Uncertainty analysis of the hygrothermal properties of rammed earth for application in thermal energy simulation

Análise da incerteza das propriedades higrotérmicas da taipa de pilão para uso na simulação termoenergética

Análisis de incertidumbre de las propiedades higrotérmicas de la tapia para uso en simulación termoenergética

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Authors contribution: Formal analysis; Data curation; Methodology; Software; Validation; Writing – original draft; Visualization: SILVA, M. T. C.; Conceptualization; Data curation; Supervision; Writing – revision and editing: MILANI, A. P. S.

Conflicts of interest: The authors certify that there are no conflicts of interest.

Ethical approval: The authors certify that there was no need for Ethics Committee approval.

AI: The authors certify that there was no use of artificial intelligence in the preparation of the work.

Editors: Daniel Sant'Ana (Editor-in-Chief); Vanda A. G. Zanoni (Associate Editor); Pedro G. Cardoso (Editorial Assistant).

Abstract

This study explores the use of rammed earth as a sustainable solution to promote thermal comfort. By parameterizing its hygrothermal properties established the significance of different computer simulations methods and the confidence intervals to assess its thermal energy performance. Simulations in the rammed earth building were conducted using the EnergyPlus and JePlus, applying the conduction transfer function (CTF) and effective moisture penetration depth (EMPD) models. ANOVA was used to analyze the sensitivity and uncertainty of the following variables: wall thickness, empirical hygrothermal properties, and building occupancy patterns. Results show that the CTF model maintains accuracy for simulations of rammed earth, particularly in tropical climates with wet summers and dry winters. Also, wall thickness and rammed earth conductivity, as well as the occupancy patterns significantly influence energy consumption. Confidence intervals for the rammed earth hygrothermal properties were: density (1780–2025 kg/m^3), thermal conductivity (0.85–0.93 W/m·K), specific heat (750–800 J/kg·K), and water vapor diffusion resistance factor (13–14).

Keywords: Earth construction; density; thermal conductivity; specific heat; water vapor diffusion factor.

Resumo

Considerando a taipa de pilão uma alternativa sustentável na promoção do conforto térmico, suas propriedades higrotérmicas foram parametrizadas para determinar a significância de diferentes métodos de simulações computacionais e os intervalos de confiança a serem aplicados na avaliação de desempenho termoenergético. Foi simulada uma edificação com paredes de taipa nos softwares EnergyPlus e JePlus por meio dos modelos conduction transfer function (CTF) e effective moisture penetration depth (EMPD). Estas simulações foram analisadas por ANOVA, sensibilidade e incerteza com as seguintes variáveis: espessura das paredes, propriedades higrotérmicas empíricas e rotina de uso da edificação. Os resultados demonstraram que o método CTF pode ser utilizado sem perdas significativas de precisão para as simulações termoenergéticas da taipa em clima tropical com verões úmidos e invernos secos. A espessura e a condutividade da taipa, junto a rotina de uso e ocupação mostraram influência significativa no consumo energético. Os intervalos de confiança para as propriedades higrotérmicas da taipa foram: 1780 a 2025 kg/m^3 para densidade; 0,85 a 0,93 W/m.K para condutividade térmica; 750 a 800 J/kg.K para calor específico; 13 a 14 para fator de resistência à difusão de vapor de água.

Palavras-Chave: Construção com terra; densidade; condutividade; calor específico; resistência à difusão de vapor de água.

Resumen

Considerando la tapia como una alternativa sustentable en promoción de confort térmico, sus propiedades higrotérmicas fueran parametrizó para determinar la importancia de diferentes métodos de simulación computacional y los intervalos de confianza en la evaluación del desempeño termoenergético. Un edificio con tapia se simuló en el software EnergyPlus y JePlus utilizando los modelos de función de transferencia de conducción (CTF) y profundidad de penetración de humedad efectiva (EMPD). Estas simulaciones se analizaron mediante ANOVA, sensibilidad e incertidumbre con las siguientes variables: espesor de pared, propiedades higrotérmicas empíricas y rutina de uso del edificio. Los resultados demostraron que el método CTF se puede utilizar sin pérdida significativa de precisión para los indicadores de las simulaciones termoenergéticas de tapia en un clima tropical con veranos húmedos e inviernos secos. El espesor y la conductividad de la tapia, junto con la rutina de uso y la ocupación, mostraron una influencia significativa en el consumo de energía. Los intervalos de confianza para las propiedades higrotérmicas de la tapia fueron: 1780 a 2025 kg/m^3 para densidad; 0,85 a 0,93 W/m.K para conductividad térmica; 750 a 800 J/kg.K para calor específico; 13 a 14 para factor de resistencia a la difusión del vapor de agua.

Palabras clave: Construcción con tierra; densidad; conductividad térmica; calor específico; factor de resistencia a la difusión del vapor de agua.

1   Introduction

Rammed earth is an ancient construction technique that has recently gained attention due to its aesthetic appeal, reversibility, and reduced carbon footprint throughout its life cycle (Ben-Alon *et al.*, 2021; Milani; Iunes, 2023). Developed countries are increasingly reviving earth-based construction methods, driven by commercial interest and the need to promote building decarbonization (Marsh; Kulshreshtha, 2022). Rammed earth is emerging as a culturally adaptive and sustainable solution in building design, offering an energy-efficient and accessible approach to quality housing (Harries; Sharma, 2020).

One of the most important features of earth construction is its capacity to regulate indoor thermal environments. According to Giuffrida, Caponetto and Nocera (2019), the rammed earth's thermal mass and porous structure allow moisture within the walls to evaporate during hot periods, absorbing latent heat and cooling the environment. Conversely, condensation releases stored latent heat during colder periods, contributing to heating the space.

Studies based on on-site measurements have confirmed that rammed earth can maintain adequate thermal comfort and indoor air quality, particularly in hot climates with mild winters (Fernandes *et al.*, 2019; Samadianfard; Toufigh, 2020; Giuffrida *et al.*, 2021; Jiang *et al.*, 2023). However, in regions with severe winters, rammed earth walls do not offer better thermal performance compared to conventional buildings unless they are sufficiently thick and include an insulating layer (Yu *et al.*, 2022b).

The thermal behavior of rammed earth is closely tied to the processes of moisture adsorption and desorption, which depend on factors such as temperature, water vapor pressure, and surface area. Li *et al.* (2023) and Losini *et al.* (2023b) highlight that rammed earth shows high adsorption capacity at low relative humidity, classifying it as a hygroscopic material that significantly contributes to creating buildings with better thermal performance.

One of the main challenges in studying rammed earth is the variability of its hygrothermal properties. Characteristics such as grain particle size distribution, percentage of clay mineral (silt and clay), porosity, variations in compaction and curing methods influence the material's thermal conductivity (λ), specific heat (c), density (ρ), and water vapor permeability (Losini *et al.*, 2023a). This variability challenges the prediction of thermal performance, often hindering the large-scale use of rammed earth in architectural projects.

Hygrothermal properties must be parametrized due to their importance in designing efficient earth buildings, optimizing their experimental determination, and improving data reliability across different soil compositions. In this sense, models such as the effective moisture penetration depth (EMPD) available in EnergyPlus software are adopted to simulate the adsorption and desorption processes in buildings. Huerto-Cardenas *et al.* (2021) found that applying the calibrated EMPD model led to more accurate results when evaluating the air infiltration rate in a historic Italian building.

Recognizing the difficulty of standardizing hygrothermal property values due to variations in rammed earth's physical and thermal characteristics, this research analyzes the uncertainty in these properties using different computational simulation methods. The significance of different computer simulation methods and the confidence intervals

hygrothermal properties were determined to evaluate the thermal energy performance of earth buildings. Finally, the study recommended to the application of rammed earth's hygrothermal properties tailored to different soil types and humidity conditions tropical climate with wet summers and dry winters.

2   Materials and methods

The methodology involved modelling and the computational simulation of a building with rammed earth walls using EnergyPlus (version 9.4) and JePlus (version 2.1.0). The thermal energy simulation results were statistically analyzed in RStudio (version 4.3.2). To evaluate the impact of different thermal energy simulation methods, the study applied the Conduction Transfer Function (CTF) method and the Effective Moisture Penetration Depth (EMPD) model.

Building on the findings of Yu *et al.* (2022a), Tan *et al.* (2022), Far, Ahmed and Mackee (2022), and Mamani *et al.* (2022) regarding factors influencing energy performance, the study adopted rammed earth wall thicknesses of 12, 20, and 30 cm, as well as use and occupancy patterns for mixed-use and dormitory-style buildings. Thus totaling 12 different modelling scenarios for the rammed earth structure. This resulted in The EnergyPlus model was based on a room from an actual building constructed with rammed earth walls (Figure 1).

The simulation used climate data from city of Campo Grande, Brazil, which has a Köppen-Geiger Aw classification, indicating a tropical climate with wet summers and dry winters. The choice of this location was motivated by the scarcity of research on earth construction in tropical climates, as most studies focus on hot, arid regions (Beckett *et al.*, 2017; El-Bichri *et al.*, 2022; Kaitouni *et al.*, 2024). Investigating the performance of rammed earth in hot and humid climates offers valuable insights into the adaptability and efficiency of this construction technique in different regions.

The air conditioning system was modelled using the ideal loads air system in EnergyPlus, which simplifies heating and cooling by adjusting air temperature directly to meet setpoint conditions. The heating setpoint was set to 21°C and the cooling setpoint to 23°C, with the system operating only during occupied periods. Natural ventilation was modelled with an air exchange rate of 10 air changes per hour during unoccupied periods.

For the building occupancy patterns, no distinction was made between weekdays, weekends, or holidays. Two occupancy scenarios were modeled: Mixed-use – the room is occupied from 2 pm to 8 am, with artificial lighting from 6 am to 7 am and 10 pm to 11 pm; Dormitory-type – the room is occupied from 10 pm to 8 am, with artificial lighting from 6 am to 7 am and 2 pm to midnight.

The input data for the thermal energy simulations included fixed thermophysical properties of the building's complementary materials (Table 1). For the rammed earth walls, the values of the hygrothermal properties varied within the ranges defined according to the proportion of sand and clay in the soil (Table 2). However, the type and content of stabilizer and the degree of compaction are improvements that can influence the hygrothermal behavior of rammed earth during the construction life cycle in different regions and climates.

Because the EMPD model follows the mathematical equations proposed by Kerestecioglu *et al.* (1988), material-specific coefficients had to be provided as input data. These coefficients were predefined by the authors for a series of materials, with earth bricks being the closest to rammed earth. Due to the lack of specific values for the rammed earth construction system, a variation of ±10% was adopted for the values available for earthenware blocks, resulting in the following variation ranges:

• coefficient a: 0.009420 (0.0085 to 0.0104);

• coefficient b: 5.393850 (4.85 to 5.93);

• coefficient c: 0.003607 (0.0032 to 0.0040);

• coefficient d: 0.205223 (0.1847 to 0.2257).

Figure 1: 3D model and photo of the simulated building facade.
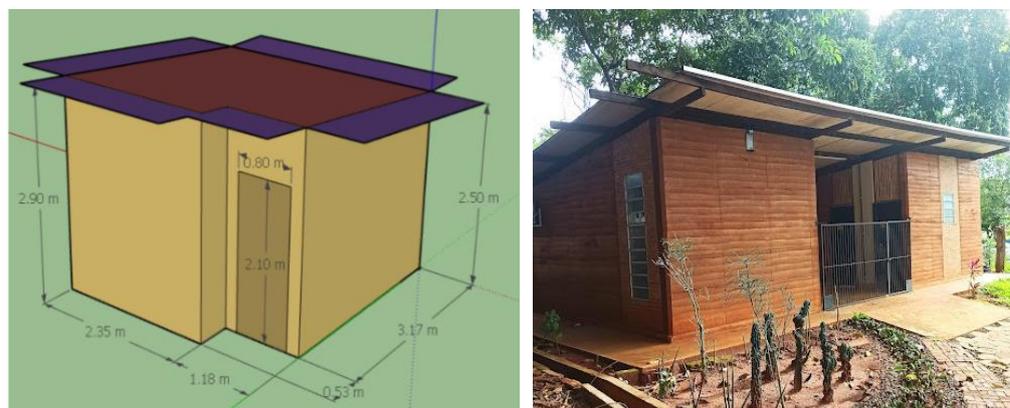
Source: Authors (2025).

Table 1: Values of the thermophysical properties of the complementary.

Construction material Application Area	Polished concrete Floor	Aluminum sheet Thermoacoustic tile	Polystyrene	Plywood Door	Common glass Window
Thickness e (cm)	10.00	0.20	3.00	5.00	0.30
Thermal Conductivity λ (W/m·K)	2.86	230.00	0.04	0.14	0.90
Density ρ (kg/m^3)	2400	2700	16	530	-
Specific Heat c (J/kg·K)	1010	880	1420	1880	-
Thermal Emissivity	0.90	0.12	0.90	0.90	0.84
Solar Absorptance	0.70	0.15	0.20	0.70	0.088
Visible Absorptance	0.70	0.15	0.20	0.70	0.021

Source: Authors (2025).

Table 2: Hygrothermal properties of rammed earth.

Properties	Minimum value	Maximum value	Range considerations
Thermal Conductivity λ (W/m·K)	0.7	1.1	Values determined based on experimental data reported by Silva and Milani (2022) in their bibliometric review
Density ρ (kg/m^3)	1490.0	2190.0	Minimum value defined by Pectu *et al.* (2023) and maximum value by Losini *et al.* (2023a), both derived from the authors' experimental studies
Specific Heat c (J/kg·K)	664.0	910.7	Minimum value defined by Li *et al.* (2023) and maximum value by Liang, Tan and Jiang (2022), both derived from the authors' experimental studies

Source: Authors (2025).

Another required input was the water vapor diffusion resistance factor, which measures a material's ability to resist the passage of water vapor through it. The higher the diffusion

resistance factor, the greater the material's resistance to the passage of water vapor. According to Fraunhofer (2018), this factor can be calculated using the following Equation 1.

$$\mu = \frac{\delta_a}{\delta_m} \tag{1}$$

Where:
μ = water vapor diffusion resistance factor [dimensionless];
δ_a = water vapor permeability of still air [kg/m·s·Pa];
δ_m = vapor permeability of the material [kg/m·s·Pa].

$$\delta_a = \frac{1.968 \times 10^{-7} \times (\vartheta + 273)^{0.81}}{P} \tag{2}$$

Where:
ϑ = air temperature [°C];
P = barometric pressure [Pa].

Considering the barometric pressure at sea level to be 101,325Pa, at a temperature of 25°C, the water vapor permeability of still air is 1.96×10^{-10}kg/m·s·Pa approximately. To determine the value of the water vapor permeability of rammed earth, the equation proposed by Tan *et al.* (2022) was adopted, which describes the water vapor permeability of earth materials with a specific study on rammed earth walls.

$$\delta_m = 1.220 \times 10^{-11} + 5.114 \times 10^{-12} \times \varphi^{3.21} \tag{3}$$

Where:
φ = relative humidity [%].

The humidity range was set between 10% and 100%, resulting in a water vapor diffusion resistance factor for the rammed earth of 16.07 at the lower end and 11.32 at the upper end.

To assess the variability of hygrothermal properties, a random sample of 1,000 simulations was generated for each of the 12 modeled scenarios using the JePlus software. For the CTF method, three independent variables – thermal conductivity, density, and specific heat – were varied across 10 iterations. In the EMPD method, additional variables, including water vapor diffusion resistance and coefficients a, b, c, and d, were considered, with five possible values assigned to each.

The simulation outputs included two key performance indicators: annual thermal cooling load and hours of discomfort during occupancy. The tropical climate, characterized by hot, humid summers and mild, dry winters, emphasizes the importance of energy consumption for cooling. The impact of climate change further highlights the growing demand for cooling energy, which has significantly increased over the past two decades (Scoccimarro *et al.*, 2023). The hours of discomfort during annual use provided a measure of indoor environmental quality and were used to evaluate the building's thermal performance, directly affecting occupants' health and productivity (Mujan *et al.*, 2019).

3 Results and discussion

3.1 Thermal energy behavior of rammed earth

We analyzed the annual average thermal cooling load to identify trends in the thermal energy performance of rammed earth. The results highlight the significant impact of wall thickness on energy consumption across different use and occupancy patterns (Figures 2 and 3).

Figure 2: Average annual values of the CTF simulated scenarios for the annual thermal cooling load indicator.
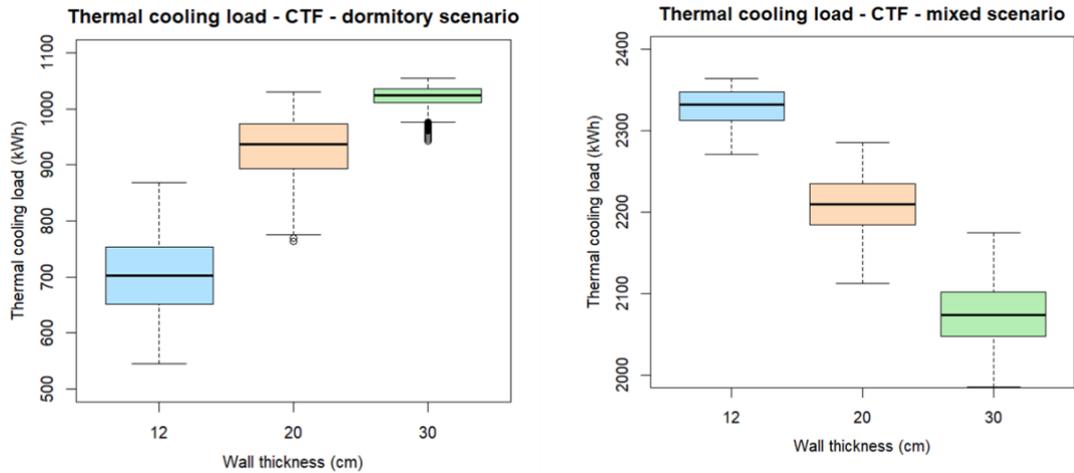
Source: Authors (2025).

Figure 3: Average annual values of the EMPD simulated scenarios for the annual thermal cooling load indicator.
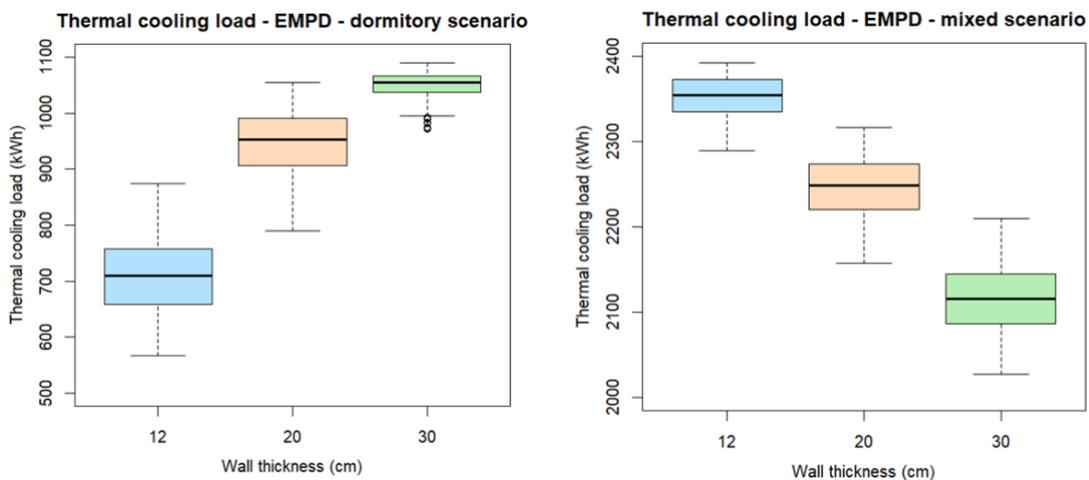
Source: Authors (2025).

In the dormitory-use scenario, energy demand progressively increased with greater wall thickness. Conversely, in the mixed-use scenario, energy demand decreased as wall thickness increased. This contrasting behavior is attributed to the rammed earth's thermal delay, which ranges from 4 to 7 hours (Milani; Labaki, 2012).

During the hottest hours of the day, peak heat can penetrate the interior after a delay of up to 7 hours, which increases cooling energy demand in spaces occupied mainly at night. Additionally, thicker walls provide greater thermal mass, improving resistance to

temperature fluctuations. As a result, thicker rammed earth walls exhibit higher thermal inertia, requiring more time to dissipate heat. This explains the increased energy consumption observed in dormitory-use scenarios with thicker walls.

In addition, there was variation in the thermal cooling load values between the two scenarios. In dormitory-use cases, maximum energy demand reached around 1000 kWh, while in mixed-use scenarios, it climbed to approximately 2300 kWh – an increase of over 100%. This demonstrates a strong correlation between occupancy patterns and building energy consumption. As noted by Samadianfard and Toufigh (2020), the energy performance of buildings is not only influenced by material properties but also by the occupants' behavior and habits.

3.2 Sensitivity analysis

For the sensitivity analysis, we calculated linear correlation coefficients between the thermal energy indicators and the hygrothermal properties of the rammed earth. The results suggest that thermal conductivity (λ) had the most significant impact on both the thermal cooling load and the hours of discomfort during occupancy, showing moderate to very strong correlations between the variables (Table 3). As thermal conductivity increased, the thermal energy indicators also rose, aligning with established principles of building physics (Figure 4).

In contrast, density (ρ) demonstrated weak to moderate negative correlations with the thermal energy indicators, suggesting an inverse and proportional relationship. This means that as the density of the rammed earth increased, the values of the thermal energy indicators decreased (Figure 5). This can be attributed to the greater thermal inertia of denser materials, which allows the construction system to absorb, store, and release significant amounts of heat, helping to stabilize interior temperatures (Harries and Sharma, 2020).

The hygrothermal properties specific to the EMPD method showed very weak correlations, suggesting that the water vapor diffusion resistance factor (δm) and the specific coefficients a, b, c, d had minimal influence on the thermal energy performance of the rammed earth. Consequently, there was no significant difference between the CTF and EMPD simulation methods in terms of their effect on the simulated model.

In the analysis of variance (ANOVA), the thermal energy indicators were treated as the dependent variable and compared against the independent variables – hygrothermal properties of the rammed earth – using a 95% significance level. An important aspect was the degrees of freedom between groups: for the CTF method, nine degrees of freedom were used due to ten observations per parameter, while for the EMPD method, four degrees of freedom were considered due to five variations per property. Across all simulations, the dependent variables of specific heat (c), density (ρ), and thermal conductivity (λ), which are common to both methods, were statistically significant in all scenarios. This reinforces the importance of reliable thermophysical property values for ensuring the accuracy of the simulation models.

Table 3: Linear correlation coefficient between the hygrothermal properties of the rammed earth and the indicators.

	e	Coeff.	c	ρ	λ
EMPD	12 cm	CTL[1]	0.20	0.30	0.89
		HD[2]	0.60	-0.66	0.34
	20 cm	CTL	-0.27	-0.41	0.85
		HD	0.73	-0.54	0.94
	30 cm	CTL	0.48	-0.32	0.80
		HD	0.40	-0.25	0.98
	HT[3]		776.46 J/kg·K	1793.16 kg/m³	0.898 W/m·K
CTF	12 cm	CTL	0.06	0.10	0.93
		HD	0.52	-0.70	0.36
	20 cm	CTL	-0.34	-0.49	0.80
		HD	0.68	-0.57	0.95
	30 cm	CTL	-0.37	-0.53	0.76
		HD	0.82	-0.45	0.98
	HT		795.00 J/kg·K	1854.50 kg/m³	0.889 W/m·K

Source: Authors (2025).

Figure 4: Example of the type of dispersion of thermal conductivity as a function of thermal energy indicators - 20cm rammed earth.
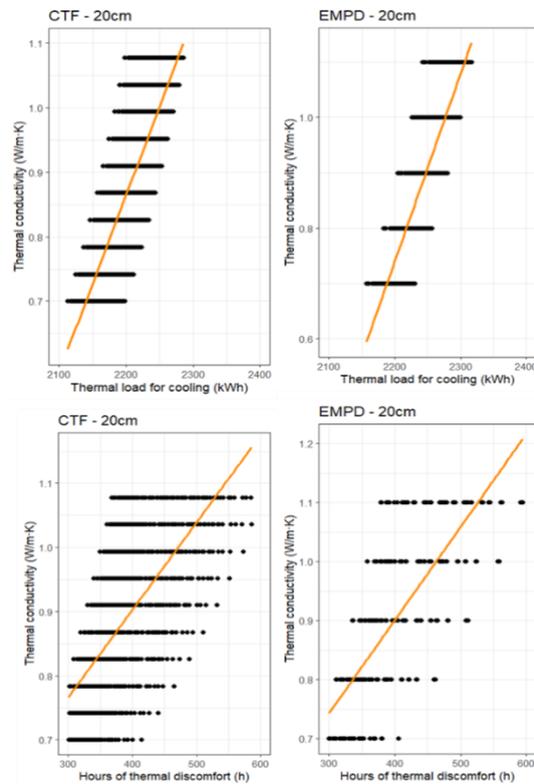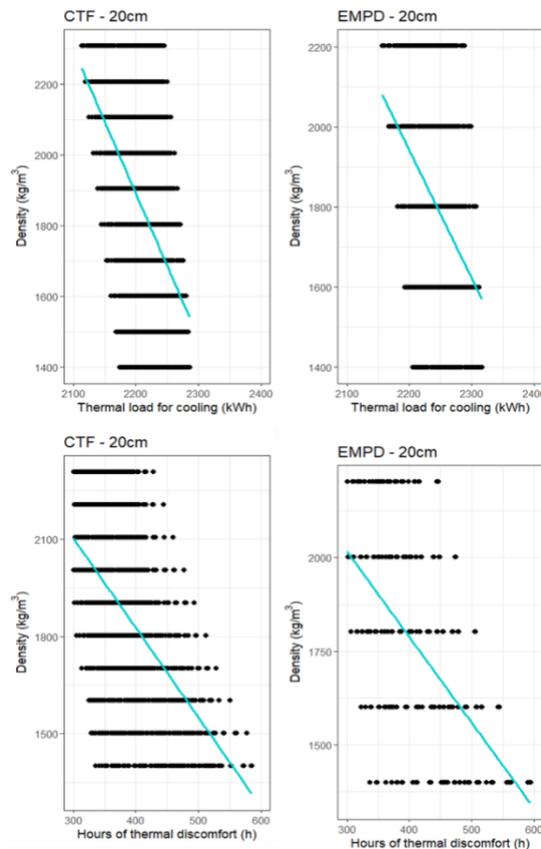

Source: Authors (2025).

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[1] CTL is the linear correlation coefficient of cooling thermal load

[2] HD is the linear correlation coefficient of hours of discomfort

[3] HT is the average value of the hygrothermal property of rammed earth

Figure 5: Example of the type of dispersion of density as a function of thermal energy indicators - 20cm rammed earth.

Among the properties exclusive to the EMPD method, the water vapor diffusion resistance factor (δm) showed significant influence across all scenarios. However, for the material coefficients a, b, c, and d, there was no consistent pattern; only coefficient d was not significant in any of the simulated scenarios. These coefficients, essential for the EMPD simulations, suggest that using values similar to those found in the literature for related materials, such as earth bricks, is feasible without significantly compromising model accuracy. In the absence of specific coefficient values for rammed earth in sources like Kerestecioglu *et al*. (1988), adopting reference values for similar materials offers a practical solution without substantial deviations in the simulation results.

3.3 Uncertainty analysis

To assess the uncertainty in the thermal energy simulations, we analyzed the occurrence density and confidence intervals for the parameterization of the hygrothermal properties of rammed earth. As shown in Figures 6 and 7, the normal distribution curves are nearly identical between the EMPD and CTF methods, with only slight variations attributable to wall thickness. An increase in occurrence density was observed as the thickness of the rammed earth increased, highlighting the significant role of the material's high thermal mass in reducing reliance on artificial air conditioning systems for maintaining suitable indoor temperatures.

Serrano *et al*. (2017) note that while thicker rammed earth improves thermal performance, it also introduces drawbacks, such as higher construction costs and reduced usable space within buildings. Therefore, further research is necessary to determine the optimal wall

thickness, possibly incorporating insulating layers, to balance good thermal performance with practical concerns, especially in the face of climate change and the need for sustainable adaptation strategies.

The confidence interval differences between the EMPD and CTF simulation methods, shown in Figures 6 and 7, were under 2% for all wall thicknesses. This indicates no significant variation in the thermal energy indicators when applying different simulation methods, confirming the CTF method's effectiveness for producing reliable energy estimates through simplified simulations of earthen constructions. This finding is consistent with the material's hygroscopic properties, as the adsorption and desorption of moisture in rammed earth, particularly under high humidity in tropical climates, had minimal impact on the simulation results.

Table 4 provides the estimated maximum and minimum values for the hygrothermal properties of rammed earth, along with their upper and lower confidence intervals at a 95% confidence level. All variables followed a normal distribution and showed no statistical difference between the intervals parameterized by the EMPD and CTF methods.

Figure 6: Density of occurrence of thermal cooling load energy indicators.
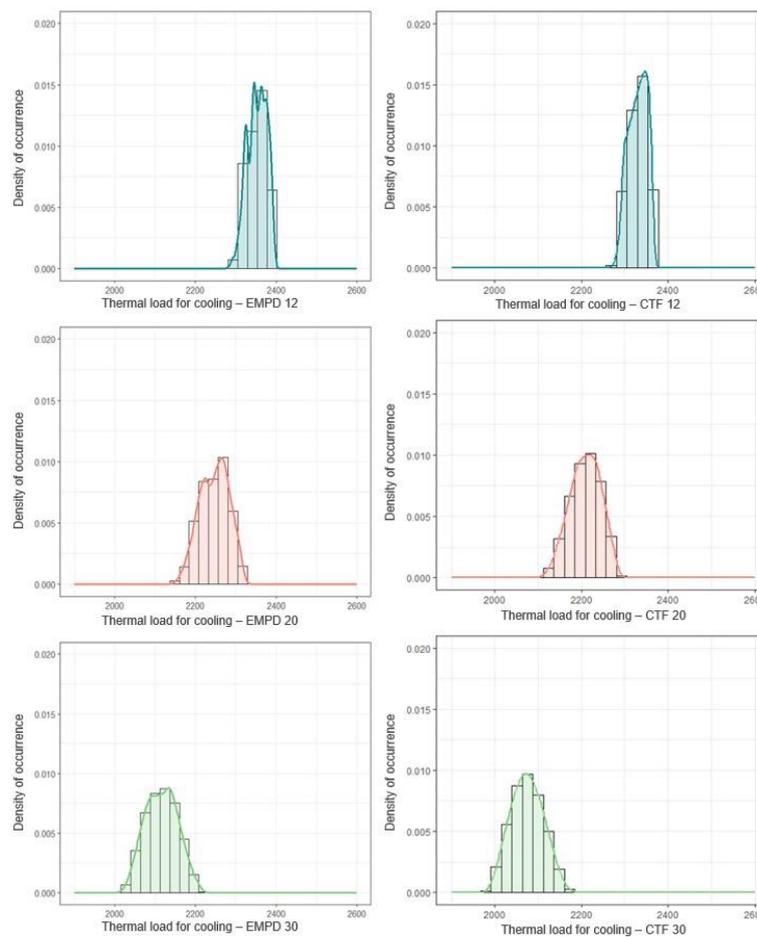
Source: Authors (2025).

Figure 7: Density of occurrence of hours of thermal discomfort energy indicators.
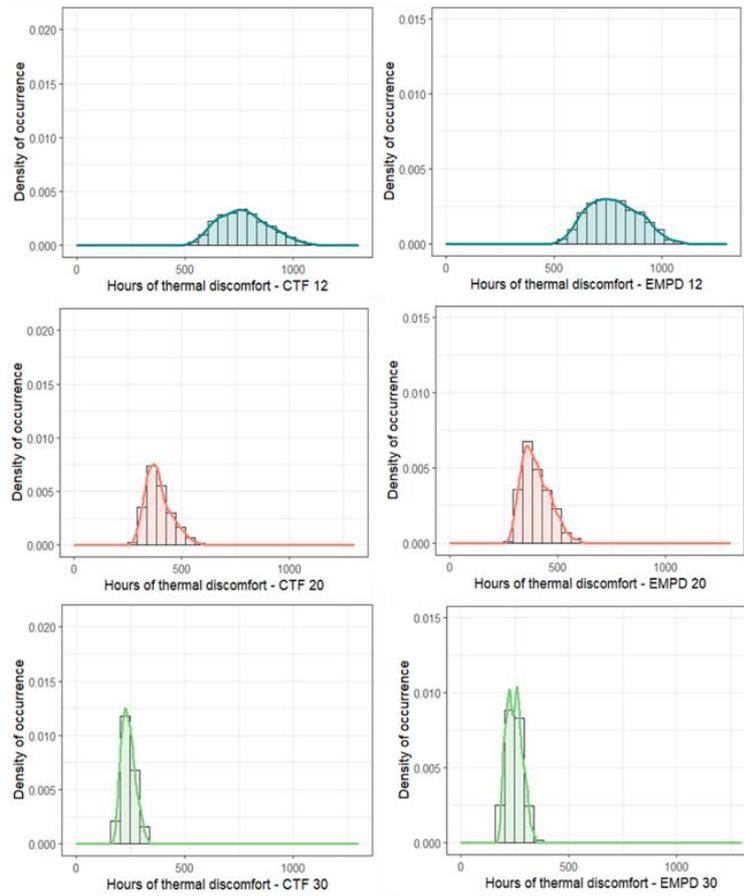
Source: Authors (2025).

Table 4: Parameterization of the hygrothermal properties of rammed earth.

Variable	Method	Confidence Interval	
		Lower	Upper
c(J/kg·K)	EMPD	748.19	780.42
	CTF	737.43	799.06
ρ(kg/m^3)	EMPD	1780.08	1999.82
	CTF	1840.85	2025.14
λ(W/m·K)	EMPD	0.85	0.91
	CTF	0.88	0.93
δ_m	EMPD	13.20	13.60
a	EMPD	0.00928	0.00935
b	EMPD	5.26	5.36
c	EMPD	0.0035	0.0036
d	EMPD	0.203	0.205

Source: Authors (2025).

Based on the confidence intervals for the hygrothermal properties of rammed earth, a way for your application was proposed, taking into account two main premises: the variability in the physical composition of the soil used in the rammed earth walls and the specific climate of the building's location.

Zhang *et al*. (2017) emphasize that minerals like quartz, commonly found in sandy soils, have high thermal conductivity, significantly affecting the hygrothermal properties of rammed earth. Consequently, it is recommended that these density, thermal conductivity,

specific heat properties be adjusted based on the mineralogical composition of the soil, using values closer to the maximum limits of the confidence interval for soils with high sand content and values closer to the minimum limits of this range for clay soils.

Another aspect is the climate of the building's location, as the water vapor permeability of rammed earth is influenced by the relative humidity of the air. The higher the relative humidity, the lower the material's water vapor permeability. Therefore, given the inverse relationship between the water vapor diffusion resistance factor and water vapor permeability (see Equation 1), it is advised to select a value closer to the upper limit of the water vapor diffusion resistance factor range in more humid tropical climate.

Thus, the confidence intervals of rammed earth's hygrothermal properties are crucial for making assertive design decisions that optimize the thermal energy performance of earthen structures. Moreover, these guidelines enable adjustments to accommodate specific soil and climate conditions for the start of design thermal simulation, mainly when detailed laboratory testing of the material's properties is not feasible.

4   Conclusion

This study parameterized empirical hygrothermal properties of rammed earth from bibliographic references, applying different thermal energy simulation methods. The statistical analysis emphasized the critical role of the material's intrinsic thermophysical properties – specific heat, density, and thermal conductivity – in accurately modelling the thermal performance of rammed earth. Linear correlation analysis identified thermal conductivity as the most influential property, regardless of whether the simulation accounted for the material's hygroscopic behavior. The ANOVA results showed that the specific coefficients required by the EMPD method did not significantly affect the outcomes, suggesting that using approximate values from theoretical references for these coefficients does not compromise the accuracy of thermal energy simulations for rammed earth.

The findings indicated that the CTF simplified method can be effectively used instead of the EMPD method without significant loss of accuracy, particularly for thermal energy simulations in tropical climates classified as Aw with wet summers and dry winters. Moreover, the study revealed that building use and occupancy patterns have a substantial impact on the cooling load over time, highlighting the need for a holistic approach when evaluating a building's energy performance.

The establishment of confidence intervals and design guidelines for the hygrothermal properties of rammed earth marks a significant step toward standardizing material specifications, fostering greater replicability and reliability in earth construction systems. However, further empirical research is necessary to expand the database and refine these confidence intervals. Future studies should also incorporate climate change projections, as the need for resilient buildings capable of adapting to emerging environmental challenges becomes increasingly critical.

Acknowledgments

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