Enhancing Energy Efficiency in Affordable Housing: A Comparative Study of Construction Methods

Layla Iskandar[1], Carlos Faubel[2], Antonio Martinez-Molina[2,3], Saadet Toker-Beeson[1]

School of Architecture and Planning, Klesse College of Engineering and Integrated Design, The University of Texas at San Antonio UTSA, 501 W. César E. Chávez Blvd, San Antonio, TX 78207, USA.[1]

Department of Architecture, Design & Urbanism, Antoinette Westphal College of Media Arts and Design, Drexel University, 3501 Market St., Philadelphia, PA 19104, USA.[2]

Department of Civil, Architectural & Environmental Engineering, College of Engineering, Drexel University, 3141 Chestnut St., Philadelphia, PA 19104, USA.[3]

Abstract

As urban areas confront the dual challenges of housing affordability and climate change, sustainable building solutions are becoming increasingly essential. This paper presents an applied research project in San Antonio, Texas, in the United States, focused on constructing energy-efficient homes for low-income families. The project involves designing and building two prototype homes: one using conventional wood-frame construction with enhanced energy-efficient features, and another utilizing rammed earth construction. Both prototypes, sharing similar design configurations, were modeled using DesignBuilder to assess and optimize energy performance. Multiple iterations were conducted to improve components such as roof, floor, and wall insulation, windows, and air infiltration. The research compared the thermal performance of the two prototypes using energy efficiency indices like cooling and heating loads, indoor temperatures, and solar heat gains. The findings showed that optimizing the wood-frame design led to significant reductions in energy use, particularly in heating and cooling loads. The rammed earth building demonstrated similar energy performance to the optimized wood-frame prototype, with even lower cooling loads. The study also underscored the importance of infiltration rates and well-sealed building envelopes, especially in hot and humid climates. The findings provide valuable insights for affordable housing design and offer guidance for future policies and energy-efficient construction methods to promote sustainable housing solutions in regions facing similar challenges.

Introduction

As urban populations continue to grow, the challenges of housing affordability and energy efficiency have become increasingly critical. The building sector is a significant contributor to global energy consumption, accounting for 26% of global CO_2 emissions and 30% of global final energy consumption in 2022 (IEA, 2023). In the context of climate change, the need for sustainable building practices is more urgent than ever, particularly in regions experiencing rapid urbanization and economic disparity (United Nations, 2018). Moreover, energy costs can significantly increase the overall financial burden of housing, making it unaffordable for many low-income families.

In San Antonio, Texas (TX), United States (USA), the demand for deeply affordable homeownership has surged, as many households face housing instability and the city continues to grow (The City of San Antonio, 2022). This demographic often encounters barriers to accessing energy-efficient housing, which can exacerbate financial strain due to high utility costs. Therefore, innovative construction methods and solutions that prioritize both affordability and energy efficiency are crucial for addressing these challenges. In response, the City of San Antonio, in collaboration with the San Antonio Affordable Housing (SAAH) non-profit organization, approved the Single-Family Prototype Pilot Project for families at or below 80% Average Median Income. This paper presents the outcomes of this applied research project exploring two distinct construction methods: optimized conventional wood-frame and rammed earth. Using advanced modeling tools such as DesignBuilder (DesignBuilder Software Ltd, n.d.) and THERM (Lawrence Berkeley National Laboratory (LBNL), n.d.), the study evaluates the energy performance of both prototypes, aiming to identify the best strategies that can enhance sustainability in affordable housing in the city of San Antonio.

Previous research underscores the importance of sustainable construction that uses key resources such as energy, materials, land, and water more competently. This approach can significantly reduce energy consumption, lower electricity and gas costs, decrease emissions, and improve competitiveness by enhancing health, productivity, and comfort in indoor environments (Alassaf, 2024; Balaban et al., 2017). Studies have also shown that sustainable buildings are not necessarily more expensive than conventional ones, especially when considering the long-term financial benefits of reduced operation and maintenance costs (Kats, 2003). A 2018 guide by the U.S. Environmental Protection Agency on energy efficiency in affordable housing (U.S. Environmental Protection Agency, 2018) suggests that new affordable homes can achieve better energy efficiency by incorporating features like effective insulation for the walls, floors, and roof, high-performance windows, tight construction and ducts, energy-efficient heating and cooling equipment, and energy-saving products like lighting fixtures and ventilation fans, along with third-party testing to verify the energy performance. Additionally, building with natural materials such as rammed earth has been shown to improve thermal properties compared to conventional methods (Ben-Alon et al., 2021), offering significant advantages in reducing energy-intensive construction practices.

Through this comparative analysis, the project seeks to contribute valuable insights into the design and construction of energy-efficient homes for low-income families, ultimately informing future policies and practices in sustainable housing development in the city of San Antonio and similar regions.

Methodology

The goal of the Single-Family Prototype Pilot Project is to address the significant demand for deeply affordable homeownership in San Antonio for families at or below 80% of the Average Median Income. The project aimed to provide informed design solutions for new and existing construction that are both energy-efficient and affordable, while also reducing their energy operation costs. To achieve this, two adjacent residential building prototypes were to be designed and constructed using two different methods: one with conventional wood-frame construction and the other with rammed earth construction. By partnering with experienced architectural designers, builders, academic researchers, and other technical professionals, these buildings were optimized for both energy efficiency and affordability. The project methodology includes the following steps:

1- Designing two adjacent single-family houses, one using conventional wood-frame construction and the other using rammed earth construction.
2- Optimizing the energy efficiency of the two buildings before construction and documenting the optimization process and results.

3- Comparing the energy performance of the designed buildings to each other, as well as to two additional construction types: a standard “control” building (an existing newly constructed conventional wood-frame single-family house) and a rehabilitated existing older structure.
4- Performing a Life Cycle Assessment to evaluate and compare the cradle-to-grave environmental impact of the selected houses.

This paper focuses on the energy performance and optimization process of the designed wood-frame and rammed earth buildings. It begins by describing the buildings and their context, followed by an explanation of the energy performance simulation methods. The paper then presents the energy optimization process and specific considerations for each structure, before discussing and comparing the results, including energy performance indices such as cooling and heating loads, indoor temperatures, and solar heat gains. These results informed the construction of both buildings and will guide the upcoming Life Cycle Assessment.

Case Study Buildings Description

The wood-frame and rammed earth buildings are located adjacent to each other, occupying two neighboring lots (Figure 1). They are situated 3.8 miles east of downtown San Antonio, which is classified as climate zone 2A (hot and humid) according to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (ASHRAE, 2021).

San Antonio experiences hot summers, with annual mean temperatures ranging from 52.2 °F to 85.5°F over the past 30 years, and the mean maximum temperature in August typically reaching 96 °F (National Weather Service, n.d.). Under these conditions, managing cooling and dehumidifying loads inside buildings through passive strategies alone is quite challenging (Iskandar et al., 2024; Faubel et al., 2024). Therefore, additional solutions, such as the integration of appropriate active systems, are necessary to ensure the thermal comfort of occupants (Iskandar et al. 2024).

The two buildings are designed as single-story structures with a rectangular shape, sharing a similar layout that includes two bedrooms, one bathroom, an open living room, kitchen, and dining area, as well as a utility closet. Both buildings feature a porch at their west entrance and have been designed to accommodate the potential for future extensions. The first building has an area of 1,120 ft^2, while the second has an area of 1,220 ft^2.

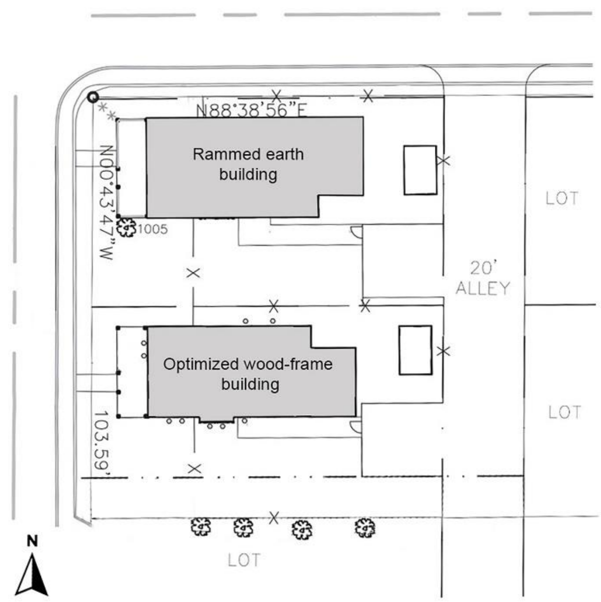

Figure 1. Site plan of the studied buildings.

The wood-frame building has already been constructed and sold to a qualifying owner (Figure 2). It features external walls framed with 2” x 4” studs spaced 16" on center, with batt insulation. The exterior is sheathed with oriented strand board (OSB), protected by building wrap, and finished with cement fiberboard. The interior is finished with painted gypsum board. The roof has a gable shape with a 6/12 pitch and features a scissor truss system, insulated with blown-in cellulose. The roof deck is covered with underlayment and finished with asphalt shingles. The foundation is a slab-on-grade. The windows are single-hung with vinyl frames and double-pane glazing. For an energy-efficient choice, mechanical systems featured a mini-split air conditioning system for cooling and heating, as well as an Energy Recovery Ventilator (ERV) for mechanical ventilation, and a standalone dehumidifier unit.

Figure 2: The two studied buildings: Top: Wood-frame building; Bottom: Rammed earth building (Source: SAAH, 2024).

The rammed earth building is currently under construction (Figure 2) and features 18'' thick rammed earth walls built using a mix of compacted earth, Portland cement, and water. The rammed earth walls are left without exterior or interior finishes, fully showcasing the construction material. The roof has a gable shape with a 6/12 pitch and is made of structural insulated panels. The roof deck is protected by underlayment and finished with asphalt shingles. The building's foundation consists of a concrete slab-on-grade, supporting the exterior rammed earth walls. The windows are single-hung with vinyl frames and double-pane glazing. The mechanical systems are similar to those of the wood-frame building.

Energy performance simulation

The goal of the study was to estimate the energy performance of the designed buildings and optimize it before construction. The buildings' designs had already been completed by the architectural and engineering teams prior to the energy efficiency analysis. To achieve this goal, building energy simulations and statistical analysis were conducted. The simulations were performed using DesignBuilder (DesignBuilder Software Ltd, n.d.), an EnergyPlus-based software tool that helps simulate, analyze, and optimize building designs for sustainability and comfort.

Each building was modeled separately, referencing the architectural, structural, mechanical, and electrical drawings and documents to ensure an accurate representation within the software (Figure 3). Several variables were held constant across the simulations for comparison between the two buildings, such as the TMY3 local weather files collected from the San Antonio International Airport, occupancy density (0.002 people/f^2), heating setpoint (68 °F) and setback (64 °F), and cooling setpoint (72 °F) and setback (78 °F). The simulation parameters including timestep, duration, output data parameters, and performance metrics were consistent across both buildings as well. Other parameters, such as building geometry, construction materials, thermal and surface properties, and mechanical systems, were specific to each construction method.

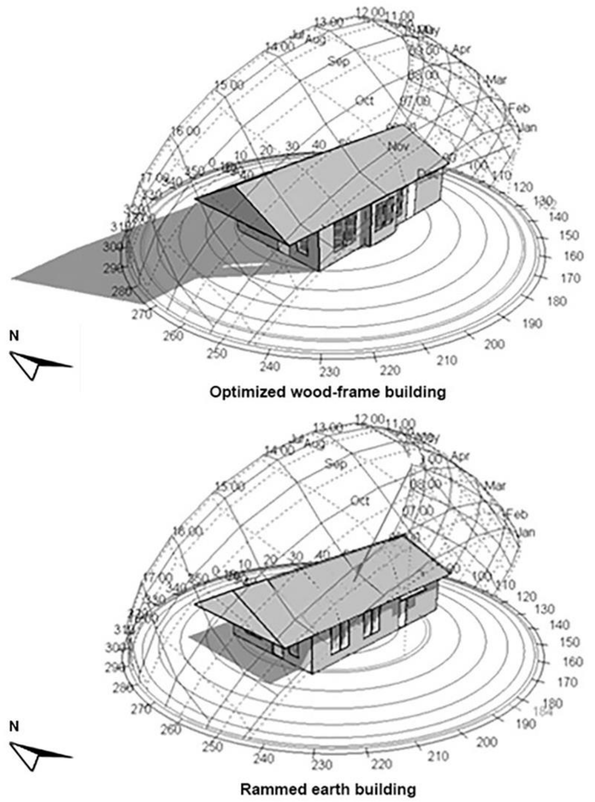

Figure 3. Energy models of the studied buildings in DesignBuilder.

Results and discussion

Energy optimization process of the wood-frame building

Different iterations were simulated in DesignBuilder to examine the influence of optimizing each envelope component separately, including the roof, walls, floors, windows, and infiltration rate, beyond the requirements of the San Antonio Energy Conservation Code (Code City of San Antonio, 2024). The iterations were selected based on the availability of products with similar specifications in the market, as well as affordability, ensuring that the chosen products remain within the set budget to keep the building affordable for low-income families. The simulations were conducted over the course of an entire year to ensure comprehensive results. These results were then evaluated by assessing improvements in measurable energy performance indices, including solar heat gains, indoor temperatures, and heating and cooling loads. These were compared with the cost-effectiveness of the selected materials after obtaining quotes for the chosen products. It is important to note that mechanical systems were not evaluated at this stage in order to isolate the impact of passive design solutions on the energy performance of the studied prototypes. However, the construction of these buildings incorporates energy-efficient mechanical systems, as detailed in the methodology section.

Roof: The minimum thermal resistance (ft^2·°F·h/Btu) requirement for roof insulation per code is R-38. Six iterations were simulated by varying only the R-Value of the roof insulation, namely R-40, R-42.5, R-45, R-47.5, R-50, and R-52.5. The results showed no significant improvement in the examined indices. For instance, while the difference between R-38 and R-52.5 resulted in a 13.9 % decrease in solar heat gains through the roof (707 Btu/ft^2), no change in indoor operative temperature was perceived. Additionally, total cooling loads were reduced only by 2.5 % (963 Btu/ft^2), and heating loads by 1 % (318 Btu/ft^2). Therefore, R-38 was selected as the optimal value for roof insulation, balancing both energy efficiency and affordability.

Walls: The minimum required R-value (ft^2·°F·h/Btu) for wall insulation in San Antonio is R-13. Six iterations were simulated, exceeding this minimum, including R-15.5, R-18, R-20.5, R-23, R-25.5, and R-28. While the first three iterations showed some improvements in energy performance indices, R-23 resulted in the most significant improvements. For example, R-23 led to a 33.2 % reduction in solar heat gains through the walls (583 Btu/ft^2), a 15.5 % decrease in total cooling loads (6,216 Btu/ft^2), and 14.0 % decrease in heating loads (4,426 Btu/ft^2). No considerable differences were observed with higher R-values (less than 1% in all indices). Therefore, R-23 was selected for optimal energy performance and cost-effectiveness.

Floor: According to the energy code in San Antonio, slab-on-grade floors do not require insulation. However, to ensure energy optimization, six iterations were simulated for floor insulation including R-5, R-10, R-15, R-20, R-25, and R-30. None of these values yielded great enhancements in the studied indices (less than 3 % in all indices), and thus no additional optimization beyond code requirements was considered for the floors.

Windows: While the energy code specifies a maximum value of 0.25 for glazed fenestration solar heat gain coefficient (SHGC), it doesn't have particular requirements for thermal transmittance (U-Factor). According to the original building design and market availability of conventional windows used in similar building types, the original U-Factor (Btu/ ft²·°F·h) was considered U-0.38. In the optimization process, SHGC-0.25 was kept unchanged due to budgeting constraints after careful examination of available products in the market. However, two iterations were simulated for the windows U-Factor, including U-0.3 and U-0.25. The results revealed that U-0.25 was a price-conscious option with great energy improvements. For instance, total cooling loads decreased by 13.5 % (5,397 Btu/ft^2) and heating loads decreased by 8.9 % (2,914 Btu/ft^2). Therefore, this value was selected.

Infiltration rate: The infiltration rate in the original construction was 4 ACH at 50 Pascals (Pa) based on prior testing of similar buildings in the city. Four additional iterations were simulated to lower this value to 3 ACH, 2 ACH, 1 ACH, and 0.6 ACH (passive house standard) (International Passive House Association, n.d.). Infiltration rate proved to have the biggest impact on energy efficiency as the lower the rate, the larger the energy savings. Reaching 0.6 ACH in air infiltration results in a decrease of 49.3 % in total cooling loads (19,794 Btu/ft^2), and 75.8 % in heating loads (24,965 Btu/ft^2).

After selecting the best specifications for all envelope components, a simulation was performed to test the accumulative impact of all optimizations. The results are presented in Figure 4. While solar heat gains through windows was 5,143 Btu/ft^2 in the original construction, the optimization resulted in a decrease of 52.5 % in that index. The most prominent impact was perceived on the cooling loads with an 80.7 % decrease leading to a value of 5,973 Btu/ft^2 post-optimization. This is especially important since San Antonio is a cooling-dominant climate, making cooling loads an impactful factor in electricity costs for cooling. Heating loads were also decreased by 39.7 % from a 13,884 Btu/ft^2 value before optimization. Finally, operative temperatures declined by 2.3 °F. These results reflect great improvements in the energy efficiency of the wood-frame structure. Therefore, they were applied when the building was constructed. A post-occupancy evaluation of the building is required to verify the simulated results.

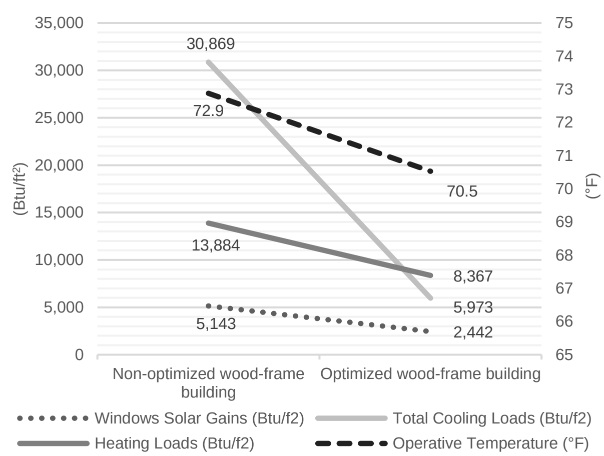

Figure 4. Results of the optimization of the wood-frame building.

Energy optimization process of the rammed earth building

The rammed earth building was designed following the optimization of the wood-frame building. As a result, many decisions regarding materials and thermal specifications were influenced by the experience gained from the first building. Other decisions were directly related to the unique characteristics of rammed earth construction. The same energy performance indices used in the wood-frame building were applied in the evaluation of the energy performance of the different building components. The observations were as follows:

Walls: Rammed earth walls have high thermal inertia and, therefore, no additional insulation was considered in this study. The specific mixture used in this building (3% Portland cement by weight, 8% water, and A2 base) was tested, yielding R-1 per inch of wall thickness, totaling an R-value of 18 ft²·°F·h/Btu for the entire wall.

Roof: Since the walls were constructed with rammed earth, the roof material offering the best results in terms of integration with the rammed earth and affordability was structural insulated panels. These panels have a thermal resistance value of R-38, similar to the wood-frame building. To prevent thermal bridging at the connection between the walls and the roof, the structural bond beam connecting the walls to the roof is lined with a rigid insulation board and covered with trim. The THERM software ((Lawrence Berkeley National Laboratory (LBNL), n.d.), which uses two-dimensional conduction and radiation heat-transfer analysis to evaluate the thermal performance of building components, was used to validate the outcomes of this strategy. The results showed that no heat was transferred into the interior of the building through the connection, as shown in Figure 5, confirming the efficacy of the design.

Floor: Similar to the wood-frame building, a slab-on-grade with no insulation was selected for this building. The exposed concrete footing is insulated on the exterior with 3-inch rigid foam insulation along the perimeter to prevent thermal bridging in the connection between rammed earth and concrete. A damp proofing membrane and trim are also installed to avoid moisture penetration to the insulation. The solution's effectiveness was also tested using the THERM software, which showed no heat transfer at the location of the insulation (Figure 5).

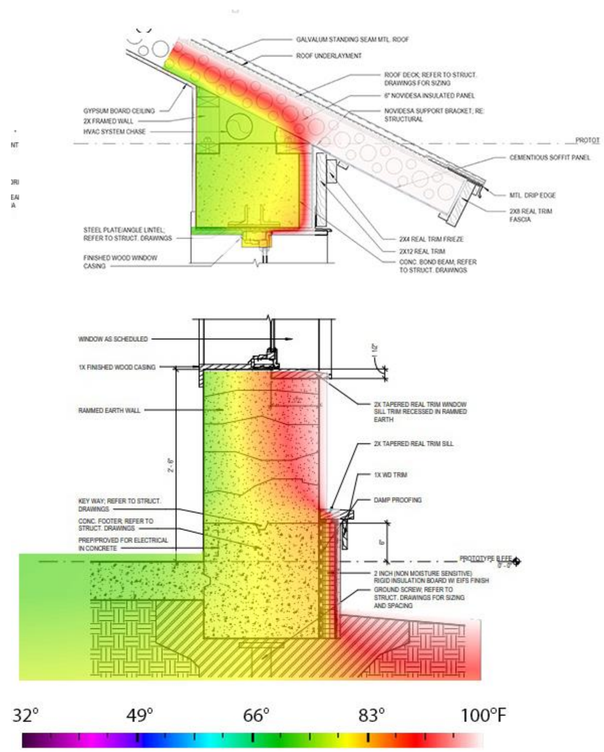

Figure 5. Thermal transfer analysis for different envelope components in the rammed earth building.

Windows: The window selection was based on the same analysis conducted for the wood-frame building. As a result, double-glazed windows with U-value of 0.25 and SHGC = 0.25 were selected for this building.

Infiltration rate: As with the wood-frame house, achieving a low infiltration rate of 0.6 ACH at 50 Pa has a profound effect on the overall performance of the building, and thus was targeted through effective air sealing of all envelope components and outdoor penetrations such as ducts.

The impact of the design and energy performance decisions made for the rammed earth building was tested through a simulation that incorporated all the aforementioned values. The results, shown in Figure 6, indicate that the overall energy efficiency of the rammed earth building was very similar to that of the optimized wood-frame building, even exceeding it in some indices.

The solar heat gains through the windows in the rammed earth house were 4,314 Btu/ft², higher than those in the optimized wood-frame house (2,442 Btu/ft²). This difference can be attributed to variations in window sizes and placement, which were influenced by the distinct characteristics of each construction type. While heating loads were similar for both buildings, 8,701 Btu/ft² for the rammed earth house and 8,367 Btu/ft² for the optimized wood-frame house, the total cooling loads were lower in the rammed earth building (4,889 Btu/ft²) compared to the wood-frame building (5,973 Btu/ft²). Additionally, the average indoor operative temperature in the rammed earth building was 2.0 °F lower than in the wood-frame building.

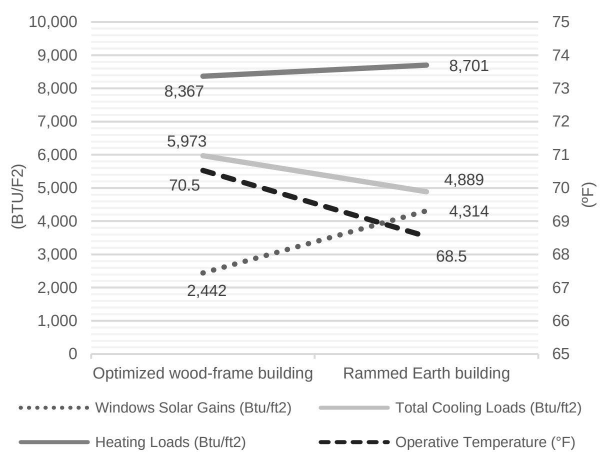

Figure 6. Energy performance of the rammed earth building compared to the optimized wood-frame building.

Conclusions

This study explored the energy performance of two adjacent single-family houses, one constructed using conventional wood-frame methods and the other with rammed earth construction, as part of the Single-Family Prototype Pilot Project. The goal was to optimize these buildings for both energy efficiency and affordability, while addressing the increasing demand for deeply affordable homeownership in San Antonio. The energy performance of the two buildings was evaluated through detailed simulations and comparisons, revealing important insights for sustainable and affordable housing design.

The results demonstrated that both the wood-frame and rammed earth buildings achieved high levels of energy efficiency. After optimizing the wood-frame building's thermal specifications, including walls, roof, floor, windows, and air infiltration, significant reductions in heating and cooling loads were observed, particularly in cooling loads, which were reduced by over 80%. These improvements, coupled with a decrease in operative temperature, showed the potential for substantial energy savings, making the wood-frame building more affordable for low-income families in a cooling-dominant climate like San Antonio.

The rammed earth building, while optimized based on the lessons learned from the wood-frame design, presented similar overall energy performance, with a few noteworthy differences. The solar heat gains through the windows were higher in the rammed earth house, primarily due to differences in window sizes and placements, reflecting the unique characteristics of rammed earth construction. Despite this, the rammed earth building demonstrated lower cooling loads, and a lower average indoor operative temperature compared to the wood-frame house. These advantages suggest that the thermal mass properties of the rammed earth walls played a significant role in reducing the need for active cooling.

The study also highlighted the importance of achieving low infiltration rates in both buildings. A reduced infiltration rate of 0.6 ACH, consistent with Passive House standards, had a profound effect on overall energy performance, particularly in reducing heating and cooling loads.

In conclusion, both the wood-frame and rammed earth buildings show promise as energy-efficient, affordable housing options. While the rammed earth building's performance was similar to the optimized wood-frame building, it outperformed the latter in certain areas, particularly cooling loads and indoor temperature regulation. These findings suggest that rammed earth construction can be a viable alternative to conventional building methods, offering substantial energy savings and thermal comfort in hot and humid climates. Future work, including a Life Cycle Assessment, will further evaluate the environmental impact of these construction types, providing valuable data for sustainable building practices aimed at addressing the housing affordability crisis in San Antonio and similar regions.

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