THERMAL COMFORT IN TRADITIONAL RURAL HOUSINGS WITH PROPOSAL TO REPLACE THE ENVELOPE: COMPUTATIONAL SIMULATION

CONFORTO TÉRMICO EM HABITAÇÕES RURAIS TRADICIONAIS COM PROPOSTA DE SUBSTITUIÇÃO DA ENVOLVÓRIA: SIMULAÇÃO COMPUTACIONAL

CONFORT TÉRMICO EN VIVIENDAS RURALES TRADICIONALES CON PROPUESTA DE SUSTITUCIÓN DE LA ENVOLVENTE: SIMULACIÓN COMPUTACIONAL

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ABSTRACT

To seek proposals to promote viable living conditions and quality of life in rural communities in Northeastern Brazil, this research investigates the thermal performance of low-income housing using rammed earth and straw roofs, located in the municipality of Bequimão, Maranhão. Using computer simulations in SketchUp®, OpenStudio®, and EnergyPlus® software, three construction scenarios were evaluated: S0 (rammed earth with straw roof), S1 (masonry with chipped tiles), and S2 (masonry with ceramic tiles). The original configuration (S0) presented the highest annual thermal comfort percentage (45.49%), followed by S1 (44.35%) and S2 (44.06%), according to ISO 7730. Although conventional masonry and tile solutions result in a slight reduction in thermal comfort, they are justified by the greater durability and structural safety of the buildings. The thermal sensation was also investigated and obtained the following results for the conditions defined as ST (without forced ventilation) and STV (with forced ventilation): 27.18°C (S0), 27.48°C (S1), and 27.59°C (S2) in ST; and reduction to 26.07°C (S0), 26.70°C (S1), and 26.36°C (S2) in STV, with the insertion of a table fan. The study reveals that simple mechanical ventilation mitigated the thermal sensation experienced and reinforces the usefulness of simulations in the development of safe housing solutions adapted to the regional climate.

Keywords: Thermal Satisfaction. Housing Safety. Bioclimatic Architecture. Computational Modeling.

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RESUMO

A fim de buscar propostas para promover viabilizar condições de habitabilidade e qualidade de vida em comunidades rurais do Nordeste brasileiro, esta pesquisa investiga o desempenho térmico de habitações populares em taipa com cobertura de palha, localizadas no município de Bequimão-MA. Por meio de simulações computacionais nos softwares SketchUp®, OpenStudio® e EnergyPlus®, foram avaliados três cenários construtivos: S0 (taipa com cobertura de palha), S1 (alvenaria com telha tipo cavaco) e S2 (alvenaria com telha cerâmica). A configuração original (S0) apresentou o maior percentual de conforto térmico anual (45,49%), seguida de S1 (44,35%) e S2 (44,06%), conforme a ISO 7730. Ainda que as soluções em alvenaria e telhas convencionais resultem em leve redução do conforto térmico, justificam-se pela maior durabilidade e segurança estrutural das edificações. A sensação térmica também foi investigada e obteve os seguintes resultados para as condições definidas como ST (sem ventilação forçada) e STV (com ventilação forçada): 27,18°C (S0), 27,48°C (S1) e 27,59°C (S2) em ST; e redução para 26,07°C (S0), 26,70°C (S1) e 26,36°C (S2) em STV, com inserção de um ventilador de mesa. O estudo revela que a ventilação mecânica simples amenizou a sensação térmica experimentada e reforça a utilidade das simulações no desenvolvimento de soluções habitacionais seguras e adaptadas ao clima regional.

Palavras-chave: Satisfação Térmica. Segurança Habitacional. Arquitetura Bioclimática. Modelagem Computacional.

RESUMEN

Para buscar propuestas que promuevan condiciones de vida viables y calidad de vida en comunidades rurales del noreste de Brasil, esta investigación investiga el desempeño térmico de viviendas de bajos ingresos con techos de tierra apisonada y paja, ubicadas en el municipio de Bequimão, Maranhão. Utilizando simulaciones por computadora en los software SketchUp®, OpenStudio® y EnergyPlus®, se evaluaron tres escenarios de construcción: S0 (tierra apisonada con techo de paja), S1 (mampostería con tejas desportilladas) y S2 (mampostería con tejas cerámicas). La configuración original (S0) presentó el mayor porcentaje de confort térmico anual (45,49%), seguida de S1 (44,35%) y S2 (44,06%), según ISO 7730. Si bien las soluciones convencionales de mampostería y tejas resultan en una ligera reducción del confort térmico, se justifican por la mayor durabilidad y seguridad estructural de los edificios. También se investigó la sensación térmica, obteniéndose los siguientes resultados para las condiciones definidas como ST (sin ventilación forzada) y STV (con ventilación forzada): 27,18 °C (S0), 27,48 °C (S1) y 27,59 °C (S2) en ST; y una reducción a 26,07 °C (S0), 26,70 °C (S1) y 26,36 °C (S2) en STV, con la inserción de un ventilador de mesa. El estudio revela que la ventilación mecánica simple mitigó la sensación térmica experimentada y refuerza la utilidad de las simulaciones en el desarrollo de soluciones de vivienda seguras adaptadas al clima regional.

Palabras clave: Satisfacción Térmica. Seguridad de la Vivienda. Arquitectura Bioclimática. Modelado Computacional.

1 INTRODUCTION

The use of land as a building material dates back to around 8,000 B.C., with records in ancient Middle Eastern settlements such as Jericho (present-day West Bank) and Çatal Hüyük (present-day Turkey) (Santos, L., 2022). In Brazil, during the colonization period, construction techniques were perpetuated that were based on the use of land and other aggregates as raw material by Afro-descendant peoples brought from the African continent, using clay in construction structures, in a similar way to techniques employed by national tribes, in addition to European construction references, such as the Portuguese. European immigration to Brazil, driven by the end of the slave trade and the Industrial Revolution, resulted in the adaptation of traditional land techniques (Gasparini, 2008; Cappelletti, 2022). In this period, the rammed earth technique used in Brazil can be subdivided into two categories, they are rammed earth and rammed earth.

According to Colin (2010), rammed earth employs a wooden base structure, usually Aroeira and Braúna, forming a mesh of horizontal and vertical pieces that support rounds, sticks and wattle and daub, tied with fibers such as hemp or buriti, then receiving the manual application of clay for sealing. In buildings with thatched roofs, the assembly of the structure precedes the placement of plant material, followed by sealing the walls with clay, protecting the structure from rain and facilitating drying. Rammed earth, on the other hand, consists of the construction of walls from compacted layers of earth, for which a form of wood known as taipal is used (Pisani, 2004).

Brazil has the largest collection of rammed earth constructions in Latin America, with the majority of houses produced from rammed earth (Fernandes, 2013). In the state of Maranhão, in the Northeast region of Brazil, some cities still preserve examples of popular houses built with traditional mud systems (Lima; Bessa, 2022). A residence is considered "popular" when it has a total area not exceeding 70 m² (Federal Revenue, 2021). According to a study by the Economic Research Institute Foundation (Fipe), the average size of low-income housing in Maranhão is 34.4 m² (Santos, A., 2022), which is the lowest value among the capitals surveyed in the country. This data reflects the importance of housing financing programs to expand access to adequate housing.

When evaluating the housing conditions of houses generated from rammed earth, one of the fundamental parameters for evaluating the quality of the environment is thermal comfort. This does not have a universal definition, that is, it depends on numerous parameters, quantifiable or not. Therefore, the feeling of thermal comfort can have considerable variations depending on the particular conditions of each individual. Thus, in order for the thermal comfort of an environment to be established, it is necessary to use standards to define parameters to be established (Silva, 2006 *apud* Gallo and Ribeiro, 2007). The ISO 7730 standard establishes that: "thermal comfort is the state of mind that expresses satisfaction with the thermal environment" (Gallo; Ribeiro, 2007).

One way to assess the thermal satisfaction condition in environments is through computer modeling. From this method, it is possible to carry out analyses of real systems in a cost-effective, safe and efficient way. From mathematical and physical models, it is possible to predict physical phenomena and environmental parameters to be established, based on hypothetical circumstances, enabling the optimization of variables aimed at improving the performance of systems (Gavira, 2007).

Preliminary analyses reveal that, compared to conventional masonry, the use of rammed earth provides better thermal comfort by achieving lower internal temperatures of the houses with less environmental impacts and reduced production cost (Natal, 2019). However, when evaluating the physical integrity of the residents, masonry added to a more resilient roof, provides better structural stability, because, despite the low cost and ease of construction, rammed earth constructions have limitations in terms of durability and resistance, becoming susceptible to degradation in the face of bad weather and other external agents such as rain, strong winds and erosion, with direct implications for the health and safety of occupants (Gonçalves *et al.* 2023).

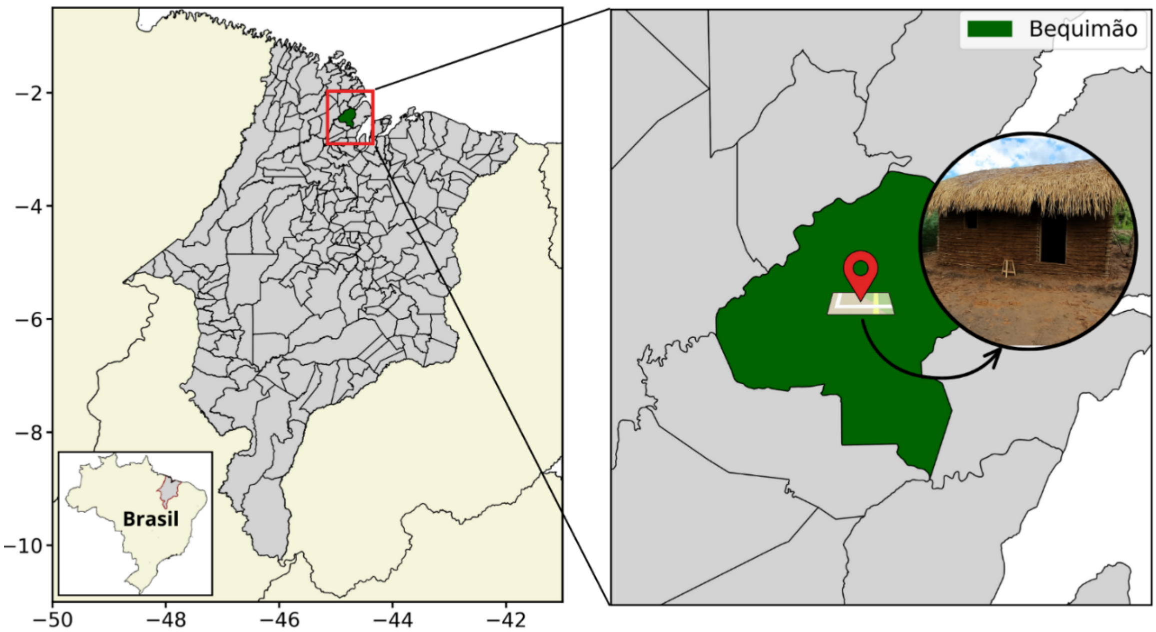
This study investigates the thermoenergetic behavior of low-income housing built in rammed earth with straw roof, crowded in Bequimão-MA, in order to propose structural interventions that promote greater durability and safety for the occupants. Computer simulations were used as a resource in the *softwares SketchUp*®, *OpenStudio*® and *EnergyPlus*® to evaluate the thermal performance of three construction scenarios – S0 (rammed earth and straw roof), S1 (masonry and chip tiles) and S2 (masonry and ceramic tiles) – based on the criteria of the ISO 7730 (2005) standard. The relevance of this work lies in its contribution by suggesting improvements in the living conditions of rural populations in the Northeast. The replacement of natural materials by masonry and conventional roofs is justified for structural reasons, although it reduces the levels of thermal comfort due to the greater thermal conductivity of traditional materials (Dantas *et al*., 2023; Borges *et al*., 2023). The results can support the formulation of more effective public policies for social housing and guide the adoption of viable constructive solutions.

2 METHODOLOGY

The investigation of the thermoenergetic performance of houses built with natural materials in the Northeast region of Brazil was conducted through integrated computer simulations using the SketchUp®, *OpenStudio*® and *EnergyPlus*® software, which allowed to accurately analyze the internal thermal conditions over a full year. The study focused on a typical single-family building in Bequimão, Maranhão, built with the traditional technique of rammed earth and vegetable straw roofing, for which structural improvements were proposed, replacing the rammed earth walls with masonry and the vegetation cover with chip tiles and ceramics. To ensure climate fidelity, a climate archive was used. EPW (*EnergyPlus Weather File*) from the TMY (*Typical Meteorological Year*) database, with data collected between 2009 and 2023, containing detailed meteorological information such as air temperature, relative humidity, solar radiation and wind speed, available on the *Climate One Building platform*. Figure 1 shows the geographical location of the municipality of Bequimão, where the use of the construction technique in rammed earth is verified.

Figure 1

Location of Bequimão (MA), with emphasis on the typical popular housing in rammed earth present in the municipality



The first stage consisted of the three-dimensional geometric modeling of the building, based on its actual dimensions, including volumetry, orientation and openings. Three distinct models were created (S0, S1 and S2) that differ only in the construction materials. To evaluate the impact of ventilation on indoor thermal performance, each model was tested under two operating conditions: natural ventilation, according to local climate data, and forced ventilation, simulated by the inclusion of a common table fan that reaches a maximum air velocity of 5.15 m/s (WAP, 2025). Table 1 shows the simulation scenarios performed in this research.

Table 1

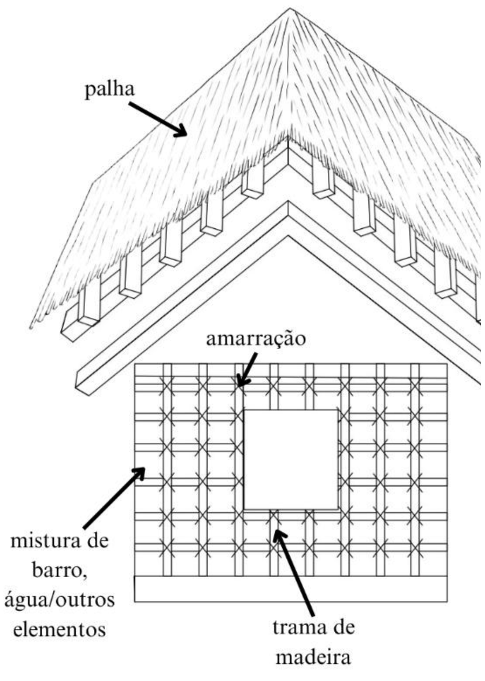
Configurations of the construction elements in scenarios S0, S1 and S2

Scenario	Configuration	Conditions
S0	Rammed earth walls + vegetable straw cover	Natural ventilation; Forced ventilation
S1	Ceramic brick walls + ceramic tile roofing	
S2	Ceramic brick walls + chip tile roof	

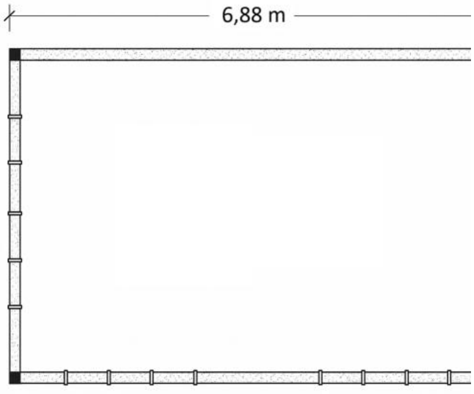
Figure 2a illustrates a synthesis of the main constructive elements of buildings in rammed earth with straw roofing, highlighting the composition of the wall with a wooden weave and filling based on a mixture of clay, water and other elements, as well as the structural fastening system and the use of vegetation cover. Figure 2b shows the dimensions adopted in the three-dimensional modeling developed and Figure 2c shows a popular housing built in rammed earth with a rammed earth roof in the municipality of Bequimão-MA.

Figure 2

Architecture of rammed earth and straw constructions: a) Diagram of rammed earth construction; b) Average dimensions of low-income housing in the Northeast region1; c) Popular housing built in rammed earth and straw in the municipality of Bequimão-MA2. Source: 1Adapted from Santos (2022); 2Adapted from Almeida (2022)



(a)



(b)

(c)

The geometry of the building was replicated in *SketchUp*® (as shown in Figure 3) and exported in *.osm* format to *OpenStudio*®. In it, the layers of the construction materials were assigned to the model surfaces, defining thermophysical properties such as thickness (*h*), thermal conductivity (*λ*), specific mass (*ρ*) and specific heat (c), as detailed in Table 2.

Figure 3

Three-dimensional architectural model of the reference building in the SketchUp® interface

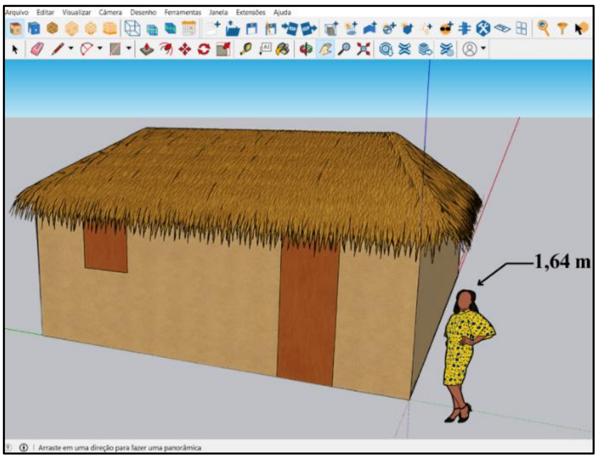


Table 2

Thermophysical properties of the materials used in the simulations

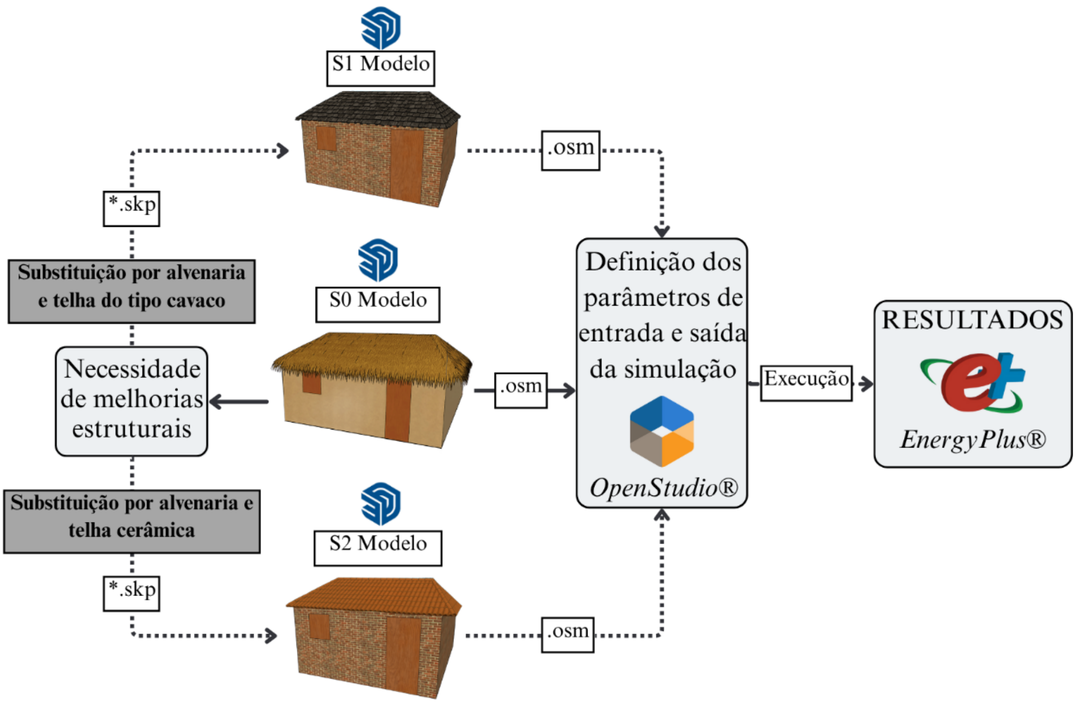
Material	*h* (m)	*λ* (W/mK)	*ρ* (kg/m³)	*c* (J/kgK)	Reference
Rammed earth	0,090	0,790	1833,90	664	Li *et al.* (2023)
Straw	0,020	0,066	185	-	Cicelsky *et al.* (2024)
Dirt	0,050	0,520	1700	840	ABNT (2003)
Chip type tile	0,020	0,230	600	1340	ABNT (2003)
Ceramic Tile	0,020	0,700	1000	920	ABNT (2003)

Ceramic brick	0,090	0,900	1300	920	ABNT (2003)

The third and last stage consisted of the execution of the simulations in the *OpenStudio®* , with support from *EnergyPlus®* , which carried out hourly energy balance calculations to generate the results, which were processed and evaluated according to the criteria of the ISO 7730 (2005) standard, which defines thermal comfort ranges between 20-26°C. Figure 4 exemplifies the general steps of execution of the simulations.

Figure 4

Flowchart of the steps involved in the execution of the simulations of this research



3 RESULTS AND DISCUSSIONS

This research investigated the thermal performance of mud houses with thatched roofs in Bequimão-MA, through computer simulations, considering the impact of local climatic conditions on habitability in rural communities in the Northeast. The region has a hot and humid climate throughout the year, with an average annual dry bulb temperature of 26.83°C, wet bulb of 24.34°C and relative humidity of 84.37% (Table 3). These factors demonstrate the challenges related to thermal comfort in buildings in the region.

Monthly direct radiation peaked between August and November, with values above 240 W/m², while diffuse radiation ranged from 52.99 W/m² (June) to 85.10 W/m² (March). The combination of high solar incidence and high temperatures imposes a considerable thermal load on buildings, especially those built with materials with high thermal conductivity. On the other hand, the average wind speed remained low throughout the year (0.82 m/s), with an increase in the warmer months, such as September (1.18 m/s) and October (1.25 m/s), as shown in Table 3. These values suggest that natural ventilation, although present, is limited, making it necessary to use complementary strategies of forced ventilation to reduce the internal thermal sensation.

Table 3

Monthly averages of climatic conditions in the region studied

Month	T dry bulb (°C)	T Wet Bulb (°C)	Tx. Rad. Dir. (W/m2)	Tx. Rad. Dif. (W/m2)	Vel. Wind (m/s)
Jan	26,82	24,66	170,24	80,58	0,81
Feb	26,27	24,63	146,00	82,39	0,63
Mar	25,81	24,43	128,81	85,10	0,47
Apr	26,24	24,79	121,78	81,47	0,59
May	26,47	24,82	189,04	63,46	0,55
Jun	26,43	24,26	227,87	52,99	0,57
Jul	26,41	24,07	221,40	53,41	0,64
Aug	26,85	24,08	243,25	55,94	0,88
Set	27,41	23,87	250,36	60,62	1,18
Oct	27,73	23,97	256,97	66,16	1,25
Nov	27,73	24,14	257,77	63,72	1,15
Dec	27,80	24,34	236,27	65,77	1,08
Total	26,83	24,34	204,49	67,53	0,82

The results of the computer simulations in the three construction scenarios (S0, S1 and S2) show the direct impact of the materials used in the roof and walls on the internal conditions of temperature, humidity and thermal sensation. The initial scenario with rammed earth walls and vegetable straw cover (S0) presented the lowest average annual internal temperature (27.18°C) and the highest relative humidity (82.61%), a fact attributed to the low thermal conductivity of the natural materials used, as well as their porosity, which favors heat exchange with the environment and moisture retention. In contrast, scenarios S1 (masonry with chip tiles) and S2 (masonry with ceramic tiles) presented higher average temperatures, of 27.48°C and 27.59°C, respectively. The difference, although apparently subtle, reveals the effect of using conventional materials on the market which, because they are denser and less porous, absorb and retain more heat, raising the internal temperature of the environments.

The average indoor relative humidity was lower than the initial scenario. In S1 it was 81.25% and in S2 it reached 80.81%. The greater moisture retention in environments built with rammed earth and straw contributed positively to thermal comfort. Figure 5 shows the temperature profiles throughout the day inside the building in the 3 scenarios studied. Figure 6 shows the thermal sensation obtained in the 3 scenarios, comparing the conditions with natural ventilation (ST) and forced ventilation (STV) from the insertion of a table fan.

Figure 5

Annual profiles of internal temperature and relative humidity in simulations S0, S1 and S2

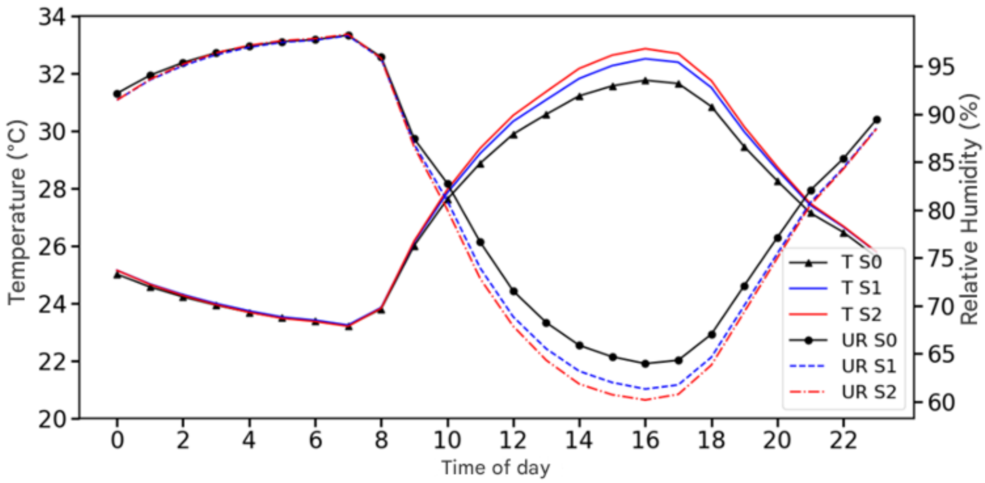
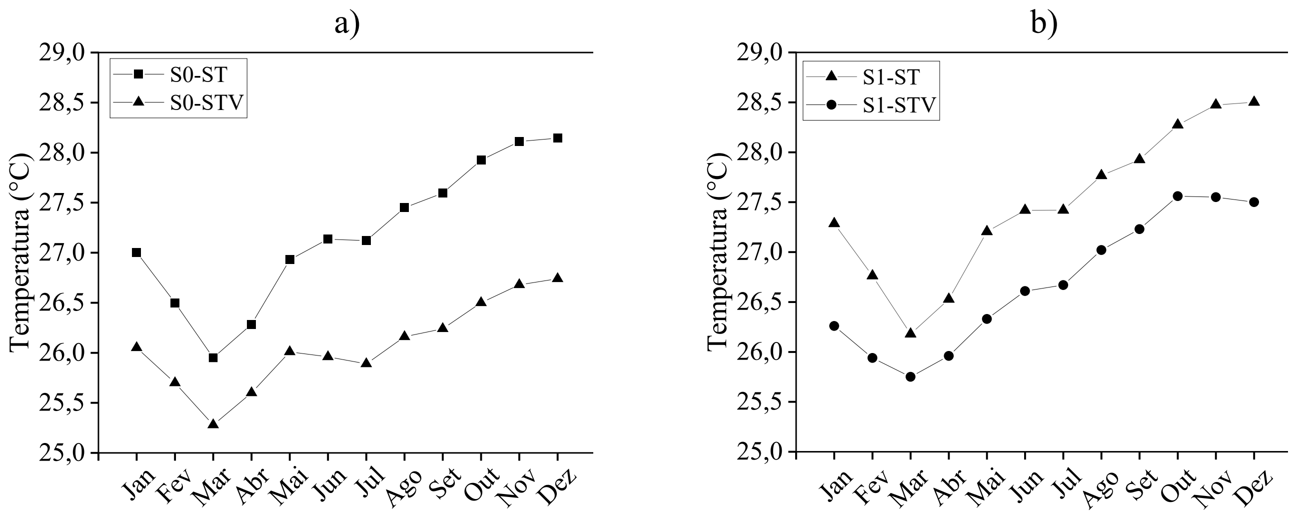
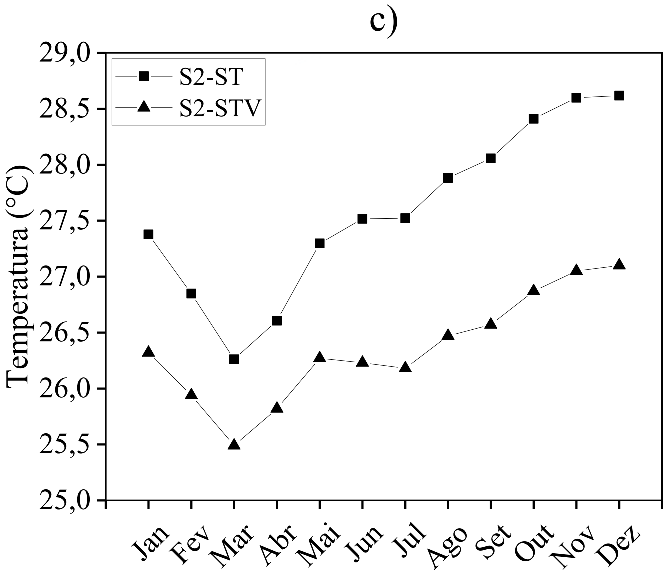


Figure 6

Thermal sensation experienced with and without the use of a fan: a) S0; b) S1; c) S2



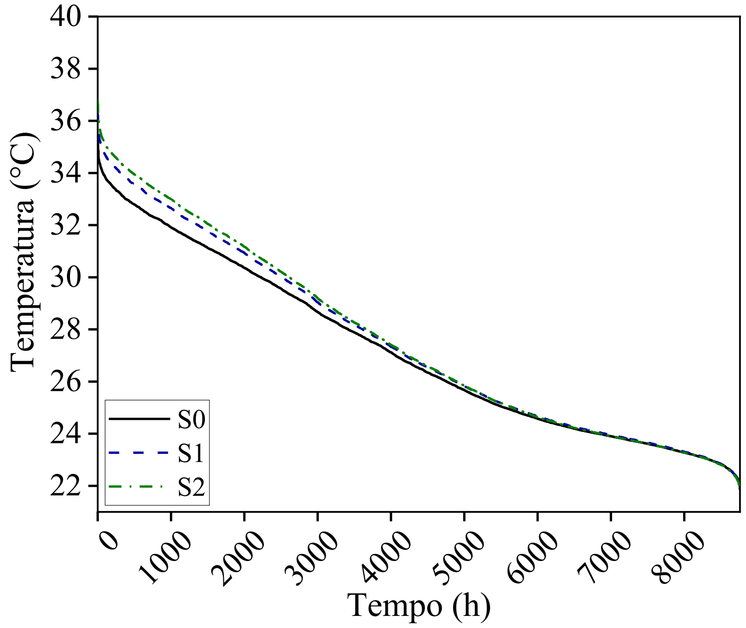


Without the use of a fan (TS), the values of thermal sensation were 27.18°C in S0, 27.48°C in S1 and 27.59°C in S2. These results exceed the upper limit of 26°C defined by the ISO 7730 (2005) standard, indicating that, under natural conditions, the three construction systems presented thermal discomfort for a good part of the year. However, with the introduction of forced ventilation (STV), a significant reduction in the thermal sensation of the environments is observed. The greatest benefit was observed in the S0 scenario, whose thermal sensation fell to 26.07°C, approaching the upper limit of comfort. Scenarios S2 and S1 presented values of 26.36°C and 26.70°C, respectively, much closer to the level considered comfortable. These results highlight the importance of mechanical ventilation as a mitigating strategy, especially in buildings that use less thermally efficient materials, such as ceramic bricks and chip-type tiles.

Figure 7 shows the curves for the duration of internal temperature throughout the year for the three scenarios. Scenario S0 showed better performance, with a greater number of hours between 20°C and 26°C, which suggests greater permanence within a temperature range considered tolerable for human comfort (ISO 7730/2005). In contrast, scenarios S1 and S2 exhibited a higher concentration of hours with higher temperatures, with less frequency of conditions below 26°C.

Figure 7

Internal temperature duration curves in the simulations over the annual period



The data indicate that the S0 scenario was the one that remained for the longest time within the thermal comfort range established by ISO 7730, totaling 45.49% of the annual hours, while the S1 and S2 scenarios registered 44.35% and 44.06%, respectively. As previous studies have shown, it was already expected that the higher thermal conductivity of traditional materials could increase thermal discomfort (Dantas *et al*., 2023; Borges *et al*., 2023).

Therefore, it was evaluated that houses produced from the rammed earth technique promote lower internal temperatures and higher relative humidity, factors attributed to the use of porous materials in the constitution of walls and roof, favoring the maintenance of humidity and air circulation. The use of rammed earth is valued in the sense of promoting thermal comfort at a lower cost compared to traditionally used materials, in addition to valuing a sustainable ideal through the use of natural and renewable raw materials. However, masonry houses have greater structural stability, enabling greater constructive safety for occupants from the greater ability to resist adverse environmental conditions such as heavy rains with high-speed winds. The replacement of wood, earth and other complementary materials used in rammed earth with masonry, as well as the replacement of straw roofing with chip or ceramic tiles is made possible by affordable costs and constructive advantages.

5 CONCLUSION

This study demonstrates that construction materials exert a direct influence on the thermal performance of buildings, especially in regions with hot and humid climates such as Bequimão-MA. The computer simulations revealed that the scenario with traditional construction technique of rammed earth and straw roofing (S0) presented the lowest internal temperatures and higher relative humidity, promoting better thermal comfort conditions compared to the masonry scenarios with chip tiles (S1) and ceramic tiles (S2). The data obtained reinforce the potential of natural and porous materials to favor thermal exchange with the external environment, reducing the sensation of heat. In addition, the use of forced ventilation, even with simple equipment such as table fans, proved to be effective in reducing the thermal sensation in the three scenarios, being more expressive in S0, which highlights the importance of complementary ventilation strategies in places with low air circulation.

Despite the thermal benefits of rammed earth construction, masonry systems offer greater structural strength and protection from extreme weather events, such as heavy rainfall and strong winds. Among the suggestions for improvement, the S1 configuration (masonry + chip tile) provided better thermal performance and is considered the construction technique that best balances thermal comfort, safety and economic viability. In this sense, the responsibility of the public authorities to formulate and implement housing policies that guarantee rural populations access to stable housing adapted to local climatic conditions, promoting the social well-being of these populations, is highlighted.

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