Experimental study and thermal simulation of a clay-based material reinforced with date palm fibers: Application to the climatic context of Oujda city (Morocco)

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Abstract. The building sector represents a major source of energy consumption and greenhouse gas emissions, particularly in arid and semi-arid regions such as eastern Morocco, where temperature fluctuations are significant. As an alternative to conventional materials, unfired clay bricks offer ecological benefits but still require thermal optimization. This study explores the incorporation of 1–3 wt% date palm fibers (DPF), an abundant agricultural waste, into clay bricks to enhance their thermophysical performance. The raw materials were characterized using standard geotechnical, mineralogical (XRD), and thermal methods. Results revealed that adding 3% DPF reduced thermal conductivity by 32.44% and thermal diffusivity by 29.7%, while increasing specific heat capacity by 10.27%, thus improving thermal inertia. A decrease in density of about 10.54% was also observed. TRNSYS simulations showed that using 3% DPF reduced annual cooling and heating energy demands by approximately 19.74% and 12.5%, respectively, with an overall energy saving of 19.17%. These enhancements contribute to stabilizing indoor temperatures and reducing reliance on mechanical systems. This study confirms the potential of DPF as a low-cost, bio-based additive for improving the energy efficiency of earthen materials and promoting sustainable construction practices in hot climate regions.

1 Introduction

The building sector is facing growing environmental and energy challenges, especially in regions affected by climate variability and resource scarcity. In Morocco, the sector accounts for approximately 25% of the country's final energy consumption and is responsible for nearly 20% of national greenhouse gas emissions [1]. This situation is exacerbated by the widespread use of conventional construction materials, such as fired bricks and cement, which contribute to soil depletion, high energy demand, and CO_2 emissions [2]. In contrast, earthen architecture particularly using clay has historically offered a low-carbon alternative thanks to its local availability, thermal mass, and climate adaptability [3]. However, raw clay-based materials still require performance enhancements to comply with modern building

codes and to improve thermal comfort and energy efficiency [4]. In parallel, Morocco produces large quantities of agricultural residues, particularly date palm fibers, as by-products of palm cultivation and pruning, especially in the Oriental and Saharan regions [5]. According to recent studies, these residues including fibers, leaflets, rachis, and petioles represent approximately 104,000 tonnes per year in Morocco, out of a total of 758,000 tonnes generated annually across the MENA region [6]. These lignocellulosic fibers, known for their lightweight and porous structure, offer excellent potential as natural reinforcements for building materials, supporting both environmental valorization and the development of bio-based construction solutions [7]. Incorporating such renewable plant-based waste into clay composites not only reduces reliance on non-renewable resources but also aligns with circular economic goals by valorizing local agricultural waste while improving the insulation capacity of the resulting materials [8]. This approach is especially relevant in semi-arid regions such as Oujda, where extreme temperature fluctuations lead to high seasonal energy demands for heating and cooling.

Numerous studies have explored the use of natural fibers in clay or cement matrices to improve thermal insulation and mechanical performance. Bouhabila and al. [9] demonstrated that incorporating date palm fibers into clay bricks improves thermal insulation by significantly reducing thermal conductivity, making them suitable as eco-friendly insulating materials for energy-efficient buildings. Zeroual et al. [10] demonstrated that adding date palm fibers to clayey soil significantly mitigates desiccation cracking, improving the material's dimensional stability and durability under drying conditions. Dawood et al. [11] showed that adding 0–2% date-palm fibers to fine soil decreases dry unit weight, increases optimum moisture content by about 10%, and raises unconfined compressive strength by around 30%, thus improving soil strength and sustainability for construction applications. While these studies confirm the thermomechanical benefits of date palm fibers, most are limited to laboratory-scale characterization of individual properties. Few works have addressed the effect of such composites on the overall energy performance of buildings, particularly through dynamic simulation of heating and cooling loads. Belhous et al. [12] conducted thermal simulations in TRNSYS, showing that walls incorporating date palm fibers improved indoor comfort and reduced energy needs. However, their study focused on Atlantic coastal climates and did not include experimental validation of the material properties. Therefore, there remains a clear research gap in integrating the experimental thermophysical characterization of clay–fiber composites with building energy performance simulation, especially under the semi-arid climate conditions of Oujda. Such an approach is essential to quantify the real energy-saving potential of these local bio-based materials and to promote their adoption in sustainable construction practices.

This study aims to investigate the potential of date palm fiber–reinforced clay as an eco-friendly building material suitable for the climate of Oujda, Morocco. Specifically, the objectives are: To experimentally evaluate the thermophysical properties (thermal conductivity, specific heat capacity, and density) of clay composites incorporating various proportions (0% to 3%) of date palm fibers. To assess the impact of these materials on building energy performance by integrating the measured properties into a dynamic thermal simulation model of a typical residential structure, using TRNSYS software. By coupling laboratory testing and simulation, this research contributes to the development of local, bio-based insulating materials, and offers practical insight into how agricultural waste can be leveraged for energy-efficient construction in arid and semi-arid climates.

Fig. 1. Date Palm Fiber (DPF).

2 Materials and sample preparation

2.1 Materials

The clayey soil used in this study was collected from the Alouana region, located in Taourirt Province, northeastern Morocco (33°58'48.5"N, 3°07'25.2"W). This region is traditionally known for its use of earth materials in construction and pottery. The raw soil was air-dried, manually crushed, and sieved to obtain a fine fraction suitable for laboratory testing and composite preparation. To evaluate its geotechnical and mineralogical characteristics, several tests were performed, including Atterberg limits, particle size distribution, and X-ray diffraction (XRD) analysis.

The date palm fibers (DPF) used in this study were obtained from pruning residues collected in palm groves around the Oujda region, where date palm cultivation is widespread for both agricultural and decorative purposes. Prior to incorporation, the fibers were manually cleaned, sun-dried, and cut into lengths of 0.5 to 2 cm, ensuring homogeneous mixing and effective dispersion within the clay matrix. Their mineralogical composition was also examined using X-ray diffraction (XRD) analysis to assess the presence of residual crystalline or inorganic content.

2.2 Sample preparation

To ensure consistency and comparability between different formulations, all samples were prepared according to the following protocol:

- The fibers were manually cleaned, sun-dried, and cut into 0.5 and 2 cm lengths to facilitate uniform distribution.
- The dry materials were mixed thoroughly to achieve a uniform matrix.
- A fixed water-to-clay ratio of 0.33 was maintained for all mixtures to ensure consistent workability.
- Four clay–fiber mixtures were prepared, incorporating 0%, 1%, 2%, and 3% of date palm fibers by dry weight of clay Table 1.
- The paste was cast into steel molds of size $5 \times 5 \times 5$ cm^3.
- All specimens were manually compacted to reduce poverty and improve cohesion.
- After 24 hours, the samples were demolded and then cured for 7 days at ambient temperature and relative humidity.

This preparation process ensured the reproducibility of the specimens and their suitability for subsequent thermal testing.

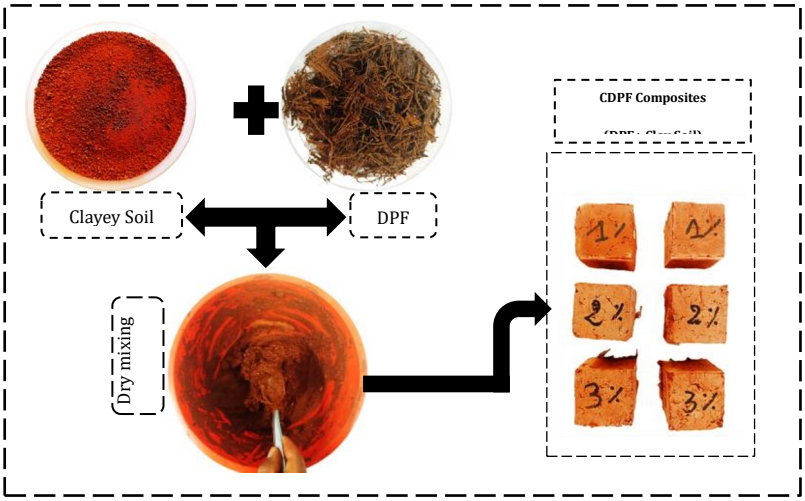

Fig. 2. Preparation procedure of clay-based specimens reinforced with DPF.

Table 1. Composition of clay brick samples with DPF (CDPF).

Specimen Identification	C (Clay brick)		DPF	
CDPF	**Wt%**	**g**	**Wt%**	**g**
$CDPF_0$	100	200	0	0
$CDPF_1$	99	198	1	2
$CDPF_2$	98	196	2	4
$CDPF_3$	97	194	3	6

3 Method

The physical and mineralogical characterization of raw materials was conducted using standardized laboratory methods. Particle size distribution of the clayey soil was determined by sedimentation analysis according to NF P 94-057 [13], which classifies particles based on their settling velocity in a liquid medium, allowing the estimation of equivalent diameters. To evaluate soil plasticity, Atterberg limits were measured on the fine fraction (<0.4 mm) following NF P 94-051 [14]. The liquid limit (WL) and plastic limit (WP) were obtained using the Casagrande method, and the plasticity index (Ip = WL – WP) was calculated to define the water content range. Mineralogical identification of the clay and Date Palm Fibers (DPF) was performed by X-ray diffraction (XRD) using a SHIMADZU XRD-6000 diffractometer operating at 40 kV and 30 mA with Cu Kα radiation (λ = 0.154 nm), scanning from 5° to 60° (2θ) at 0.02°/min. The thermophysical properties of the dried samples thermal conductivity, diffusivity, and specific heat were assessed using the Hot Disk TPS 2200 system with a Kapton 5501 sensor, following ISO 22007-2 [15]. This transient plane source method is well-suited for solids and composites, as it allows simultaneous and accurate measurement by placing the sensor between two identical specimens under controlled conditions.

4 Results and discussion

4.1 Geotechnical and mineralogical identification

The raw clay used in this study was characterized by a high proportion of fine particles, with 46.8% clay ($d < 2$ µm), 45.4% silt (2–50 µm), and only 7.8% sand (50 µm–10 mm), as determined by granulometric and sedimentometric analysis (Fig. 3). According to the Unified Soil Classification System (USCS), this composition classifies the soil as clayey silt, known for its strong cohesion and favorable compaction behavior. Atterberg limit tests conducted on the fine fraction (<0.4 mm) using the Casagrande method (NF P94-051) revealed a high plasticity index (Table 2), indicating good water retention and workability, which are essential for forming stable, crack-resistant composites. X-ray diffraction (XRD) analysis of the clay sample showed a mineralogical composition (Fig. 4) dominated by quartz, accompanied by illite, feldspar, and traces of anatase, with a pronounced peak near $2\theta \approx 26°$, reflecting the crystalline nature of quartz. This mineralogical profile suggests thermally stable but relatively conductive behavior, justifying the incorporation of insulating additives. The crystalline structure of the date palm fibers (DPF) was analyzed using X-ray diffraction (XRD) to assess the nature of the lignocellulosic matrix. The diffraction pattern showed characteristic peaks at $2\theta \approx 16.9°$, 21.9°, 33.7°, and 41.4°, corresponding respectively to cellulose I, amorphous hemicellulose, and lignin structures, confirming the semi-crystalline structure of the material. According to Raza et al. [8], the peak at 21.7° is typically associated with microcrystalline cellulose, which contributes to the mechanical integrity of the fibers. The broadness of other peaks, particularly around 16.7°, reflects the presence of amorphous components such as lignin and hemicellulose, consistent with the findings of Derrouiche et al. [16]. These results indicate that date palm fibers exhibit a mixed crystalline–amorphous behavior, like other natural fibers used in construction applications [17]. This microstructural profile supports the potential use of DPF in earthen composites, where their internal porosity and structural flexibility contribute to both thermal insulation and crack resistance [18].

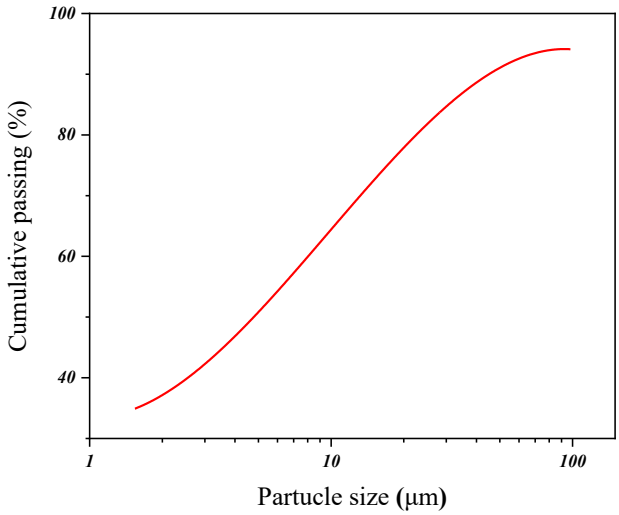

Fig. 3. Particle size distribution of clay.

Table 2. Geotechnical properties of the clay soil (%).

Properties	Value (%)	
Atterberg limits	Liquid limit	44
	Plastic limit	22.5
	Plasticity index	21.7

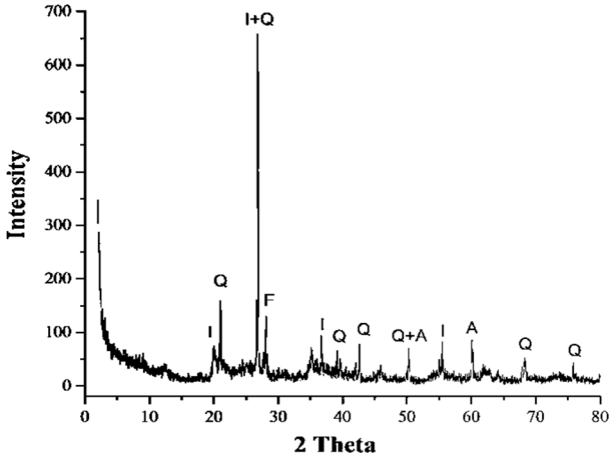

Fig. 4. XRD pattern of clay soil.

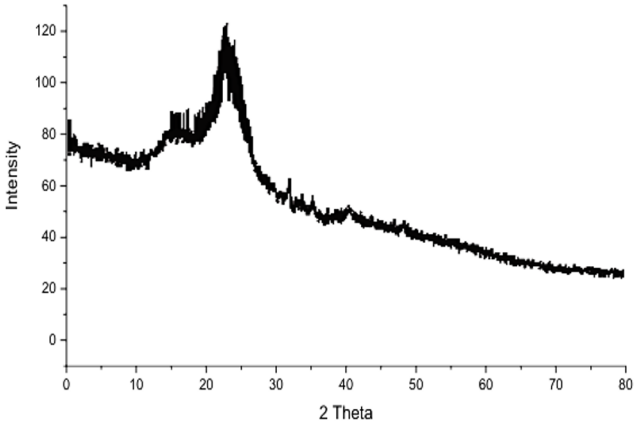

Fig. 5. XRD pattern of DPF.

4.2 Thermophysical properties of composites

The gradual incorporation of date palm fibers into raw earth results in a significant reduction in thermal conductivity, as shown in Fig. 6. This decrease is mainly attributed to the low intrinsic thermal conductivity of natural fibers and the increase in porosity within the composite matrix, which enhances air entrapment and reduces heat transfer [19]. At a fiber content of 3%, the thermal conductivity decreases by up to 32.44%, reflecting a substantial improvement in the material's insulating capacity. In parallel, thermal diffusivity also shows a consistent downward trend, dropping from 0.60 to approximately 0.43 mm²/s, representing a 29.7% reduction. This confirms that the presence of fibers effectively slows down the propagation of heat through the material. These observations are consistent with the results

of Mounir et al. [20], who reported that bio-based materials generally exhibit lower thermal diffusivity due to their porous structure and the insulating nature of natural fibers.

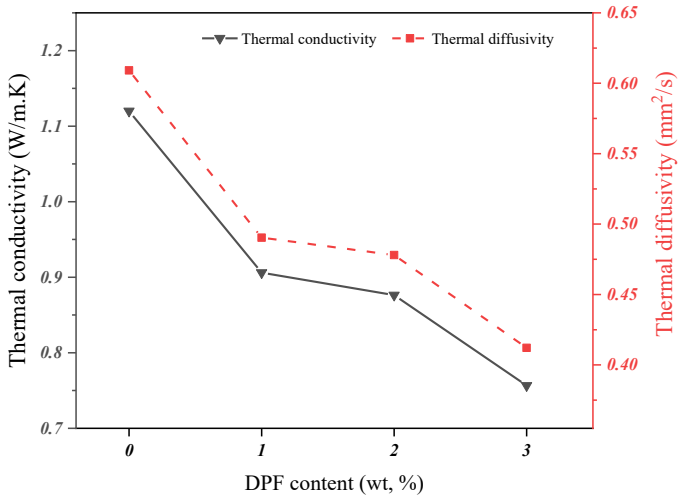

Fig. 6. Effect of DPF Content on Thermal Conductivity and Diffusivity.

The incorporation of date palm fibers (DPF) into the clay matrix significantly affects both the density and specific heat capacity of the composite material, as illustrated in Fig 7. the density decreased from 1375 kg/m³ to 1230 kg/m³ when the incorporation rate increased from 0% to 3%, a reduction of approximately 10.54%. This decrease is due to the low density of plant fibers [21] and the increased porosity of the material [20, 22]. However, this density reduction may be advantageous for applications requiring lightweight materials. Conversely, the specific heat capacity shows a noticeable upward trend, increasing from approximately 1337.6 J/kg·K at 0% DPF to nearly 1490.8J/kg·K at 3%, representing a gain of 10.27%. This enhancement is mainly due to the high thermal storage ability of lignocellulosic fibers, which enables the composite to store more heat before changing temperature [23]. As such, the increase in specific heat capacity contributes to improving the material's thermal inertia an essential parameter in passive building applications, especially in arid and semi-arid climates.

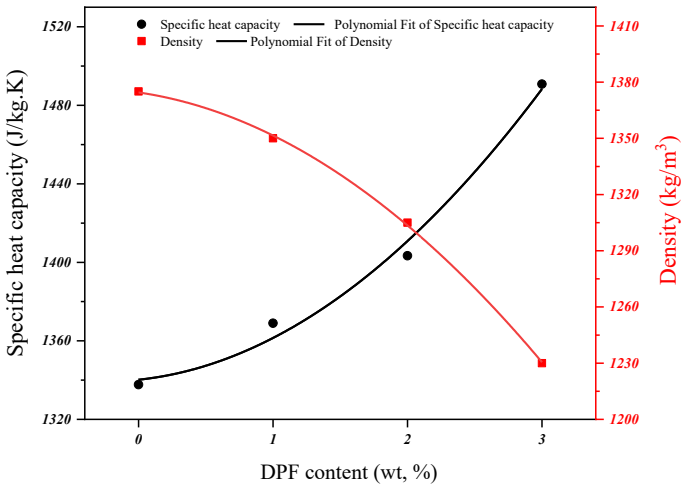

Fig. 7. Evolution of Specific Heat Capacity and Density of Clay Composites with DPF Content.

4.3 Dynamic thermal simulation (Indoor temperature and Annual Energy Consumption)

Dynamic thermal simulation was performed using TRNSYS16 software to evaluate the annual energy performance of a typical room with a volume of 18 m³ (Fig. 8), located in the Oujda City (34° 41′ 12″ N, 1° 54′ 41″ W), characterized by a semi-arid climate with hot summers and moderately cold winters. The study focused on different types of wall construction materials in table 3, including the reference mud brick, and clay which contains 3% DPF. The climatic boundary conditions were defined from typical local meteorological data (Oujda meteonorm file).

As illustrated in Fig. 9, the dynamic thermal simulation results display the annual temperature variation for the simulated building located in Oujda. During the cold periods (from hour 0 to 2000 and from 8000 to 8760), the interior temperature of the reference clay brick walls is approximately 2 to 3 °C lower than that of the walls modified with 3% date palm fibers (DPF), indicating that DPF significantly improves the material's thermal retention capacity, limiting heat loss and helping to maintain a warmer indoor environment. Conversely, during the hot periods (around hour 3000 to 7000), the DPF-modified walls exhibit 1.5 to 2 °C lower interior temperatures on average compared to the reference, reflecting that DPF also acts as an effective natural insulator, reducing heat transfer from the outside and maintaining cooler indoor conditions. These findings highlight that the incorporation of DPF enhances the thermal inertia of the walls, effectively attenuating indoor temperature fluctuations throughout the year. This passive thermal regulation reduces the need for active heating or cooling systems, offering a particularly valuable benefit in Oujda's semi-arid climate, characterized by strong diurnal and seasonal thermal variations.

Table 3. Details of the building materials and their thermal characteristics.

N°	Material	Thickness m	Thermal conductivity W/mK	Specific heat capacity J/kgK	Density kg/m³	U-value W/m²K
(a)	Clay	0.40	1.12	1337.69	1375	1.897
(b)	Clay containing 3% DPF	0.40	0.756	1490.84	1230	1.431

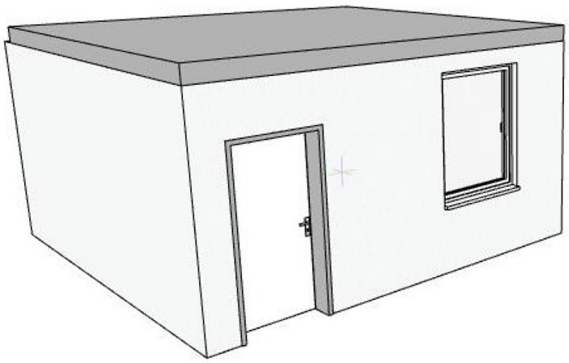

Fig. 8. 3D plan of the room building.

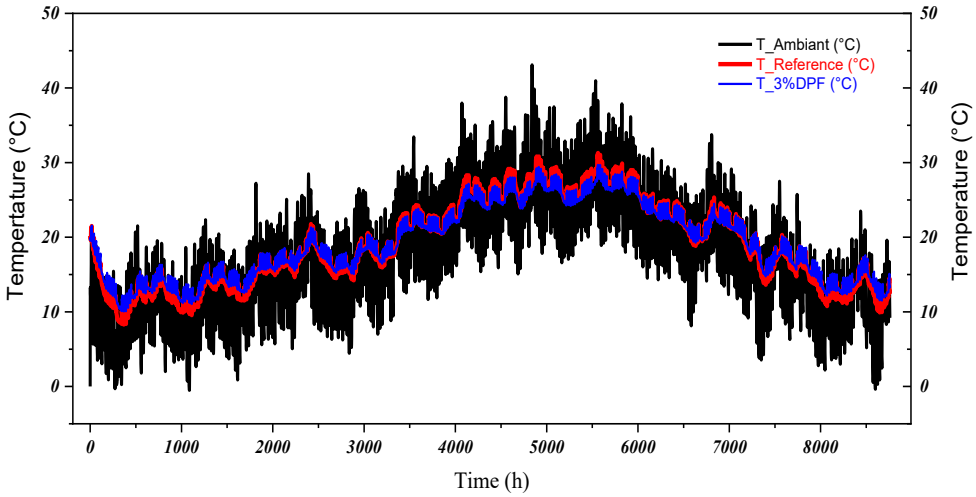

Fig. 9. Annual indoor and outdoor temperature profiles for clay and 3% DPF-clay walls.

Fig. 10 illustrates the annual variation in energy demand for cooling and heating as a function of wall composition, highlighting the impact of incorporating 3% date palm fiber (DPF) into unfired clay bricks. The reference building, constructed with traditional clay bricks, has an annual cooling demand of approximately 85.1kWh/m³, which decreases to 68.3kWh/m³ with the addition of DPF, representing a reduction of nearly 19.74%. In contrast, the heating demand decreases from 7.2kWh/m³ for pure clay to approximately 6.3kWh/m³ for DPF-reinforced clay, representing a decrease of approximately 12.5%. The total annual energy demand thus decreases from 92.3kWh/m³ to approximately 74.6kWh/m³, which equates to an overall reduction of around 19.17%. These improvements in thermal performance are particularly relevant in the semi-arid climate of Oujda, characterized by long, hot summers with temperatures frequently exceeding 40°C, requiring intensive cooling, and short, moderately cold winters. The integration of date palm fibers improves the thermal insulation properties of clay bricks, thus contributing to a significant reduction in energy consumption throughout the year and supporting sustainable construction practices adapted to local climatic conditions.

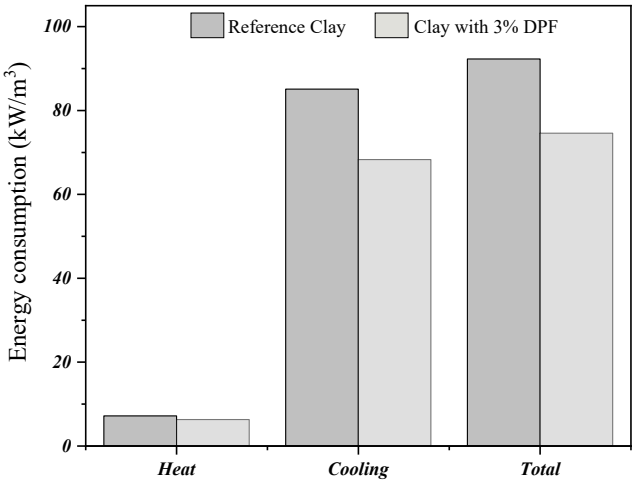

Fig. 10. Annual energy consumption of clay and 3% DPF-clay bricks.

5 Conclusion

An experimental and numerical study was carried out on raw clay soil from Taourirt, enhanced by the gradual incorporation of date palm fibers (DPF) at rates ranging from 0% to 3%, with the objective of improving thermophysical performance for sustainable building applications. The main findings are summarized as follows:

- Thermal conductivity decreased by up to 32.44%, and thermal diffusivity by 29.7% with 3% DPF.
- Specific heat capacity increased by 10.27%, enhancing the thermal inertia of the composite.
- Density decreased by 10.54%, resulting in a lighter material.
- Annual cooling demand dropped from 85.1 kWh/m^3 to 68.3 kWh/m^3 with 19.74%, and heating demand from 7.2 kWh/m^3 to 6.3 kWh/m^3 with 12.5%.
- The total energy demand was reduced by 19.17%, confirming improved energy performance.
- Indoor thermal comfort was enhanced, with attenuated temperature fluctuations throughout the year.

Overall, the integration of DPF into clay bricks offers a promising solution for reducing energy consumption, valorizing agricultural waste, and advancing environmentally friendly construction in semi-arid climates like that of Oujda.

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