buildings

MDPI

Article

Harnessing Natural Pozzolan for Sustainable Heating and Cooling: Thermal Performance and Building Efficiency in Moroccan Climates

Khadija Annaba [1], Sara Belarouf [2], Fatima Zohra El Wardi [3], Khalid Ibaaz [4], Mouha Cherkaoui [4], Céline Florence [1], Johan Colin [1], Romain Mege [1] and Yassine El Mendili [1,*]

[1] Institute of Research, ESTP Graduate School of Engineering in Construction, 28 Avenue du Président Wilson, CEDEX, 94234 Cachan, France; kannaba@estp.fr (K.A.); cflorence@estp.fr (C.F.); jcolin@estp.fr (J.C.); rmege@estp.fr (R.M.)
[2] Physics Unit, Department of Fundamental and Applied Sciences (DSFA), Agronomic and Veterinary Institute of Hassan II, Rabat 10000, Morocco; belarouf.sarah@gmail.com
[3] Physics Department, LPMAT Laboratory, Faculty of Sciences Ain Chock, Hassan II University, Casablanca 20000, Morocco; fatima.zohra.elwardi@gmail.com
[4] Applied Mathematics and Computer Science Decision Laboratory, National High School of Mines, Rabat 10000, Morocco; khalid.ibaaz@enim.ac.ma (K.I.); cherkaoui@enim.ac.ma (M.C.)
* Correspondence: yelmendili@estp.fr

Abstract: The need to construct environmentally friendly buildings to meet current environmental and ecological standards is urgent. This study introduces a new multi-layer construction material with two outer layers of ordinary mortar and an inner layer of a pozzolane-limes composite to meet this need. The thermal efficiency of this material in building construction is investigated using TRNSYS18 simulations for two distinct climatic zones in Morocco, with a particular focus on its impact on heating dynamics. The primary objective is to evaluate the thermal performance of multi-layered pozzolanic materials, for which mortar samples are meticulously prepared as a reference in the two different climatic zones (Azilal and Errachidia). Using the asymmetric hot plate method under both stable and transient conditions, the authors conduct thermal characterization experiments. The results underscore the improvement in thermal performance made possible by the incorporation of pozzolan as an aggregate in the multi-layer material compared to ordinary mortar. Specifically, thermal conductivity improves significantly, from 0.735 W m^{-1} K^{-1} for ordinary mortar to 0.4 W m^{-1} K^{-1} for multi-layered pozzolanic materials, representing a 46% mass gain. Additionally, effusivity decreases from 730 to 604 J m^{-2} K^{-1} $s^{-1/2}$, while diffusivity decreases from 3.78 to 2.23×10^{-7} m^2 s^{-1}, further attesting to the material's thermal efficacy. TRNSYS18 simulations corroborate the viability of using multi-layered materials as building envelopes, revealing potential annual heating gains of 25% in Azilal and 5% in Errachidia. These findings underscore the promising prospects of integrating these materials into sustainable construction practices.

Keywords: natural pozzolan; thermal performance; multi-layered pozzolanic materials; building efficiency; dynamic thermal simulation

Citation: Annaba, K.; Belarouf, S.; El Wardi, F.Z.; Ibaaz, K.; Cherkaoui, M.; Florence, C.; Colin, J.; Mege, R.; Mendili, Y.E. Harnessing Natural Pozzolan for Sustainable Heating and Cooling: Thermal Performance and Building Efficiency in Moroccan Climates. *Buildings* **2024**, *14*, 2633. https://doi.org/10.3390/buildings14092633

Academic Editor: Antonio Caggiano

Received: 2 July 2024
Revised: 9 August 2024
Accepted: 21 August 2024
Published: 25 August 2024

1. Introduction

The building sector plays a significant role in global energy consumption and CO_2 emissions [1–3]. It currently accounts for a substantial share of energy use and emissions, with projections indicating a 75% increase in built floor area by 2050, primarily in emerging markets and developing economies [4]. In developed countries, buildings already consume around 40% of total energy [1]. The integration of energy efficiency measures in buildings is crucial for addressing the energy crisis, as they can significantly reduce energy consumption and greenhouse gas emissions. The adoption of high-performance, low-embodied-energy technologies and the use of local materials with low embodied energy are essential strategies to enhance energy efficiency in the building sector [4,5]. Efforts to optimize technical and social strategies within the construction industry are vital for achieving highly energy-efficient renovations.

In Morocco, the buildings sector is notably energy-intensive, accounting for up to 33% of the total energy consumption, comprising 7% from commercial buildings and 26% from residential buildings [6,7]. A significant initiative is the Nationally Determined Contribution (NDC), which underscores Morocco's commitment to reducing greenhouse gas emissions by 42% by 2030 [7]. Maintaining the desired thermal comfort at the lowest heating and cooling energy cost and the impact on the energy environment is an essential factor in this context [8]. Hence a growing interest in lightweight composite materials based on environmentally friendly and renewable additives is being developed for various applications [9,10]. Other studies have shown a significant relationship between the type of materials of the building envelope and cooling and the reduction of energy consumption in buildings [11–13] between 29 and 59% of the heat losses occurring in buildings [14,15]. Thermal insulation materials can be used in residential and commercial construction to reduce energy loss, it decreases energy loss throughout the year by increasing the efficiency of heating and cooling systems. Furthermore, the use of insulating materials in construction will lead to reduced electricity consumption costs for the proposed cooling and heating, as well as lower initial fixed costs for the cooling and heating equipment [16]. Electricity consumption Savings, on the other hand, will benefit the environment by lowering carbon emissions [17].

In the same context scientific research indicates that traditional building materials, such as double brick constructions, can notably decrease energy requirements by 22% to 25% compared to standard brick buildings, particularly in different climatic zones of Morocco [18]. Furthermore, innovative approaches utilizing locally sourced materials, like plaster reinforced with straw, have demonstrated a 13% reduction in greenhouse gas emissions from buildings, accompanied by cost savings in numerous cities across the country [19]. Additionally, the integration of solutions such as lightweight concrete with cork, olive pomace, or hemp in building envelopes can substantially decrease energy needs by up to 22.5% [20]. These findings underscore the importance of implementing energy-efficient practices to mitigate energy consumption and lessen the environmental impact in Moroccan buildings.

In this context, there's been a surge in intelligent and ecological solutions aimed at reducing energy consumption, among which the utilization of pozzolan stands out. A plethora of studies have delved into the characteristics of pozzolans, with a specific focus on their lightweight nature, porosity, and thermal attributes [21,22]. Additionally, considerable research effort has been dedicated to exploring pozzolanic cement and concrete as environmentally sustainable binding agents [23–27].

The utilization of pozzolan in thermal insulation applications has garnered significant attention in recent research. Various studies have investigated the thermal properties of natural pozzolan and its potential to enhance energy efficiency in buildings [28]. Notably, Sarooj mortar, which incorporates pozzolan, has been subjected to thorough examination for its mechanical and thermal insulation capabilities, exhibiting promising results compared to conventional building materials [29]. Pozzolan concrete has also been investigated for its thermal conductivity and compressive strength, highlighting its potential as an insulating material [30]. Furthermore, the addition of natural pozzolan to mortars has been found to enhance their thermal properties, contributing to the overall thermal comfort of buildings [31]. The impact of thermal treatment on the mechanical properties of pozzolan-based materials has also been studied, emphasizing the importance of thermal conductivity in determining insulation properties [32]. Additionally, lime-pozzolan mortars have been assessed for their performance in thermal insulation applications, further demonstrating the potential of pozzolan as an insulating material [33]. Innovative approaches, such as incorporating recycled crushed brick pozzolan, have shown promise in enhancing the hygrothermal performance of insulation materials [34]. Research on eco-friendly insolating composite mortars based on natural pozzolan has also been conducted to evaluate their thermal properties for energy conservation [35]. Overall, pozzolan has been recognized for its potential to improve the thermal performance of building materials, offering excellent insulation properties [36].

In this context, the main objective of this research work is to propose a new natural and local pozzolan-based mortar with improved energy performance compared with ordinary mortar. The overarching goal is to enhance the value of using local and natural materials; such as natural pozzolan, in the development of new sandwich materials with excellent insulation performance, in order to compete with current construction materials. The developed mortar is a multi-layer material with two outer layers of ordinary mortar and an inner layer of a pozzolana-limestone composite. Integrating the new mortar into the construction applications as a coating layer will generate several benefits. First, it will enhance the insulation and thermal inertia of the building envelope, enabling reduced energy consumption and lower heating and cooling bills. Second, it will reduce environmental impact by minimizing carbon emissions of construction field. Third, it will promote the use of local, natural, and sustainable materials such as pozzolan and natural lime as previously indicated.

This study aims to address existing research gaps by analyzing the physico-chemical and mineralogical properties of pozzolan, cement, and lime used in construction. Then, an experimental study was conducted to evaluate the thermal performance of a multi-layer material composed of mortar and pozzolan-lime compared to reference mortars. In this context, various specimens were prepared, tested, and simulated using the TRNSYS18 software. The results obtained showed that the 3–7 mm granulometry provided the best thermal performance compared to the reference mortars. The thermal results obtained were then simulated using meteorological data from two Moroccan cities with different climatic conditions: Errachidia (hot zone) and Azilal (cold zone). The thermal characterization was performed using the asymmetric hot plate method in steady-state conditions to determine the thermal conductivity of the tested blocks. The results demonstrated that the new material had improved thermal qualities, encouraging its use in construction applications. The multilayer material developed in this study is intended to be used as wall plaster, offering advantages in terms of durability and thermal insulation. This innovation could help reduce the energy consumption of buildings, leading to lower costs and reduced greenhouse gas emissions.

2. Materials and Methods

2.1. Materials

2.1.1. Natural Pozzolan

The natural pozzolan was utilized as lightweight aggregates to create an eco-friendly and lightweight concrete. The pozzolan was obtained by crushing volcanic rock from Taza, Morocco, and the pozzolanic aggregates had a diameter of 3–7 mm (Figure 1). Chemical composition of Taza's Pozzolan as determined by X-ray fluorescence (XRF) analysis. The chemical composition is expressed in mass percentages (%) us presented in Table 1.

These values represent the relative mass percentages of each element or compound present in the Taza's Pozzolan sample analyzed using XRF. Pozzolan is a material used in cement and concrete production as a supplementary cementitious material to enhance certain properties of the final product. The specific chemical composition can have significant effects on its behavior when mixed with cement, affecting the strength, durability, and other characteristics of the concrete. The sum of silicon oxide (SiO_2), aluminium oxide (Al_2O_3), and ferric oxide (Fe_2O_3) for the raw natural pozzolan is 73.78%, slightly exceeding the upper limit of 70% [37], This indicates that the material falls under class 1 N-type material classification, which is recognized as a class N pozzolan according to ASTM C618 [37]. The pozzolan's thermal conductivity ranges from 0.15 to 0.20 $W.m^{-1}.K^{-1}$, corresponding to a density of 850 $kg.m^{-3}$.

Table 1. Chemical composition of natural pozzolan using X-ray Fluorescence test.

Chemical Element	Mass Composition (%)
SiO_2	46.48
Al_2O_3	10.01
Fe_2O_3	17.29
CaO	10.71
MgO	9.16
SO_3	0.47
Na_2O	1.52
K_2O	1.64
PAF	2.71

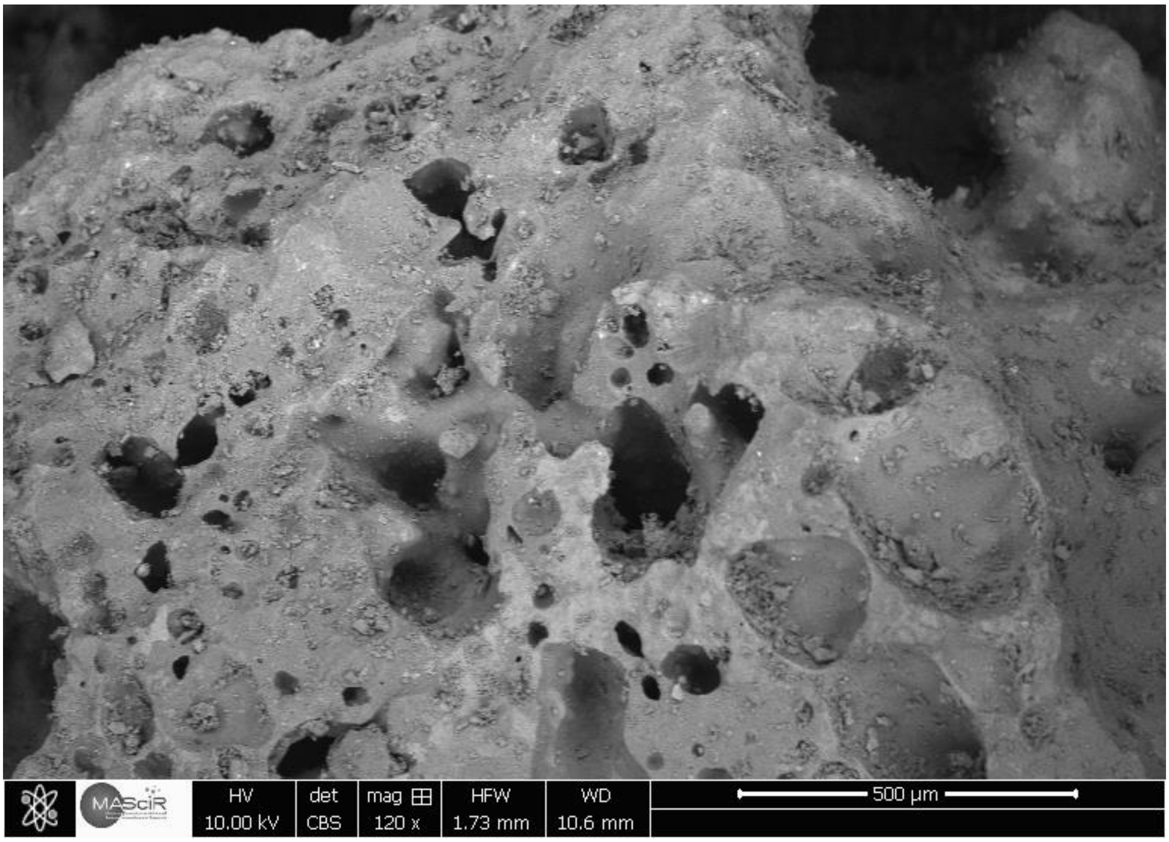


Figure 1. MEB image of pozzolanic granule.

2.1.2. Cement

Cement mortar is a mixture of sand, cement, and a certain amount of water. It has various uses: it can serve as a binder to connect construction materials, or as a protective layer for these materials, as is the case here. The CEM I cement used in this project complies with the NM 10.1.004 standard [16]. The mortar consists of 50% sand.

2.1.3. Lime

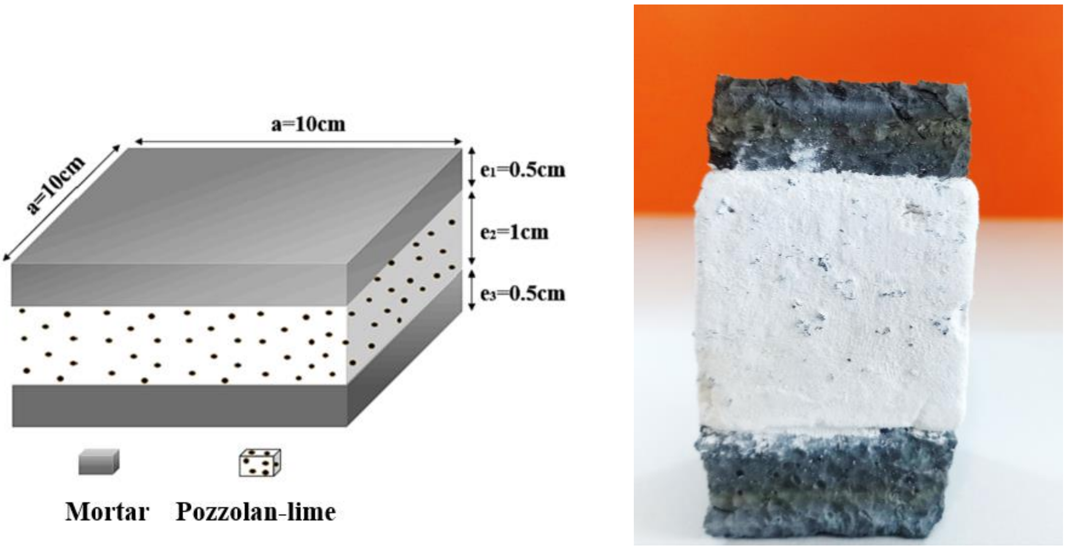
Quicklime (CaO) used as a hydraulic binder for pozzolanic aggregate in this study was sourced from the Sefrou region. The thermal properties of the lime were experimentally assessed on prepared specimens. The chemical composition of the lime was determined using X-ray Fluorescence technique (Table 2).

Table 2. Chemical composition of lime and cement using X-ray Fluorescence test.

Chemical Element	**Mass Composition (%)**	
	Lime	**Cement**
SiO_2	0.89	15.17
Al_2O_3	0.46	4.11
Fe_2O_3	0.17	4.17
CaO	97.41	68.69
MgO	0.7	1.9
SO_3	-	4.33
K_2O	-	1
SrO	-	0.09
TiO_2	0.06	0.34

2.1.4. Procedure of Samples' Preparation

In the experimental mixing process, lime constitutes 30% of the total mass of pozzolanic aggregates. The water ratio (water to the total mass of the pozzolan-lime intermediate layer) is maintained at 0.4. For all samples, the mortar, using CIMI cement, is prepared in accordance with the NM 10.1.004 standard. The water ratio for the mortar is set at 0.5. By incorporating natural pozzolan as a lightweight aggregate with the appropriate amount of lime, a lightweight, environmentally friendly multilayer construction material is obtained (Figure 2).



(**a**) (**b**)

Figure 2. Specimens for thermal properties testing: (**a**) typical presentation of the pozzolan-mortar multilayer [16]; (**b**) Multilayer material (Pozzolan-lime).

The obtained mixtures are then molded into specimens with dimensions of $10 \times 10 \times 2$ cm^3 for thermal properties testing, as shown in Figure 2. The molds are left to rest for 24 h to ensure proper setting. Additionally, a sample of the intermediate layer was prepared to compare the results with other specimens.

The multi-layer Pozzolan-limestone material consists of three layers: two outer layers of ordinary mortar and an inner layer of a pozzolana-limestone composite. In this work, experimental studies and simulations determined that this three-layer configuration, used as a trial to demonstrate the validity of the multi-layer concept, provided the best balance between thermal performance and structural integrity.

2.2. Methods

2.2.1. Thermal Characteristics

The steady-state hot plate was used to determine the thermal conductivity of the multilayer materials studied. The experimental setup is shown in Figure 3a [38–42]. In transient regime, the asymmetric hot plate was used to measure the thermal Effusivity value (Figure 3b) [39,42,43]. Three samples were tested three times to obtain accurate results.

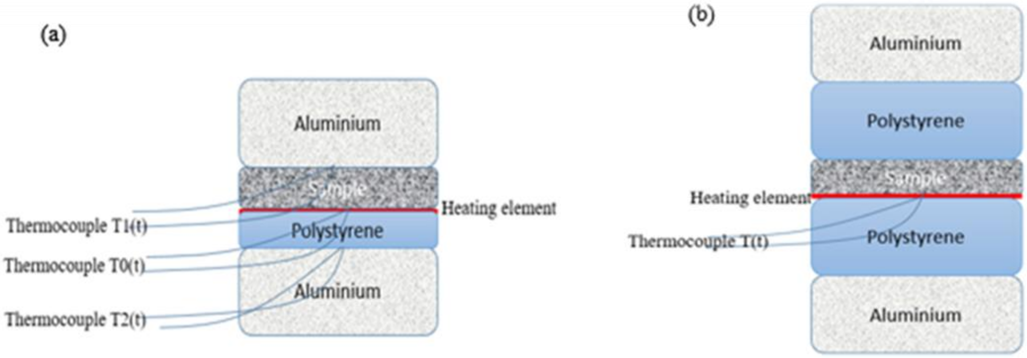


Figure 3. (**a**) schema of the Hot Plate method in steady state regime; (**b**) Asymmetrical transient Hot Plate device.

The Flash method is used to calculate thermal diffusivity. As shown in Figure 4, a (m^2/s) is used to characterize the rate of heat flow through a given material. A Laplace heat transfer model was used in the sample to estimate the thermal diffusivity [44–46].

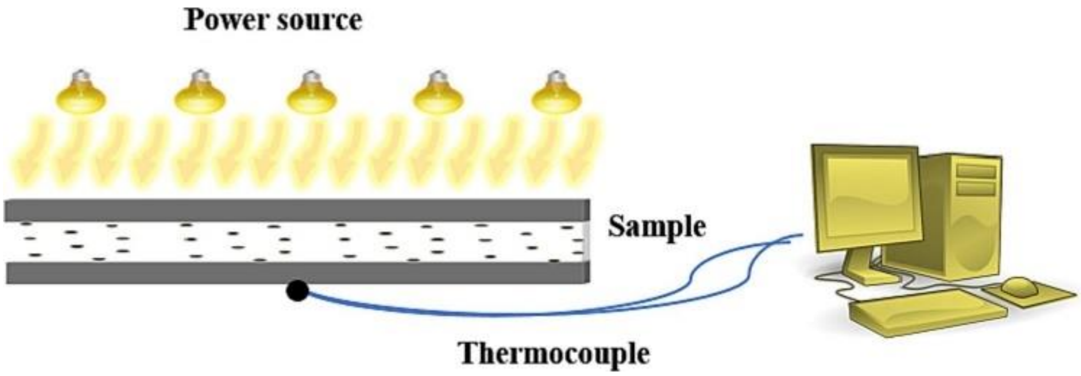


Figure 4. Principle of the Flash Method [16].

2.2.2. Thermal Simulation

Thermal modeling and energy analysis of a prototype building was done by TRNSYS building energy modeling (BEM) program, which is recognized as a powerful energy simulation tool for researchers and engineers [47]. The prototype is constructed using mortar with pozzolan material. Nowadays, the local building material has been the subject of numerous research into chemical and physical characterization [48–50], indeed the pozzolan used as a mineral admixture to the mortar attests to its suitability in terms of mechanical properties and durability within the composite structure. However, these studies neglect the thermal diagnosis of the studied material and its efficiency, which are the core of sustainability in construction and an essential feature of the life cycle analysis. Otherwise, compared to conventional mortar, the elaborated materials allow reducing significantly thermal transfers through the building's envelope in which they are incorporated, so the consideration of the thermal insulation coupled to the buildings is desirable to study. For that purpose, TRSNSYS is used to conduct a dynamic analysis of building shell parameters. TRNSYS is a flexible and extensible tool for the simulation of transient systems, with modular structure. The reference building adopted in this case study is an existent building, designated as a collective living building with a surface area of 86.4 m^2 and a height of 3 m as depicted in Figure 5 (the image on the left and the image on the right represent the same model. both images show the same model viewed from two different directions.).

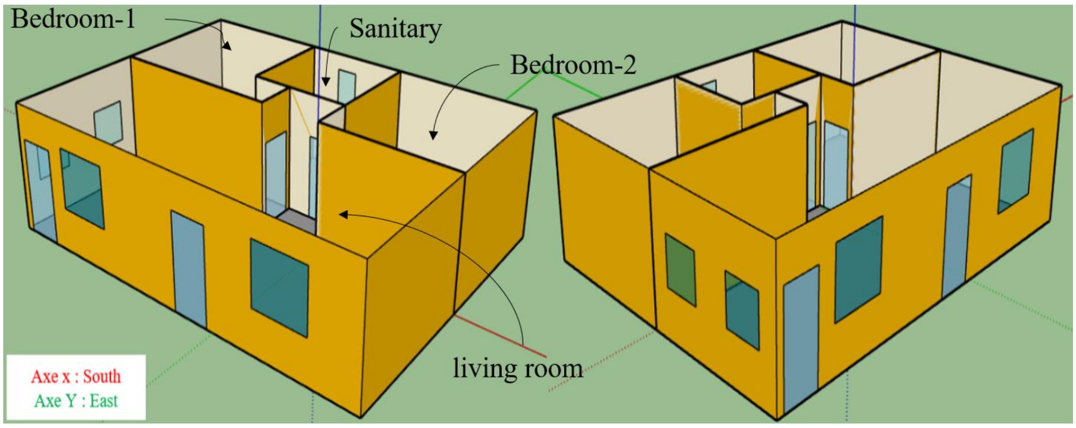


Figure 5. Prototype building 3D geometry.

In terms of climatic conditions, the prototype is tested for distinct locations (two different zones with different meteorological data). The meteorological data of the two thermal zones is defined in the Thermal Building Regulations in Morocco (RTCM) also divides the country into different climatic zones, each with specific thermal characteristics that influence building requirements for insulation, heating, and cooling. Zones 3 and 6 are part of this classification, each with unique climatic conditions.

Zone-3 generally represents regions with moderate climatic conditions. These areas experience relatively mild winters and warm summers. As a result, buildings in Zone-3 require moderate levels of insulation to maintain indoor comfort. The insulation helps in reducing heat loss during winter and heat gain during summer. Due to the warm summers, buildings are designed to minimize excessive solar gains while still allowing for passive solar heating during cooler months. Proper ventilation is also crucial to maintain air quality and thermal comfort, particularly during the warmer periods.

Zone-6, on the other hand, represents regions with harsher climatic conditions, typically characterized by cold winters and hot summers. Buildings in Zone-6 need higher levels of insulation compared to Zone-3 to cope with the extreme temperatures. This includes thicker insulation materials for walls, roofs, and floors. Minimizing solar gains is essential to reduce cooling loads during the hot summer months, while maximizing passive solar heating in winter. Enhanced ventilation systems and shading devices are often required to maintain thermal comfort. These systems help in reducing overheating during summer and ensuring proper air circulation.

The thermal characteristics of Zones 3 and 6 under the RTCM significantly impact a building's thermal performance. Improved thermal performance through appropriate insulation and design strategies leads to lower energy consumption for heating and cooling. Adequate insulation and ventilation improve indoor comfort by maintaining stable indoor temperatures regardless of the external climatic conditions. This is particularly important in Zone-6 due to the extreme temperatures. Enhanced thermal performance also results in reduced operational costs. For Zone-3, the focus is on achieving a balance between heating and cooling needs, while for Zone-6, the emphasis is on minimizing the energy needed for both heating in winter and cooling in summer. By optimizing the thermal characteristics based on the specific needs of each zone, buildings can achieve better sustainability, contributing to the overall goal of reducing greenhouse gas emissions and promoting energy efficiency.

Azilal and Errachidia were specifically chosen for this study due to their distinct climatic conditions, which provide a comprehensive evaluation of the thermal performance of the materials in both hot and cold environments. Additionally, the abundant presence of natural pozzolana in these areas makes them ideal for this research:

Azilal: Represents a cold climatic zone, characterized by lower temperatures, which allows for the assessment of the material's insulation properties and effectiveness in reducing heating demands during cold weather.

Errachidia: Represents a hot climatic zone, characterized by higher temperatures, which enables the evaluation of the material's performance in mitigating heat transfer and reducing cooling demands during hot weather. These locations were selected to ensure that the material's performance is tested in extreme and contrasting climatic conditions, thus providing a robust analysis of its thermal properties.

The temperature and humidity of the two cities are presented in Figures 8 and 9. As indicated, the maximum and minimum temperatures reached for both cities are 44.75/−0.75 °C for Azilal and 42.90/−0.40 °C for Errachidia City. In terms of average temperatures, the variation can reach 5 °C with an average temperature of 15.7 °C for Azilal and 19.8 °C for Errachidia city. The reasoning behind the choice of these two cities is that they belong to the different thermal zones adopted by the RTCM (Zone-3 and Zone-6). In fact, Zone-3 has a characteristic of warm Mediterranean climate, it is generally Mediterranean with an oceanic influence and more continental as you go deeper into the mountains. Whereas Zone-6 is a semi-desert city characterized by a hot and arid climate with a strong thermal amplitude, very cold in winter and very hot in summer. These characteristics are mainly due to its location between the High Atlas and the Sahara. Cities meteorological data are obtained from Meteonorm-7 software (version 7.3.3.17983), especially the Typical Meteorological Year (TMY-2) second edition which is a set of meteorological data with data values for every hour in a year. The reason behind such type of data (TMY-2) is the clarity of the simulation results since TRNSYS is one of the powerful commercial softwares packages that can run simulations using TMY-2 data. Using a simple and basic simulation by TRNSYS of the Weather data component with the desired city external file, the two fundamental parameters; temperature and humidity (T/H-t) are considered and plotted in order to contemplate their variation during the year.

As previously reported, the main purpose of the current study is to determine the thermal performance of the building based on the analysis of wall construction materials impact and building envelope. To go further, it focuses on the evaluation of thermal performance of the studied multi-layered pozzolanic materials (Mortar/P) against the sample of ordinary mortar. The composition and construction materials of the building for the two configurations are shown in Tables 3 and 4.

In order to respect the Moroccan Thermal Regulation of Construction standards during the simulation, with the evaluation of the influence and gain of the studied multilayers composite, a number of parameters and assumptions are implemented in TRNSYS program structure for all simulations. In otherwise, to get meaningful and significant results it is necessary to compare what is comparable, in our case the impact of the envelope on energy consumption. Therefore, to conduct a sensitivity analysis of the building envelope parameters, a number of assumptions and Inputs are taken into account:

- Ventilation profile (Table 5).
- Infiltration profile is set to 0.6 V/h for all zones.
- The initial indoor air temperature and humidity for different cities (Table 6).
- The prototype building is occupied by individuals according to Table 7.
- Equipment occupation (Table 8).
- the geometry, orientation of the building and location of the windows/doors is the same
- The sensible heating and cooling equipment power are unlimited with a radiative fraction equal to zero.
- The setpoint temperatures schedule for heating and cooling (Table 9)

Table 3. Characteristics of the building envelope: Construction—Mortar/P.

Building Component	Material	Thickness (cm)	λ (kJ/h.m.K)	Cp (kJ/kg.K)	ρ (kg/m^3)	Uglobal
External Wall	Mortar/P	2	1.44	0.615	1450	0.498 W/m^{2}K
	red brick	10	0.84	0.76	925	
	insulation-1	5	0.198	1.03	8.5	
	red brick	10	0.84	0.76	925	
	Mortar/P	2	1.98	1	1125	
Ground Floor	Concrete	20	5.94	1	2150	2.916 W/m^{2}K
	Mortar/P	2	1.98	1	1125	
	tile	2	4.68	0.84	2300	
Adjacent Wall	Mortar/P	2	1.98	1	1125	0.909 W/m^{2}K
	red brick	20	1.2	1	1100	
	Mortar/P	2	1.98	1	1125	
External Roof	bitumen	2	0.83	0.96	2400	2.069 W/m^{2}K
	hollow core slab	25	4.73	1	1327.3	
	Mortar/P	2	1.98	1	1125	

Table 4. Characteristics of the building envelope: Construction—Mortar/Ord.

Building Component	Material	Thickness (cm)	λ (kJ/h.m.K)	Cp (kJ/kg.K)	ρ (kg/m^3)	U_{global}
External Wall	Mortar/Ord	2	2.646	1.033	1880	0.502 W/m^{2}K
	red brick	10	0.84	0.76	925	
	insolation-1	5	0.198	1.03	8.5	
	red brick	10	0.84	0.76	925	
	Mortar/Ord	2	2.646	1.033	1880	
Ground Floor	concrete	20	5.94	1	2150	2.996 W/m^{2}K
	Mortar/Ord	2	2.646	1.033	1880	
	tile	2	4.68	0.84	2300	
Adjacent Wall	Mortar/Ord	2	2.646	1.033	1880	0.925 W/m^{2}K
	red brick	20	1.2	1	1100	
	Mortar/Ord	2	2.646	1.033	1880	
External Roof	bitumen	2	0.83	0.96	2400	2.109 W/m^{2}K
	hollow core slab	25	4.73	1	1327.3	
	Mortar/Ord	2	2.646	1.033	1880	

Table 5. Sanitary ventilation Schedule.

Name	Type	Value	Specific Fan Power	Supply Air Conditioning	T_Suplply Air Flow	Air Flow Humidity
Sanitary Vent	air change rate	2/h	300	external by other component	Outside air	relative humidity with outside air

Table 6. Simulations initial values (on January 1st at 0:00).

	Temperature (°C)	Humidity (%)
Azilal	6.5	65
Errachidia	5.2	45

To carry out the simulation with TRNSYS, the thermal modeling process primarily requires a 3D geometric representation of the building made with Google SketchUp-18. In fact, TRNSYS includes Trnsys-3d. a plugin for SketchUp that enables the creation of multizone buildings and the direct importation of the geometry (including building self-shading and internal view factors for radiation exchange) into the TRNSYS software main interface. The thermal reference information of the prototype model is implemented in the "TYPE 56" component. Figure 6 depict the process simulation with TRNSYS ranging from the building modeling through virtual interface to the desired Outputs.

Table 7. Person occupation profile.

Zone	00h–8h	8h–12h	12h–13h	13h–14h	14h–20h	20h–22h	22h–00h
Bedroom-1	1	0	1	0	0	0	1
Bedroom-2	2	0	1	0	0	0	2
living room	0	1	1	3	1	3	0

Table 8. Equipment occupation schedule.

Zone	Type	Schedules	Energie
Bedroom-1	Lighting	Sched- Bedroom 1	7 W
	PC with monitor	----	180 W
	People	-----	185 W
Bedroom-2	Lighting	Sched- Bedroom 2	5 W
	TV	Sched- Bedroom 2	250 W
	People	-----	185 W
Living room	Lighting	All day	3 W
	People	-----	185 W
	TV	9 h à 18 h	300 W

Table 9. Setpoint temperatures schedule for heating and cooling.

Zone	Profil	00h00–08h00	08h00–12h00	12h00–14h00	14h00–18h00	18h00–24h00
Bedroom-1	Heating (°C)	19	22	22	22	19
	Cooling (°C)			25		
Bedroom-2	Heating (°C)	19	22	22	22	19
	Cooling (°C)			25		
Living room	Heating (°C)	19	24	24	24	19
	Cooling (°C)			25		

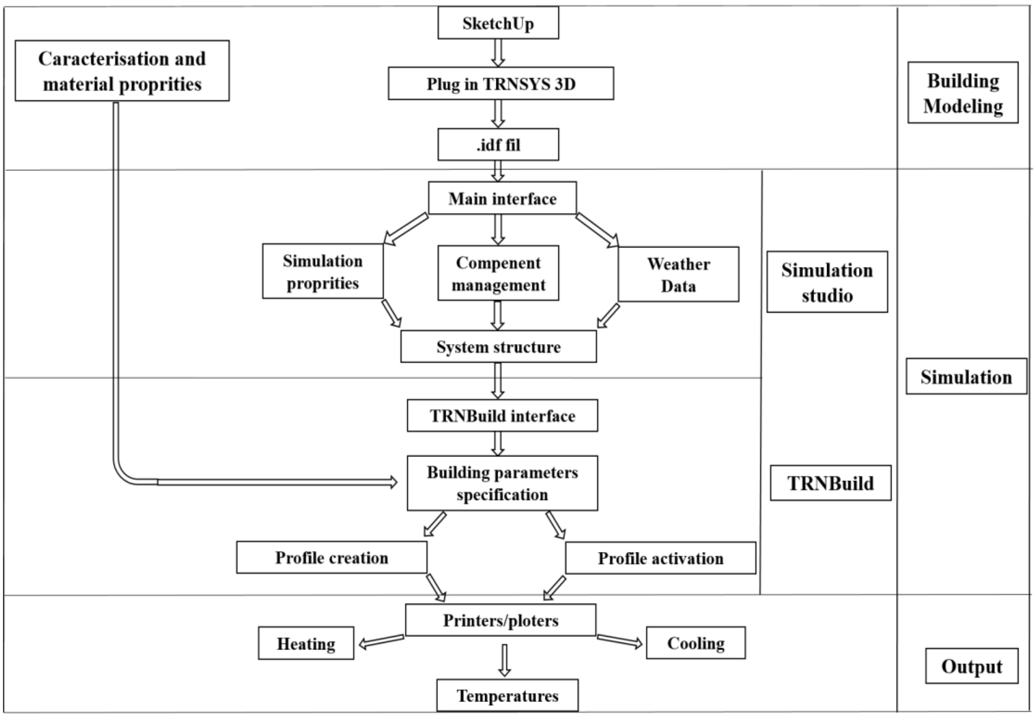


Figure 6. simulation procedure.

3. Results

Table 10 presents the experimental results of thermal characterization of multilayer and reference material tested in this study:

Table 10. Experimental results of thermal characterization of multilayer and reference material.

Samples	**Density ρ ($Kg\ m^{-3}$)**	**Thermal Conductivity λ ($W\ m^{-1}\ K^{-1}$)**	**Thermal Effusivity E ($J\ m^{-2}\ K^{-1}\ s^{-1/2}$)**	**Thermal Diffusivity a $10^{-7}(m^2\ s^{-1})$**	**Specific Heat Capacity C ($J\ kg^{-1}\ K^{-1}$)**
Reference material (Ordinary mortar)	1880	0.735	730	3.78	1033
Multilayer material	1450	0.4	604	2.23	1237
Intermediate layer	------	0.28	----	-----	1252
Gain	23%	46%	17%	41%	40%

3.1. Density

The density measurement results of the reference material and the multilayer material are reported in Table 10 above. The results show that the incorporation of pozzolan as aggregate in the multilayer material improves its lightness compared to the reference material by 23%. In other words, after adding an intermediate layer based on the composite gypsum-pozzolan aggregate, the density of cement mortar decreases from 1880 $Kg.m^{-3}$ to 1450 $Kg\ m^{-3}$. This result can be justified by the porous nature of the pozzolan aggregates, which allows creating porosity inside the multilayer material and leads to this decrease in density. A review of the literature confirms this finding result. Annaba et al. [16] have tested the effect of pozzolan addition on the thermomechanical properties of concrete, it proved that the concrete-pozzolan composite becomes more lightweight when increasing the rate of pozzolan aggregates incorporated. A work carried out by El Wardi et al. [51] tests the reinforcement of clay bricks mixed with cork aggregates by lime and sheep wool fibers. The obtained results show that the addition of 13% by mass of cork aggregates improves the lightness of the clay by more than 59% compared to the clay alone. Another work investigates experimentally the effect of artificial porosity on the lightness and thermal qualities of rammed earth bricks [52]. Two types of clays are tested in this work: the Bensmim clay and the Benhmed clay. The results show that creating porosity inside the bricks improves their lightness for both types of clays tested. This results in a part of the material being replaced by air-filled pores with a very low density of about 1.2 $kg.m^{-3}$. Another work reports that adding straw in its natural porous form reduces the density of the clay-straw composite from 1209 to 934 $kg\ m^{-3}$ for a straw mass fraction from 4 to 8% [41].

3.2. Thermal Conductivity

A simple analysis of the results of Table 10 shows that the multilayer material has twice the thermal resistance of cement mortar alone, with a reduction in thermal conductivity exceeding 46%. This is mainly due to the intermediate layer based on the composite gypsum—Pozzolan aggregates. The achieved result shows the good thermal insulation properties of the pozzolan in the form of aggregates and the interest in incorporating this additive in the building materials. In other words, adding pozzolan in granular form to building materials results in composite products with improved thermal properties compared to reference materials. This is mainly due to the porous structure of the pozzolan aggregates resulting in air-filled pores with a low thermal conductivity of 0.026 $W\ m^{-1}\ K^{-1}$ [45–49]. The results obtained are in good agreement with many previous works in the literature. The same behavior is observed in a work of Maaloufa et al. [53] testing the effect of adding perlite aggregates on the thermal behavior of earth bricks before and after calcination. A reduction in thermal conductivity of 30% is reported for clay saturated with perlite aggregates compared to clay alone before and after calcination. In addition, an experimental investigation was conducted to analyze the thermomechanical properties of a multilayer material based on the clay-cork aggregate composite that constitutes its intermediate layer and two layers of cement mortar and gypsum coating [38]. The results show that the thermal conductivity of the multilayer material decreases as the thickness of the interlayer increases. This result involves that the intermediate layer is responsible for the good thermal insulation qualities of the multilayer material. The observation of the clay-cork composite under the scanning electron microscope indicates that the cork in its granular form maintains its natural porosity and introduces an additional porosity inside the clay-cork composite [54].

3.3. Thermal Effusivity

A comparison of the thermal effusivity of the multilayer material with that of cement mortar shows that adding the layer of the plaster-pozzolan aggregate slightly reduces the thermal effusivity (17%) of the multilayer material compared to the reference material (Table 10). In other words, the multilayer material becomes more thermally insulating and reduces its surface heat exchange with its surrounding environment compared to cement mortar. The same result was reported by a work of El Wardi et al. [54] testing the thermal insulation qualities of a multilayer material based on clay-cork composite and cement mortar as a coating layer. The results show that the thermal effusivity of the multilayer material decreases when the thickness of the intermediate layer increases. Another work by Maaloufa et al. [52] indicates that adding perlite aggregates to earth blocks reduces the thermal effusivity of the clay from 862 to 641 J m^{-2} K^{-1} $s^{-1/2}$ for the clay-perlite composite saturated with perlite aggregates. An experimental study of the thermal properties of a new construction material based on peanut shells and gypsum revealed that the addition of porous fibers allows lowering the thermal effusivity of the developed material by more than 36% for a mass fraction of peanut shells of 20% [55].

3.4. Thermal Diffusivity and Specific Heat Capacity

Experimental measurements of the thermal diffusivity of the multilayer material and that of the cement mortar indicate that adding pozzolan as aggregate significantly reduces the thermal diffusivity of the multilayer material by more than 41% compared to the cement mortar alone (Table 10). This result involves using pozzolan in its natural form (aggregates), allowing it to maintain its porous structure, filled with air. This air helps slow down the propagation of heat within the material, reducing and limiting it, which improves the material's thermal insulation performance. This result is well confirmed by the high specific heat capacity of the multilayer material compared to cement mortar, revealing its ability to store heat and release it as needed. The same behavior is observed at the level of a multilayer material, based on the composite clay-cork aggregates and an interior coating by gypsum and exterior by cement mortar, developed in the framework of a work of El Wardi et al. [54].The results indicate that the layer composed of clay-cork aggregates is responsible for reducing the thermal diffusivity and increasing the specific heat capacity, which go from 3.62×10^{-7} m^2 s^{-1} and 1083 J kg^{-1} K^{-1} for the cement mortar to 3.08×10^{-7} m^2 s^{-1} and 1022 J kg^{-1} K^{-1} for the multilayer material with a volume percentage of the clay-cork layer of 44%, respectively. Another work reported that the integration of perlite aggregates in clay bricks reduces the thermal diffusivity of the reference material from 5.06 to 3.71×10^{-7} m^2 s^{-1}. Moreover, a work by Atbir et al. [56] related that the addition of wool allowed reducing the diffusivity of clay-wool composite. The authors explained the results found by the porous structure of the introduced wool and the additional porosity that appeared inside the composite, as shown by the observation under scanning electron microscopy. In general, the claim that the elaborated materials significantly reduce thermal transfers compared to conventional mortar is supported by specific quantitative data from the present study, which demonstrates the enhanced thermal performance of the new multi-layer material. The numerical comparisons reveal a 46% decrease in thermal conductivity (from 0.735 W.$m^{-1}$$K^{-1}$ for ordinary mortar to

0.4 W.m^{-1}K^{-1} for the multi-layered pozzolanic material), a 17% reduction in thermal effusivity (from 730 J.m^{-2}K^{-1}s^{-1}/2 to 604 J.m^{-2}K^{-1}s$^{-1/2}$), and a 41% decrease in thermal diffusivity (from 3.78×10^{-7} m^{2}s^{-1} to 2.23×10^{-7} m^{2}s^{-1}). These experimental comparisons provide robust evidence supporting the claim that the newly developed multi-layer material significantly reduces thermal transfers compared to conventional mortar.

3.5. Thermal Simulation Results

After system structure (TRNSYS main interface) and building parameters specification (TRNBuild interface), to maintain the set temperatures for the heating and cooling of various zones and to achieve the required thermal comfort, the energy system profiles are activated. Figures 7 and 8 illustrate the dynamic simulation results for the multizones temperatures. For each figure, the orange color curve refers to the ambient temperature variation. Interacting with the environment, when the zone temperature exceeds the desired temperature, the system is activated to adjust the temperature to the imposed set point, which is indicated by the blue curve (living room zone). The same thing for the curve in purple (which refers to the bedroom-2 zone), in reality this curve coincides with the curve in red (which refers to the bedroom-1 zone) since these two zones have almost the same dimensions. During the periods roughly between 0–3300 and 6800–8760 h, which correspond to the colder months, the heating system needs to maintain a comfortable temperature. This heating system operates in such a way that it keeps the temperature between 19 and 24 °C, hence the fluctuations. For the period between 3650 and 5840 h, it's summer, and cooling is needed to ensure comfort. The cooling system maintains a fixed temperature of 25 °C defined as the comfort temperature, as clearly indicated by the green curve in Figure 10 (cooling demand).

Figures 9 and 10 illustrate dynamic simulation results of yearly cooling and heating load to maintain the multizones set temperatures. These two curves refer to the mortar-based pozollan construction for both locations (Azilal and Errchidia). For all figures (Figures 11–13), To present the results in a non-repetitive manner, we aimed to show the temperature inside different rooms (Bedroom-1, Bedroom-2, and the Living Room) and the heating demand over time (excluding the cooling demand). The blue curve represents the consumption when using pozzolan material, and the violet curve represents the consumption when using ordinary material. It is clear that during the summer period, there is no need for heating in the studied zones, which explains the disappearance of both the blue and violet lines during this period.the blue color curve indicates the variation of heating amount required to ensure winter comfort in living room zone. According to the curve, the maximum heating requirements are reached in January. February and December, which is reasonable for both locations, while these needs are neglected in summer showing the validity of the studied material (there is no contradiction with the literature). The same thing for both zones bedroom-1 and bedroom-2, the curves in purple and red are almost coincident (since there is no significant difference between the zones in terms of dimension). What is attractive about these curves is the amount of heating energy that must be supplied to maintain the desired temperature for different zones. The sweep volume of the blue curve is very important when compared to the red and purple curves, this is very significant since the conditions of the living room zone and especially the dimensions are very influential with regards to bedroom-1 and bedroom-2 zones. For the summer comfort, it is clear that the cooling system is inactive in the cold periods. This result shows the clarity of the constructed system (Studio and TRNBuil interface). In reality, air conditioning refers to the summer period, as reflected by the green, orange, and sky-blue curves, which indicate that the cooling system is activated from the end of May until the end of September, depending on the schedule.

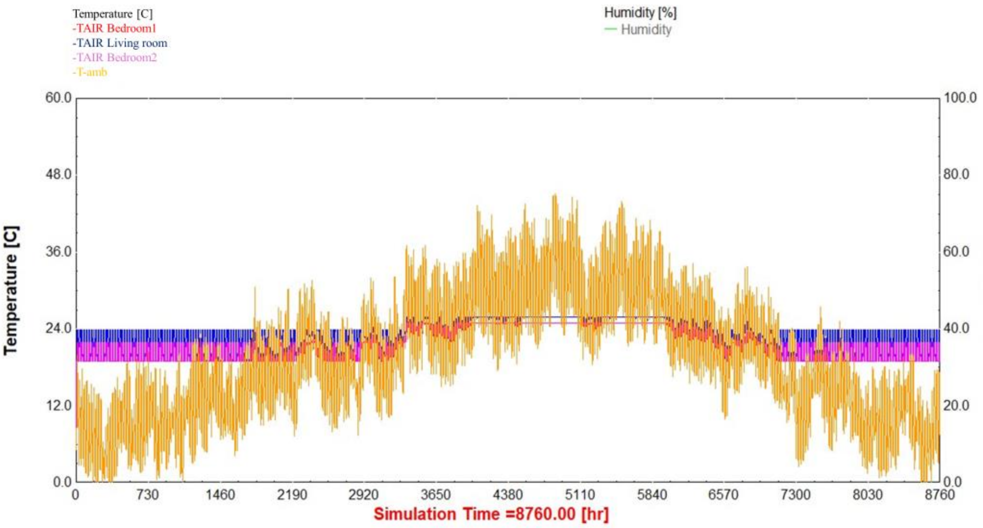


Figure 7. Multizone simulated temperatures for the Moerar based Pozzolanin Azilal location (T-Azilal/P).

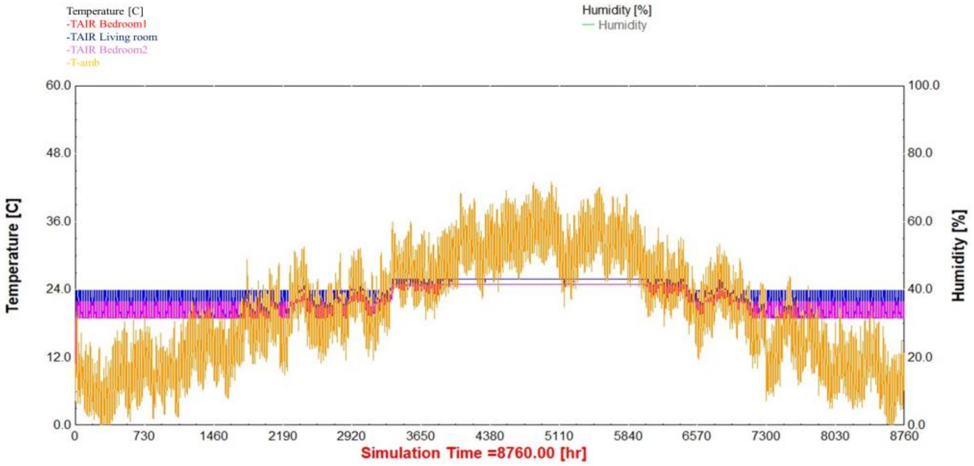


Figure 8. Multizone simulated temperatures for the Mortar based Pozzolan in Errachidia location (T-Errachidia/P).

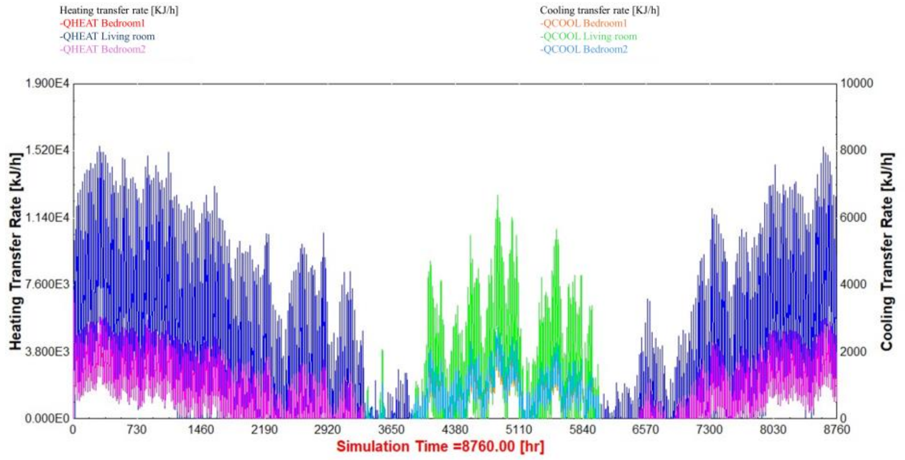


Figure 9. Heating and cooling demands for the mortar based Pozzolan in Azilal location (Q-Azilal/P).

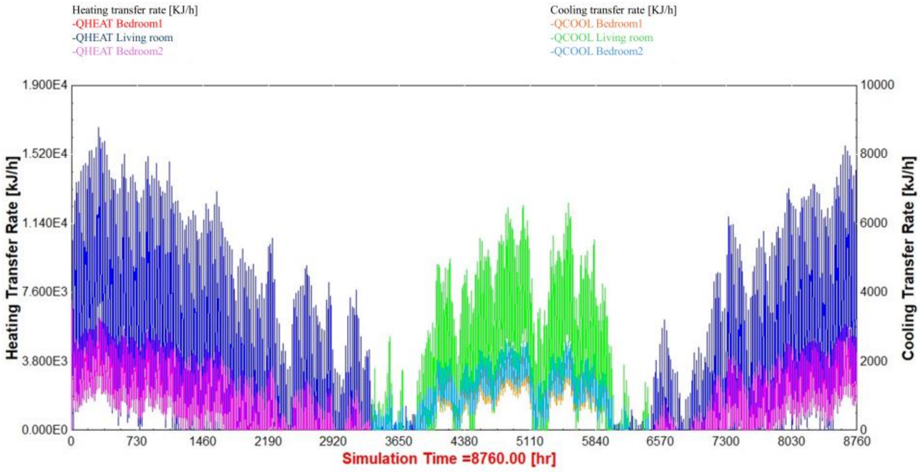


Figure 10. Heating and cooling demands for the mortar based Pozzolan in Errachidia location (Q-Errachidia/P).

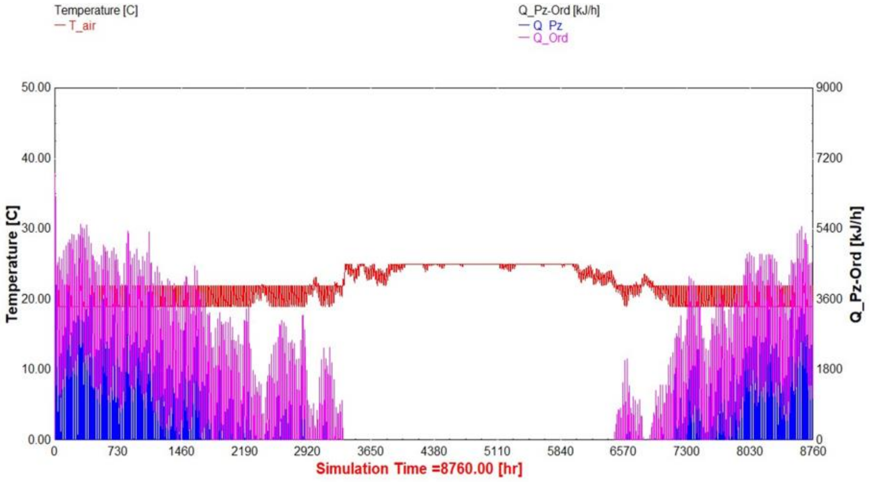


Figure 11. Heating demands for both mortars based Pozzolan and ordinary mortar in Azilal location for bedroom-1 zone.

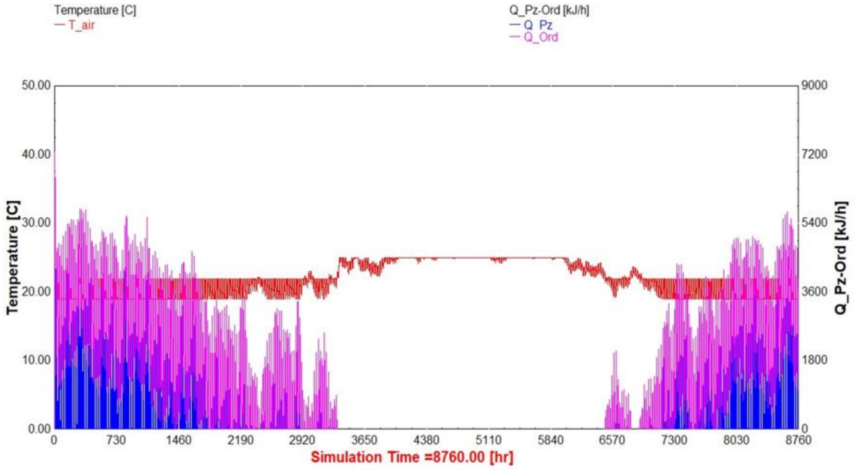


Figure 12. Heating demands for both mortar based Pozzolan and ordinary mortar in Azilal location for bedroom-2 zone.

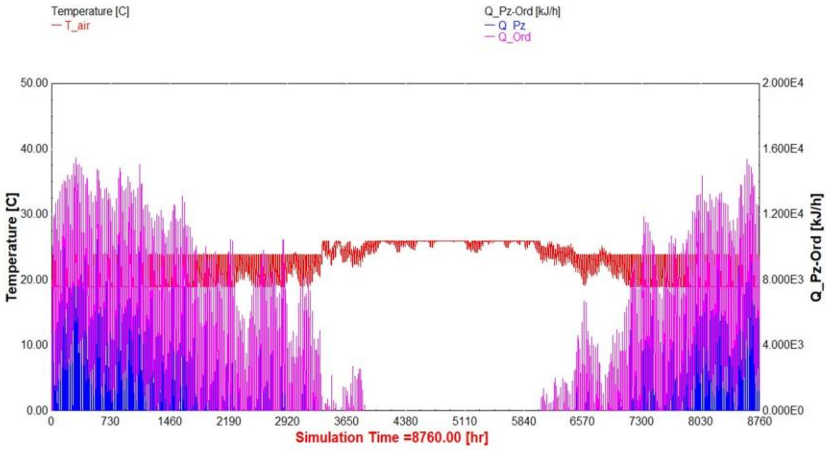


Figure 13. Heating demands for both mortar based Pozzolan and ordinary mortar in Azilal location for living room zone.

Based on the provided simulation results, a significant comparison emerges between two distinct construction materials, namely "Ordinary mortar" and "mortar based Pozzolan" utilized in Azilal city (Table 11). The dataset delineates the total consumption (energy required) for heating and cooling for each material. as well as the percentage of gain or reduction achieved by one type over the other. "Ordinary mortar" demands a total energy consumption of 12,830.06 kWh/year for heating and 1893.75 kWh/year for cooling, while "Mortar based Pozzolan" necessitates a total energy consumption of 9603.85 kWh/year for heating and 1455.11 kWh/year for cooling. The "Gain" parameter denotes the percentage of energy reduction accomplished by the "Pozzolan" material relative to the "Ordinary" material within each category. For heating, the "Pozzolan" material exhibits a 25% decrease in energy consumption compared to the "Ordinary mortar" while for cooling, it showcases a 23% decrease in energy consumption. Based on the simulation results, the "Ordinary mortar" and "Pozzolan" systems are juxtaposed regarding their energy consumption for heating and cooling. yielding the following observations: The "mortar-based Pozzolan" demonstrates significantly lower energy consumption in cooling and heating (11,058.96 kWh/year) compared to "Ordinary mortar" (14,723.81 kWh/year), resulting in a 25% reduction in energy utilization for heating. This translates to an energy saving of 3665 kWh/year for the simulated house with the "Pozzolan" construction material. Besides. the simulation results reveal reduction in total heating consumption when using the high-performing local material in Errachidia city. decreasing heating needs (resp. cooling needs) from 11,836.49 kWh/year (resp. 3032.96 kWh/year) with the base material to 11,247.04 kWh/year (resp. 3004.73 kWh/year) with the local material.

Table 11. the total energy consumption for heating and cooling for each material in Azilal and Errachidia cities.

City	Energy Consumption (kWh/year)			
	Type of Mortar	**Heating Needs**	**Cooling Needs**	**Total Energy Consumption**
Azilal city	Ordinary	12,830.06	1893.75	14,723.81
	Pozzolan	9603.85	1455.11	11,058.96
	gain	25%	23%	25%
Errachidia city	Ordinary	11,836.49	3032.96	14,869.45
	Pozzolan	11,247.40	3004.73	14,252.13
	gain	5%	1%	4%

This reduction represents a total annual energy saving of 617.32 kWh/year, demonstrating an improvement in building energy efficiency. Other research work confirms that the use of high-performance materials considerably reduces the energy required for heating and cooling. A muti-layer material based on clay, cork and cement mortar developed in a work of El Wardi et al. [54] showed interesting energy saving of about 45% and 31% compared to ordinary hollow clay bricks and clay alone when used in a model house external walls. Another study that investigates natural concrete-pozzolan composite reveals clearly that the new concrete with pozzolan aggregates enables a reduction in heating and air-conditioning needs of over 22% and 14% compared with hollow bricks and ordinary concrete, respectively [16]. A sustainable material based on plaster reinforced by the use of sheep's wool tested in a work of Atbir et al. [57] reached a significant Heating and cooling energy-savings between 40 and 48.5% compared with reference material of plaster alone.

This substantial decrease suggests potential benefits in terms of reducing energy costs and environmental impact related especially to gas houses emissions. Regarding air conditioning consumption especially for Errachidia city, although the difference between the two materials is minimal, with 3032.99 kWh/year for the local material and 3004.73 kWh/year for the base material. It is worth noting that the local material could offer additional benefits beyond energy consumption alone (Table 11). By way of illustration, it could contribute to better thermal regulation of buildings, thereby promoting more comfortable indoor conditions for occupants throughout the year. This potential improvement in thermal comfort is a crucial aspect to consider, as it can have a significant impact on occupant satisfaction and overall well-being. More stable and pleasant indoor temperatures can not only enhance comfort but also increase productivity and reduce climate-related complaints. Looking ahead, widespread adoption of the high-performing local material could have significant implications for Errachidia City and beyond. In addition to energy savings and comfort benefits, this could also contribute to the creation of more sustainable and resilient buildings, capable of addressing the challenges of climate change and promoting a better quality of life for residents.

In conclusion, the simulation results highlight the significant advantages of the high-performing local material in terms of energy efficiency, occupant comfort, and building durability. These findings underscore the importance of considering innovative and locally adapted solutions to address the growing challenges of urbanization and climate change. Additionally, it should be noted that the advantage of this coating is that, without changing its thickness when filling the material, the aesthetics remain generally similar, and its impact is significant even with a minimal thickness. Also, the reduction in thermal transfers achieved by the multi-layered pozzolanic material significantly impacts overall energy consumption and thermal comfort in buildings. By lowering thermal conductivity, the material minimizes heat loss in winter and heat gain in summer, leading to more stable indoor temperatures and reducing the demand on heating and cooling systems. TRNSYS18 simulations estimate potential annual energy savings of up to 25% for heating in Azilal and around 5% for cooling in Errachidia, showcasing its effectiveness in diverse climates. This translates into lower utility bills and a reduced carbon footprint. Furthermore, improved insulation properties ensure more consistent indoor temperatures, reducing drafts and overheating, which enhances occupant comfort and well-being by providing a more pleasant and stable living environment.

4. Conclusions

This study evaluated the thermal properties and energy consumption impacts of various construction materials, comparing a reference material (ordinary mortar) and a multilayer material (two layers of mortar with an intermediate layer of pozzolane and lime) used in buildings (TRNSYS simulation) located in two Moroccan cities with distinct climates: Azilal (cold region) and Errachidia (hot region).

The experimental analysis of thermal properties revealed significant improvements in the performance of the multilayer material compared to the reference mortar. The multilayer material showed a 23% reduction in density (1450 kg/m^3), a 46% improvement in thermal conductivity (0.4 W/m·K), a 17% gain in thermal effusivity (604 J/m^2·K·s$^{1/2}$), a 41% improvement in thermal diffusivity (2.23 $\times$ 10^{-7} m^2/s), and a 40% increase in specific heat capacity (1237 J/kg·K). These enhancements underscore the superior insulating properties of the multilayer material, making it a more efficient option for thermal management in construction. The intermediate layer (Pozzolane-lime), with a thermal conductivity of 0.28 W/m·K and a specific heat capacity of 1252 J/kg·K, also supports the effectiveness of advanced materials for improved energy efficiency.

In terms of energy consumption, the study demonstrated significant differences between buildings constructed with ordinary mortar and those using multilayer mortar. In Azilal, the use of multilayer mortar reduced total annual energy consumption by 25%, from 14,723.81 kWh for ordinary mortar to 11,058.96 kWh. Heating needs decreased by 25%, and cooling needs dropped by 23%, highlighting the superior efficiency of the pozzolanic material in cold climates. In Errachidia, the pozzolanic mortar also showed benefits, with a 4% reduction in total energy consumption (from 14,869.45 kWh to 14,252.13 kWh), a 5% reduction in heating needs, and a 1% reduction in cooling needs. These results indicate that the multilayer material can offer energy efficiency benefits even in hot climates, though to a lesser extent.

The new multi-layered pozzolanic material outperforms existing mortars due to several key factors. Its higher porosity reduces thermal conductivity by increasing air pockets that act as insulation barriers. Additionally, the pozzolana-limestone composite in the inner layer enhances thermal performance through its mineral properties, as pozzolan reacts with lime to form a more stable insulating compound. The layered structure of the material combines the structural integrity of ordinary mortar with the insulating benefits of pozzolana-limestone, optimizing thermal resistivity. Improvements in thermal effusivity and diffusivity are achieved as the material absorbs and releases heat more slowly and distributes heat more uniformly. Overall, the material's superior performance is due to its optimized composition, including high porosity, the unique properties of the pozzolana-limestone composite, and the effective multi-layer design.

In conclusion, this comprehensive analysis demonstrates that the choice of construction materials, such as multilayer materials, can significantly impact the thermal performance and energy consumption of buildings. The use of multilayer materials offers substantial thermal performance advantages, including lower thermal conductivity, higher specific heat capacity, and improved thermal diffusivity and effusivity. Similarly, pozzolanic mortar can lead to notable energy savings, particularly in colder climates. Promoting the use of these advanced materials in construction can contribute to improved energy efficiency, reduced heating and cooling needs, and a lower carbon footprint, addressing current energy and environmental challenges. From our perspective, the study of the effect of layer thicknesses and the mechanical behavior of the samples will be the objectives of our forthcoming articles.

Author Contributions: Conceptualization, K.A., S.B., F.Z.E.W., K.I., M.C. and Y.E.M.; methodology, K.A., F.Z.E.W., M.C. and Y.E.M.; software, K.A. and K.I.; validation, K.A., M.C. and Y.E.M.; formal analysis, K.A., S.B., F.Z.E.W., K.I., M.C. and Y.E.M.; investigation, K.A., S.B., F.Z.E.W., K.I. and Y.E.M.; resources, K.A., S.B., F.Z.E.W., K.I., M.C., C.F., J.C., R.M. and Y.E.M.; data curation, K.A., S.B., F.Z.E.W., K.I., M.C., C.F., J.C., R.M. and Y.E.M.; writing—original draft preparation, K.A., S.B., F.Z.E.W., K.I., M.C., C.F., J.C., R.M. and Y.E.M.; writing—review and editing, K.A., S.B., F.Z.E.W., K.I., M.C., C.F., J.C., R.M. and Y.E.M.; visualization, K.A., S.B., F.Z.E.W., K.I., M.C., C.F., J.C., R.M. and Y.E.M.; supervision, M.C. and Y.E.M.; funding acquisition, C.F., R.M. and Y.E.M. All authors have read and agreed to the published version of the manuscript.

Funding: The results presented in this article were obtained in the framework of the Chair IdB.

Data Availability Statement: The experimental and computational data presented in this paper are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Mariane, T.; Antonio, C.; Neto, F.; Wurtz, F.; Delinchant, B. The Evolution of Knowledge and Trends within the Building Energy Efficiency Field of Knowledge. *Energies* **2022**, *15*, 691. [CrossRef]
2. Kim, K.G.; Choi, H.S. *Market Mechanisms in the Building Sector from an Urban Perspective: Creative Building Solutions*; Springer: Berlin/Heidelberg, Germany, 2022. [CrossRef]
3. Reindl, K.; Palm, J. Energy Efficiency in the Building Sector: A Combined Middle-Out and Practice Theory Approach. *Int. J. Sustain. Energy Plan. Manag.* **2020**, *28*, 3426. [CrossRef]
4. Aste, N.; Del Pero, C.; Leonforte, F. Toward Building Sector Energy Transition. In *Handbook of Energy Transitions*, 1st ed.; Taylor & Francis: Oxford, UK, 2022; pp. 127–150. [CrossRef]
5. Asif, M. Buildings for Sustainable Energy Future. In *Handbook of Energy and Environmental Security*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 171–181. [CrossRef]
6. Kasseh, Y.; Touzani, A.; EL Majaty, S. Exemplarity of the State for the Energy Efficiency of Buildings Institutional—Case of Morocco. *Nat. Environ. Pollut. Technol.* **2023**, *22*, 169–177. [CrossRef]
7. El Alaoui, H.; Bazzi, A.; El Hafdaoui, H.; Khallaayoun, A.; Lghoul, R. Sustainable Railways for Morocco: A Comprehensive Energy and Environmental Assessment. *J. Umm Al-Qura Univ. Eng. Archit.* **2023**, *14*, 271–283. [CrossRef]
8. Aditya, L.; Mahlia, T.M.I.; Rismanchi, B.; Ng, H.M.; Hasan, M.H.; Metselaar, H.S.C.; Muraza, O.; Aditiya, H.B. A Review on Insulation Materials for Energy Conservation in Buildings. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1352–1365. [CrossRef]
9. Abu-Jdayil, B.; Mourad, A.-H.; Hittini, W.; Hassan, M.; Hameedi, S. Traditional, State-of-the-Art and Renewable Thermal Building Insulation Materials: An Overview. *Constr. Build. Mater.* **2019**, *214*, 709–735. [CrossRef]
10. Väisänen, T.; Haapala, A.; Lappalainen, R.; Tomppo, L. Utilization of Agricultural and Forest Industry Waste and Residues in Natural Fiber-Polymer Composites: A Review. *Waste Manag.* **2016**, *54*, 62–73. [CrossRef] [PubMed]
11. Dubois, M.-C.; Blomsterberg, Å. Energy Saving Potential and Strategies for Electric Lighting in Future North European Low Energy Office Buildings: A Literature Review. *Energy Build.* **2011**, *43*, 2572–2582. [CrossRef]
12. Fang, Z.; Li, N.; Li, B.; Luo, G.; Huang, Y. The Effect of Building Envelope Insulation on Cooling Energy Consumption in Summer. *Energy Build.* **2014**, *77*, 197–205. [CrossRef]
13. Mirrahimi, S.; Mohamed, M.F.; Haw, L.C.; Ibrahim, N.L.N.; Yusoff, W.F.M.; Aflaki, A. The Effect of Building Envelope on the Thermal Comfort and Energy Saving for High-Rise Buildings in Hot–Humid Climate. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1508–1519. [CrossRef]
14. Pérez-Lombard, L.; Ortiz, J.; Pout, C. A Review on Buildings Energy Consumption Information. *Energy Build.* **2008**, *40*, 394–398. [CrossRef]
15. Sutcu, M.; Akkurt, S. The Use of Recycled Paper Processing Residues in Making Porous Brick with Reduced Thermal Conductivity. *Ceram. Int.* **2009**, *35*, 2625–2631. [CrossRef]
16. Annaba, K.; Elourdi, F.Z.; Ibaaz, K.; Bouyahyaoui, A.; Cherkaoui, M.; Ouaki, B.; Oubanmouh, S. Thermomechanical Characterization and Thermal Simulation of a New Multilayer Mortar and a Light-Weight Pozzolanic Concrete for Building Energy Efficiency. *Constr. Build. Mater.* **2022**, *346*, 128479. [CrossRef]
17. Abu-Jdayil, B.; Al-Malah, K. Jordanian Clay-Based Heat Insulator Composites: Mechanical Properties. *J. Reinf. Plast. Compos.* **2008**, *27*, 1559–1568. [CrossRef]
18. Abdel-illah, A.; Seyed Soheil, M.A.; Mohsen, S.P.; Jamal-Eddine, S.; Abdelkarim, D. An Investigation towards Optimizing the Construction Materials and Configurations of Buildings for Improving Energy Efficiency and Consumption in Morocco. *Buildings* **2023**, *13*, 1705. [CrossRef]
19. Cherki, A.B.; Khabbazi, A.; Mounir, S.; Maaloufa, Y. Thermal Properties of a New Ecological Building Material: Granular Cork Embedded in White Cement. *Int. Congr. Mater. Struct. Stab.* **2014**, *11*, 01017. [CrossRef]
20. El Kafazi, I.; Bannari, R.; Boubii, C.; Elbhiri, B. Energy Efficiency for Laboratory Building: A Case Study. In Proceedings of the 2022 4th Global Power, Energy and Communication Conference (GPECOM), Nevsehir, Turkey, 14–17 June 2022. [CrossRef]
21. Juimo Tchamdjou, W.; Cherradia, T.; Abidi, L.; Pereira-de-Oliveira, L. Mechanical Properties of Lightweight Aggregates Concrete Made with Cameroonian Volcanic Scoria: Destructive and Non-Destructive Characterization. *J. Build. Eng.* **2018**, *16*, 134–145. [CrossRef]
22. Mouli, M.; Khelafi, H. Performance Characteristics of Lightweight Aggregate Concrete Containing Natural Pozzolan. *Build. Environ.* **2008**, *43*, 31–36. [CrossRef]
23. Salazar, R.A.R.; de Gutiérrez, R.M. Natural Volcanic Pozzolans as an Available Raw Material for Alkali-Activated Materials in the Foreseeable Future: A Review. *Constr. Build. Mater.* **2018**, *189*, 109–118. [CrossRef]
24. Hossain, M.M.; Karim, M.R.; Hossain, M.K.; Islam, M.N.; Zain, M.F.M. Durability of Mortar and Concrete Containing Alkali-Activated Binder with Pozzolans: A Review. *Constr. Build. Mater.* **2013**, *93*, 95–109. [CrossRef]
25. Lemougna, P.N.; Wang, K.; Tang, Q.; Nzeukou, A.N.; Billong, N.; Chinje Melo, U.; Cui, X.-M. Review on the Use of Volcanic Ashes for Engineering Applications. *Resour. Conserv. Recycl.* **2018**, *137*, 177–190. [CrossRef]
26. Yin, K.; Ahamed, A.; Lisak, G. Environmental Perspectives of Recycling Various Combustion Ashes in Cement Production—A Review. *Waste Manag.* **2018**, *80*, 401–416. [CrossRef] [PubMed]
27. Celik, K.; Jackson, M.D.; Mancio, M.; Meral, C.; Emwas, A.-H.; Mehta, P.K.; Monteiro, P.J.M. High-Volume Natural Volcanic Pozzolan and Limestone Powder as Partial Replacements for Portland Cement. *Cem. Concr. Compos.* **2013**, *45*, 136–147. [CrossRef]

28. Hamadache, M.; Mouli, M.; Bouhamou, N.; Benosman, A.S.; Dif, F.; Chaib, O. The Thermal Properties of Natural Pozzolan-Based Cement Mortar. *Energy Procedia* **2017**, *139*, 201–207.
29. Meddah, M.S.; Benkari, N.; Al-Saadi, S.N.; Al Maktoumi, Y. Sarooj Mortar: From a Traditional Building Material to an Engineered Pozzolan—Mechanical and Thermal Properties Study. *J. Build. Eng.* **2020**, *32*, 101754. [CrossRef]
30. Al-Rbaihat, R.; Eayal Awwad, K.Y. Thermal and Mechanical Characteristics of Pozzolana Concrete. *IOSR J. Mech. Civ. Eng.* **2021**, *18*, 28–35. [CrossRef]
31. Bariş, K.E.; Tanaçan, L. Performance of Natural Pozzolan-Based Geopolymer Reinforced with Banana Fibers. *J. Green Build.* **2024**, *19*, 51–76. [CrossRef]
32. Hamadache, M.; Mouli, M.; Bouhamou, N.; Benosman, A.S.; Dif, F.; Chaib, O.; Berrabah, H.M. Use of Pozzolanic Mortars for the Thermal Comfort of Buildings. *J. Adv. Res. Mater. Sci.* **2017**, *34*, 1–7.
33. Alraddadi, S. The Impact of Thermal Treatment on the Mechanical Properties and Thermal Insulation of Building Materials Enhanced with Two Types of Volcanic Scoria Additives. *Heliyon* **2023**, *9*, e20814. [CrossRef]
34. Kaplan, M.M. Performance Assessment of Lime-Pozzolan Mortars with Straw Aggregate for Sound and Thermal Insulation Purposes. Master's Thesis, Building Science in Architecture, Middle East Technical University, Ankara, Turkey, 2019.
35. Abdellatef, Y.; Khan, M.A.; Khan, A.; Alam, M.I.; Kavgic, M. Mechanical, Thermal, and Moisture Buffering Properties of Novel Insulating Hemp-Lime Composite Building Materials. *Materials* **2020**, *13*, 5000. [CrossRef]
36. Doughmi, K.; Baba, K. Eco-Friendly Isolant Composite Mortars Based on Natural Pozzolan, Fly Ash, and Plastic Fibers. In Proceedings of the International Conference on Innovation in Modern Applied Science, Environment, Energy and Earth Studies (ICIES'11 2023), E3S Web Conf., Rabat, Morocco, 27–28 August 2023; Volume 412. [CrossRef]
37. *ASTM C618-15*; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2015.
38. El Wardi, F.Z.; Cherki, A.; Mounir, S.; Khabbazi, A.; Maaloufa, Y. Thermal Characterization of a New Multilayer Building Material Based on Clay, Cork, and Cement Mortar. *Energy Procedia* **2019**, *157*, 480–491. [CrossRef]
39. Cherki, A.; Remy, B.; Khabbazi, A.; Jannot, Y.; Baillis, D. Experimental Thermal Properties Characterization of Insulating Cork–Gypsum Composite. *Constr. Build. Mater.* **2014**, *54*, 202–209. [CrossRef]
40. Jannot, Y.; Felix, V.; Degiovanni, A. A Centered Hot Plate Method for Measurement of Thermal Properties of Thin Insulating Materials. *Meas. Sci. Technol.* **2010**, *21*, 035106. [CrossRef]
41. El Wardi, F.Z.; Khabbazi, A.; Bencheikh, C.; Ennaceri, H.; Khaldoun, A. Insulation Material for a Model House in Zaouiat Sidi Abdessalam. In Proceedings of the 2017 International Renewable and Sustainable Energy Conference (IRSEC), Tangier, Morocco, 4–7 December 2017; pp. 1–6. [CrossRef]
42. Jannot, Y.; Cherki, A.-B.; Khabbazi, A.; Remy, B.; Baillis, D. Granular Cork Content Dependence of Thermal Diffusivity, Thermal Conductivity and Heat Capacity of the Composite Material/Granular Cork Bound with Plaster. *Energy Procedia* **2013**, *42*, 83–92. [CrossRef]
43. Mounir, S.; Maaloufa, Y.; Cherki, A.B.; Khabbazi, A. Thermal Properties of the Composite Material Clay/Granular Cork. *Constr. Build. Mater.* **2014**, *70*, 183–190. [CrossRef]
44. Jannot, Y. *Théorie et Pratique de la Métrologie Thermique*; LEMTA: Sumeru City, Sumeru, 2011; Volume 26, p. 29.
45. Degiovanni, A.; Batsale, J.C.; Maillet, D. Mesure de la Diffusivité Longitudinale de Matériaux Anisotropes. *Rev. Générale Therm.* **1996**, *35*, 141–147. [CrossRef]
46. Mesure Automatique de la Diffusivité Thermique—Archive Ouverte HAL. Available online: https://hal.archives-ouvertes.fr/jpa-00244681/ (accessed on 13 April 2022).
47. Bae, Y.; Yoon, Y.; Malhotra, M.; Jung, S.; Im, P. Prototype College Building Energy Model: Building Characteristics and Energy Simulation Results. In *Technical Report: Prototype College Building Energy Model: Building Characteristics and Energy Simulation Results*; OSTI: Colorado Springs, CO, USA, 2022. [CrossRef]
48. Oumar, A.A.; Soultan, M.; Ali, A.; Togdjim, J.; Saleh, M.S.A. Physico-Chemical and Mechanical Characterization of Local Building Materials in Chad. *Int. J. Adv. Res.* **2023**, *11*, 744–754. [CrossRef]
49. Annaba, K.; El Mendili, Y.; Stout, H.; Ech-chebab, A.; Ouaki, B.; Cherkaoui, M.; Florence, C. Mechanical, Electrochemical (EIS), and Microstructural Characterization of Reinforced Concrete Incorporating Natural Volcanic Pozzolan. *Case Stud. Constr. Mater.* **2023**, *19*, e02620. [CrossRef]
50. Mahomed, M.A.; Moundi, A.; Dawai, D.; Ntieche, B.; Ganou, B.M.; Koungang, G.; Michel, F. Effect of the Use of Volcanic Pozzolan from Mbepit Massif (West-Cameroon) on the Mechanical Properties of Mortar and Composite Cements Production. *Eng. Res. Express* **2021**, *3*, 015034. [CrossRef]
51. El Wardi, F.Z.; Ladouy, S.; Khabbazi, A.; Ibaaz, K.; Khaldoun, A. Unfired Clay-Cork Granules Bricks Reinforced with Natural Stabilizers: Thermomechanical Characteristics Assessment. *Civ. Eng. J.* **2021**, *7*, 2068–2082. [CrossRef]
52. El Wardi, F.Z.; Mounir, S.; Atbir, A.; Khabbazi, A.; Ibaaz, K. Effect of Artificial Porosity on the Thermal Behavior and the Lightness of an Eco-Friendly Building Material Based on Clay and Granular Cork. *AIP Conf. Proc.* **2021**, *2345*, 020008. [CrossRef]
53. Maaloufa, Y.; Mounir, S.; Khabbazi, A.; Kettar, J.; Khaldoun, A. Thermal Characterization of Materials Based on Clay and Granular: Cork or Perlite. *Energy Procedia* **2015**, *74*, 1150–1161. [CrossRef]
54. El Wardi, F.Z.; Khabbazi, A.; Cherki, A.-B.; Khaldoun, A. Thermomechanical Study of a Sandwich Material with Ecological Additives. *Constr. Build. Mater.* **2020**, *252*, 119093. [CrossRef]

55. Lamrani, M.; Laaroussi, N.; Khabbazi, A.; Khalfaoui, M.; Garoum, M. Experimental Study of Thermal Properties of a New Ecological Building Material Based on Peanut Shells and Plaster. *Case Stud. Constr. Mater.* **2017**, *7*, 294–304. [CrossRef]
56. Atbir, A.; Khabbazi, A.; Cherkaoui, M.; Ibaaz, K.; El Wardi, F.Z.; Chebli, S. Improvement of Thermomechanical Properties of Porous Plaster Reinforced with a Network of Morocco Sheep Wool Skeletons for Energy Efficiency. *Build. Environ.* **2023**, *234*, 110171. [CrossRef]
57. Atbir, A.; El Wardi, F.Z.; Khabbazi, A.; Cherkaoui, M. Thermophysical Study of a Multi-Layer Brick of Grids Made of Sheep's Wool Yarn and Clay. *AIP Conf. Proc.* **2019**, *2123*, 30002. [CrossRef]