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# Energy performance of rammed earth building: A Kathmandu valley case study

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## Abstract

As the world's energy demands soar, the building sector is under pressure to innovate. Rammed earth (RE) construction emerges as a sustainable and efficient alternative that could revolutionize building design. With the right materials, preparation methods, and a focus on energy use efficiency, RE can significantly reduce our reliance on conventional heating and cooling systems by leveraging the natural thermal mass of the walls to maintain a consistent internal temperature year-round. Despite growing interest, particularly in the Kathmandu valley, there is a lack of research on the actual energy performance of RE buildings. This study aims to evaluate the energy performance of RE buildings using thermal imaging and energy simulation to compare RE walls with traditional brick walls. Results indicate that RE buildings perform better, with temperature differences of 2.9°C and 2.1°C in the south and west walls, respectively, as measured by a thermal imager at a distance of 1 meter and a height of 1.5 meters. Furthermore, simulation results reveal that RE construction exhibits the lowest heating and cooling loads, while brick masonry construction shows the highest. These findings suggest that incorporating RE construction can lead to significant energy savings and enhanced thermal comfort in buildings, offering practical applications for sustainable building practices and broader generalizability in similar geographical and climatic contexts.

***Keywords:*** *Brick wall construction, energy efficiency, rammed earth construction, thermal comfort, thermal performance*

## 1. Introduction

The surge in industrial development and population has resulted in the significant rise in the energy demand. In 2009, the building sector alone consumed 40% of the energy consumed in the United States and the European Union (Cabeza et al., 2013). The increase in the demand of thermal comfort has also caused the rise in energy demand. Thus, under these circumstances, it is of utmost necessity to use material that can enhance thermal performance without being expensive. As earth is one of the oldest and widely used building material, it can be utilized in the construction of more innovative and sustainable building structures.

Rammed earth (RE) walls produce very little carbon and are energy efficient (Reddy & Kumar, 2003). RE is constructed by compacting processed dirt in successive layers, which are sometime cemented with cement and other binders.

The primary constituents of RE are clay (15–25%), sand (50–60%), gravel (15–20%), with/without a small percentage of stabilizer such as cement (3–5%), and minimal water (8–12%), and finally tamping the mix in needed formwork using simple methods and tools (Alkadri & ÇETİN, 2021). The use of RE technology is justified as a low user of resources and energy compared to other construction methods (Reddy & Jagadish, 2001). RE construction can be classified into two types: stabilized and unstabilized. Stabilizers, such as cement, are added to stabilize RE blocks, whereas unstabilized RE blocks are more susceptible to saturation and erosion (Reddy & Kumar, 2003). Although RE is not a modern building technology, it offers a valuable approach to promoting sustainable development, which is essential in today's world.

When comparing a RE house to a conventional concrete house, the energy used in transportation can be decreased by 85 percent (Kariyawasam & Jayasinghe, 2016). The use of soil and cement to build unfired masonry blocks results in a 62 percent reduction in embodied energy compared to reinforced concrete and a 45 percent reduction compared to burnt clay brick masonry and reinforced concrete (Reddy & Kumar, 2003). Moreover, RE performs better in tropical climates than in temperate climates regarding energy efficiency (Anderson & Hasan, 2016). RE construction is also affordable as the main material, soil, is cheap and readily available. It offers endless possibilities for color and texture, creating unique and beautiful finishes, thus reducing rendering costs (Jaquin, 2012). RE external walls can be alternative to both lightweight and heavyweight construction (Medvey & Dobszay, 2020). The study "Embodied Energy of Cement Stabilized RE Wall" by Reddy & Kumar (2003) involved constructing an RE building in Bangalore and analyzing it through field observations, focusing on energy in transportation, mixing, and compaction. Their research highlights the significant thermal energy performance benefits of RE construction. Moreover, the study "Investigation of Energy Performance of RE Built Residential Houses in Sub-tropical, Tropical, and Temperate Climates of Australia" (Mahmudul Hasan et al., 2016) utilized NatHERS-accredited software to compare the energy consumption patterns of RE and brick constructions.

Despite extensive studies on the thermal performance and energy efficiency of rammed earth (RE) buildings, there is a notable gap in research specifically addressing RE structures in the unique climate and geography of the Kathmandu valley. Furthermore, while simulation software is commonly used for energy performance evaluation, field-based analysis is limited. This study bridges this gap by combining field observations with software simulations to assess the thermal performance and energy efficiency of an RE building compared to a conventional brick masonry building in Budhanilkhanta, Kathmandu. The findings inform about practical applications in sustainable building practices and provide generalizable insights for similar climatic regions.

## 2. Materials and Methods

This study used two-pronged approach – field observation and modeling tools for evaluating thermal performance of RE buildings.

### 2.1 Field observation

For the field-based study, a case building located at Budhanilkhanta area in the northern part of the Kathmandu valley in Nepal was selected. The ground floor of the building has an area of 510 sq. ft. The external walls have a thickness of 450 mm, while the internal walls measured are 300 mm in thickness. The windows were double glazed, and the building was oriented towards the northern direction. To ascertain the difference in outdoor and indoor temperature, a thermal imager was used. The instrument was positioned at a distance of 1m and at a height of 1.5 m from the wall. Temperature readings were taken from the south and west walls between 2 PM to 5 PM for eleven days during the monsoon season, although maintaining uniformity in time was challenging due to rainfall. Temperature readings were avoided during rainfall. The difference in temperature between the outer and inner walls was analysed to determine the thermal performance of the building. Figure 1 shows the thermal imager used, with essential specification:

i. Accuracy: At ambient temp. 15 to 35°C (59 to 95°F) and object temperature above 0°C (32°F), 0 to 100°C (32 to 212°F): ±3°C (±5.5°F), 100 to 400°C (212 to 752°F): ±3%

ii. Object temperature range: -20 to 400°C (-4 to 752°F)

iii. IR sensor: 160 x 120 (19,200 pixels)

iv. Battery operating time: 4 hours

v. Screen size: 3.5 in


**Figure 1:** Thermal imager

## 2.2 Energy modeling

Energy modeling in the building was conducted using the 'Ecotect' modeling tool. Building energy simulation is increasingly utilized as a cost-effective method to support energy efficient planning and subsequent operation and maintenance of buildings (Amani et al., 2022). Among available tools, Ecotect stands out for its capability to conduct simple yet fairly accurate thermal performance analysis, supported by visually responsive features. It employs a wide range of graphical methods for result verification, savable as Metafiles, Bitmaps, or animations. Researchers frequently employ Ecotect for evaluating required design configurations (Crawley et al., 2001).

Meteorological parameters for the Budhanilkhanta area, including annual temperature, radiation, relative humidity, and wind direction for the Budhanilkhanta area were determined using this tool. Due to unavailability of data specific to the area of the building, Kathmandu's average temperature data was used, with an average deviation of 2.3°C between the two regions. The weather file of Kathmandu was used for thermal analysis, with the analysis set on January 1st at 12:45 PM. Occupancy levels and activities were considered for a restaurant scenario, with sedentary occupants emitting a biological heat output of 70 W. Average relative humidity was set at 60%, and air speed at 0.5 m/s. The building's operational hours were considered from 8 AM to 8 PM. Thermal properties were determined for various building materials: rammed earth walls (0.35-0.7 W/m²K), double-glazed windows (1.2-3.7 W/m²K), single-glazed windows (4.8-5.8 W/m²K), solid brick walls (2 W/m²K), and solid timber doors (3 W/m²K). The thermal performance, including heating and cooling loads, was analyzed across three scenarios:

- Case 1- Base case scenario (Scenario 1): The building was simulated with existing rammed earth construction.
- Case 2- Modification scenario (Scenario 2): Changes in the thickness of outer and inner walls were simulated.
- Case 3- Replacement scenario (Scenario 3): Rammed earth walls were replaced with brick walls.

## 3. Literature Review

Rammed earth (RE) construction dates back to the development of civilization, with evidence found in various river valley civilizations such as the Tigris and Euphrates, Nile, Indus, Jordan, Murghab, and Yellow River valleys (Jaquin, 2012).

### 3.1 Energy efficiency and earth construction

Brick kilns contribute 500,000 tons of carbon monoxide annually, along with nitrogen oxide, sulfur dioxide, and 829 million tons of carbon dioxide (Gowda, 2016) posing significant threat to human health and environment. This has promoted research into stabilized earth blocks, which require less than 10% of the energy input for manufacturing compared to fired clay and concrete masonry units (Gowda, 2016). RE structures, due to their availability, ease of preparation, energy use efficiency, and environmental impact are a viable alternative (Samadianfard & Toufigh, 2020). RE materials are environment-friendly and possess high thermo-buffering capability ( Samadianfard & Toufigh, 2020), enabling them to conserve and store heat throughout the day and release it as temperature drop at night. RE construction offer significant embodied energy savings compared to conventional systems (Treloar et al., 2001).

### 3.2 Energy performance of rammed earth

The construction industry, responsible for the majority of new structures, consumes 36 percent of total energy and 51 percent of electricity (Mishra & Rai, 2017). To assess the energy efficiency of RE, a hygrothermal chamber was devised and erected, and Fourier's law was utilized to determine the thermal conductivity of these materials. Research on the thermal performance of RE indicates superior performance with a 3°C reduction in indoor temperature compared to brick walls (Kariyawasam & Jayasinghe, 2016), suggesting lower energy demand for maintaining thermally comfortable buildings with compressed stabilized rammed construction. Stablized RE demonstrates proper thermal efficiency compared to masonry materials, with the added benefit of acrylic coating, leading to acceptable thermal comfort limits according to the ASHRAE 55 standard (Samadianfard & Toufigh, 2020). Moreover, RE materials stabilized with cement show greater efficiency than masonry materials, indicating good thermal mass due to their long time lag and low heat flux (Samadianfard & Toufigh, 2020). A study in Wolver Hampton, United Kingdom, revealed that the embodied energy consumed by the RE ranged from 5 to 20 kWh/m$^3$, while fired brick consumed 1140 kWh/m$^3$ and cement consumed 2640 kWh/m$^3$ (Egenti & Khatib, 2010). Rammed-earth structures naturally control internal environments by cooling interiors during hot summers and absorbing heat in winters, effectively reducing carbon dioxide emissions related to energy consumption during construction and over the structure's lifetime (Chang Recavarren et al., 2013).

In contrast, solid clay brick as a building often entails high energy consumption and low thermal comfort. Rammed earth construction remains cool in summer and warm in winter due to its low coefficient of thermal conductivity and thermal inertia (Lu & Liu, 2013) making it an environmentally friendly, green, and energy-efficient building choices (Cheikhi et al., 2018). The study done in Marrakech, Morocco, by Cheikhi et al. (2018) demonstrates through dynamic thermal simulation (DTS) in design builder software that rammed earth as an ecological, renewable and energy-saving building material aligning perfectly with energy efficient approaches. Similarly, previous research by Hardin et al. (2003), Taylor and Luther (2004), Mani et al. (2007), and Soebarto (2009) have explored the indoor efficiency of RE structures worldwide (Table 1) with reduced internal thermal fluctuations observer across various locations (Ciancio & Christopher, 2012).

**Table 1:** Thermal lag and internal air temperature variations for investigated RE structures (S="summer", W= "winter")

| Source | Location | External daily Temperature range (°C) | Wall Thickness (mm) | Thermal lag | Internal diurnal air temperature variation (°C) |
|---|---|---|---|---|---|
| Hardin et.al (2003) | Sonoran Desert, North America | 21-40 | 450-610 | 12-16 | Maxima and minima unreported, 4.5 range for all cases |
| Taylor and Luther, 2004 | New South wales, Australia | 18-31 | 300 | 3 | 23-27 (1.1m above floor level) |
| Mani et.al | Banskuti, West Bengal | 21-33 | 300 | 5 | 23.5-25.5 |
| Soebarto 2009 | Willunga, South Australia | 6-15 (w, worst case) 17-30 (s) | 220 | 6 | 12-15 (w, worst case) 21-32(s, worst case) |

RE structures effectively reduce carbon dioxide emissions during both construction and their lifetime (Recavarren, Fiori, & Schexnayder, 2014). Finding reveled that burnt clay brick masonry exhibits the highest embodied energy, ranging from 2.00 to 3.40. Unstable RE buildings have the lowest embodied energy, ranging from 0.00 to 0.18 while the stable RE buildings range from 0.45 to 0.60 which compares favorably to burnt clay brick masonry (Reddy & Jagadish, 2009). Rammed earth buildings worldwide provide suitable living conditions across various climates without relying on active HVAC regulation (David Allinson, 2007). A study on Matoghar, Kathmandu reveals that modern RE structures are generally 1-2°C warmer than the traditional and modern residential structures (Yonzan & Bajracharya, 2022). Raw earth also offers excellent sound and heat insulation properties, along with superior fire proofing compared to brick construction (Lu & Liu, 2013).

## 4. Findings and Discussion

To conduct a thermal analysis of rammed earth building, a specific case building located in Budhanilkantha Municipality was selected (Figure 2). This building serves as a public facility. In order to determine thermal temperature differences, thermal imager was utilized to identify the maximum and minimum temperatures of the walls.

**Figure 2:** Case study building

The study focused on south and west walls. Thermal imaging was conducted on both exterior and interior walls and temperature data were recorded. Analysis was performed based on the temperature difference between the exterior and interior over an eleven-day period. Thermal images were captured at a distance of 1 m from the wall and at the height of 1.5 m.Data readings were taken twice a day. Due to the monsoon season, temperature readings were omitted during rainfall.

### 4.1 Observed thermal efficiency

*4.1.1 Temperature reading of south wall*

The results of the south wall measurements are presented in the Table 2. It reveals that the maximum temperature difference between the outer and inner walls is 4.8°C, observed on 8/19/2021. The average temperature difference is calculated to be 2.9°C. Moreover, the minimum temperature difference is recorded at 0.5°C, noted on 8/20/2021.

**Table 2:** Temperature reading of south wall

| Date | Block | Direction | Type | Time (PM) | Exterior (ºC) | Interior (ºC) | Difference (ºC) |
|---|---|---|---|---|---|---|---|
| 17/7/2021 | Main | South | Wall | 1:30 | 25.9 | 23.4 | 2.5 |
| | | South | Wall | 4:00 | 25.3 | 23.8 | 1.5 |
| 18/7/2021 | Main | South | Wall | 12:25 | 29.9 | 26.45 | 3.45 |
| | | South | Wall | 4:00 | 27.3 | 23.3 | 4.00 |
| 22/7/2021 | Main | South | Wall | 2:13 | 29.7 | 26.4 | 3.30 |
| 25/7/2021 | Main | South | Wall | 12:30 | 26.2 | 23.6 | 2.60 |
| | | South | Wall | 4:00 | 24.6 | 22.05 | 2.55 |
| 26/7/2021 | Main | South | Wall | 12:30 | 26.9 | 23 | 3.90 |
| | | South | Wall | 4:30 | 25.75 | 22.75 | 3.00 |
| 29/7/2021 | Main | South | Wall | 2:45 | 29.8 | 26.4 | 3.40 |
| 30/7/2021 | Main | South | Wall | 2:45 | 27.9 | 23.4 | 4.50 |
| | | South | Wall | 4:30 | 28.4 | 25.7 | 2.70 |
| 17/8/2021 | Main | South | Wall | 2:45 | 27.3 | 24.15 | 3.15 |
| | | South | Wall | 4:30 | 26.7 | 24.35 | 2.35 |
| 18/8/2021 | Main | South | Wall | 2:45 | 26.85 | 23.3 | 3.55 |
| | | South | Wall | 4:30 | 25.4 | 22.6 | 2.80 |
| 19/8/2021 | Main | South | Wall | 2:45 | 28.4 | 23.6 | 4.80 |
| | | South | Wall | 4:30 | 27.45 | 24.2 | 3.25 |
| 20/8/2021 | Main | South | Wall | 2:25 | 26.85 | 24.9 | 1.95 |
| | | South | Wall | 4:30 | 24.1 | 23.6 | 0.50 |

*4.1.2 Temperature reading of west wall*

The results from the west wall measurement are presented in the Table 3. It indicates that the maximum outdoor temperature was 4.8°C recorded on 7/19/2021. The average temperature difference between the outer and inner walls was found to be 2.1°C.

**Table 3:** Temperature reading of west wall

| Date | Block | Direction | Type | Time (PM) | Exterior (ºC) | Interior (ºC) | Difference (ºC) |
|---|---|---|---|---|---|---|---|
| 17/7/2021 | Main | West | Wall | 1:30 | 24.9 | 23.1 | 1.80 |
| | | West | Wall | 4:00 | 26.7 | 24.9 | 1.80 |
| 18/7/2021 | Main | West | Wall | 12:25 | 25.9 | 23.6 | 2.30 |
| | | West | Wall | 4:00 | 28.6 | 25 | 3.60 |
| 22/7/2021 | Main | West | Wall | 2:13 | 29.4 | 22.2 | 2.20 |
| 25/7/2021 | Main | West | Wall | 12:30 | 25.8 | 25.3 | 0.50 |
| | | West | Wall | 4:00 | 25.9 | 23.55 | 2.35 |
| 26/7/2021 | Main | West | Wall | 12:30 | 27 | 24.7 | 2.30 |
| | | West | Wall | 4:30 | 26.9 | 24.2 | 2.70 |
| 29/7/2021 | Main | West | Wall | 2:45 | 28.5 | 24.5 | 4.00 |
| 30/7/2021 | Main | West | Wall | 2:45 | 28.6 | 25.5 | 3.10 |
| | | West | Wall | 4:30 | 29.35 | 24.55 | 4.80 |
| 17/8/2021 | Main | West | Wall | 2:45 | 25.9 | 25.3 | 0.60 |
| | | West | Wall | 4:30 | 26.9 | 24.65 | 2.25 |
| 18/8/2021 | Main | West | Wall | 2:45 | 25.55 | 24.3 | 1.25 |
| | | West | Wall | 4:30 | 25.2 | 23.9 | 1.30 |
| 19/8/2021 | Main | West | Wall | 2:45 | 26.6 | 23.6 | 3.00 |
| | | West | Wall | 4:30 | 27.95 | 26 | 1.95 |
| 20/8/2021 | Main | West | Wall | 2:25 | 24.9 | 23.95 | 0.95 |
| | | West | Wall | 4:30 | 24.45 | 23.85 | 0.60 |

## 4.2 Simulated thermal efficiency

In case 1, the base case scenario involved simulating the building with existing construction technology, comprising a rammed earth wall of 300 mm thickness, a 125 mm slab and double-glazed window with aluminum frames. The height of the ground floor of the building is 2700 mm. Case 2 entailed an improved scenario achieved by modifying the internal planning of the building. The external wall was increased to 500 mm thickness while the internal wall remained at 300 mm. The building was converted into one bed room apartment, utilizing the existing construction materials with double glazed aluminum framed windows.

In case 3, the building was simulated with a brick wall of 250 mm thickness for the outer wall and 125 mm thickness for the inner wall. The window in this scenario was assumed to be single glazed with an aluminum frame.

Figures 3 and 4 depict the monthly heating and cooling loads comparison, respectively, in North direction among the various scenarios created. The figure illustrates that scenario 2 has the maximum heating load, whereas scenario 1 exhibits the minimum heating load based on the data analysis for January. Moreover, as per Figure 4, the cooling load is maximum in scenario 3 and minimum in scenario 1 based on the data analysis for the month of August.

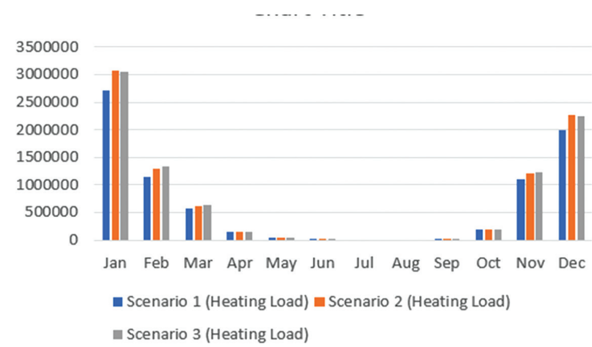


**Figure 3:** Comparison of heating load in north direction in different scenarios

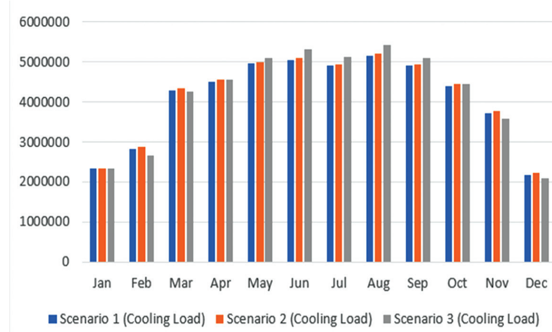


**Figure 4:** Comparison of cooling load in north direction in different scenarios

Although the existing building is north oriented, the analysis was conducted in all directions. The Figures 5 and 6 show the building's analysis in the south direction. The minimum heating load is observed in the base scenario (scenario 1), which uses rammed earth. The maximum heating load occurs in scenario 3 which uses brick construction. The maximum cooling load is also in scenario 3 during August, while, the minimum cooling load is in scenario 1, the existing rammed earth construction.

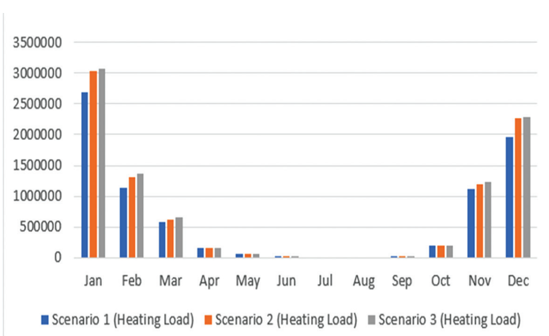


**Figure 5:** Comparison of heating load in south direction in Different Scenarios

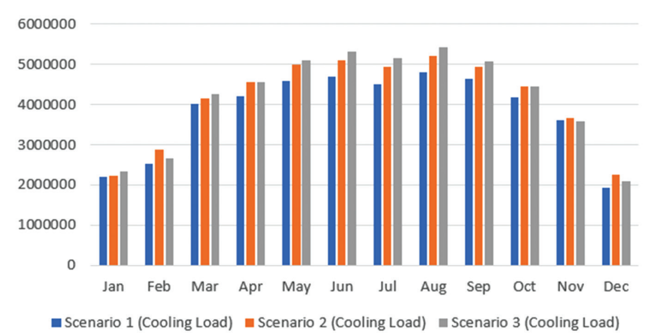


**Figure 6:** Comparison of cooling load in south direction in different scenarios

Figure 7 shows that the minimum heating load in west direction is in the base scenario (scenario 1) which uses rammed earth. The maximum heating load occurs in scenario 3, which uses brick masonry construction.

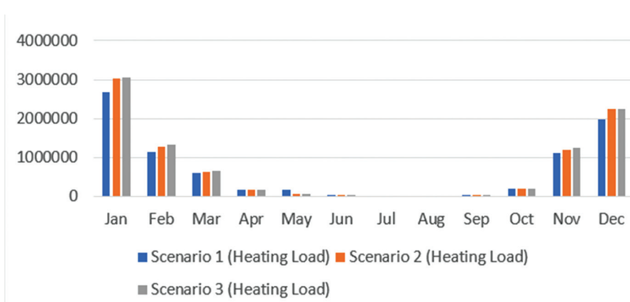


**Figure 7:** Comparison of heating load in west direction in different scenarios

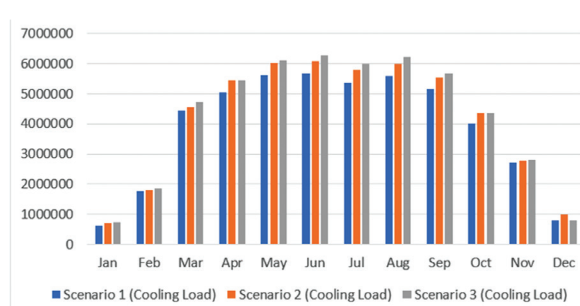


**Figure 8:** Comparison of cooling load in west direction in different scenarios

Figure 9 indicates that the minimum heating load in east direction is in the base scenario (scenario 1) while the maximum heating load is in scenario 3 which uses brick masonry construction. The table shows that the maximum cooling load is in scenario 3 in June while the minimum cooling load is in scenario 1 - the existing rammed earth construction.

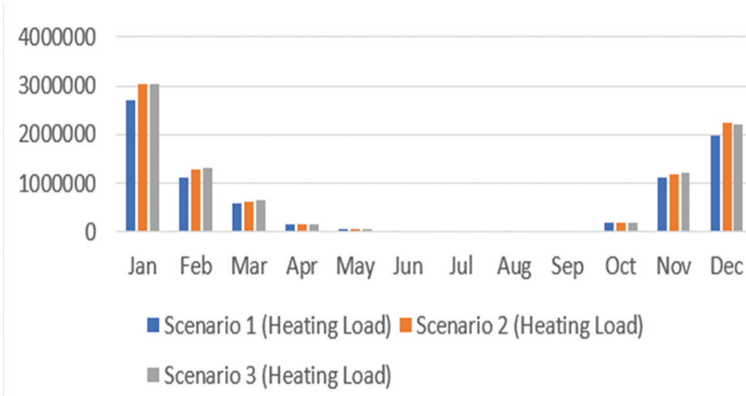


**Figure 9:** Comparison of heating load in east direction in different scenarios

### 4.3 Discussion

The analysis of thermal imaging data from rammed earth construction revealed crucial insights into its thermal performance. Specifically, it showed an average temperature difference of 2.9°C between the outer and the inner walls in the southern direction. This substantial difference underscores the efficient heat insulation properties of rammed earth, suggesting its potential as an energy-saving building material. Moreover, the comparison with brick masonry construction further highlighted the advantages of rammed earth. The average temperature difference of 2.10°C observed in brick masonry structures indicated less effective thermal insulation compared to rammed earth. This emphasizes the importance of selecting appropriate construction materials to achieve optimal thermal comfort and energy efficiency. However, it's essential to note that the absence of a comparable building design for further thermal comparison limited the scope of the observation. Despite this limitation, the focused analysis provided valuable insights into the thermal performance of rammed earth buildings, laying the foundation for future research and practical applications in similar contexts.

The simulation results complemented the field observations by offering a broader comparative analysis of rammed earth and brick construction under various conditions. The simulations confirmed the superior thermal performance of rammed earth, demonstrating minimal heating and cooling loads compared to brick masonry. This reinforces the notion that rammed earth is not only energy-efficient but also capable of providing superior thermal comfort in diverse climatic conditions. These findings are consistent with existing literature, such as the study by Yonzan & Bajracharya (2022), which emphasized the warmer temperatures observed in rammed earth buildings compared to contemporary structures. This alignment with previous research underscores the reliability and generalizability of the conclusions drawn from the current study, further validating the potential of rammed earth as a sustainable building material for enhancing thermal comfort and energy efficiency.

## 5. Conclusions

Rammed earth (RE) is one of the ancient and sustainable material of construction. RE stands as a testament to ancient wisdom, offering both sustainability and significant energy efficiency benefits. Analysis of an RE building in Budhanilkantha, Kathmandu, revealed notable temperature differences compared to brick walls. Thermal imaging showed an average temperature difference of 3.0°C on the southern wall and 2.1°C on the western wall, emphasizing RE's thermal advantages.

Moreover, simulation results provided further insights, enabling a comprehensive comparative analysis between rammed earth and brick masonry construction. This combined approach, integrating field observations with simulation data, demonstrated that rammed earth outperforms brick masonry in terms of thermal performance.

While acknowledging the absence of a comparable building design for further thermal comparison, which limited the scope of the observation, it's important to note potential variations in geographical settings, architectural designs, and construction methodologies as limitations. However, the demonstrated benefits of RE offer practical applications for energy-conscious building practices. These findings underscore the feasibility and efficacy of integrating RE into modern construction, providing a pathway towards more sustainable and energy-efficient buildings, particularly in similar geographical and climatic contexts.

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