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Achieving Thermal Comfort through Passive Design Strategies in Energy-Efficient Rammed Earth Building

Ankita Yonzan [a], Sushil B. Bajracharya [b]

[a, b] *Department of Architecture, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
✉ [a] ankitayyonzan12@gmail.com

Abstract

Rammed earth is an ancient technological marvel that has been constructed in various parts of the world and refined for better mechanical performance and sustainability with a low carbon footprint. In recent years, rammed earth investigations point out its cheap nature, durability, low embodied energy, and high thermal mass. In the context of Nepal, rammed earth construction is slowly growing in numbers despite some skepticism about it's thermal and mechanical performance compared to modern concrete structures. This study highlights the thermal comfort based on the thermal performance of two energy-efficient rammed earth structures, namely, Mato-Ghar and Madan Puraskar Pustakalaya in the warm temperate climate of Nepal during the winter season. Both of these buildings incorporate modern passive design strategies. The comparison between the indoor thermal comfort of traditional houses,modern houses, and energy-efficient rammed earth buildings showed that both Mato-Ghar and Madan Pustakalaya appear warmer than the historic and contemporary structures in Kathmandu, with Matoghar being the warmest of all of them. Mato-Ghar structure is atleast 1-2℃ warmer than the other structures. Moreover, it requires less energy to maintain thermal comfort in rammed earth structures than in other contemporary structures.

Keywords

Rammed earth,Thermal comfort, Thermal Performance, Comfort Temperature, Passive design strategies

1. Introduction

1.1 Background

In recent years, the rejuvenated emergence of raw earth construction is associated with its cheap nature, durability, and low embodied energy. Rammed earth, one of the most long-lasting earth materials, is an ancient technological marvel that has been constructed in various parts of the world and refined for better mechanical performance and sustainability with a low carbon footprint. While comparing with widely used concrete, it has a less environmental impact and good insulation for heat and sound [1]. The reason is due to it's high thermal mass property which is also an important aspect of the passive design strategies[2]. It has allowed people to build completely load-bearing high buildings up to 4 stories in high seismic zones while also providing high thermal comfort, waterproof, fireproof, sustainable buildings[3].

In Nepal, the Annapurna region, Mustang, traditional rammed earth structure can be seen in both monumental and vernacular architecture of the high altitude dry region of the Mustang Kingdom[4]. These traditional structures provide insights into how people used their practical knowledge to obtain climate-responsive designs to fulfill their desired levels of thermal comfort. Modern rammed earth construction, which is an updated form of traditional rammed earth technology, have been constructed in different locations of Nepal. The most fascinating aspect of these rammed earth structures is their blend with the local nature even when seen in clusters and different arrangements from an architectural viewpoint. It is necessary to understand the thermal behavior of rammed earth to assess the thermal environment as it impact the individuals in their day to day life and health.

Maintaining thermal comfort by decreasing the hours of thermally uncomfortable periods is necessary for better day to day performance, which can be achieved in rammed earth houses. If thermal comfort conditions are provided, then the increased confidence along with good health conditions helps to improve the output efficiency in both physical as well as intellectual tasks. This fact has been proven in many studies related to office buildings and research facilities[5]. In recent times, thermal comfort studies have been done by many scholars to advance technologies for low thermal energy consumption, sustainability, and carbon efficiency[6]. Examination of residential rammed earth dwellings in Lalitpur, Nepal, and local people have admired its decent thermal performance with temperature variance between outside and inside the room nearly (15–20°C) in cold and around (9–12°C) in hot summer[7].

The main significance of this study is gaining more information about the traditional and present rammed earth construction techniques, their performance difference, and their feasibility in the context of Nepal to establish rammed earth as a sustainable and thermally stable construction material.

1.2 Problem Statement

Thermal performance studies for rammed earth structures have been previously done, showing the immense possibility of it being used in small-scale housing construction and replacing the concrete jungle that we live in in the name of urbanization. However, despite its emerging innovations and advantages, rammed earth construction has not taken the height of the common concrete structures. This down surge may be due to the ignorance of its positive aspects, which is based on a lack of research in comparison to the concrete structures, difficulty in gathering required labor for rammed earth construction, and difficulty in construction. People's opinion is largely based on the skepticism that whether rammed earth houses can withstand the various static(self-weight) and dynamic loads(earthquakes) and maintain the thermal standards for living inside the house. Their judgment might be based on the traditional rammed earth structures, which were not designed with modern technologies to enhance thermal properties like thermal resistance. In the context of Nepal, the gap between the number of rammed earth and concrete construction is higher. Some organizations like UN-habitat have working projects to spread awareness about sustainable structures that produce fewer greenhouse gases which is important to reduce urban poverty[1]. In terms of rammed earth building, it is a surprise that even with low cost and sustainability, such structures are limited to only a handful. Bodach et al. defined the bio-climatic zones in Nepal by using the psychrometric chart to identify passive design strategies for each location [1]. Taylor has suggested that in hot climates, the width of the rammed earth walls may be increased for the structure to perform better as less heat is conducted due to more width[8]. The theoretical heat transfer analysis and the in-situ site experiments have shown that rammed earth provides good thermal performance due to its low thermal conductivity and high heat capacity allowing thermal control[9]. More analysis is necessary for more clarification and comparison between rammed earth structures and conventional structures. The research is focused on fulfilling the gaps in understanding the relationship between thermal comfort, thermal performance, and the local climatic conditions to understand the influencing factors that affect the structure's thermal performance.

1.3 Research Objective

The scope and limitation of research are limited to the following question:

- What is the condition of thermal comfort in energy efficient rammed earth buildings in Nepal?
- Is the thermal performance of rammed earth structure consistent throughout the morning, noon and evening?
- Compared to common construction methods, does present rammed earth technology help to achieve better thermal comfort conditions?

2. Methodology

2.1 Investigated area

Budanilkantha and Patan are study areas for modern rammed earth buildings which is located in the valley of Kathmandu. Both cities are located in Kathmandu Valley which generally has a relatively mild, warm, and temperate. There is significantly less rainfall in the wintertime than in the summertime. Köppen and Geiger classify this location as Cwb. This study is conducted to effectively quantify the thermal performance to achieve the occupant's needs for thermal comfort and direct further research towards the alternatives of thermal comfort by considering adaptation to a comfortable environment. Therefore, quantitative analysis with both a field questionnaire survey and site measurement of physical properties of the surrounding is done. Thermal conditions within buildings are assessed utilizing field data, sample analysis, regression analysis, discussion, and an effort to arrive at findings. Below is a detailed explanation of the study's methodology. With the aid of the SPSS program, all of the field data was statistically examined.

2.2 Investigated buildings

The two rammed earth structures that are investigated in this study are shown in Figure 1. Madan Puraskar Pustakalaya(M.P.) was established in 1955; however, it was reconstructed in 2016. The building was planned and constructed at the edge of the site with orientation North-South to gain maximum north light creating a welcoming and comfortable environment. The building walls are constructed of rammed earth that contains clay, some gravel dust, and stone. Wattle and daub are used as binding materials. Reinforcements are used to make the building a single unit. The thickness of the wall is 16 inches having large windows on the north side to allow the natural light to enter throughout the day. The size of the window openings is 5'x5', consisting of 2 numbers on the ground floor and 3 on the first floor on both the north and south side. In addition, the size of the main door on the west side is 4' x 7'. The roof is constructed using bamboo as the primary support in which the other layer is laid and covered with tiles. Similarly, struts are used to support the external bamboo.

Another rammed earth structure, Mato-Ghar(M.G.) of Buddhanilkantha, was built around 2011 and designed with passive solar techniques. Mud or "Mato" in the local Nepalese language is the main ingredient for construction. The building form is rectangular, and its form and utility have been described in previous studies[10]. The room has been arranged linearly along the east-west direction, with living spaces on the southern side while other utility rooms are towards the north. The structure has also been referred to be an autonomous structure because no problems were encountered throughout the blockade The structure was created using passive design methods. The project took 1.5 years to complete in all, with a lot of trial and error along the way. The foundation was built of stone with a maximum depth of 2' and a 6' coat of bitumen to avoid the cold. The outer walls are 18" thick, while the internal walls are only 4". Linseed oil is used to finish the flooring in the structure.

2.3 Measurement of air temperature

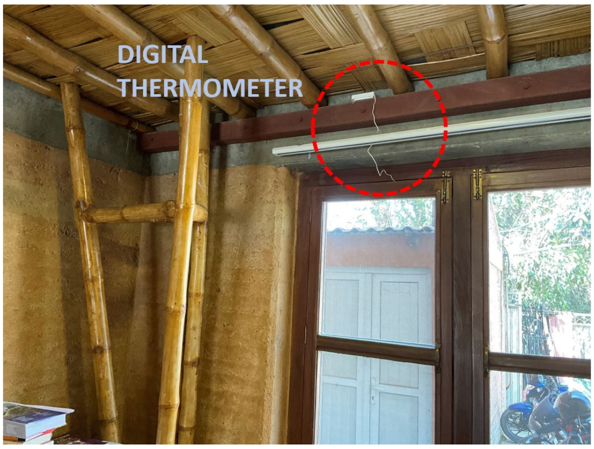


Figure 2: Digital Thermometer placed for thermal measurement

A digital hygrometer is used to determine both the inside and outside temperatures. The Digital Hygrometer comes with a thermo-hygrometer that measures relative humidity as well as air temperature. It features a large LCD to allow users to view both time and humidity. The device comes with a sensor affixed to the thermometer that is connected outside the building to measure the temperature from the outside, while the thermometer is situated within the building to measure the temperature from the inside. Field measurements of the structure's environmental characteristics were taken from February 17 to February 23, covering the whole week of the winter season. For both buildings, same type of thermometer was used. The placement of the digital thermometer is shown in Figure 2. The main screen of the thermometer is 150 cm above each floor level for interior measurement stations. To measure the temperature of the outdoors, a wire that was attached to a thermometer within the structure was placed outside beneath the roof overhang. Nearly 30 cm below the level of the roof, the external measurement point was carefully recorded as displayed on the LCD screen. The thermometer was shielded from the sun the entire day. By using a digital hygrometer, all data were manually monitored three times every day for one week. Every day at seven in the morning, one in the afternoon, and seven in the evening, all data were collected. The obtained data were used for further regression analysis as well as for determination of comfort and preferred temperature.

Figure 1: Two Rammed earth structures:(Madan Pustakalaya and Matoghar)

2.4 Thermal comfort survey

The thermal comfort survey was done to find the comfort temperature and preferred temperature of the users of the respective rammed earth buildings. More emphasis is given to Madan Pustakalaya as it is a library with a more significant number of users that can be surveyed. A total of 13 respondents were surveyed, among which 3 respondents were the citizens of Matoghar while the other 10 were readers from the library. The thermal measurements were also carried during the time of survey. The survey was conducted at the same time of the same day during the winter period along with the temperature measurements. The comfort temperature and preffered temperatures are calculated based on the modified Griffith's calculation[11]. To evaluate the overall thermal responses, the 'thermal comfort zone' of this research are classified as ± 1 for thermal sensation (on a 7- point scale), ±1 for thermal preference (5-point scale), and ±1 for overall comfort (6-point scale). The comfort temperature (T_c) and preferred temperature (T_p) are calculated using the equations below. It is considered useful when linear regression is unreliable to estimate the comfort temperature. Based on the respondents' votes of thermal sensation and the corresponding values of measured indoor globe temperature, we estimated the comfort temperature by using the equation:

$$T_c = T_g + \frac{(4 - mTSV)}{a^*} \tag{1}$$

$$T_p = T_g + \frac{(4 - TP)}{a^{**}} \tag{2}$$

Where; T_c, T_g, T_p, a^* are the comfort temperature, globe temperature, preferred temperature, increment of thermal sensation vote, assumed increment of preference vote corresponding to an increase of 3 ℃ in global temperature respectively. More details about the equation (1) (2) in reference[11].

3. Data Presentation and Analysis

3.1 In-Out temperature difference between Madan Pustakalaya and Mato Ghar

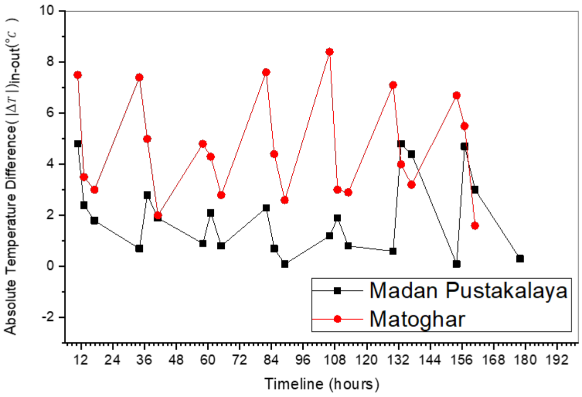


Figure 3: 7 days in-out temperature difference

Figure 3 shows that the indoor to outdoor temperature difference in Matoghar is greater than that in the Madan Pustakalaya. The average absolute in-out temperature difference for Madan Pustakalaya and Matoghar is 1.778°C and 4.638°C,respectively. The plausible reason for such results may be due to the presence of additional insulation layers in Matoghar and the difference in thickness of walls. The wall thickness of Matoghar is 2 inches thicker than the thickness of Madan Pustakalaya, the walls have a higher thermal mass for stabilizing the temperatures for a longer duration during the winter. Furthermore, The application of these results primarily suggests more research on the thickness optimization of the rammed earth walls. This helps in reducing dependencies on other non-energy efficient methods of heating and helps save energy while maintaining comfort.

3.2 Comparison of thermal performance during the morning, day, and evening

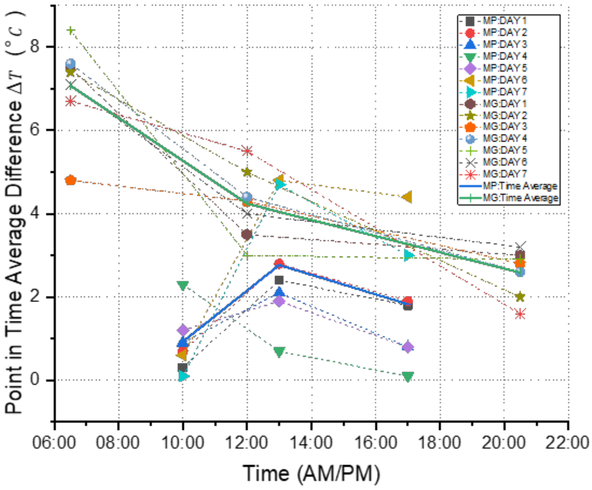
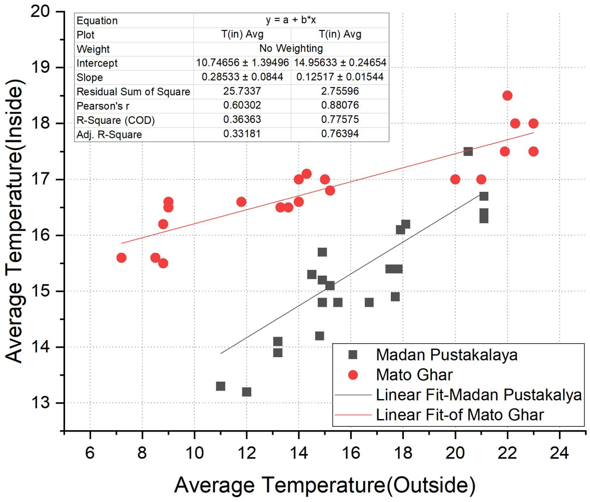


Figure 4: Morning, day and Evening Temperature Differences

Figure 4 shows the point-in-time average difference between indoor and outdoor temperature between Matoghar and Madan Pustakalaya for the 7 days in the morning, day, and evening period. The in-out temperature difference in Matoghar in the morning period shows very good insulation as the morning outside temperature is lower than the temperature inside the structure for all the 7 days in the winter period. This implies that the rammed earth walls and floors of Matoghar provide better thermal performance in the morning hours than the walls of Madan Pustakalaya. The calculated hourly average temperature gradients from morning to noon for Madan Pustakalaya and Matoghar are +0.61 and -0.51 respectively. Similarly, the values for noon to evening for Madan Pustakalaya and Matoghar are -0.23 and -0.19 respectively. This shows that the temperature in Matoghar rises rapidly with the increasing outside temperature in the morning whereas for Madan Pustakalaya the increasing temperature gradient indicates a slower temperature rise. From, the afternoon to the evening period, Madan pustakalaya cools down faster than the Matoghar.

3.3 Comfort and Preferred Temperature

Before calculating the comfort and preferred temperature, a linear fit between outside and inside temperature for Madan Pustakalaya was done which is shown in Figure 5. In Gautam et al.'s article, our linear fit was compared with the linear fit curve of the three different regions of Nepal in the article for the winter period[11]. The comparison showed that the linear regression equation for the temperate region is similar to Madan Pustakalaya and Matoghar; hence, we used their regression equation to calculate the indoor globe temperature given by Gautam et al. for the winter period in the temperate region. The applied regression equation is shown in Equation 4, The comfort temperature and preferred temperature are calculated according to the equations 3 and 4.



Equation	y = a + b*x	
Plot	T(in) Avg	T(in) Avg
Weight	No Weighting	
Intercept	10.74656 ± 1.39496	14.95633 ± 0.24654
Slope	0.28533 ± 0.0844	0.12517 ± 0.01544
Residual Sum of Square	25.7337	2.75596
Pearson's r	0.60302	0.88076
R-Square (COD)	0.36363	0.77575
Adj. R-Square	0.33181	0.76394

Figure 5: Linear fit of in-out temperature for both rammed earth

The linear fit curve for the temperate region in the winter period is given by[12]:

$$T_i = 0.15T_0 + 13.5 \tag{3}$$

Where; T_i = Indoor temperature,T_0 = Outdoor Temperature, T_g = Indoor Globe Temperature

$$T_g = 0.47T_0 + 9.1 \tag{4}$$

The comfort and preferred temperatures for all the respondents were calculated using equation 1 and 2 with globe temperature and thermal sensation vote as the input parameter. The obtained comfort temperature and preferred temperature for Madan Pustakalaya and Matoghar are binned within 0.5 for Madan Pustakalaya and 1 for Matoghar in temperature and shown in Figure 6. The mean value of the comfort temperature in Madan Pustakalaya and Matoghar during the winter season from the obtained data is 18.75°C and 14.83°C respectively. As respondents are more comfortable in the lower temperature of Matoghar than Madan Pustakalaya, it requires less energy to maintain the comfort temperature in Matoghar than in Madan Pustakalaya. The comfort temperature ranges from 16.75°C to 20°C in the Madan Pustakalaya and from 14°C to 16°C in the Matoghar. However, the mean preferred temperature of Matoghar and Madan Pustakalaya is 18.26°C and 18.18°C respectively which is similar to each other. The gap between preferred temperature and comfort temperature for Matoghar is high, indicating that residents of Matoghar desire warmer conditions to maintain their preferred temperature for thermal comfort. Considering the mean value of the comfort temperature and preferred temperature, the preferred temperature is quite close to the comfort temperature for Madan Pustakalaya which indicates that Madan Pustakalaya requires less energy to rearch their preferred thermal comfort than Matoghar.

3.4 Traditional and modern structures vs rammed earth structures in Nepal

The data for this study is taken from previous research conducted on traditional and modern residential buildings in Kathmandu Valley for thermal performance and thermal comfort survey for temperate climates in Nepal[11, 13]. As the location of the sites is in the vicinity of Kathmandu Valley, the climate is complex due to the temperate climate and high altitude hills around the valley of around 1300 meters. Table 1 shows the comparison between indoor, outdoor and comfort temperatures of different types of structures found in Nepal with the rammed earth structure. The comfort temperature lies around 15°C [13]. The outdoor mean maximum air temperature for residential buildings ranges from 11 to 14°C whereas indoor mean maximum air temperatures range from 12 to 15°C during morning till evening.

Through the data analysis, it is observed that the comfort temperature for traditional buildings is less than that of the Madan Pustakalaya, whereas, it is almost equal to that of the Mato-Ghar. It implies that Madan Pustakalaya requires more energy to maintain thermal comfort than the traditional houses as well as Mato-Ghar. For Matoghar, since the comfort temperature is less than both traditional and Madan Pustakalaya, it requires less energy.

Table 1: Comparison of mean indoor,outdoor and comfort temperatures

	Temperature in C		
Type	Indoor	Outdoor	Comfort
Traditional	12-15	11-14	15
Modern	10.5-11.5	11.5	15
M.P.	16.3	15.2	18
M.G.	16.8	15	14

However, for Madan Pustakalaya, even though the indoor temperature matches the comfort temperature of previous studies, the response votes have increased the comfort temperature. When comparing the temperature difference between indoor and comfort temperature between the two rammed earth structures with the contemporary structures, Mato-Ghar has the most thermally comfortable environment as the difference between comfort temperature and indoor temperature is the lowest among them. In addition, both Matoghar and Madan Pustakalaya seem warmer than the traditional and modern buildings in Kathmandu; Matoghar being the warmest of them all. Therefore, it can be implied that rammed earth structures are thermally superior in maintaining and regulating indoor temperatures close to comfort temperatures than other types of structures.

4. Conclusion

The earlier sections of this study has covered the respective objectives which show the better thermal performance of rammed earth structures in the context of Nepal, especially during the winter period. This study agrees with the existing plethora of knowledge about rammed earth structure and its superior thermal performance as a result of high thermal mass and temperature stabilizing properties. Because of the current energy crisis which is becoming a global problem, this research contributes toward how effective is the natural thermal stability when rammed earth is used. Hence, this research quantifies the thermal performance of rammed earth structures in Nepal and compares it with traditional and modern structures to clarify the position of rammed earth structures as a viable, sustainable, and cheaper option. The findings from this study suggest that rammed earth structures can perform slightly better than traditional and modern structures in terms of thermal

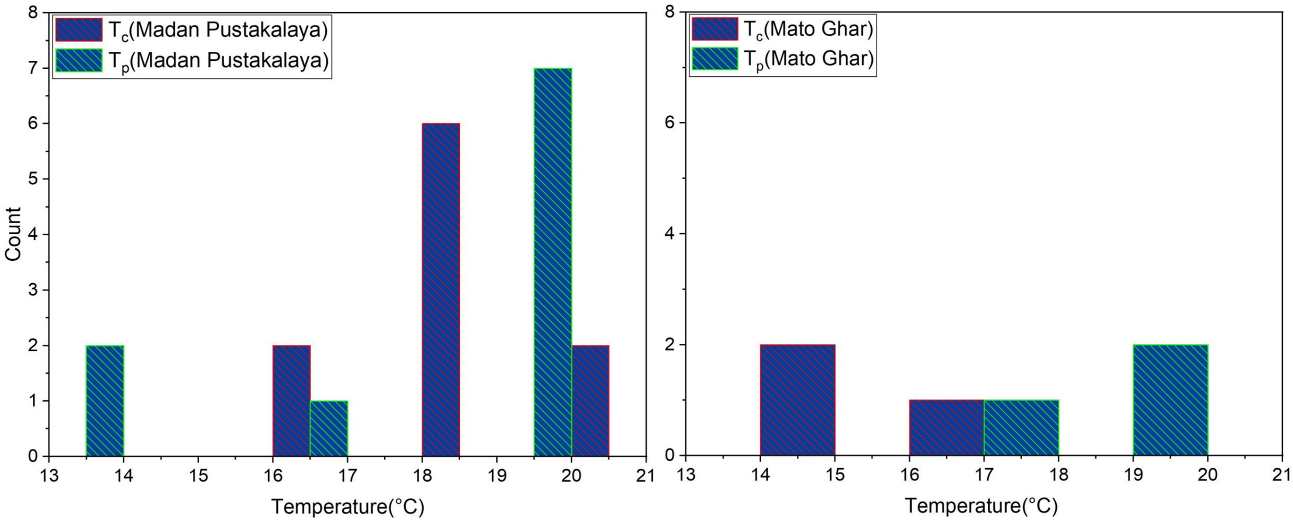


Figure 6: Comfort and Preferred Temperature Comparison between Madan Pustakalaya and Mato Ghar

performance while maintaining thermal comfort. The thermal performance is related to the thermal characteristics of the rammed earth walls and thermal comfort depends on the physical and psychological conditions of the users.

- Modern Rammed earth structures are generally 1-2°C warmer than the traditional and modern residential structures. The maximum outdoor to indoor temperature differences range from 2-7°C in rammed earth structures which shows that there is heat stored in rammed earth structures.
- The indoor temperature exceeds the outdoor temperature in the morning and the evening, whereas, at noon time, the outdoor temperature exceeds the indoor temperature. However, this temperature difference is greater in the morning and evening than in the afternoon. Hence, it is good for maintaining thermal conditions inside the structure to a close-range during the winter period.
- The comfort temperature and preferred temperature are very close to the existing indoor temperatures for the rammed earth structure. Therefore, it requires less energy to maintain the thermal comfort in rammed earth structures than the contemporary structures. In addition, the average preferred temperature comparison showed that it requires more energy for Matoghar residents to reach their preferred temperature for thermal comfort compared to Madan Pustakalaya.

4.1 Recommendations and Future Works

From the above investigation of thermal performance, the following recommendations are proposed. The findings might not be applicable in all the regions but they mostly can be applied to rammed earth structures in colder regions. The recommendation mainly concerns the effective construction of rammed earth structures for a thermally comfortable environment.

- The research is limited to only a certain period of winter season. Therefore, an all season thermal performance and comfort can be carried out in the future with additional climatic and architectural parameters like humidity, air velocity, orientation, compactness, etc.
- Considering the effective performance of energy efficient rammed earth technology in terms of thermal performance, it is highly suggested that this technology should be used to replace unsustainable materials for thermal stability on roof, walls and floors.
- Space is very important as an architect, however, the wall thickness of rammed earth structures is huge compared to the equivalent concrete structures. More methods should be explored in reducing the size of the wall to create usable space in the future.

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