footprint of clay-wool, clay-cork, and clay-plastic composites. The study presents experimental results highlighting the thermal properties and ecological impacts of these materials, emphasizing their potential use in sustainable construction. Moreover, an extensive review and analytical ranking were conducted by Hetimy et al. [15] to evaluate sheep wool's eco-friendliness compared to other materials, considering their physical and environmental properties. The paper critically assesses sheep wool as a sustainable alternative to traditional insulation materials and designs a framework for its implementation in green building projects. Findings highlight the favorable thermal performance of sheep wool insulation, positioning it as a promising, viable, and eco-friendly solution for sustainable construction. Experiments of Charai et al. [16] revealed a beneficial influence of sawdust on the thermal characteristics of earthen blocks. Raj Kumar Dahal et al. [17] highlight the potential of hemp-based materials in sustainable construction. Their review addresses the benefits and challenges of using hemp in biocomposites, emphasizing its role in reducing greenhouse gas emissions and improving indoor air quality. Furthermore, thermal performance of plaster mixed with varying weights of Moroccan Hemp Fibers [18] has also been evaluated through experimental tests, demonstrating significant improvements in thermal insulation properties. Chihab et al. [19] studied the effect of incorporating hemp fibers into earth bricks and found that a wall constructed with clay-hemp bricks, 22 cm thick with an additional 6 cm thick insulating layer, effectively mitigates the risk of overheating during summer period.

Nowadays, the use of hemp as a high-performance bio-based building material is growing around the world [20], but in developing countries, such as Morocco, it is neglected and considered as waste used for rural domestic purposes. To contribute to the promotion of new types of ecological, low-cost, and high-energy efficiency housing, our study will concern the thermal characterization of composite based on clay reinforced with hemp fibers. The main objective is to improve the thermal properties of the earth's material to offer better energy efficiency in traditional constructions. The thermal properties of this composite will be identified using the Hot Disc method for measuring conductivity and thermal capacity.

2. Materials Properties

2.1. Binder

The earth-clay material (Figure 1) proposed as the mixture's binder, was collected near the Moroccan city of Salé. There was no additional binder or substance used to stabilize the clay. It was dried for 24 hours at 105 ℃ in the oven, then crushed and sieved through a square mesh sieve with a 2 mm side.

2.2. Hemp Fibers

In this study, hemp-clay composite mortars were made using hemp stems from the Taounate region of Morocco. To ensure a homogenous combination, the whole hemp stems were cut into 10–20 mm lengths, as shown in Figure 2.

To observe the morphology of the hemp fibers in use, SEM analysis was utilized. The SEM micrographs of the fibers (Figure 3) reveal the presence of micro-pores which may improve the thermal insulation of construction materials.

Figure 1. Moroccan Clay used in this study before and after crushing

Figure 2. Moroccan Hemp Fibers

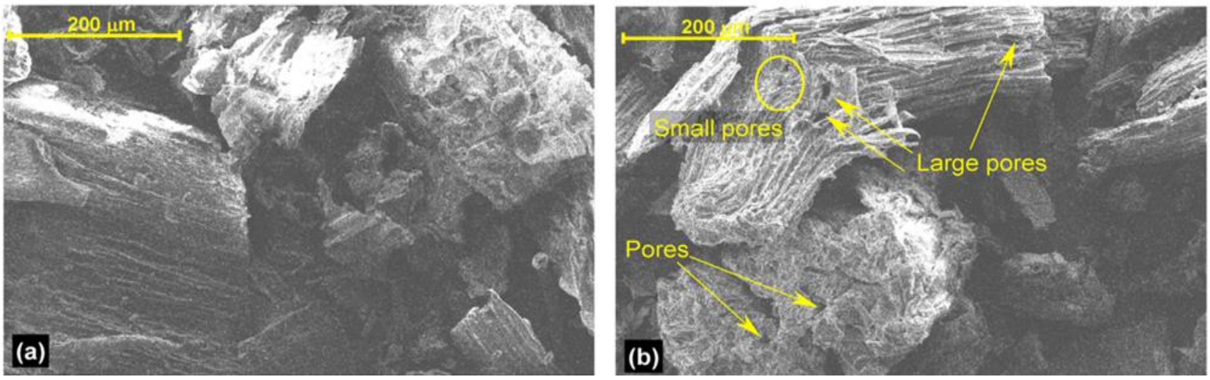

Figure 3. SEM micrograph of Hemp Fibers

3. Samples Preparation

In this study six clay and hemp based mixtures are considered to prepare prismatic specimens of 20x40x60 mm³ Natural Clay was systematically replaced with 0%, 1%, 2%, 3%, 4%, and 5% mass fractions of Hemp (Table 1). A constant water/clay (W/C) ratio of 0.7 was used in all mixtures.

Table 1. Mix proportions used for one prismatic specimen

Mix	Clay (g)	Hemp (%)	Hemp (g)	Water (g)	W/C
0	130	0%	0	91	0,7
1	128,7	1%	1,3	90,09	0,7
2	127,4	2%	2,6	89,18	0,7
3	126,1	3%	3,9	88,27	0,7
4	124,8	4%	5,2	87,36	0,7
5	123,5	5%	6,5	86,45	0,7

The Moroccan hemp fibers and local clay were dry-mixed for two minutes at room temperature to produce the samples, and then the necessary amount of water was gradually added. Next, the mixture prepared following the composition described in Table 1 was put in parallelepipedic molds (Figure 4).

Figure 4. Samples Preparation

A reference clay sample without fibers is prepared to study the influence of hemp fibers incorporation on the thermal properties of the clay matrix. For each fiber content, three samples were prepared to ensure the reproducibility of the results.

After 24 hours, the specimens were unmolded and kept in the sun. Before testing, the samples were oven-dried for 48h at 60 ℃ to reach zero moisture content (dry state).

4. Experimental Methods

4.1. Density Measurement

At the age of 28 days, the density of the specimens was measured according to ASTM C642. Knowing the dry mass and dimensions of the studied samples the bulk density was carried out using the formula (1). Three measurements were performed for each prepared sample and the mean value was taken out, which allows the measurement error to be taken into consideration. The relative error is less than 0.3%.

$$\rho = m/V \tag{1}$$

where ρ is the apparent density of the sample, m is the dry mass and V is the apparent volume of the sample.

4.2. Thermal Characterization

The objective was to evaluate the thermal properties of mortars and underscore the influence of substituting local clay with hemp. Testing was conducted using a TPS1500 Hot Disc Analyzer (Figure 5). The Transient Plane Source (TPS) method, currently regarded as the most accurate and convenient technique for analyzing thermal transport properties, was employed. Adhering to ISO 22007-2 standards, this method provides insights into the thermal conductivity and volumetric heat capacity of the material under examination. A sensor that functions as both a heater and a temperature sensor is sandwiched between two similar specimens, and then experimental parameters such as heating power and measuring time are selected. The temperature of the hot plate is then increased and the temperature response of the sample is recorded. Utilizing the temperature response of the sample and the known temperature difference, the TPS1500 calculates both the thermal conductivity and the heat capacity of the sample. The experiment measures were performed using a Kapton, the power ranges from 0.08 to 0.12 W, with a measurement duration of 80 seconds conducted in a room with ambient temperature.

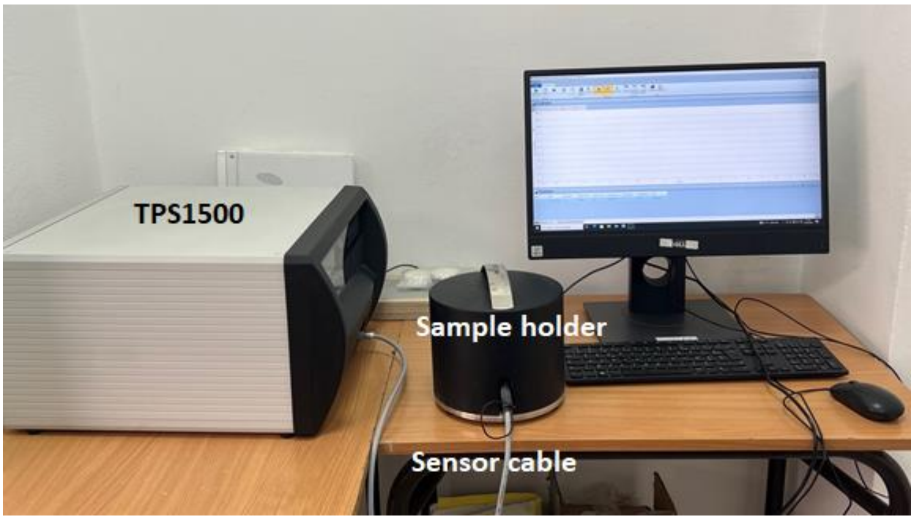

Figure 5. Hot Disk Experimental Setting up

5. Experimental Results

5.1. Samples Density

The mean values of the sample densities measured at 28 days are shown in Table 2. The density of the specimens is significantly affected by the incorporation of hemp fibers. As the partial clay replacement percentage increases from 0% to 5%, the average density values decrease from 2.28 g/cm³ to 2.14 g/cm³.

Table 2. Composite Densities

Fiber mass fraction (%)	ρ (g/cm³)	Variation rate (%)
0	2,28	-
1	2,19	3,9
2	2,18	4,4
3	2,17	4,8
4	2,16	5,3
5	2,14	6,1

It can noticed (Figure 6) that the density decreases significantly with the incorporation of 1% mass fibers and it decreases slightly as the fiber content increases. However, this reduction (Table 2) remains low. A maximum drop of 6% in density is obtained for the composite with 5% fiber mass fraction.

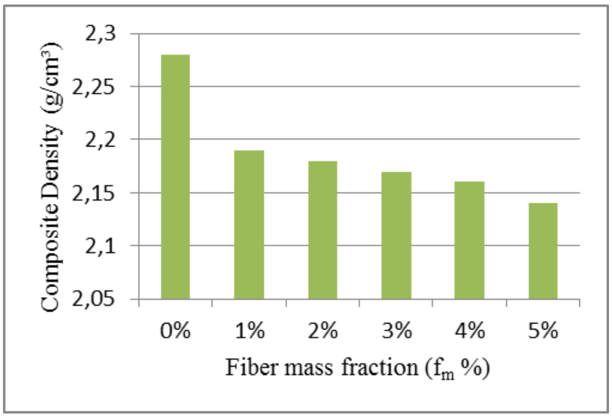

Figure 6. Composite Density evolution as a function of Fiber mass fraction at 28 days

5.2. Thermal Properties

The tests carried out with a Hot Disk analyzer offer Thermal Conductivity and Volumetric Heat Capacity for each sample studied. The mean data acquired at 7, 14, and 28 days from the tests performed are summarized in Tables 3 and 4 respectively.

Table 3. Composites Thermal Conductivity

Fiber mass fraction (%)	Thermal Conductivity (W/m.k)		
	7 days	14 days	28 days
0	0,852	0,721	0,7
1	0,716	0,698	0,676
2	0,647	0,59	0,569
3	0,525	0,515	0,479
4	0,47	0,43	0,382
5	0,429	0,38	0,333

Table 4. Composites Volumetric Heat Capacity

Fiber mass fraction (%)	Volumetric Heat Capacity (MJ/m^3.K)		
	7 days	14 days	28 days
0	0,725	0,948	1,085
1	0,882	0,969	1,042
2	0,915	0,99	1,05
3	0,996	1,05	1,106
4	1	1,12	1,415
5	1,009	1,54	1,57

6. Discussion of the Thermal Characteristics Obtained

6.1. Thermal Conductivity

The variation of thermal conductivity of the composites examined at different ages is illustrated by the histogram in Figure 7. It can be seen that the thermal conductivity decreases when the composite age increases. Furthermore, at all ages (7, 14 and 28 days), a decrease in thermal conductivity was observed as the percentage of hemp fibers increased.

At 28 days of age, the Thermal Conductivity undergoes a significant evolution with varying fiber content (Table 5). It decreased by 46% and 53% for 4% and 5% fiber fractions respectively.

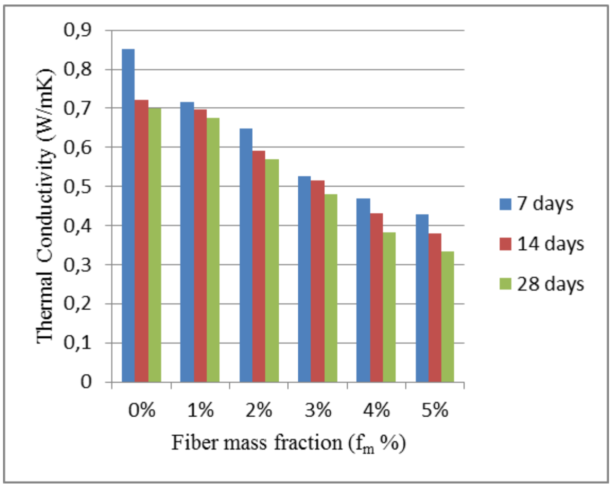

Figure 7. Thermal Conductivity of Clay-Hemp Composites at different ages

Table 5. 28-day Composite Thermal Conductivity Evolution

Fiber mass fraction (%)	λ (W/m.k)	Variation rate (%)
0	0,7	-
1	0,67	4,3
2	0,56	20,0
3	0,47	32,9
4	0,38	45,7
5	0,33	52,9

It can also be seen (Figure 8) that the thermal conductivity of composites evolves linearly as a function of the mass fraction of the fibers while the density of the material decreases slightly (Figure 9). This means that the decrease in the thermal conductivity is not only related to the density but it is mainly affected by the fibers thermal conductivity.

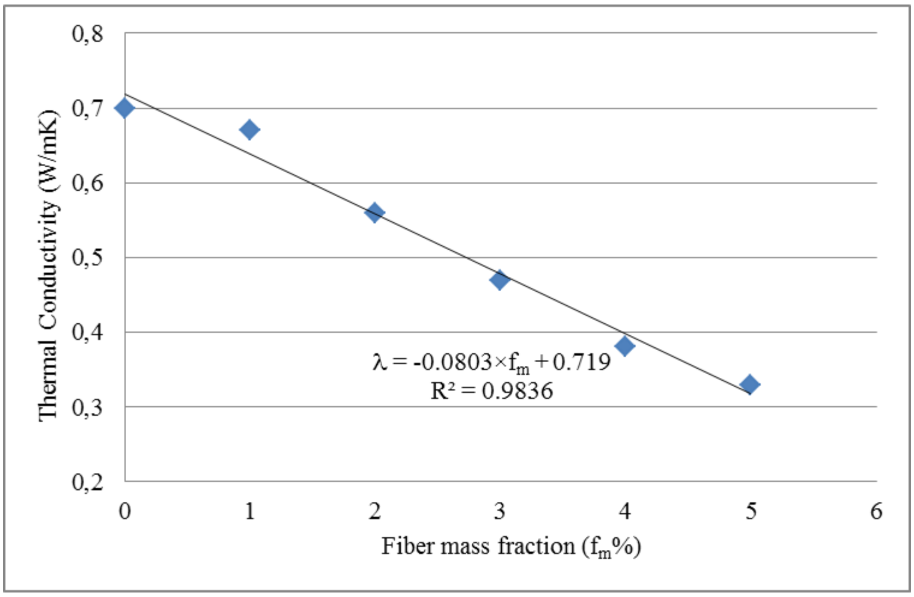

Figure 8. 28-day Composite Thermal Conductivity evolution as a function of Fiber mass fraction

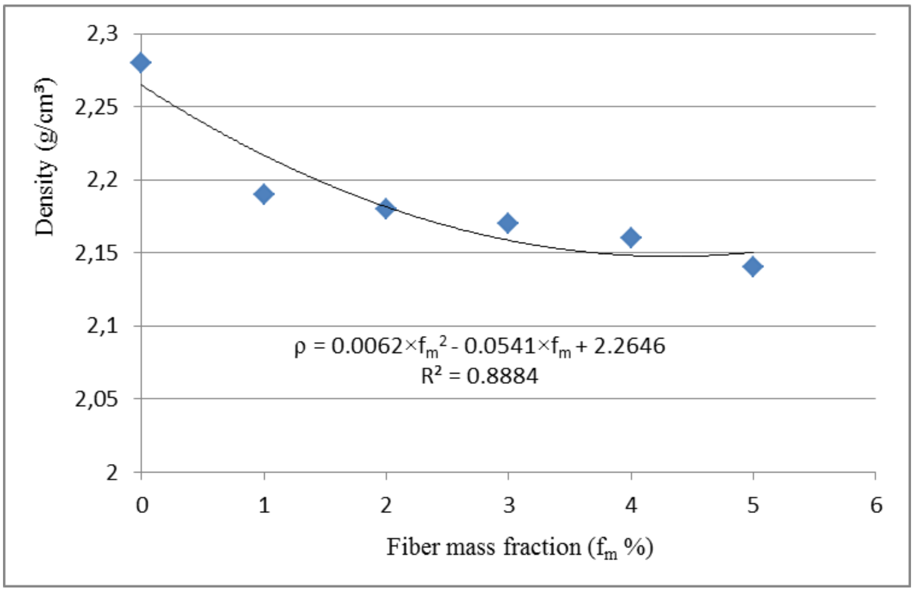

Figure 9. 28-day Composite Density evolution as a function of Fiber mass fraction

6.2. Thermal Heat Capacity

The variation of the volumetric heat capacity of the composites as a function of the fiber mass fraction at different ages of the composite (7, 14 and 28 days) is illustrated by the histogram in Figure 10. In general, the volumetric heat capacity increases as the percentage of incorporated fibers increases. However, it is slightly affected with the incorporation of 3% fiber mass fraction while it increases significantly with 4 and 5% fibers at 14 and 28 days of age.

At 28 days of age, the specific heat capacity deduced from the volumetric heat capacity is represented in relation to the fiber content in Figure 11. The Heat Capacity increases significantly with the incorporation of 4 and 5% hemp fiber mass fraction. Moreover, unlike the composites with 1 to 3% fiber content, the thermal energy storage capacities of matrices with 4 and 5% hemp fibers, are higher than that of the reference clay matrix by 39% and 55% respectively (Table 6).

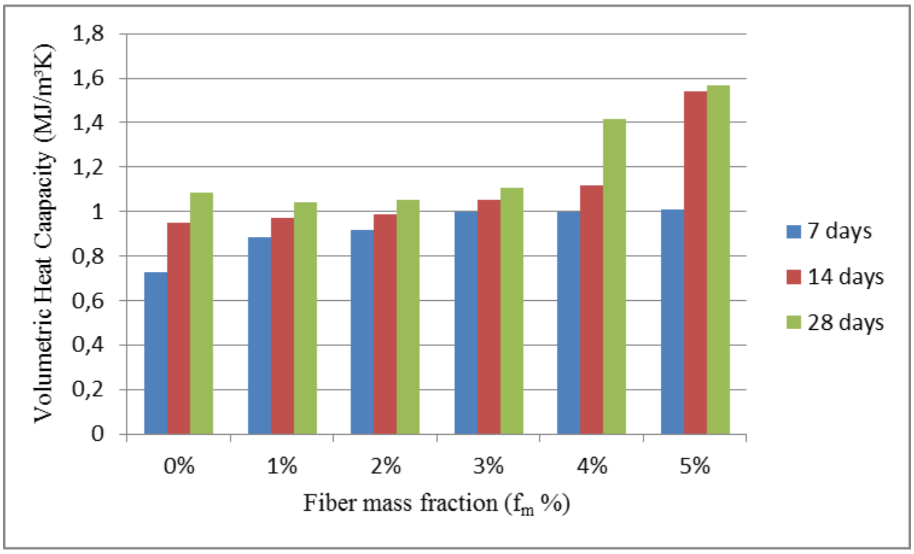

Figure 10. Volumetric Heat Capacity of Clay-Hemp Composites at different ages

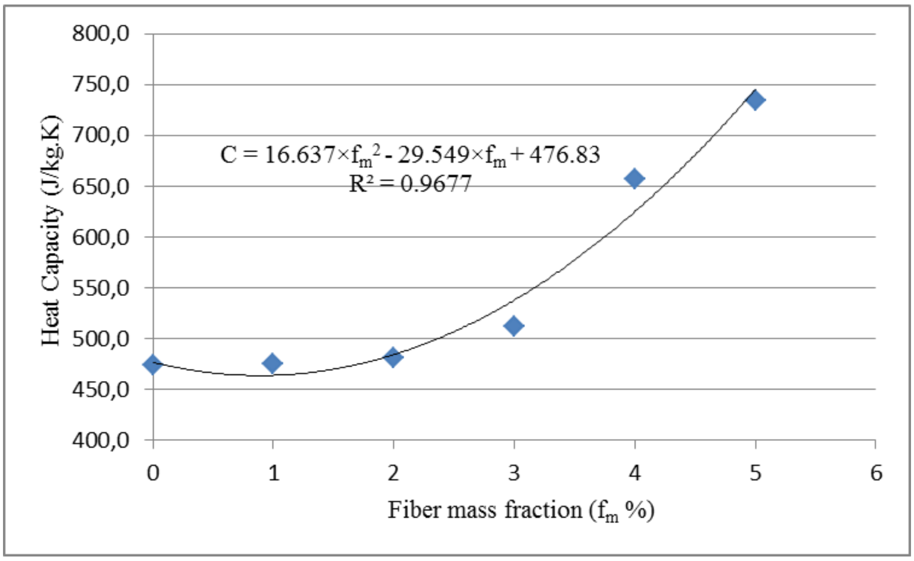

Figure 11. 28-day Composite Heat Capacity evolution as a function of Fiber mass fraction

Table 6. 28-day Composite Thermal Heat Capacity Evolution

Fiber mass fraction (%)	c (J/kg.K)	Variation rate (%)
0	473,7	-
1	474,9	0,3
2	481,7	1,7
3	511,5	8,0
4	657,4	38,8
5	733,6	54,9

7. Thermal Inertia of Clay-Hemp Composite

The thermal inertia is essentially quantified by:

- The thermal diffusivity "α" of the material, representing its tendency to promote the diffusion of heat. Therefore, in the building environment, a low diffusivity is often considered to be a “good” value.
- The characteristic time T for heat diffusion which is the time necessary to get close to a steady state, depending on the thermal diffusivity "α" and the thickness "e" of the wall and is of the order of e^2/α;
- The thermal effusivity of the wall representing its capacity to exchange thermal energy with its environment.

7.1. Thermal Diffusivity and Effusivity

The values of calculated thermal diffusivity (2) and thermal effusivity (3) are presented in Table 7.

$$\alpha=\lambda/\rho c \tag{2}$$

$$E^2= \lambda\rho c \tag{3}$$

Table 7. Thermal Diffusivity and Effusivity of Clay-Hemp Composites

Fiber mass fraction (%)	*Thermal Diffusivity*		Thermal Effusivity	
	a (m^2/s)	variation rate (%)	E (J/m^{2}s$^{1/2}$K)	variation rate (%)
0	$6{,}48\times10^{-7}$	-	869	-
1	$6{,}44\times10^{-7}$	0,6	835	4,0
2	$5{,}33\times10^{-7}$	17,7	767	11,8
3	$4{,}23\times10^{-7}$	34,7	722	16,9
4	$2{,}68\times10^{-7}$	58,7	735	15,5
5	$2{,}10\times10^{-7}$	67,6	720	17,2

The thermal diffusivity has decreased by 67% with a 5% fiber fraction while the effusivity has decreased only by 17%.

In Figures 12 and 13 representing the evolution of thermal diffusivity and effusivity with fiber content, it can be noted that thermal diffusivity decreases linearly with increasing fiber mass fraction while effusivity remains almost constant after 3% fiber mass fraction.

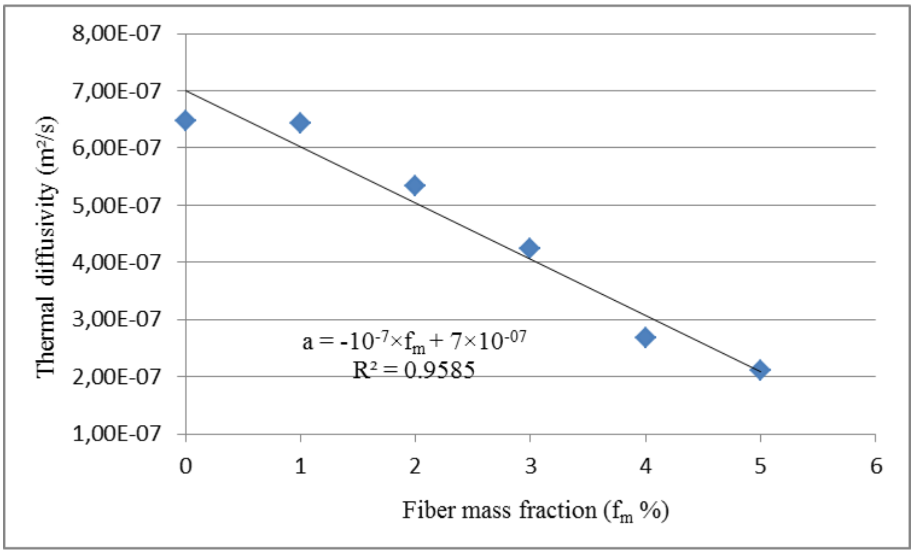

Figure 12. 28-day Composite Thermal Diffusivity evolution as a function of Fiber mass fraction

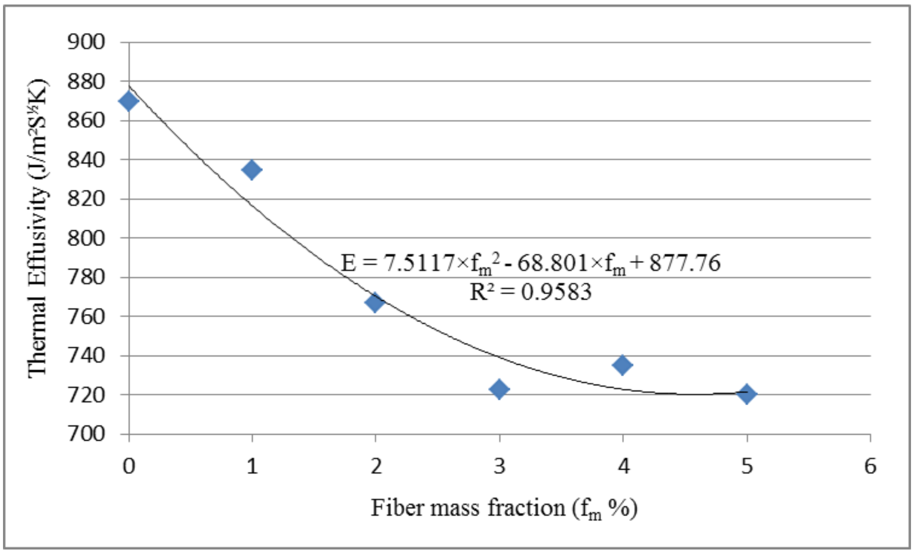

Figure 13. 28-day Composite Thermal Effusivity evolution as a function of Fiber mass fraction

7.2. Thermal Resistance and Characteristic Time

The calculated thermal resistance (4) and the diffusivity characteristic time (5) for a 20 cm thick wall are shown in Table 8. It should be noted that the thermal resistance R_{th} and the characteristic time T have increased by 67% and 208% respectively with the incorporation of a 5% fiber mass fraction.

$$R_{th}=e/\lambda \quad (4)$$

$$T=e^2/\alpha \quad (5)$$

Table 8. 28-day Thermal Resistance and Characteristic Time of Clay-Hemp (e=20 cm)

Fiber mass fraction (%)	*Thermal* Resistance		Characteristic Time	
	R_{th} (m K/W)	variation rate (%)	T (hours)	variation rate (%)
0	0,286	-	17	-
1	0,299	0,6	17	0,6
2	0,357	17,7	21	21,5
3	0,426	34,7	26	53,1
4	0,526	58,7	42	142,2
5	0,606	67,6	53	208,4

8. Conclusions

The primary aim of this study was to assess the viability of incorporating hemp fibers in construction materials and to explore their impact on thermal properties through the application of the hot disk method. According to the experimental testing, adding Moroccan hemp fibers to local clay results in a small decrease in material density but it leads to a significant enhancement of its thermal insulation properties. It was established that all thermal properties of the clay matrix were improved with increasing hemp fiber content with a very significant improvement when incorporating a fiber mass fraction of 5%. Thus, at 28 days of age and with a fiber mass fraction of 5%, the thermal conductivity of the clay matrix was reduced by 53% and its thermal diffusivity by 68% while its thermal heat capacity was increased by 55%. Furthermore, the material inertia was significantly affected by 5% fiber replacement, so, the thermal resistance of the 20 cm thick wall was increased by 68% while the diffusivity characteristic time was increased by 208%.

Since clay exhibits significant improvements in thermal insulation properties when mixed with hemp fibers, the use of this composite material will improve the comfort of residents in cold areas of northern Morocco where these materials are abundant and inexpensive.

Although research on clay-hemp composites highlights their potential as interesting insulators, key areas require further research. These include comprehensive studies on mechanical properties, long-term durability under various environmental conditions as well as chemical interactions.

REFERENCES

[1] EL Azhary K., Ouakarrouch M., Laaroussi N., Garoum M., Mansour M., "Impact of Traditional Architecture on the Thermal Performances of Building in South Morocco," Green Buildings and Renewable Energy, Chapter, pp. 339-347, 2019. https://doi.org/10.1007/978-3-030-30841-4_24

[2] Smirnova, O., Kazanskaya, L., Kopl k, J., Tan, H. and Gu, X. "Concrete based on clinker-free cement: Selecting the

functional unit for environmental assessment," Sustainability, vol. 13, no. 1, p. 135, pp. 1-12, 2021. https://doi.org/10.3390/su13010135

[3] Smirnova, O.M., "Low-Clinker cement with low water demand," Journal of Materials in Civil Engineering, Vol. 32, no. 7, p.06020008, 2020. https://doi.org/10.1061/(ASCE) MT.1943-5533.0003241

[4] Lkouen A., Lamrani M., Meskini A., Khabbazi A., "Thermal Behavior of Clay-Based Building Materials: A Numerical Study Using Microstructural Modeling", Journal of Power and Energy Engineering, vol. 10, pp. 63–73, 2022. https://doi.org/10.4236/jpee.2022.104005

[5] Dejeant F., Garnier P., Joffroy T., "Local materials, materials of the future: Local resources for sustainable cities and territories in Africa," CRAterre, pp. 96, 2021, 979-10-96446-38-4.

[6] Lkouen A., Meskini A., Lamrani M., Khabbazi A., "Thermophysical characterization of a new clay-based construction material from the Atlas region," IOP Conf. Series: Materials Science and Engineering, vol. 783, p. 012007, 2020. https://doi.org/10.1088/1757-899X/783/1/012007.

[7] Elazhary K., Ouakarrouch M., Laaroussi N., Garoum M., "Energy efficiency of vernacular building design and materials in the hot arid region of Morocco: Experimental and numerical approach", Int. Journal of Renewable Energy Development (IJRED), vol. 10, no. 3, pp. 481-494, 2021. https://doi.org/10.14710/ijred.2021.35310.

[8] Petcu, C., Dobrescu, C. F., Dragomir, C. S., Ciobanu, A. A., Lăzărescu, A. V., & Hegyi, A. "Thermophysical Characteristics of Clay for Efficient Rammed Earth Wall," Construction. Materials (Basel), vol. 16, no. 17, p. 6015, 2023. https://doi.org/10.3390/ma16176015

[9] El Azhary K., Chihab Y., Laaroussi N., Mansour M., Garoum M., "Energy efficiency and thermal properties of the composite material clay-straw," (International Conference on Power and Energy Systems Engineering, CPESE 2017, 25-29 September 2017, Berlin, Germany), Energy Procedia, vol. 141, pp. 160-164, 2017. https://doi.org/10.1016/j.egypro.2017.11.030

[10] Lamrani M., Laaroussi N., Lkouen A., Khalfaoui M., "Thermal and mechanical characterization of composite building material based on clay and date palm fibers, in: Plant Fibers, Their Composites, and Applications", Woodhead Publishing, pp. 305–322, 2022. https://doi.org/10.1016/B978-0-12-824528-6.00014-X.

[11] Lamrani M., Lkouen A., Laaroussi N., Ouakarrouch M., "Thermal Behaviour Assessment of a New Local Clay-Based Building Material and Peanut Shell Waste: Experimental and Numerical Approaches" Civil Engineering and Architecture, vol. 11, no. 6, pp. 3451-3470, 2023. https://doi.org/10.13189/cea.2023.110616

[12] Arena J.P., Del Rey R., Alba J. Oltra R., "Sound-Absorption Properties of Materials Made of Esparto Grass Fibers," Sustainability, vol. 12, no. 14, p. 5533, 2020. https://doi.org/10.3390/su12145533

[13] Parlato M.C.M., Cuomo M., Porto S.M.C., "Natural fibers reinforcement for earthen building components: Mechanical performances of a low-quality sheep wool," Construction and Building Materials, vol. 326, p. 126855, 2022. https://doi.org/10.1016/j.conbuildmat.2022.126855

[14] Mounir S., Maaloufa Y., Abdelhamid K., El Harrouni K., "Characterization of Thermal Inertia and Footprint Carbon of Clay-Wool, Clay-Cork, and Clay-Plastic Composites", Key Engineering Materials, vol. 886, pp. 213–227, Trans Tech Publications, Ltd., 2021. https://doi.org/10.4028/www.scientific.net/kem.886.213

[15] Sulava Hetimy, Naglaa Megahed, Osama Abu Eleinen, Dalia Elgheznawy, "Exploring the potential of sheep wool as an eco-friendly insulation material: A comprehensive review and analytical ranking", Sustainable Materials and Technologies, vol. 39, p. e00812, 2024. https://doi.org/10.1016/j.susmat.2023.e00812

[16] Charai M., Sghiouri H., Mezrhab A., Karkri M., Elhammouti K., Nasri H., "Thermal Performance and Characterization of a sawdust-Clay Composite Material," Procedia Manufacturing, vol. 46, pp. 690-697, 2020. https://doi.org/10.1016/j.promfg.2020.03.098.

[17] Raj Kumar Dahal, Bishnu Acharya, Animesh Dutta, "Mechanical, Thermal, and Acoustic Properties of Hemp and Biocomposite Materials: A Review" Journal of Composites Science, vol. 6, no. 12, p. 373, 2022. https://doi.org/10.3390/jcs6120373

[18] Charai M., Sghiouri H., Mezrhab A., Karkri M., "Thermal insulation potential of non-industrial hemp (Moroccan cannabis sativa L.) fibers for green plaster-based building materials", Journal of Cleaner Production, vol. 292, pp. 1-15, 2021. https://doi.org/10.1016/j.jclepro.2021.126064

[19] Chihab Y., Laaroussi N., Garoum M., "Thermal performance and energy efficiency of the composite clay and hemp fibers," Journal of Building Engineering, vol. 73, p. 106810, pp. 1-17, 2023. https://doi.org/10.1016/j.jobe.2023.106810.

[20] Salim Barbhuiya, Bibhuti Bhusan Das, "A comprehensive review on the use of hemp in concrete", Construction and Building Materials, vol. 341, p. 127857, 2022. https://doi.org/10.1016/j.conbuildmat.2022.127857