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Research Article

Thermal conductivity analysis of clay pottery-gypsum composite for Moroccan construction

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ABSTRACT

Clay has always been considered a traditional building material, offering various environmental, cultural, and economic benefits. This study explores the improvement of clay from the town of Salé, northwest Morocco, by introducing a mixture with Moroccan gypsum plaster. Three samples were created: two were composed of 100% pottery clay and gypsum plaster, while the third was a composite mixture of 50% each. Thermal analysis is essential for assessing manufacturing quality and provides insight into cooking processes. The hot plate method, known for its accuracy, yielded an average thermal conductivity (λm) value of 0.426 W/m·K for the composite mixture, indicating potential for construction applications. However, limitations include the small sample size and focus on a single location, suggesting the need for broader research under varied conditions.
The energy and thermal simulations conducted on a typical residential structure using Design Builder software demonstrated that the composite material composed of pottery clay and gypsum plaster effectively contributed to a modest reduction in cooling and heating energy requirements. Specifically, the simulations indicated a 0.7% decrease in cooling needs during the summer and a 0.5% reduction in heating requirements during the winter.

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INTRODUCTION

Development is a primary objective for less developed countries in all areas, and Morocco is no exception, particularly when it comes to the thermal properties of construction materials. In the same vein, this study aims to understand the variation in thermal conductivity of a new mixture comprising commercial gypsum plaster (GP) commonly used in construction and pottery clay (PC) extracted and processed from the city of Salé.

The introduction of new materials in construction requires a thorough understanding of their thermal behavior. This study employed specialised techniques to measure the thermal conductivity of a composite material made from (GP + PC) using the steady-state hot plate method. This research contributes to the development of environmentally friendly materials, similar to previous studies on Moroccan-origin materials. The thermal conductivity values obtained were 0.315 W/m·K for plaster and expanded clay and 0.148 W/m·K for shell panels with plaster. These values are accept-

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able compared to those typically found in brick clay used in construction, which usually has a thermal conductivity of $\lambda = 0.65$ W/m·K.

Energy and thermal simulations are important tools in modern building design. They allow us to analyze how energy is used and how heat moves in a building. By considering factors like building materials, HVAC systems, and environmental conditions, these simulations help make informed choices to improve energy efficiency and occupant comfort. They are key to creating sustainable buildings that use less energy and reduce carbon emissions, helping to address climate change.

Morocco has a diverse climate, ranging from a Mediterranean climate along the coast to a desert climate in the south, with hot, dry summers and cool winters. Therefore, construction needs to focus on durable and energy-efficient materials that suit these climate variations and ensure thermal comfort for occupants. As simulation technology advances, it will lead to even more innovative and energy-efficient building designs.

The purpose of this study is to develop a composite material combining gypsum powder (GP) and Portland cement (PC) to take advantage of their distinct physical and thermal properties, addressing the gap in previous research that primarily focused on single-component materials. The study involves determining the thermal conductivity of the composite using the conventional hot plate method and evaluating its impact on building performance under the climatic conditions of northwestern Morocco through dynamic thermal simulations.

This research examines whether a 50/50 pottery clay -gypsum composite improves thermal efficiency compared to pure clay or gypsum plaster and the value of scientific research is enhanced when it has a technical and experimental basis strong, as shown by the cumulative results discussed in the following study. Assessment of the Thermal Properties of Gypsum Plaster with Plastic Waste Aggregates [1]. A new calculation method of efficiency for gypsum and wastewater hydrocyclones in FGD unit in a power plant [2]. Thermal and mechanical evaluation of natural fibers reinforced gypsum plaster composite [3]. Characterization of Thermal and Mechanical Properties of Red Clay Mixed with Rice Straw for Thermal Insulation of Buildings [4]. Thermal performances and environmental analysis of a new composite building material based on gypsum plaster and chicken feathers waste [5]. Three-dimensional numerical simulation of conduction, natural convection, and radiation through alveolar building walls [6]. Controlling Switchable Electrochromic Glazing for Energy Savings, Visual Comfort and Thermal Comfort: A Model Predictive Control [7]. Estimation of the thermophysical properties of date palm fibres/gypsum composite for use as insulating materials in building [8]. Measurement of thermal properties of brick materials based on clay mixtures [9]. Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements [10]. Estimation of the thermophysical properties of date palm fibres/gypsum composite for use as insulating materials in building [11] A centered hot plate method for measurement of thermal properties of thin insulating materials.

MATERIALS AND SAMPLES PREPARATION

Description

Using spectrophotometry, we present measurements of the composition of approximately 45 pottery artifacts from the Roman era, uncovering the intricate craftsmanship and untold stories behind these fascinating relics. Table 1 [12].

The clay used in the lightweight pottery from the city of Salé (PC) is prepared for use through a series of traditional manufacturing steps. The initial step involves manually crushing the clay, typically in stone form, using a wooden hammer known as a 'meijem.' Subsequently, this material is soaked in water for 48 hours in basins to soften it. Afterward, it is spread on the ground for an additional 48-hour drying period. The clay is then vigorously kneaded with the feet and hand-processed to achieve consistent clumps.

Following these delicate procedures, the raw clay is skillfully hand-shaped on a wheel ('louleb'). The artisan potter's hands guide the transformation of volumes while creating the piece. Using a wire, the potter separates the piece and places it on a board ('tbec'). Another 48-hour drying phase follows, during which the potter revisits the piece to further refine its details and apply an engobe. At this stage, the material remains fragile but is ready for further processing.

Table 1. The general components of pottery a percentage by weight (%wt) [12]

PAl_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	BaO	Four
18.8	9.52	2	0.79	0. 4	3.2	1.01	0.077	0.015	1
16.9	7.33	1.65	0.84	0. 4	3.05	0.99	0.067	0.018	1
18.2	7.64	1.82	0.77	0. 4	3.07	0.98	0.087	0.014	1
...	...	...	...	...	...	...	...	...	...
14.8	2.74	0.67	0.03	0.05	2.15	1.34	0.003	0.015	5
19.1	1.64	0.6	0.1	0.03	1.75	1.04	0.007	0.018	5

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Figure 1. Geographic coordinates of Sale, Morocco [13]

We selected this material due to its availability, affordability and simple properties, making it easy to use in various applications like construction.

The city of Salé is a Moroccan city located in the northwest, with a moderate climate throughout the year. Figure 1 [13].

Latitude: 34°03'11" North

Longitude: 6°47'54" West

Altitude above sea level : 34 meters

Plaster is a construction material that has been used since antiquity for a wide range of applications, including plasterboard for interior construction and decoration. It is a mineral compound composed of calcium sulfate dihydrate, with the chemical formula CaSO4 . 2H2O.

Plaster is known for its significant drawbacks, notably its fragility and low tensile strength. Hence, there's a growing interest in bolstering its mechanical properties through the incorporation of reinforcing fibers.

Commercial gypsum plaster (GP) primarily finds utility in construction due to its insulation and fire-resistant properties. It's manufactured industrially, with gypsum serving as the primary raw material.

Preparation

In this study, three separate samples were prepared Figure.2[14]: one consisting of 100% (GP), another made entirely of 100% (PC), and a third combining the two components in equal proportions (50% GP + 50% PC). The results will be particularly relevant for the 50% mixture, as it has the potential to yield new construction materials with innovative thermal properties.The manufacturing process spanned about a week to ensure the mass reached a stable state.

►Sample Shaping:

•Uniformity: Shape all samples into uniform cubes.

•Dimensions : Each cube should measure 100 x 100 x 20 mm³.

•Mixing Ratio : Maintain a consistent mixing ratio of 0.7 across all blends.

►Drying Procedure:

•Air Drying : Allow samples to air dry for 24 hours in ambient conditions.

•Oven Drying : After air drying, transfer samples to an oven and dry for an additional 48 hours at a temperature of 50°C.

►Final Steps:

•Sealing: Seal the samples in plastic bags to mitigate any potential moisture-related influences.

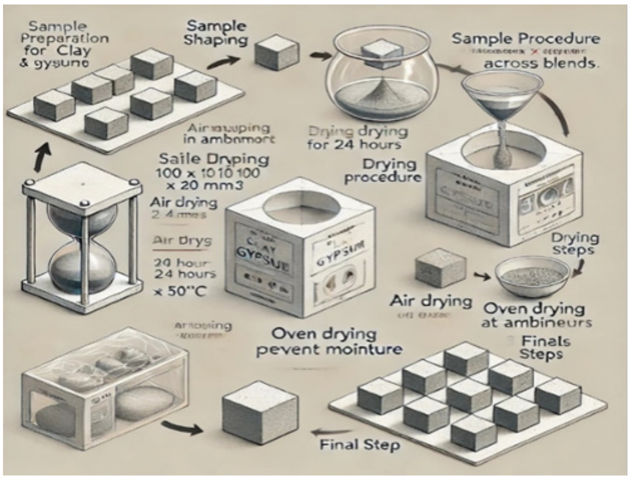

Figure 2. The diagram illustrating the preparation process for clay and plaster [14]

Notably, while (PC) necessitates a lengthier drying period, it boasts resilience to high temperatures. Conversely, gypsum plaster (GP) exhibits quicker drying characteristics. Consequently, the blend of these materials serves to mitigate the drying time of the composite. Figure 2 [14].

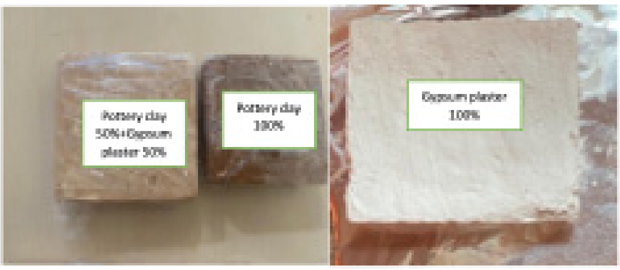

Figure 3. Test samples [15]

METHOD OF MEASUREMENT

A material displaying a certain level of heterogeneity in its complexity depends on several comparisons of results with different researchers to achieve the preferred outcomes for each method. In the same context, the steady-state small hot plate method is employed to characterize thermal conductivity. Figure 3 [15] is placed on a heating element measuring (100x100 mm2). Figure 4 [16] illustrates the experimental setup for this method: the sample (20x100x100 mm3).

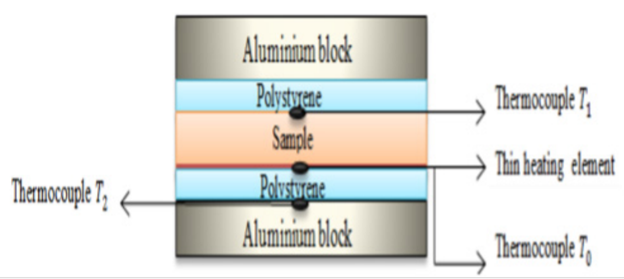

Figure 4. Experimental scheme of the steady-state hot plate method [16]

The principle behind this setup is that the majority of the thermal flux emitted by the heating element passes through the sample. The entire assembly is then placed between two aluminum blocks with dimensions of 100x100x50 mm³; these blocks serve to bring the system to a state of equilibrium as quickly as possible. A thermocouple is affixed to the center of the lower face of the heating element to measure temperature T0, another is used to measure the temperature T1 of the unheated face of the sample, and a third thermocouple is employed to measure the temperature T2 of the unheated face of the insulating foam. The applied temperatures range between 21°C and 38°C, as thermal conductivity may vary with temperature. With this configuration, we can express:

$$ø = ø_1 + ø_2;\ ø_1 = \frac{\lambda_1}{e_1}(T_0 - T_1) = ø_2 = (T_2 - T_1)\frac{\lambda_2}{e_2}$$

ø1 is the heat flux density through the sample, ø2 the heat flux density through the insulation foam ø0 the flux through both faces of the heating element.

e1 represents the thickness of the sample, and λ_1 represents the thermal conductivity of the sample to be determined. The electrical resistance is R = 81.21Ω. The method's principle involves applying a voltage U = 10.07V across the heating element, which is positioned between the sample and the insulating polyethylene foam. The foam has dimensions of 100x100x10 mm³ and a thermal conductivity of 0.037 W/m·K.

$$ø = \frac{U^2}{R.S}$$

Combining the equations we get:

$$\lambda_1 = \frac{e_1}{((T_0 - T_1)} = [\frac{U^2}{R.S} - \frac{\lambda_2}{e_2}(T_0 - T_2)]$$

The equation allows us to determine the thermal conductivity of the sample once the system reaches the equilibrium state.

SIMULATION SOFTWARE

Design-Builder" is a graphic interface based on the Energy-Plus calculation engine. It offers numerous functions available simultaneously in existing software:

•Calculation of heat losses/gains of the building envelope in winter/summer

•Heating system sizing

•Sizing of natural ventilation and air conditioning cooling

•Dynamic simulation providing comfort data, thermal balance, ventilation, etc.

•Realistic 3D construction with shadow casting view.

Case Study

Studying thermal transfers within a building envelope is a complex phenomenon. Building simulation offers the possibility to visualize a wide range of scenarios to enhance energy performance and thermal comfort of the building. In this study, the algorithm of the ENERGYPLUS software is utilized for calculating the thermal energy of the building with the DESIGNBUILDER interface. The climatic conditions of the city of Salé were obtained from the ENERGYPLUS website. ENERGYPLUS software enables building simulations for energy savings using numerical simulation. Figure 5 [17].

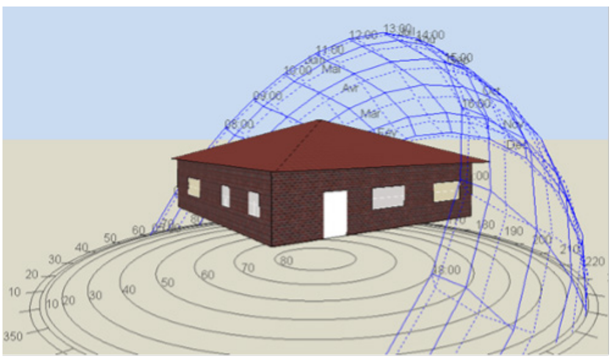

Figure 5. Simulation building model [17]

This building, although it is a simple residential house, actually spans approximately 144 m2 and consists of seven distinct zones, each with its own function and specific area. Each zone has been designed with a particular objective in mind, thereby contributing to the overall functionality of the building. Figure 6 [18].

•WC: Domestic Toilet (E1)

•Bath: Domestic Bathroom (E2)

•BED 1: Domestic Bedroom (E3)

•BED 2: Domestic Bedroom (E4)

•Living: Domestic Lounge (E5)

•Kitchen: Domestic Kitchen (E6)

•Hall: Domestic Circulation Areas (E7)

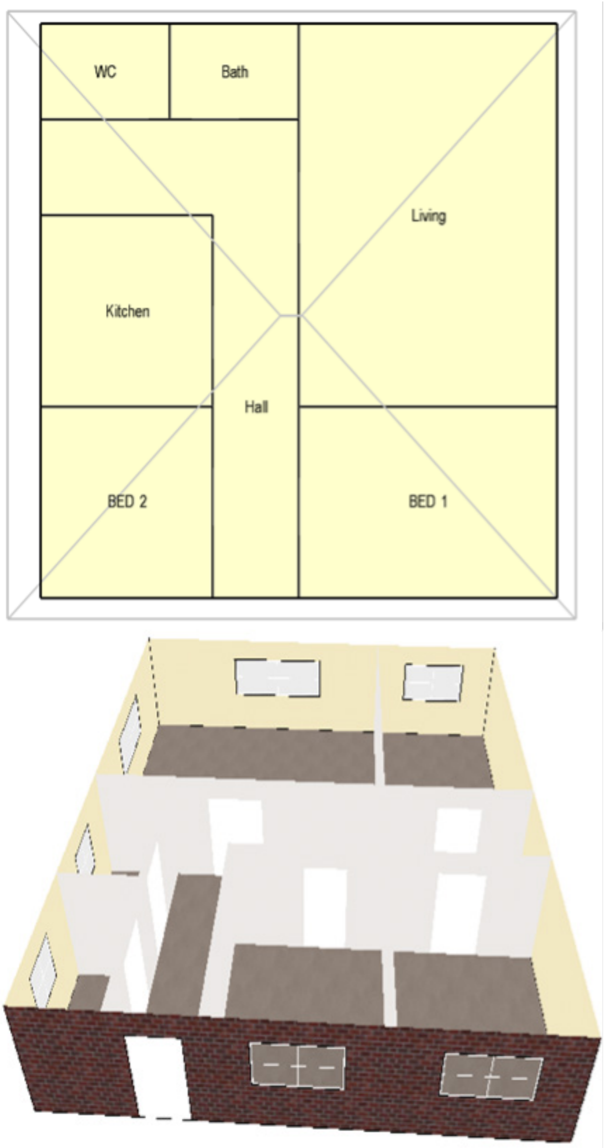

Figure 6. Different zones of the studied building [18]

The Simulation Method

Localization and geographical position are critical in determining regional climatic conditions. In the Rabat-Salé region, the climatic factors specific to Salé play a vital role in adhering to thermal standards, including the Moroccan Thermal Regulations (RTCM). Situated in Morocco, Rabat-Salé experiences distinct climatic conditions shaped by its geographic attributes, such as latitude, altitude, and proximity to water bodies. This region is characterized by an average maximum temperature of 28°C in summer and a minimum temperature of 11°C in winter. Understanding these climatic factors is essential for the design of energy-efficient buildings that ensure optimal thermal comfort. The RTCM provides guidelines for insulation, ventilation, and heating/cooling systems, specifically tailored to the region's climate, thus promoting sustainability in construction practices. A thorough understanding of local climate conditions is crucial for architects and engineers engaged in projects in Rabat-Salé, ensuring compliance with thermal performance requirements.

Integration and incorporation of new materials within DesignBuilder are facilitated by its special features, regardless of the design phase or building orientation. This functionality fosters innovation through the utilization of novel construction techniques and materials, leading to ongoing enhancements. The software provides a flexible platform that empowers users to explore diverse materials and construction methods, thereby optimizing the energy, environmental, and economic performance of buildings. With these capabilities, construction professionals can devise and implement innovative solutions to address evolving market demands and sustainability challenges.

The thermal simulation of this building, due to its simplicity, facilitates ease of analysis and generates results that can serve as useful references. Additionally, we can explore more complex cases, which is a crucial step in the design of ecological and energy-efficient structures. By utilizing standard building materials, we aim to enhance energy efficiency through the integration of an innovative composite material made from (50%GP+50%PC) in the outer layer of the building walls, which has a thermal conductivity of 0.426 W/m·K. This composite offers significant advantages, including improved thermal insulation and humidity regulation, ultimately contributing to a reduction in the building's energy consumption.

Furthermore, the installation of a split heating and ventilation system offers an efficient solution for meeting the thermal comfort needs of occupants. This system enables precise temperature control in each space, thereby reducing energy wastage and optimizing long-term operating costs.

The ultimate goal of this approach is to evaluate the overall impact of these choices on the building's energy consumption. By analyzing thermal performance under extreme climatic conditions, particularly during summer and winter, we can refine and optimize the building's design to ensure optimal comfort while minimizing its environmental footprint.

RESULTS AND DISCUSSIONS

Density

The table in question, Table 2 [19], presents the measurement results for the density of the three samples in relation to their volume and their mass after drying.

Density varies from one material to another due to the structure of each element. The increase in mass resulting from the mixture of samples E1 and E2 produces a new material with a density surpassing that of both pottery clay (E1) at 1395.2 (kg/m^3) and gypsum plaster (E2) at 1112 (kg/m^3), reaching a value of 1577 (kg/m^3) for E5.

Table 2. Sample dimensions and density [19]

No.	Samples	Thickness (cm)	Length (cm)	Mass (kg)	Density (kg/m^3)
E1	ARP/ X=100%	2	10	279.04	1395.2
E2	PL/X=100%	2	10	222.4	1112
E5	ARP/ X=50%+ PL/X=50%	2.1	10	333.31	1577

Table 3. Experimental values of thermal conductivity [20]

T_0	T_1	T_2	e_1	e_2	λ_2	U	R	S	λ_1	I
32,216	24,530	21,866	0.03	0.04	0.037	10.07	81.2096774	0.01	0.450	0.124
33,424	25,699	22,754	0.03	0.04	0.037	10.07	81.2096774	0.01	0.447	0.124
33,349	25,684	22,684	0.03	0.04	0.037	10.07	81.2096774	0.01	0.449	0.124

Table 4. The values of the thermal conductivity for the materials [21]

No.	Sample	Thermal conductivity W /mk
E1	CP/X=100%	0.450
E2	CP/X=100%	0.447
E3	CP/X=100%	0.449
E4	GP/X=100%	0.454
E5	CP/X=50%+ GP/X=50%	0.426

Thermal Conductivity

The experiment using the steady-state hot plate method is conducted for each moment before calculating the average value and determining the experimental relative measurement error. An example of the values obtained for (PC) is presented in the following table. Table 3 [20].

The average value of thermal conductivity, λm, was calculated for each composite material at the end of the experiments. The error in the estimated value of λm=0.448 W/m·K, caused by experimental uncertainties, is defined based on the differences |λ1-λm|/λm, which yields quite satisfactory results (the error in this experiment is 0.6%). The steady-state model can be considered as a precise model, and the estimation of thermal conductivity, λm, is enhanced.

The results of the mixtures between (GP) and Salé (PC) are presented in Table 4 [21]. Measurements of the thermal conductivity of Salé (PC) were taken three times to obtain values with precision.

Certainly, let's expand upon the results:

-The thermal conductivity analysis of Salé (PC) reveals a remarkable consistency, with values ranging narrowly from 0.447 to 0.450 W/m·K and averaging around 0.448 W/m·K. Intriguingly, this average closely mirrors the thermal conductivity of traditional brick clay, approximately 0.65 W/m·K. Such close alignment suggests that Salé pottery clay boasts properties well-suited for specific construction contexts where effective insulation and thermal regulation are critical.

-Contrastingly, (GP) showcases a commendably consistent thermal conductivity of 0.4 W/m·K. This unwavering stability in its thermal properties enhances gypsum plaster's appeal as a preferred construction material, particularly in contexts where factors such as fire resistance and insulation are pivotal considerations.

-The combination of (GP) and Salé (PC) in a composite material yields notable findings, notably a substantial reduction in thermal conductivity to as low as 0.426 W/m·K. This indicates a significant enhancement in insulation properties. Humidity can negatively affect the accuracy of thermal conductivity measurements of materials, but it does not necessarily influence the material's properties during the construction phase. This mixture, however, remains in the experimental stage and is not yet suitable for construction use.

-The study involves tests conducted under ambient conditions, with samples conditioned and insulated against external influences such as humidity before accurately determining their thermal properties. The durability of the 50/50 pottery clay-gypsum plaster material does not raise concerns over time, as its solid structure remains stable. Consequently, the key parameters of this resilient material do not change significantly.

This composite material offers a plethora of compelling benefits. Firstly, its reduced thermal conductivity translates to improved thermal insulation, making it ideal for applications requiring precise temperature control and energy efficiency, such as in building construction. Secondly, its quicker drying time accelerates construction projects, facilitating faster completion. Additionally, the lightweight nature of both Salé (PC) and (GP) enhances ease of handling and transportation.

Moreover, the readily available and cost-effective nature of these materials makes the composite an economically viable option for construction projects. However, it is crucial to consider that the extraction and production of gypsum plaster in Morocco consume approximately 1.5 MWh of energy per ton and emit up to 0.3 tons of CO_2 per ton produced. In contrast, traditional clay plaster requires less energy and has a lower environmental impact due to its reduced heating needs.

In conclusion, the findings of this study highlight the promising potential of the composite material composed of Salé (PC) and (GP). With its favorable thermal and physical attributes, this composite emerges as a compelling option for construction applications seeking efficient insulation, rapid drying, and cost-effectiveness. Figure 7 [22].

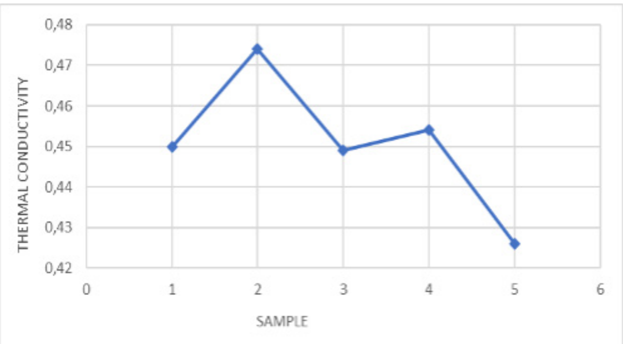

Figure 7. The thermal conductivity of materials [22]

Table 5. The energy demands of the building [23]

Before		After	
	Electricity Intensity [kwh/m2]		**Electricity Intensity [kwh/m2]**
Lighting	32.52	Lighting	32.52
HVAC	22.86	HVAC	22.60
Other	114.14	Other	114.14
Total	169.53	Total	169.27

Energy Simulation

The incorporation of a composite material comprising (GP+CP) into a layer of the building's exterior walls has a notable impact on the overall energy consumption of the structure. This impact primarily manifests in decreased energy requirements for heating and cooling through HVAC systems. While the enhancement in the building's thermal resistance is not remarkably pronounced, it remains sufficiently acceptable, with an approximate reduction of 0.26 kWh/m2. The energy use dropped from 22.86 to 22.60 kWh/m² with the addition of our composite materials, highlighting improved thermal efficiency. Table 5 [23]. These findings are evident in the comparative results obtained from simulations conducted both before and after the integration of the composite material.

This enhancement underscores a modest yet significant step towards energy optimization, potentially yielding substantial energy savings over the building's lifecycle. It's imperative to recognize that even marginal reductions in energy consumption can yield positive repercussions for the sustainability and energy efficiency of a building.

The two figures below analyze heating and cooling energy consumption before Figure 8[24] and after Figure 9[25] integrating a (50/50 GP-CP) mixture for the exterior walls of the residential structure. They illustrate correlations between temperature, lighting, HVAC, and other energy demands, highlighting the impact of each on total energy use. Temperature variations directly influence heating and cooling requirements, while lighting and HVAC systems contribute significantly to overall consumption. This analysis pinpoints key areas for optimization and potential improvements, emphasizing system efficiency and adaptive occupant behaviors. Overall, the diagrams provide critical insights for enhancing building energy efficiency and sustainability.

The exterior wall serves as a crucial interface for thermal exchanges between a building's interior and its external environment. By enhancing the thermal resistance of the exterior wall with an innovative composite material (50/50 GP-CP), significant reductions in the annual energy consumption can be achieved. Specifically, during winter, air conditioning energy consumption decreases from 8.80 to 8.75 kWh/m², resulting in a reduction of approximately 0.5%. Similarly, in summer, the heating energy requirement reduces from 14 to 13.90 kWh/m², leading to a decrease of about 0.7%. These improvements underscore the effectiveness of the composite material in optimizing energy efficiency in building design.

This enhancement is facilitated by the integration of a blend comprising pottery clay and plaster into the wall material. This infiltration not only reduces thermal conductivity, but also increases the insulation efficiency, effectively reducing heat loss through the wall surface. Furthermore, the concurrent elevation in conductivity and thermal inertia, courtesy of the introduction of terracotta, ensures adept thermal regulation in response to external temperature fluctuations. This dual-effect mechanism not only fosters a consistently comfortable indoor environment but also mitigates reliance on heating and cooling systems, thus engendering substantial long-term energy savings. Figure 10 [26]

While the present analysis is anchored in simplified scenarios and moderate temperature conditions, extrapolating this approach to more intricate or larger-scale applications holds promise for even more remarkable outcomes.

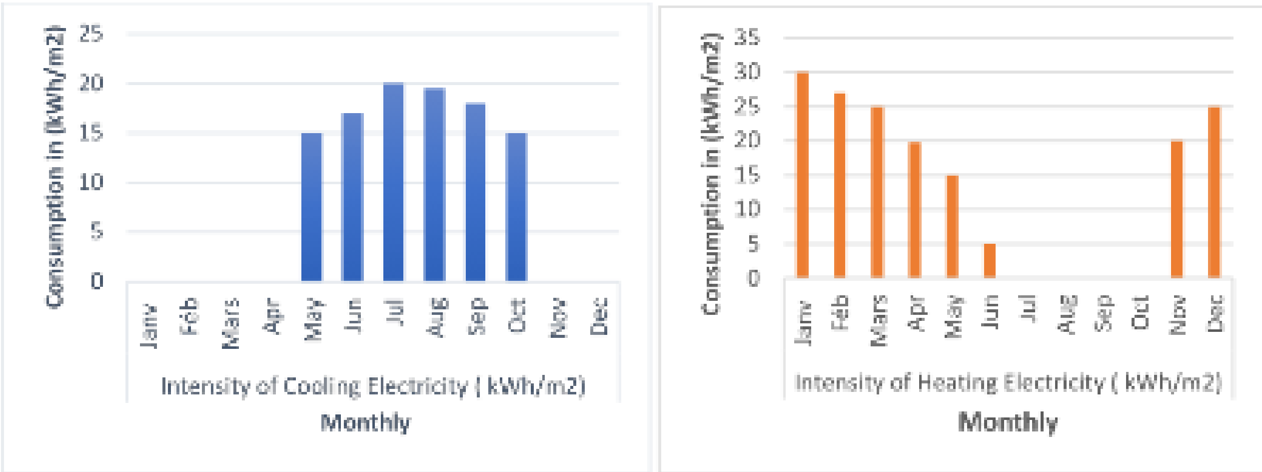

Figure 8. The annual energy consumption of the heating and cooling system before adding our insulation material. (KW h/m2) [24]

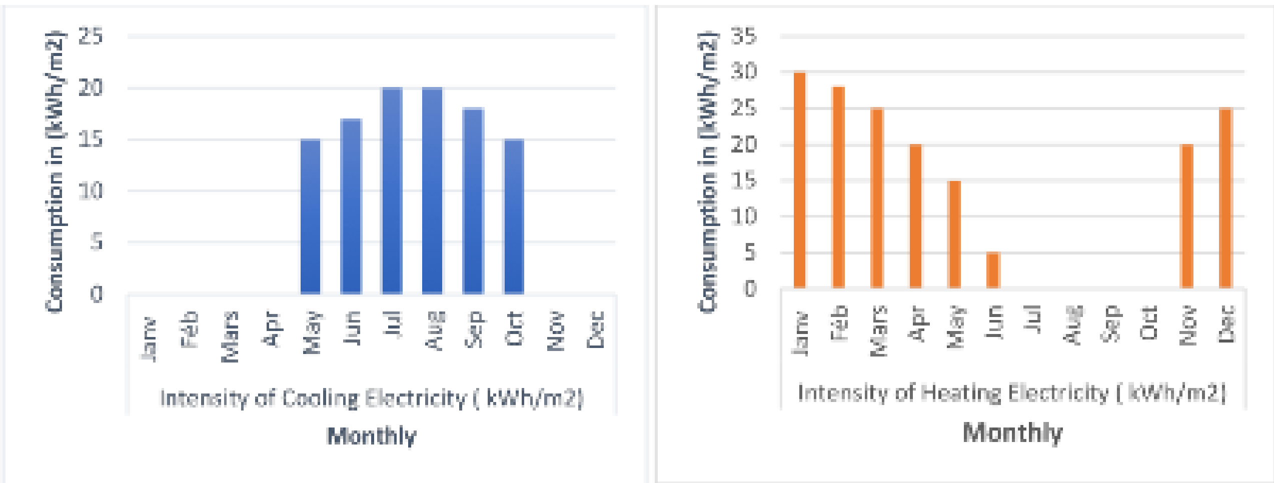

Figure 9. The annual energy consumption of the heating and air conditioning system after adding our insulating material. (KW h/m2) [25]

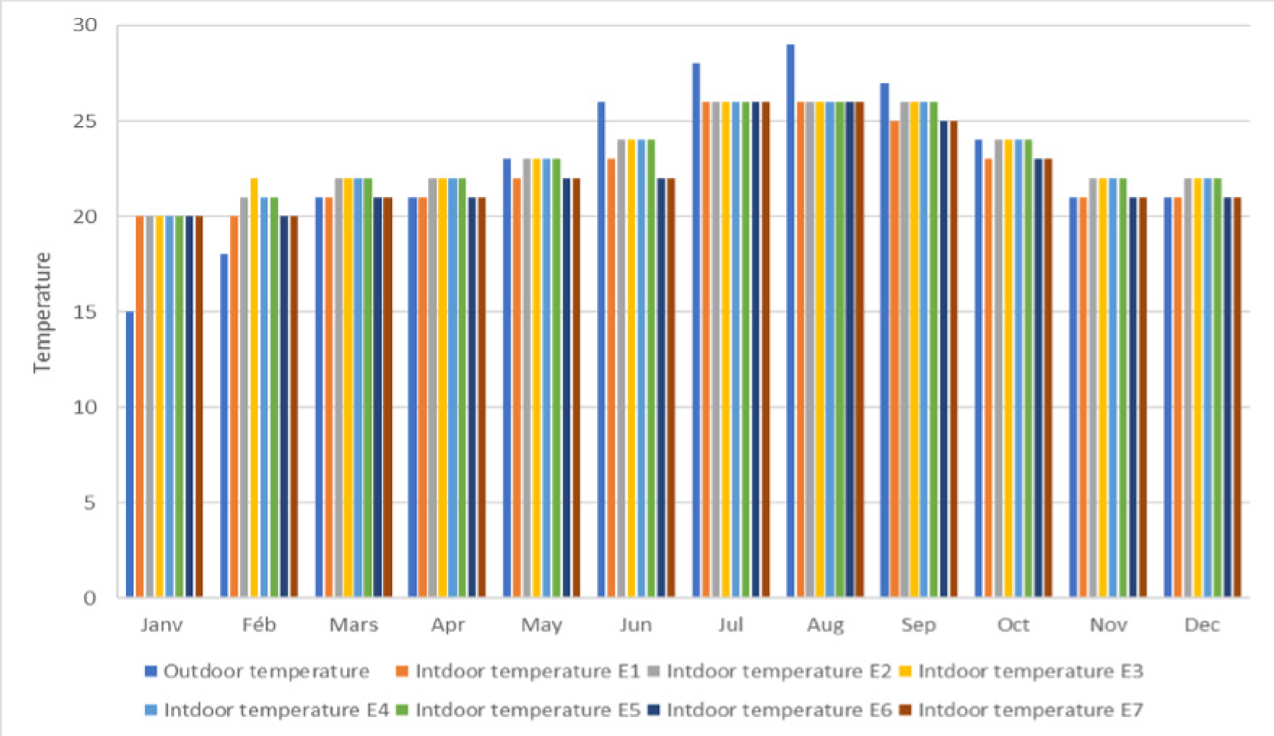

Figure 10. The hourly variation of the temperature inside and outside the building during the year 2023 [26]

CONCLUSIONS

The article delves into the findings of an extensive experimental study investigating the thermal properties of a newly developed composite material, a fusion of (50%GP+50%PC). Employing sophisticated hot plate methods for precise measurement, the research sought to scrutinize the material's thermal conductivity—a critical factor pivotal for assessing its viability in construction applications.

The reported thermal conductivity value of 0.426 W/m·K sheds light on the composite's moderate yet promising heat transfer capabilities. While this figure hints at its potential applicability in construction, it also underscores the pressing need for further refinement and optimization to unlock its full potential and enhance its competitiveness in the market.

Employing the new composite material in the construction of a standard residential building can lead to a 0.5% reduction in heating consumption during the winter season and a 0.7% decrease in cooling requirements during the summer period.

These findings underscore the critical need to enhance the composition, manufacturing processes, and structural stability of this innovative composite material. Collaboration among researchers, engineers, and industry stakeholders is essential to transitioning it from a developmental phase to a commercially viable solution. For instance, incorporating waste fibers from chicken feathers into gypsum plaster and olive tree fibers into clay has demonstrated a reduction in thermal conductivity of over 20% compared to initial values. Through ongoing innovation and rigorous optimization, this composite material has the potential to significantly impact construction practices and support sustainable building advancements.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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