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Biosourced Materials for Thermal Insulation in Housing: The Case of Rice Straw and Reed Mat

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Abstract

This study investigates the application of innovative ecological solutions involving bio-sourced materials, specifically rice straw and reed mat, for the thermal insulation of buildings. The objective is to optimize energy requirements and reduce ambient temperature loss within residential structures. To this end, an experimental cell constructed from fired clay bricks, measuring 1.60 m × 1.50 m × 1.55 m, was developed to showcase the performance of these materials. Focusing on a vertical wall and the roof insulated with rice straw and reed mat, results for the vertical wall—composed of fired clay brick, reed, rice straw, reed, and finished with a clay plaster, demonstrate that the surface heat transfer coefficient (U-value) is 0.24 W/m^{2}K, meeting the recommended limit. This configuration exhibits the thermal characteristics of an effective insulator. Consequently, there is no water condensation within the wall, and the moisture content is conducive to human comfort, with anticipated improvements in overall summer comfort. The findings indicate that this wall possesses high thermal resistance and minimizes heat transfer from the exterior to the interior. For the roof, two scenarios were analyzed: one without insulation and one with insulation. The U-value of the uninsulated roof is 1.6 W/m^{2}K, which exceeds the recommended threshold of 0.24 W/m^{2}K; however, after insulation, the U-value decreases to 0.24 W/m^{2}K. Based on these results, it can be concluded that a sheet metal roof insulated with rice straw effectively serves as a thermal insulator.

Keywords

Bio-Based Materials, Rice Straw, Reed Mat, Insulation, Thermal Properties

1. Introduction

In the 21st century, the issue of sustainable development has become increasingly prominent, prompting reflection and behavioral change across all sectors. Achieving sustainable development necessitates the formulation of economic growth strategies that simultaneously incorporate parameters aimed at environmental preservation. Within the construction sector—recognized as the second largest emitter of CO_2 after industry, significant efforts are required to reduce energy consumption. This can be achieved by selecting materials whose manufacturing processes demand minimal embodied energy. Furthermore, it is essential to integrate specific technical solutions into the design of buildings with high thermal inertia, thereby reducing reliance on mechanical air conditioning systems. Such systems emit fluorinated gases, which can have a greenhouse effect up to 23,000 times greater than that of CO_2 [1]. The United Nations Intergovernmental Panel on Climate Change (IPCC) confirmed in 2007 that human activities are exerting an increasingly destabilizing influence on the climate system [2]. As the primary contributors to this phenomenon, we also possess the means to address it. To mitigate the consequences of climate change, global greenhouse gas emissions must be reduced by half by 2050 [2]. Reports indicate that the building sector accounts for approximately 40% of global greenhouse gas emissions, reaching 37% in 2021 [3]. The prevailing trend is thus toward constructing buildings that are both environmentally friendly and healthy. In this context, substantial research is being conducted on bio-based materials for building thermal insulation. Notable examples include the use of banana leaf fibers, which demonstrated highly favorable thermal conductivity in the doctoral research of A. J Nelson [4]. Similarly, E. Antezak *et al.* investigated the hygrothermal behavior of flax shive straw used as loose-fill insulation in attics, spread horizontally at a thickness of 25 to 30 cm, with positive outcomes [5]. T. Vinceslas *et al.* explored mixtures of hemp and raw earth for construction applications, aiming to enhance thermal conductivity [6]. Research by H. Kaddouri *et al.* focused on improving thermal comfort and energy efficiency in residential buildings by incorporating three types of bio-based materials—hemp wool, wood fiber, and expanded cork—into wall assemblies. Their findings revealed that insulating a roof with 8 cm of hemp wool can yield energy savings of nearly 37% for both cooling and heating [7]. According to studies cited in references [8]-[12], analysis of the dynamic thermal behavior of building components is closely linked to energy consumption for heating and cooling, with the objective of maintaining a constant indoor temperature in buildings located in temperate climates.

Rabemanantsoa *et al.* (2021) investigated the dynamic thermal behavior of building components in residential structures, with particular emphasis on the thermal comfort provided by earth-based walls [13]. Their study employed two approaches: the international standard ISO 13786 and *in situ* measurements conducted on prototype cells. The findings demonstrated that wall thickness significantly influences both the damping factor and the time lag associated with the propagation of daily temperature fluctuations. In a related study, Adagbe (2021) utilized earth reinforced with rice straw stems as the primary material for load-bearing elements in buildings constructed with rônier reinforcement [14].

According to the World Bank in 2018, less than 20% of households in Chad have access to electricity [15]. Given these unfavorable indicators, improving living conditions in residential environments and reducing the health and productivity risks associated with thermal discomfort in buildings require adaptive strategies. This, in turn, demands a comprehensive understanding of the energy performance of building envelopes and their constituent components. Achieving this objective necessitates the adoption of ecological materials and the use of analytical tools to facilitate a thorough evaluation and comprehension of building behavior, with the aim of enhancing energy performance both during the design phase and throughout the building's operational life.

The research presented in this article is situated within the context of adherence to the principles of Sustainable Development. The primary objectives of this work are, first, to deepen the understanding of the thermal behavior of ecological materials through both experimental investigations and computational analyses, and second, to examine passive solutions that can prevent temperature increases in indoor environments, thereby reducing periods of thermal discomfort. This research has led to the selection of a prototype cell or experimental building suitable for conducting experimental studies. Subsequently, a range of bio-based materials were identified, some serving as primary insulators and others as supplementary insulators. The results obtained provide a basis for subsequent analysis and discussion.

2. Materials and Methods

To conduct these experimental tests, our initial step involved the conceptualization and fabrication of the experimental samples. Drawing upon insights from previous studies reported in the literature, we designed a prototype of an experimental cell measuring 1.60 m by 1.50 m with a height of 1.55 m, featuring a sheet metal roof. For the purposes of this investigation, four types of samples were examined: two vertical wall panels (one serving as an uninsulated control and the other as an insulated variant), and two roof configurations (one uninsulated and the other insulated with selected insulating materials).

2.1. Identification of Construction and Insulation Materials

The materials selected for the construction of our experimental samples include fired clay bricks (dimensions: 25 cm × 15 cm × 7 cm), raw earth (clay) mortar, and a plaster composed of clay mixed with sand.

For insulation purposes, reed mat and rice straw were chosen. The specific configurations of these materials define the different samples as follows:

Sample 1: wall constructed with fired clay brick and finished with a cement mortar coating (serving as the control);

Sample 2: wall constructed with fired clay brick, incorporating a reed mat, rice straw, another reed mat, and finished with a clay coating;

Sample 3: uninsulated sheet metal used at the roof level;

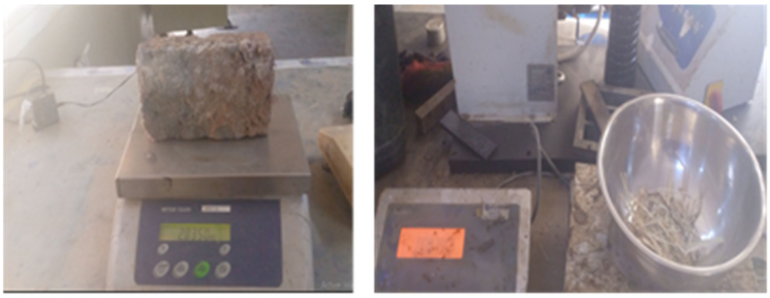
Sample 4: sheet metal at the roof level, with rice straw and reed mat as insulation layers.

2.2. Determination of Material Densities

The densities of the different materials were measured in the laboratory of the National Advanced School of Public Works (ENSTP) in N'Djamena, Chad, following the NFP18-554 standard. The main equipment employed included a 500 ml graduated burette, an electronic balance, and a tare. The process for determining the volumes and masses of the materials under investigation involved several sequential steps.

2.2.1. Weighing Measurements

Figure 1(a), **Figure 1(b)** display images illustrating the mass measurements of samples taken from a fired clay brick and rice straws.



(a) (b)

Figure 1. Weighing procedure for fired clay brick and rice straw samples.

2.2.2. Volumetric Measurements

Volumetric measurements were conducted on the materials under investigation, namely rice straw, reed, and fired clay brick. The procedure began with the use of a graduated cylinder filled with 300 ml of water. Subsequently, pre-weighed samples of each material were sequentially introduced into the cylinder for measurement. The actual volumes of the materials were determined based on the observed changes in water level. The complete set of these experiments is illustrated in **Figure 2**. It is important to note that measurements should be taken immediately after immersion to minimize water adsorption by the materials.

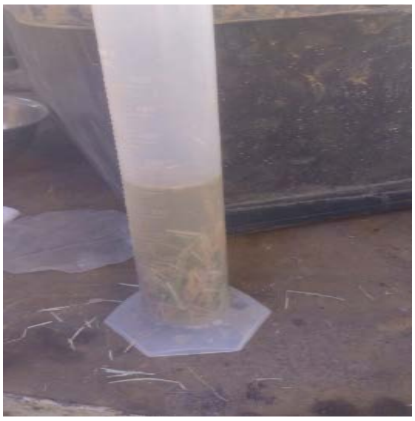


Figure 2. Immersion of rice straw material.

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The total volume, V_{total}, as given by Equation (1), represents the sum of the initial water volume and the volume of the immersed material, $V_{material}$, which is to be measured.

$$V_{total} = V_{initial,water} + V_{material} \quad (1)$$

The volume of the unknown material, V_m, is calculated by subtracting the initial water volume, $V_{iniatial}$, from the total measured volume.

$$V_{material} = V_{total} - V_{initial,water} \quad (2)$$

The density of a solid substance is determined by the ratio of its mass to its volume. The mass was measured in the initial step using a balance. The volume of the material can be obtained using Equations (1) and (2). Once the volume is known, the density of the solid is calculated as the ratio of its measured mass to its volume.

$$\rho = M_{mass\ of\ the\ material} / V_{volume\ of\ the\ material} \quad (3)$$

ρ : denotes the apparent density of the material (Kg/m^3).

$M_{mass\ of\ the\ material}$: denotes the mass of the solid (Kg).

$V_{volume\ of\ the\ material}$: denotes the volume of the solide (m^3).

2.3. Construction Details of the Experimental Prototype

Experimental tests were performed on a test cell constructed from fired clay bricks and topped with a sheet metal roof (see Figure 3). Among the four vertical walls and the horizontal roof of the cell, two vertical walls and one section of the sheet metal roof were selected as representative samples, with and without insulation, as follows:

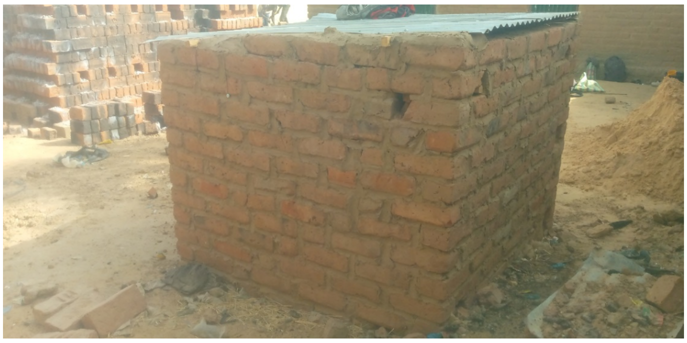


Figure 3. Experimental cell constructed as part of our study.

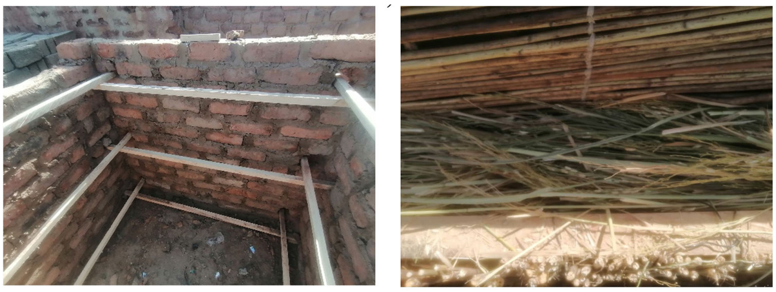
Sample 1: Fired clay brick wall finished with cement mortar plaster (reference sample);

Sample 2: Fired clay brick wall layered with reed mat, rice straw, another reed mat, and finished with clay plaster;

Sample 3: Uninsulated sheet metal roof;

Sample 4: Roof assembly comprising reed mat, rice straw, and sheet metal.

To provide space for the installation of insulation materials, chevron-shaped templates were fabricated and positioned 14.5 cm from the cell's interior surface along the three walls, enabling the secure placement of reed mats (see Figure 4(a)). These templates serve to regulate the total thickness of the insulation layer, which includes both the insulating material and the plaster finish. The use of these templates significantly streamlines the process for subsequent construction stages. Figure 4(b) illustrates the insulation configuration for sample 2.



(a) (b)

Figure 4. (a) Cladding for insulation; (b) Rice straw placed between reed mats (sample 2).

In addition to the use of templates, several supplementary techniques were employed to ensure the planar alignment of the wall surfaces. Specifically, wall-leveling strings were utilized to monitor and maintain the flatness of the template throughout its installation process. The lower-level templates were installed at a minimum height of 15 cm above the finished floor surface (Figure 4(a)). Battens or shims were attached to the joists at intervals of 80 cm to guarantee consistent spacing between the templates and the wall surfaces, thereby also contributing to the overall stability of the insulation system (Figure 4(a)).

Figure 5(a) and Figure 5(b) illustrate, respectively, the interior wall surfaces of the cell after the application of plaster over the reed mats, and the positioning of rice straw between the reed mats, with one mat affixed to the wall and the other to the templates coated with clay plaster, as exemplified by sample 2.

(a) (b)

Figure 5. (a) walls coated with a raw clay plaster; (b) rice straw placed between two reed mat walls (sample 2).

Figure 6(a) and Figure 6(b) illustrate the roofing configurations. In Figure 6(a), reed mats are installed on the underside of the roof, functioning as a support layer for the rice straw, as shown in Figure 6(b). This configuration pertains to sample 4.

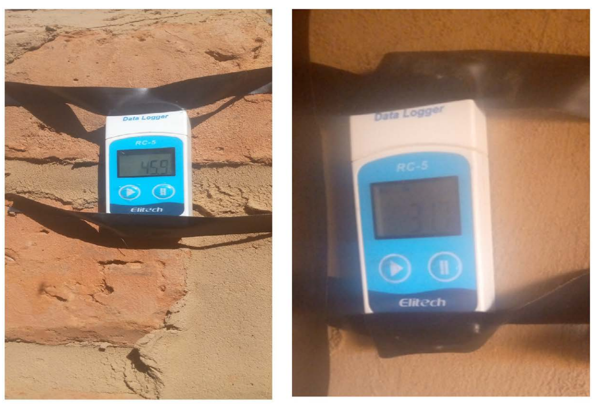
(a) (b)

Figure 6. Roof Insulation: (a) Installation of reed mats on the underside of the roof; (b) Distribution of rice straw (sample 4).

2.4. Measurement of Temperatures and Calculation of Thermal Phase Shift

2.4.1. Temperature Measurement

Temperature measurements were systematically conducted on both the interior and exterior surfaces of the four samples. In this study, the progression of thermal gradients was monitored by recording temperatures on each surface throughout a full day (see **Figure 7(a)**). The primary aim was to elucidate the mechanisms of heat transfer across each wall, regardless of whether it was thermally insulated. Such an approach enables the assessment of the thermal insulation properties of the walls. Additionally, long-term reliability and resistance to environmental factors are essential characteristics, particularly since these materials are protected from adverse weather conditions such as rainfall. It should be noted that exterior walls primarily serve as protective barriers, acting as the first line of defense to limit heat exchange between the interior and exterior environments of a room. Investigation of their thermal inertia thus necessitates monitoring the evolution of ambient air temperature in contact with the internal surface. Accordingly, changes in the internal temperature of the test cell were tracked using an Elitech rc-5 temperature data logger (refer to **Figure 7(a)**, **Figure 7(b)**). This device was installed on both the internal and external surfaces of the walls to record temperature variations for samples 1, 2, 3, and 4 examined in this study.



(a) (b)

Figure 7. (a) Exterior wall temperature; (b) Interior wall temperature of sample 2.

2.4.2. Calculation of Thermal Phase Shifts

This parameter is among the most significant in construction-oriented studies that seek to assess the thermal inertia of a wall. Accurate determination of the thermal phase shift is essential during the experimental stage. The resulting data will subsequently be compared to those stipulated in the 2012 Thermal Regulation. In general, the thermal phase shift corresponds to the time interval between the peak of an external thermal load and the moment when this peak equivalently affects the building's interior within a 24-hour period. This metric reflects the capacity of a material to delay heat transfer. Denoted as D, it is calculated using the following formula:

$$D = t_{T_{ext\_max}} - t_{T_{int\_max}} \left[h\right] \quad (4)$$

where

$$D = \frac{\sqrt{T}}{e \times \sqrt{\Pi}} \times e \times \sqrt{\frac{\rho C}{\lambda}} \quad (5)$$

Here, T represents 24 hours, equivalent to 24 × 3600 seconds; e denotes the thickness of the material, ρ is the density, and C is the specific heat capacity.

$$C_p = \frac{Q}{m\Delta T}; avec\ Q = \varphi \times \Delta t \quad (6)$$

In this context, Q denotes the amount of heat, m is the mass of the body in kilograms, and ΔT is the temperature difference in kelvin. φ represents the heat flux per unit area, and Δt is the duration over which the heat quantity is calculated, taken as one hour in this study.

2.5. Selection of the Thermal Conductivity Calculation Method

To determine the thermal conductivities of the materials investigated in this study, two empirical methods were selected: those proposed by Elangovan R. and Marie Viel [16]. The absence of suitable measurement equipment necessitated the adoption of these approaches. Specifically, the Marie Viel method is utilized for insulating materials with low bulk densities (<500 kg/m^3), and it yields results that are comparable to the λ conductivity values reported in other experimental studies.

Following the determination of the thermal conductivity for each material and the measurement of the exterior and interior temperatures of the walls—used as initial conditions, numerical simulations were performed to ascertain the temperatures at the inner surfaces and at the interfaces of each material layer composing the walls or samples.

3. Results, Analysis, and Discussion

This section presents a comprehensive analysis and discussion of all the results obtained, focusing on the densities, thermal conductivities, thermal resistances, heat capacities or coefficients, and the phase shifts of the materials studied. Ultimately, this allows for an assessment of the thermal performance of each sample based on the combination of materials used.

3.1. Temperature Measurements

Table 1 displays the results of the temperature evolution measurements conducted over a 24-hour period on both the internal and external surfaces of the samples.

Table 1. Temperatures recorded on the surfaces of samples 1, 2, 3, and 4 within the cell.

No.	Sample Description	Maximum Outdoor Temperature (˚C)	Maximum Indoor Temperature (˚C)	Percentage Reduction in Temperature (%)
1	Wall with cement plaster	45	42	6.66
2	Wall of terracotta brick, reed, rice straw, reed, and clay plaster	45	31.5	30
3	Uninsulated roof	54	51	5.55
4	Insulated roof (rice straw and reed)	56	37.9	32.32

3.2. Physical Characteristics

The density values for rice straw, reed mats, and fired clay bricks are presented in Table 2. Among these, fired clay brick exhibits the highest density. Generally, a higher density corresponds to lower insulation performance in materials.

Table 2. Physical characteristics of the materials.

	Rice Straw	Reed mats	Terracotta brick
Mass (g)	7.4	21.6	2.835
Initial water volume (ml)	300	300	2.2×10^{-3}
Final water volume (ml)	496	384	-
Volume variation (ml)	196	84	-
Density (kg/m^3)	38	257	1288.63

3.3. Thermal Properties

3.3.1. Thermal Conductivity

Table 3 presents the thermal conductivity values obtained for the various materials investigated in this study. For rice straw, the measured thermal conductivity is $\lambda = 0.041$ W/mK, which closely aligns with the value reported by Valin Colson in 2019 for bio-based fiber insulation panels and related techniques [17]. It is noteworthy that the value obtained in the present study is lower than that reported by Mariette T. ADAGBE in her 2021 dissertation, which focused on using earth reinforced with rice straw stems as a structural material for load-bearing elements in buildings reinforced with rônier [14]. However, the thermal conductivity values determined in this work differ significantly from those reported by DOUZANE *et al.*, 2016 [18], who demonstrated that the thermal conductivity of rice straw bales depends on their orientation relative to the direction of heat flow (parallel or perpendicular). Nevertheless, the conductivity measured in this study is close to the reference value of 0.04 W/mK established by the 2024 Thermal Regulation. It can therefore be concluded that rice straw exhibits good thermal insulation properties, with a conductivity nearly equal to the average value for insulating materials, which is 0.04 W/mK.

Table 3. Thermal properties of rice straw, reed mat, and fired clay brick.

	Rice Straw (14.5 cm)	Reed Mat (2 cm)	Fired Clay Brick (15 cm)	Recommended Value
Thermal Conductivity, λ (W/m·K)	0.041	0.071	0.51	≤0.06
Thermal Resistance, R (m^2·K/W)	3.53	0.281	0.294	≥2.9
Thermal Transmittance, U (W/(m^2·K))	0.28	3.55	3.40	≤0.24

For reed mat, the measured thermal conductivity is 0.071 W/mK (see Table 3), which exceeds both the regulatory threshold of 0.04 W/mK set by the 2024 Thermal Regulation and the value of 0.05 W/mK cited by architect J-M Pupile, DPLG [19]. This indicates that, while reed also functions as a thermal insulator—similar to rice straw—it serves more as a supplementary material in this study.

In contrast, fired clay brick exhibits a thermal conductivity of 0.51 W/mK, which is nearly nine times greater than the regulatory limit of 0.04 W/mK according to the 2024 Thermal Regulation. This high conductivity indicates that fired clay brick acts as a thermal bridge, allowing significant heat transfer.

3.3.2. Thermal Resistance

The ability of a material to withstand heat conduction is quantified by its thermal resistance. A higher thermal resistance value indicates superior insulating properties. As shown in Table 3, among the materials tested, rice straw exhibits the highest thermal resistance for the thicknesses considered. Specifically, with a thickness of 14.5 cm, rice straw achieves a thermal resistance of 3.53 m^2K/W, significantly exceeding the minimum recommended value of 2.9 m^2K/W for building insulation. Given that the straw layer will be combined with additional layers to form an insulating wall assembly, it can be regarded as possessing excellent thermal capacity. It is important to note that the thickness of the reed mat in this study is limited to 2 cm; increasing its thickness could further enhance its thermal performance. Thus, the reed mat can also be considered to have good resistance to heat conduction. In contrast, fired clay brick demonstrates a thermal resistance of only 0.294 m^2K/W, which is at least nine times lower than the minimum recommended threshold of 2.9 m^2K/W. Consequently, fired clay brick can be characterized as having a very low thermal resistance.

3.4. Simulation of Wall Samples

Sample 1 (control) and Sample 2 (insulated)

The simulations were conducted to determine several parameters, including thermal insulation, hygrometric conditions, and summer thermal comfort. The primary indicators for thermal comfort are the attenuation of thermal amplitude and the thermal phase shift.

Thermal resistance, temperature profiles, and thermal conductivities.

Table 4 summarizes the thermal properties, including thermal conductivity (λ), thermal resistance (R), and the minimum and maximum temperatures recorded across the various layers of Sample 1 (uninsulated control) and Sample 2 (insulated). Notably, significant temperature variations are observed. In Sample 1, temperatures range from 45˚C to 42.2˚C, with a thermal resistance of only 0.346 m^2K/W—substantially below the minimum recommended threshold of 2.9 m^2K/W. This finding confirms that the wall acts as a significant thermal bridge. In contrast, analysis of Sample 2 reveals that the thermal conductivity of the insulating materials ranges from 0.04 to 0.065 W/m·K, with the average remaining below the recommended limit of 0.06 W/m·K. Moreover, in Sample 2, the temperature difference between the exterior and interior spans from 45˚C to 31.5˚C, exceeding 10˚C. The equivalent thermal resistance of Sample 2 is 4.22 m^2K/W, which closely aligns with the 4 m^2K/W benchmark for Low Energy Consumption Building (BBC) walls as specified by the RT 2024 (Thermal Regulation 2024). These results indicate that Sample 2 provides a high level of thermal comfort.

Table 4. Values of resistances, thermal conductivities, and temperature changes. (a) sample 1 (temoin); (b) sample 2 (insulated).

(a)

#	Material	λ W/m·K	R m^2K/W	Temperature		Weight Kg/m^2
				min	max	
	surface thermal resistance*		0.130	39.7	42.2	
1	2 cm lime/cement rendering	1.000	0.020	42.2	42.5	36
2	15 cm full clay brick	0.960	0.156	42.5	44.5	300.0
	Surface thermal resistance*		0.040	44.5	45.0	
	17 cm total composition		0.346			336.0

(b)

#	Material	λ W/m·K	R m^2K/W	Temperature min	Temperature max	Weight Kg/m^2
	surface thermal resistance*		0.130	30.7	31.5	
1	3 cm clay rendering	0.800	0.038	31.5	31.6	51.0
2	1 cm reed	0.065	0.154	31.6	32.2	2.3
3	14.5 cm compressed straw	0.040	3.625	32.2	44.1	14.5
4	0.5 cm reed	0.065	0.077	44.1	44.4	1.1
5	15 cm full clay brick	0.960	0.156	44.4	44.9	300.0
	Surface thermal resistance*		0.040	44.9	45.0	
	34 cm total composition		4.220			368.9

*Thermal resistance according to DIN 6946 for U-value calculation. For moisture protection and temperature profile, Rsi = 0.25 and Rse = 0.04 were used in accordance with DIN 4108-3. (a) Interior surface temperature (min/med/max): 42.2˚C/42.2˚C/42.2˚C, Exterior surface temperature (min/med/max): 44.5˚C/44.5˚C/44.5˚C; (b) Interior surface temperature (min/med/max): 31.5˚C/31.5˚C/31.5˚C, Exterior surface temperature (min/med/max): 44.9˚C/44.9˚C/44.9˚C.

Transmittance Coefficient, Hygrometry, and Summer Comfort

The thermal insulation property, indicated by the U-value (expressed in W/(m^2·K)), also referred to as the surface transmission coefficient, is presented for samples 1 and 2. For sample 1 (the control), the U-value is 2.89 W/(m^2·K), which significantly exceeds the recommended threshold of 0.24 W/(m^2·K). A lower U-value signifies superior thermal performance of the wall. Therefore, the high U-value of 2.89 W/(m^2·K) for sample 1 demonstrates its poor insulating capability, as it allows heat to transfer from the exterior to the interior more rapidly. In contrast, the insulated sample 2 achieves a U-value of 0.24 W/(m^2·K), meeting the recommended standard and indicating effective thermal insulation. Regarding hygrometric performance, both samples 1 and 2 exhibit satisfactory results. However, thermal comfort is notably enhanced in sample 2 compared to sample 1.

Sample 3 (Uninsulated Roof) and Sample 4 (Insulated Roof)

Thermal Resistance, Conductivity, and Temperature Measurements

Table 5. Values of thermal resistances, conductivities, and temperature variations. (a) sample 3 (temoin: uninsulated roof); (b) Sample 4 (insulated roof).

#	Material	λ W/m·K	R m^2K/W	Temperature		Weight Kg/m^2
				min	max	
(a)						
1	8 cm air space (ventilated)				51,0	0,1
	surface thermal resistance*		0.170	51.0	51.8	
2	8 cm lumber	0.130	0.615	51.8	53.7	36.0
3	3 cm corrugated iron	0.750	0.040	53.7	53.9	15.0
	Surface thermal resistance*		0.040	53.9	54.0	
	19 cm total composition		0.865			54.4
(b)						
	surface thermal resistance*		0.170	36.3	37.9	
1	2 cm reed	0.065	0.308	37.3	40.0	4.5
2	0.02 cm polyethylene membrane	0.400	0.001	38.6	40.0	0.2
3	14 cm rice straw	0.040	3.500	38.6	52.9	12.6
	14 cm rafter (12%)	0.130	1.077	39.5	51.6	6.3
4	8 cm rice straw	0.040	2.000	52.9	55.4	0.0
	8 cm lumber (100%)	0.130	0.615	51.4	55.4	36.0
5	3 cm corrugated iron	0.300	0.100	55.2	55.8	15.0
	Surface thermal resistance*		0.040	55.8	56.0	
	27.02 cm total composition		4.192			74.6

*Thermal resistance according to DIN 6946 for U-value calculation. For moisture protection and temperature profile, Rsi = 0.25 and Rse = 0.04 were used in accordance with DIN 4108-3. (a) Interior surface temperature (min/med/max): 51.8˚C/51.8˚C/51.8˚C, Exterior surface temperature (min/med/max): 53.9˚C/53.9˚C/53.9˚C; (b) Interior surface temperature (min/med/max): 37.3˚C/37.5˚C/37.9˚C, Exterior surface temperature (min/med/max): 55.8˚C/55.8˚C/55.8˚C.

Table 5 provides the thermal conductivity values for samples 3 and 4, which are 0.750 W/m·K and 0.04 W/m·K, respectively. For reference, the recommended value according to RT 2012 (Thermal Regulation 2012) is 0.06 W/m·K. In terms of temperature variation, the measured temperature above the sheet metal under the rafter decreases from 54˚C (due to overheating) to 51˚C. The equivalent thermal resistances for samples 3 and 4 are 0.865 m^2K/W and 4.192 m^2K/W, respectively, with the regulatory limit for roofs set at 3.3 m^2K/W according to RT 2012. These results indicate that the sample demonstrates effective thermal insulation.

Transmittance Coefficient, Hygrometry, and Summer Comfort

The parameters relating to thermal insulation, hygrometry and summer thermal comfort characterising the uninsulated and insulated roofs corresponding to samples 3 and 4 respectively show that the thermal insulation value U of the uninsulated roof is 1.6 $W/(m^2K)$, higher than the recommended limit value of 0.24 $W/(m^2K)$. In sample 4, on the other hand, it is 0.24 $W/(m^2K)$. In view of this parameter, the sheet metal roof, insulated with rice straw and reed matting, acts as an insulator. The latter offers better thermal insulation and summer comfort than sample 3.

4. Conclusion and Perspectives

This study has highlighted the issue of heat flux generated by solar radiation throughout the day, which can impose significant thermal loads on the walls of residential buildings. As people often seek protection from intense ultraviolet radiation during the day and infrared radiation at night, comprehensive thermal insulation of buildings becomes essential. In this context, the research focused on the use of selected bio-based materials, such as rice straw and reed mats, with the aim of mitigating indoor heat gain. The approach involved integrating these bio-sourced materials either within wall assemblies or as components of insulated and non-insulated corrugated metal roofs.

The results demonstrate that, for the vertical walls of the test cell—specifically comparing samples 1 (non-insulated) and 2 (insulated), the application of thermal insulation in sample 2 significantly reduces heat transfer from the exterior to the interior. The thermal resistance improved from 2.9 to 0.24 $W/(m^2K)$, while the thermal phase shift increased from 5.5 hours to 14.3 hours, indicating superior thermal performance for the insulated configuration. Similarly, for the horizontal surfaces (roofs), samples 3 (non-insulated) and 4 (insulated) showed that insulation in sample 4 led to a marked reduction in heat transfer, with thermal resistance improving from 1.16 to 0.24 $W/(m^2K)$ and the phase shift increasing from 4.7 to 11.2 hours. Thus, the insulated samples consistently provided better thermal conditions.

Across all tested samples, satisfactory levels of hygrometry were maintained. These findings present promising prospects for civil engineering, particularly in the building sector. The adoption of bio-based materials as thermal insulators, aimed at enhancing indoor thermal comfort, is especially relevant for countries like Chad, where high temperatures prevail during certain periods of the year and energy availability remains a critical concern. During heatwaves, achieving thermal comfort in buildings is a considerable challenge. The techniques developed in this dissertation offer a foundation for further refinement and potential large-scale application.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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