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A Case Study on Thermal Performance in Residences with Laterite Stone and Rammed Earth Walling Materials in A Warm and Humid Climate

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Highlights

- Study of thermal performance of Rammed earth and Laterite stone.
- Monitoring using hand-held instruments in a built environment.
- Rammed earth wall, due to thermal properties, has an overall 2°C lower surface temperature compared to laterite stone.

Abstract

Traditionally in coastal Karnataka, mud was used in residential construction, but due to its labour-intensive nature, the construction shifted to laterite stone in the mid-20th century. Presently, with the growing need for thermal comfort and interest in sustainable approaches, there is increased interest in traditional mud architecture. A study was conducted to understand how these two materials- Rammed earth and Laterite stone perform in their built environment in a warm and humid climate. The analysis of inner surface temperatures of the east wall showed that 45% of the temperature for rammed earth and 97% of the temperature for laterite stone were more than 28°C. 1°C difference in mean WBGT showed that the indoor spaces in rammed earth residences have lower heat stress compared to laterite stone. Additionally, cooling loads can be reduced by 10%, and surface temperature can be reduced by 2°C for rammed earth compared to laterite stone walls.

Keywords: Thermal performance, Laterite stone, Rammed earth, Surface temperature, WGBT.

Introduction

Energy efficiency is the need of the hour with ever increasing population and demand for built spaces and comfort conditions. Energy consumption by the building sector constitutes a significant portion of energy use, which cannot be compromised. Energy use in buildings depends on the indoor environmental requirements and the ability of the building envelope to create an environment that is comfortable for the occupants. In warm and humid climates, passive thermal comfort is mainly attained with the building geometry, placement of openings, natural ventilation, and use of materials in the construction. Walls and roofs form a major portion of the building envelope; hence, an envelope with good thermal performance can act as an energy conservation measure to reduce energy use in a building. Thus, the study of envelope performance will help us optimize the use of energy and provide indoor thermal comfort.

In coastal regions of Karnataka, Mud was the traditional building material used in the construction of residences. The walls built of mud were generally 0.9 m to 1.2 m thick. It helped in controlling the indoor thermal conditions of the built environment. But, due to the high labour and time intensive method of construction for mud walls, the building paradigm shifted to the use of laterite stone for faster and stronger construction. As per the Indian census of 2011, Dakshina Kannada district has almost 67% of the residences built in Laterite stone, and only 22% of residences were built in mud and unburnt bricks. Today, with the introduction of stabilizing agents and better construction technologies, mud is gaining importance again as an eco-friendly, sustainable construction material in the form of rammed earth walling and compressed earth blocks for residential buildings.

The study on the thermal performance of rammed earth walls and laterite stone in a built environment has not been studied in the Indian subcontinent. Hence, the thermal performance study on the two materials will provide an insight into their potential for providing a comfortable indoor environment in naturally ventilated residences in warm and humid climates. The study aims to benefit architects and energy efficiency studies as it will provide insight into the existing building materials used and their performance.

Methodology

Study building selection

The objective of the study was to evaluate the thermal performance of the materials in their built environment; hence, a residence, each built with rammed earth and laterite stone, was considered as the building materials most used in the coastal regions of Karnataka.

The two-case study buildings are selected based on the following criteria.

- Natural ventilated residences
- Construction material used.
- Number of floors (G+1)
- Total built up area.

The rammed earth residence has 3 bedrooms and vaulted ceilings with a clay tile sloped Mangalore roof. The first storey holds a single bedroom and a toilet. The laterite house is a G+1 structure with 3 bedrooms on each floor. The built-up area, WWR, wall thickness, etc., are noted in Table 1. The floor plans are shown in Figures 1 and 2. The study was limited to only the ground floor as the number of rooms on the first floor is not the same, and conducting measurements on the exterior with hand-held devices will be difficult. Additionally, the rammed earth residence has a ventilated roof, and hence, the ground floor of the laterite house was only considered for the study as the first floor can be considered as a ventilated attic.

Table 1: Characteristics of the residences

	Rammed earth residence	**Laterite stone residence**
Total built up area	205.6sqm.	242.9sqm
Wall thickness	230mm	230mm
WWR	17%	19%
Roof	Vaulted ceiling with compressed earth block and concrete and clay tiles	Concrete slab with Ventilated floor.

Data gathering methods

The data collection technique implemented in the study was Monitoring and Measurements using hand-held instruments (onsite measurements) and simulation through thermal modelling to evaluate the dynamic thermal performance of the material over the year.

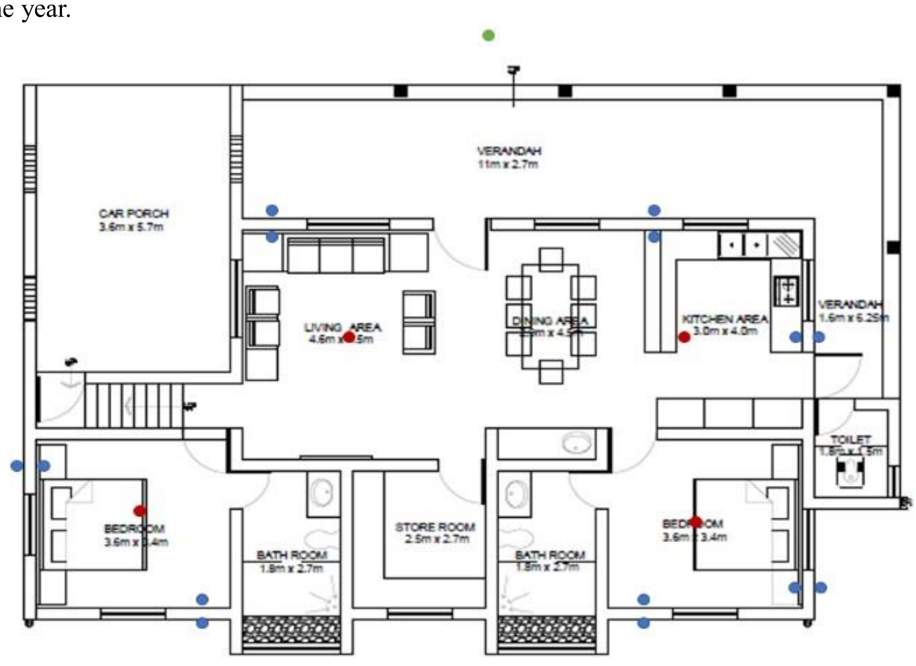


Figure 1: Floor plan and measurement points in the Rammed Earth residence

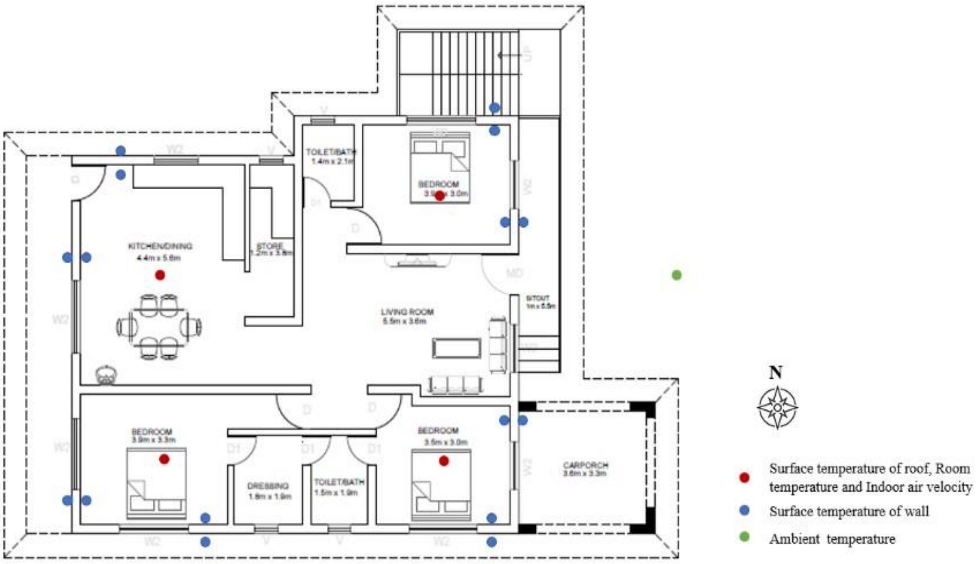


Figure 2: Floor plan and measurement points in the Laterite stone residence

Onsite measurement

Data was collected through on-spot measurements using an infrared thermal thermometer for surface temperature measurement. The surface temperature measurements are taken on different external wall surfaces and ceilings to assess the heat transfer through the day with the movement of the sun. The surface temperature was measured inside and outside of the walls at the same spot to note the decrement caused by the envelope characteristics. The measurements are taken away from any columns, fenestration, or any other composite surface that might influence the heat transfer. The points of data measurements are marked in Figures 1 and 2.

Indoor temperature, Relative humidity, and mean radiant temperature were measured with a Wet-bulb globe thermometer placed at the centre of the room. An anemometer was used to measure the wind velocity at the centre of the room. Outdoor temperature, relative humidity, and wind velocity measurements were taken away from any shaded obstruction within the premises of the residence. The instruments, their resolutions, and their accuracy are listed in Table 2.

Table 2: Parameters measured and Instruments used

Parameter measured	Model	Image of instrument	Measuring Range	Resolution	Accuracy
Surface temperature	HT668 Non-contact Infrared thermometer		0°C to 100°C	0.1°C	±0.3°C (0-35°C) ±0.2°C (35.1-42.4°C) ±1.0°C (42.5-100°C)
Temperature	GM816 Anemometer		-10°C to 45°C	0.2°C	±2°C
Wind velocity			0-30 m/s	0.1m/s	±5.0%
Wet bulb Globe temperature	METRAVI-Heat stress WBGT meter WBGT-188		0°C to 59°C	0.1°C	±1°C
Globe temperature			0°C to 80°C	0.1°C	±0.6°C
Air temperature			0°C to 50°C	0.1°C	±0.8°C
Relative humidity			1% to 99%	0.1%	±3.0% (20-80%)

Measurement protocol

Indoor air temperature, Globe temperature, Relative humidity, and wind velocity were taken at the centre of the room at the height of 1.1m from the floor surface [1]. Wind velocity was taken at the centre of the room at the height of 1.1 m from the floor surface [1], and the anemometer was oriented in the X, Y, and Z directions. Inner and Outer surface temperature measurements were taken at 10cm from the wall as per the optimum distance mentioned on the infrared thermometer. Ambient temperature and Relative humidity were measured at the location outside the residence with at least a 3 m distance from any surrounding obstructions. During the measurements, the windows of the rooms were opened, providing an effective opening area of 50 %, and fans were switched off, allowing the building to be naturally ventilated. The measurements were conducted at an interval of 1 hour from 10:00 to 18:00 hrs.

Observations

Laterite stone residence - Surface temperature

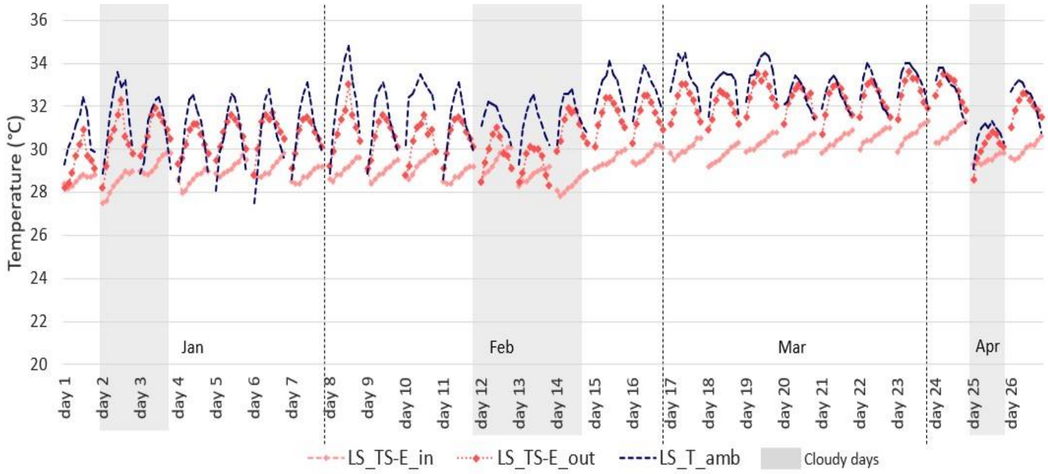


Figure 3: Measured readings of the surface temperature of laterite stone- East wall

The outdoor temperature (T_amb) measured on the premises of the residences ranged within the limits of 27.5°C to 35°C. The grey regions are days when cloudy weather conditions were observed, and hence, lower ambient and surface temperatures are measured. On the 25th day in April, thundershowers were observed on the night before hence, a lower temperature profile was observed. The surface temperature at each wall was analyzed to understand the influence each material had on heat transfer.

The east wall was shaded throughout the day due to the presence of a tiled shaded porch area adjacent to the wall, and measured data is shown in Figure 3. For the east wall, the inner surface temperature (TS_in) ranged between 27.5°C to 31.3°C with a mean of 29.5°C and the outer surface temperature (TS_out) ranged between 28.2°C and 33.6°C with a mean of 31.2°C. The standard deviation of TS_in was 0.8; hence, we can observe that it fluctuates within a narrow band of values. Meanwhile, TS_out has a deviation of 1.25, which shows that its values are 1.2 times away from the mean value. This is due to external ambient temperature and the radiant heating effect of the sun. Hence, TS_out observed a peak temperature at 15:00 hours along with the ambient temperature. From Figure 3, we can observe that the difference between TS_out and TS_in is around 2 to 3°C. This shows that the wall has a higher transmittance as the heat is transferred from the external to the internal at a higher rate.

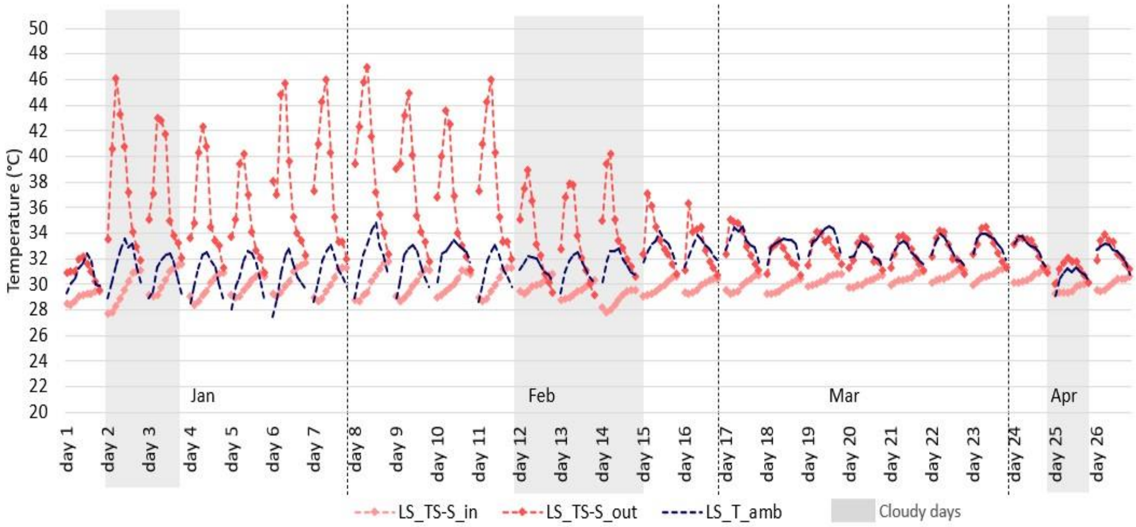


Figure 4: Measured readings of the surface temperature of laterite stone- South wall

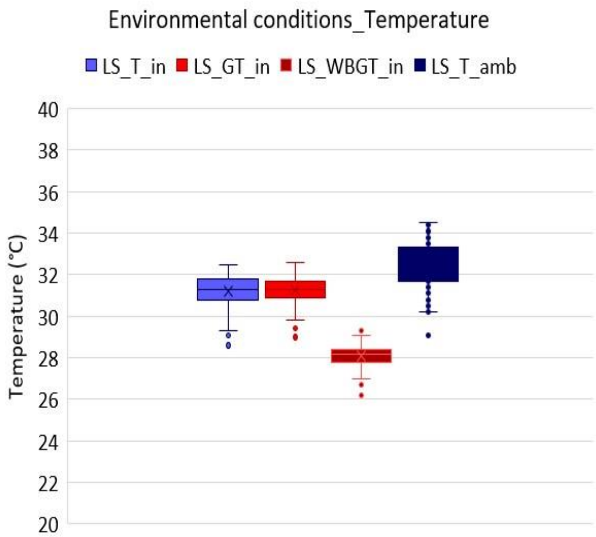
The south wall was exposed throughout the day during the months of January and February till 13:00 hours and gets shaded in the latter half of the day, as can be observed in Figure 4. On the south wall, the TS_in ranged from 27.7°C to 31.8°C with a mean of 30.0°C whereas TS_out ranged from 29.2°C to 47.0°C with a mean of 34.5°C. The standard deviation of TS_in was 0.83, and for TS_out, it was 3.9. Due to the high temperature attained due to the solar exposure on the wall surface, TS_out has a high 4 times the deviation from the mean value. In the last few days of February and the month of March, due to the earth's revolution, the south wall was shaded and not exposed to the sun, and hence

TS_out ranged between 31°C to 35°C during which the TS_in varied between 29°C to 31°C. Thus, solar exposure influences the rate of transfer of heat within the wall assembly.

The north wall was shaded throughout the year, and hence the TS_in ranged between 27.8°C to 31.2°C with a mean of 29.3°C and TS_out ranged between 27.5°C and 32.7°C with a mean of 30.6°C. As the wall surface was unexposed, we observed that the surface temperature fluctuated within a range of 2°C and 4°C, respectively. The west wall was exposed to the sun after 15:00 hours, so the outer surface temperature peaked. TS_out ranged from 28.1°C to 46.3°C with a mean of 35.4°C and TS_in ranged from 27.9°C to 32.1°C with a mean of 29.9°C. The standard deviation of TS_in was 0.82, and for TS_out, it was 5.06. Even though the wall has high exposure, during the measurement period, the TS_in fluctuations are within a 1°C range in a day and only start to increase in the latter half of the day (after 15:00 hours). It could be observed that since the wall gets time to lose the heat attained on the previous day and as the measurements are not conducted during the night-time, the steep increase in TS_in temperature is not observed, unlike the south wall.

Laterite stone residence- Indoor conditions of south east room

From Figure 5, we can observe that the Indoor temperature (T_in) ranged from 28.6°C to 32.5°C with a mean value of 30.8°C. The Globe temperature (T_GT_in) ranged from 29°C to 32.6 °C with a mean of 31.0°C. We can observe that the T_in and T_GT_in were almost the same with a very small difference of 0.2°C. This is because the building was maintained in naturally ventilated conditions; the globe temperature, which is a measure of the radiant effect of the surfaces on the air temperature, is in good correlation with an R^2 value of 0.95 with the air temperature as it fluctuates very closely with the outdoor temperature. The Wet bulb globe temperature (T_WBGT_in) is measured as a product of wet bulb temperature and globe temperature; hence, it has a lower range compared to other indoor parameters. T_WBGT_in ranged between 26.2°C to 29.4°C with a mean of 27.9°C and a standard deviation of 0.42. This shows that the T_WBGT_in fluctuates within a narrow band of values. The Indoor relative humidity (RH_in) was higher than the Ambient relative humidity (RH_amb), as its mean values are 67.7% and 64.8%, respectively. The variance for RH_in was 3.09, and RH_amb was 4.73.



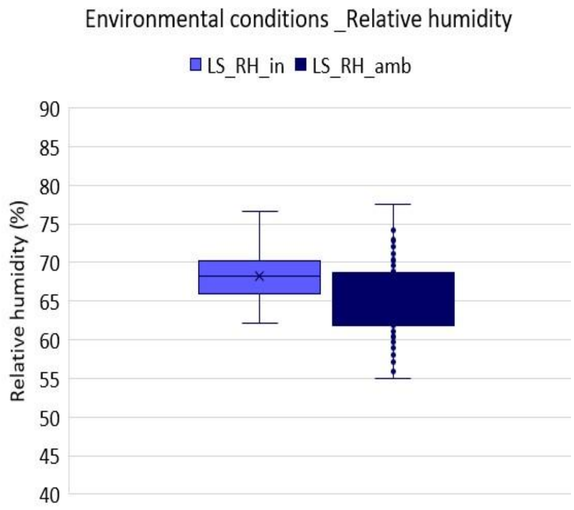


Figure 5: Indoor temperature and relative humidity with the ambient conditions in laterite stone residence

Rammed earth residence- Surface temperature

The outdoor temperature (T_amb) measured on the premises of the residences ranges within the limits of 27.4°C to 35°C. The grey regions are days when cloudy weather conditions were observed, and hence, lower ambient and surface temperatures are measured.

The east wall was shaded throughout the day due to the presence of a tiled shaded area adjacent to the wall. For the east wall, the TS_in ranged between 25.3°C to 30.7°C with a mean of 28.0°C and the TS_out ranged between 24.3°C and 34.7°C with a mean of 30.8°C. The standard deviation of TS_in was 1.33; hence, we can observe that it fluctuates within a band of 2°C. Meanwhile, TS_out had a deviation of 1.87, which shows that its values are 2 times from the mean value. As TS_out varies directly with the ambient temperature, it observes a peak at 15:00 hours along with the ambient temperature, as seen in Figure 6.

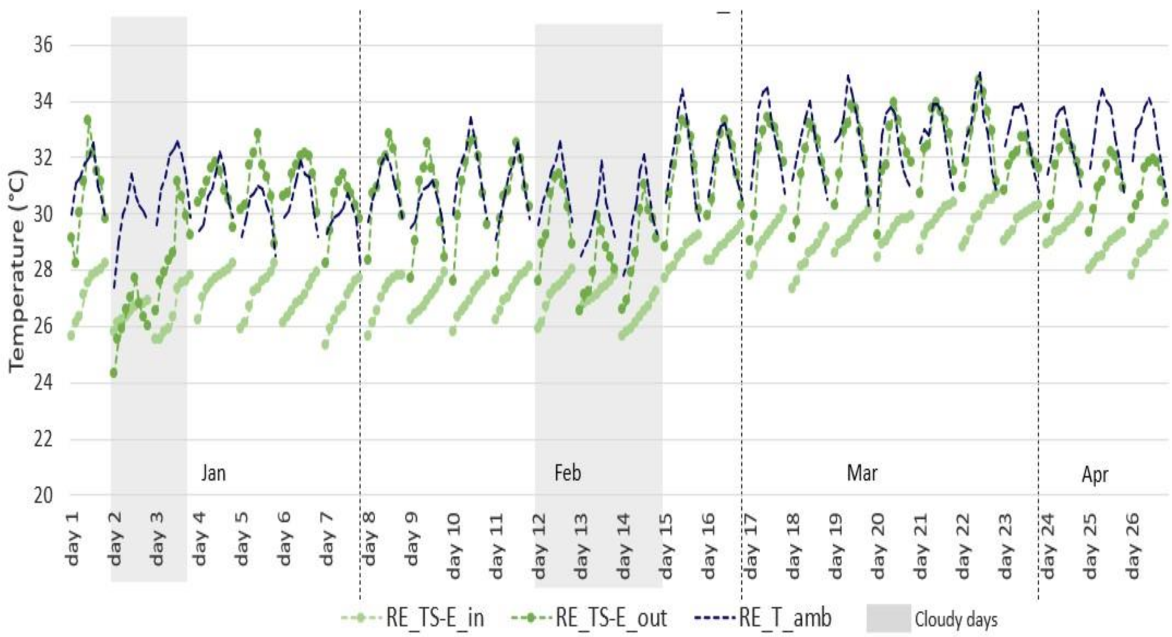


Figure 6: Measured readings of the surface temperature of rammed earth- East wall

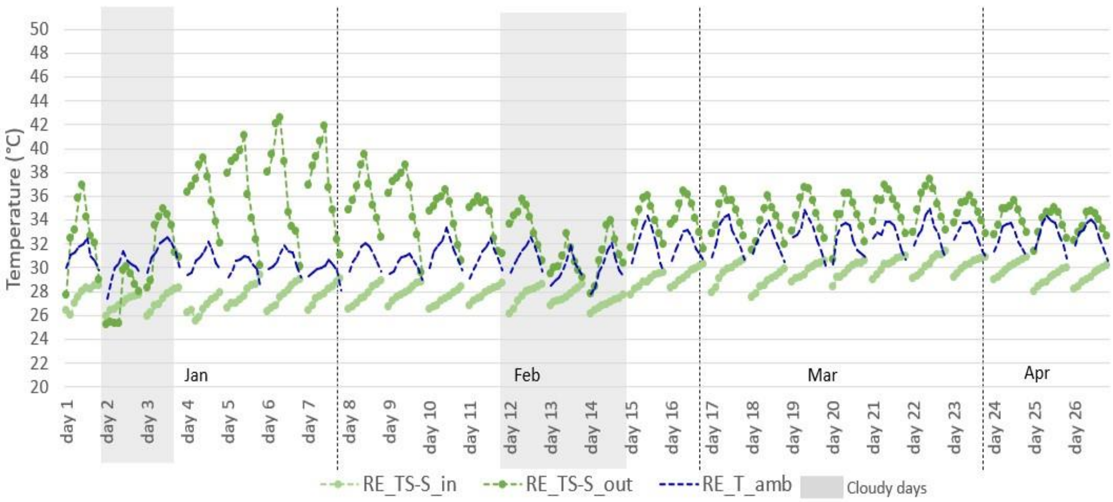


Figure 7: Measured readings of the surface temperature of rammed earth- South wall

The south wall was exposed throughout the day during the months of January and February till 13:00 hours and gets shaded on the latter half of the day, as observed in Figure 7. On the south wall, the TS_in ranged from 25.5°C to 31.3°C with a mean of 28.4°C whereas TS_out ranged from 25.2°C to 42.5°C with a mean of 34.1°C. The standard deviation of TS_in was 1.32, and for TS_out, it was 2.91. Due to the high temperature attained due to the solar exposure on the wall surface, TS_out had 3 times the deviation from the mean value. In the last few days of February and the month of March, due to the sun's path, the south wall got shaded and was not exposed to the sun; hence, TS_out ranged between 32°C to 38°C during which the TS_in varied between 28.5°C to 31°C. This shows that solar exposure and ambient temperature conditions influences the rate of transfer of heat within the wall assembly.

The north wall was shaded throughout the day as it was not exposed to the sun due to the presence of a covered veranda. TS_in ranged between 24.7°C to 30.3°C with a mean of 27.3°C and outer TS_out ranged between 24.1°C and 33.9°C with a mean of 29.4°C. As the wall surface is unexposed, we observe that the surface temperature fluctuates within a range of 2°C and 4°C, respectively. On the west wall, TS_in ranged from 24.8°C to 30.6°C with a mean of 27.8°C whereas TS_out ranged from 24.1°C to 38.1°C with a mean of 31.0°C. The surface temperature measurements of rammed earth show a large difference between TS_out and TS_in. This difference can be attributed to the low transmittance and specific heat characteristics of the wall.

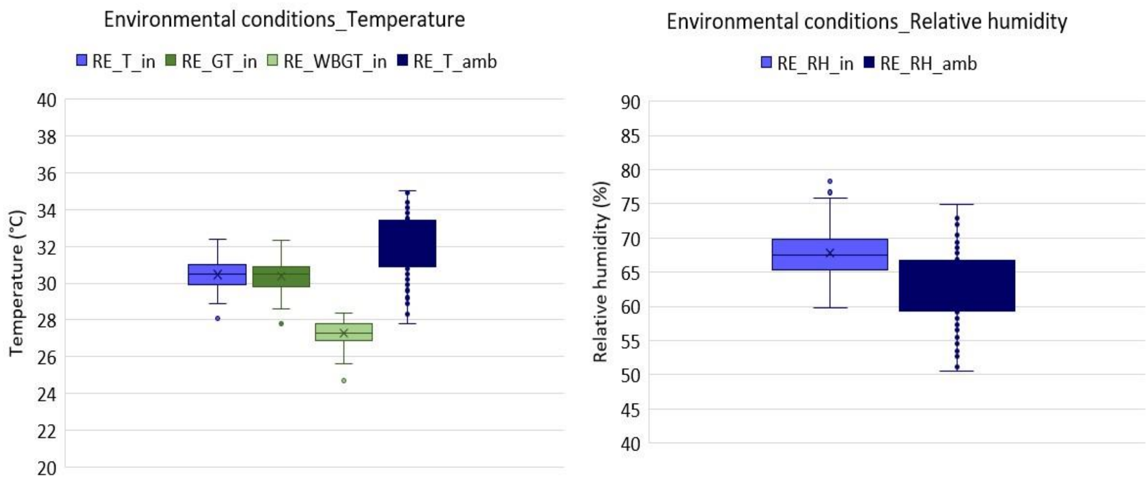


Figure 8: Indoor temperature and relative humidity with the ambient conditions in rammed earth residence

Rammed earth residence- Indoor condition of southeast room

From Figure 8, we can observe that the Indoor temperature (T_in) ranged from 28.0°C to 32.8°C with a mean value of 30.7°C. The Globe temperature (T_GT_in) ranged from 27.8°C to 32.3 °C with a mean of 0.2°C. We can observe that the T_in and T_GT_in have a very small difference where T_GT_in is less by 0.5°C, which shows the cooling effect of the wall surfaces. As the building is maintained in naturally ventilated conditions, the globe temperature, which is a measure of the radiant effect of the surfaces on the air temperature, is in good correlation with an R^2 value of 0.98 with the air temperature as it fluctuates very closely with the outdoor temperature. T_WBGT_in ranged between 24.7°C to 28.4°C with a mean of 27.1°C and a standard deviation of 0.64. The Indoor relative humidity (RH_in) was higher than the Ambient relative humidity (RH_amb), as its mean values were 67.3% and 62.1%, respectively. The variance for RH_in was 3.65, and RH_amb was 5.11. Figure 8 shows the variation of the indoor temperatures over the days the measurements were conducted.

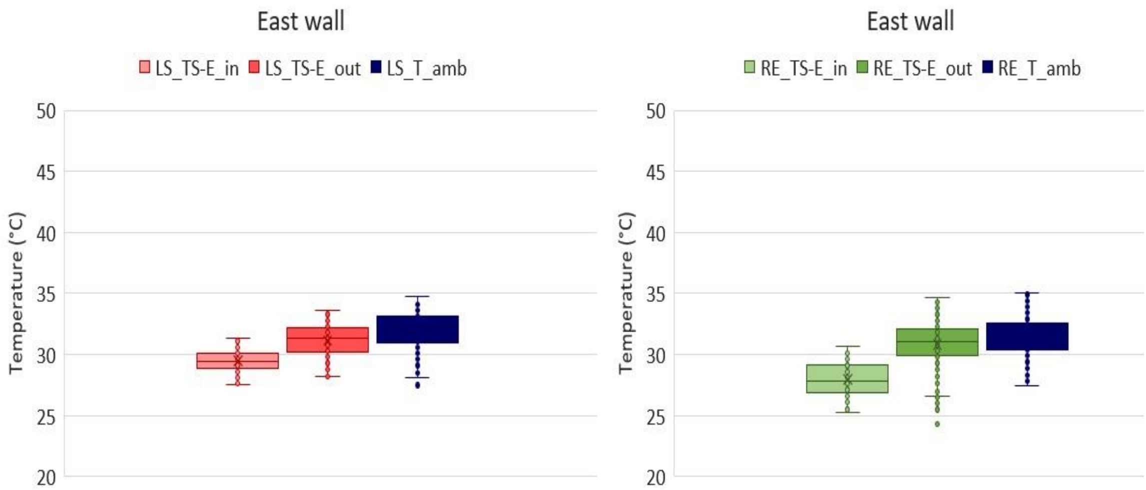


Figure 9: Surface temperature range for the east wall

Study of the buildings and the criteria for selection of similar analysis spaces

As the residences considered for the study are not identical, a direct comparison of the results will be inaccurate as internal conditions and heat transfer are influenced by their surrounding conditions. Each space was analyzed for its building surroundings, and to evaluate the suitability of the analysis space, a shading mask and external wall exposure time were used to evaluate the obstructed area in each of the cases.

Figure 9 shows the measured data range for the east wall, and Figure 10 shows the data for the south wall of the southeast room for both residences. It can be observed from the figures that 75 % of TS_in points for rammed earth residence is lower than the 25% of TS_in for laterite stone. Thus, the heat transferred in the case of the rammed earth house is lower than laterite in both the east and south wall surfaces. The standard deviation of TS_out of rammed earth was 33% higher than that of laterite stone for the east wall, and for the south wall, it was 25% lower.

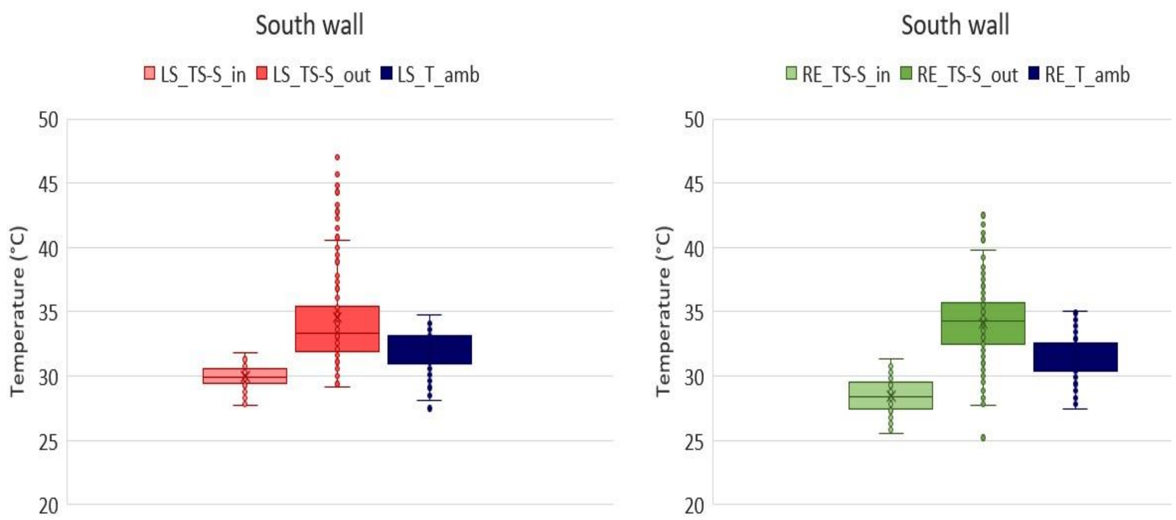


Figure 10: Surface temperature range for south wall

From the surface temperature data, it can be observed that the rammed earth wall showed 2°C lower TS_in compared to laterite stone in the months of January and February. In the months of March and April, the difference between TS_in is reduced to 1°C and could be attributed to the higher ambient conditions. TS_out of the rammed earth wall was higher compared to laterite stone throughout the measurement period of 4 months, as observed in Figure 10. This property of high TS_out and low TS_in of rammed earth compared to laterite stone is due to the thermal conductivity and thermal mass of the material.

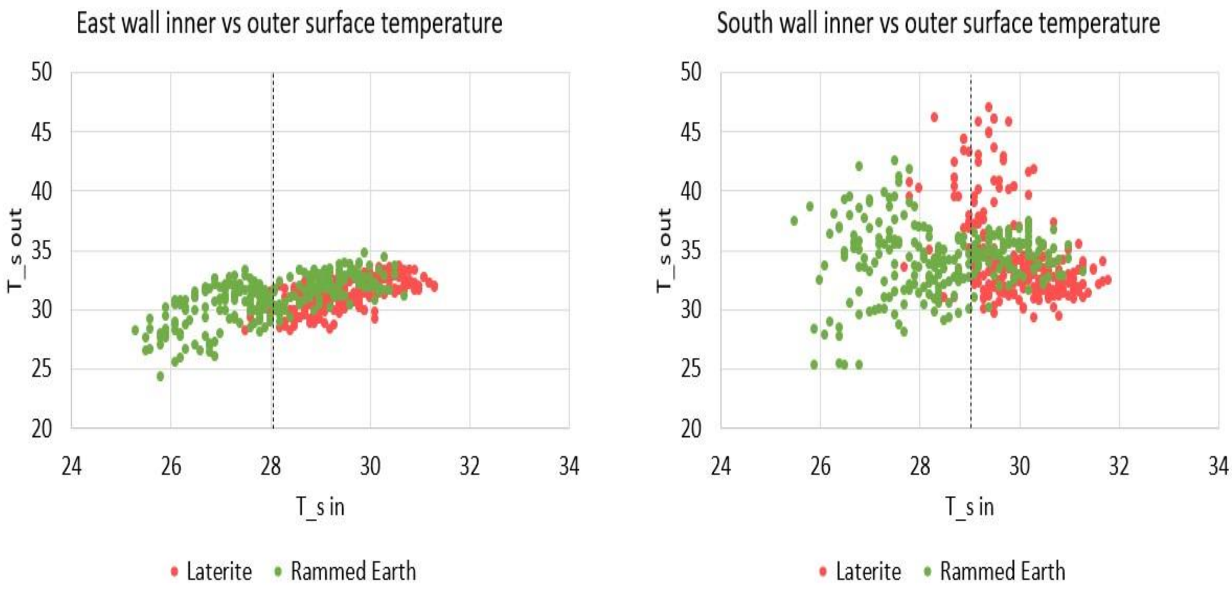


Figure 11: Distribution of the TS_in and TS_out for a) east and b) south walls

Figure 11 shows the distribution of the surface temperature of the east and south walls for the southeast room. In Figure 11 (a), we can observe that even for the same outer surface temperature of the east wall, 45% of TS_in for rammed earth and 97% of TS_in for laterite stone points are more than 28°C. In Figure 11 (b), we can observe that the TS_in shows 35% of rammed earth data points and 88% of laterite stone data points are more than 29°C. The two figures show that the rammed earth wall, due to its thermal properties, has an overall 5% lower surface temperature for both walls compared to the laterite stone wall. Hence, the rammed earth wall has a significant reduction in the heat transferred from the outside to the inside.

Evaluating the indoor air temperature and the relative humidity, it can be observed from Figure 12 that they are inversely proportional as they have equal slopes. As the study subjects are in a warm and humid climate, the relative humidity levels are more dispersed and range between 60 to 80%, whereas the air temperature ranges between 29°C to 32.5°C. Even though the ambient temperature and relative humidity ranges are similar, we can observe that 76% of the data for rammed earth observed a temperature less than 31°C while the relative humidity was less than 68% compared to laterite stone.

The indoor comfort conditions vary with the outdoor conditions in a naturally ventilated building. Hence, the WBGT is measured to assess the indoor comfort conditions as it takes into consideration the climatic conditions. From Figure 13, we can observe that the mean WBGT for rammed earth was lower by 1°C (3%) compared to the laterite stone house, while the outdoor conditions are relatively equal. 61% of the rammed earth data is less than 28°C compared to laterite stone. Hence the occupants in rammed earth houses will experience lower heat stress due to the material and thus a higher sense of indoor comfort conditions.

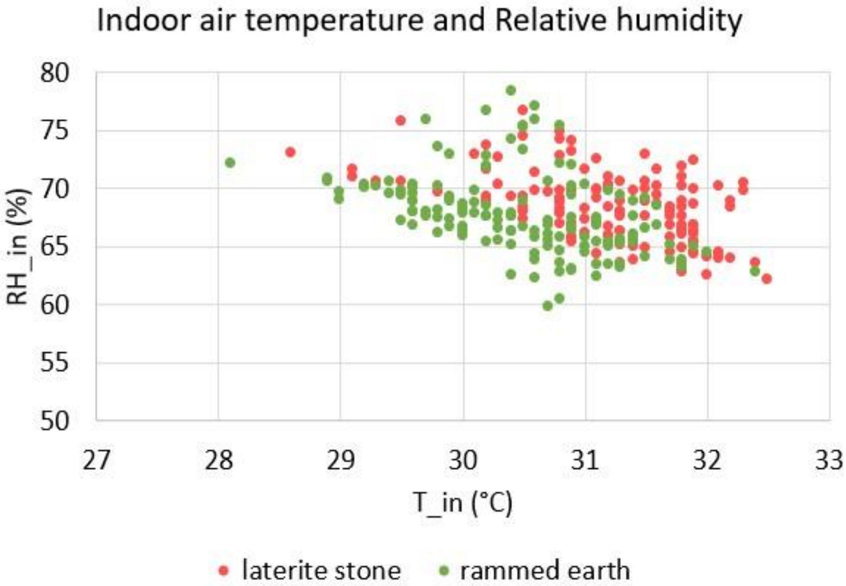


Figure 12: Distribution of Indoor air temperature and relative humidity

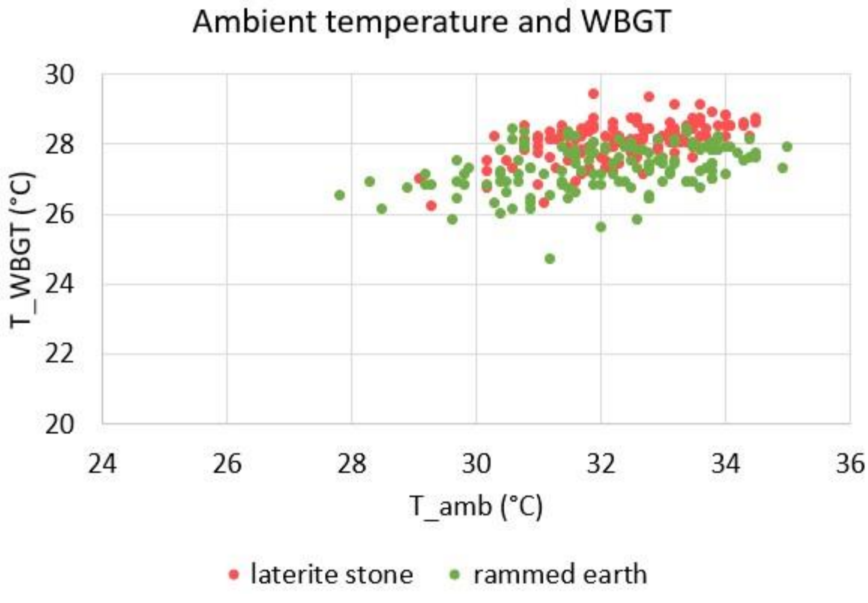


Figure 13: Distribution of WBGT with ambient temperature

Thermal simulation model and its Results

Thermal simulation of the building was conducted to analyze the year-round performance of the walling material. A thermal simulation model was developed on Design Builder software to mimic the as built conditions. The thermal properties of the building envelope are based on various research papers since the exact thermal properties of the material were unknown. The window openings are modelled with a 50% effective opening area and a wind discharge coefficient of 0.65. No HVAC system was provided, and the model was run in a naturally ventilated condition. The simulation output was compared with measured data, and the properties with the highest correlation and least variance were considered for further analysis (The final values are listed in Table 3. The TMY weather file for Mangalore (Warm and humid) was used to simulate the building, and parameters such as indoor air temperature, relative humidity, mean radiant temperature and operative temperature were analyzed.

Table 3: The final selected thermal properties with its correlation and variance w.r.t the measured data

Walling material	Density, ρ (kg/m^3)	Thermal Conductivity, k (W/mK)	Specific heat, C_p (J/kgK)	Thermal effusivity, e ($J/m^2K\ s^{1/2}$)	Thermal diffusivity, a (mm^2/s)	Correlation	Covariance difference
Laterite stone	1930 [2]	0.55 [2]	995.9 [2]	1030 [2]	029 [2]	0.96	0.04
Rammed earth	1730 [3]	0.60 [3]	648.0 [3]	820 [3]	0.54 [3]	0.97	0.02

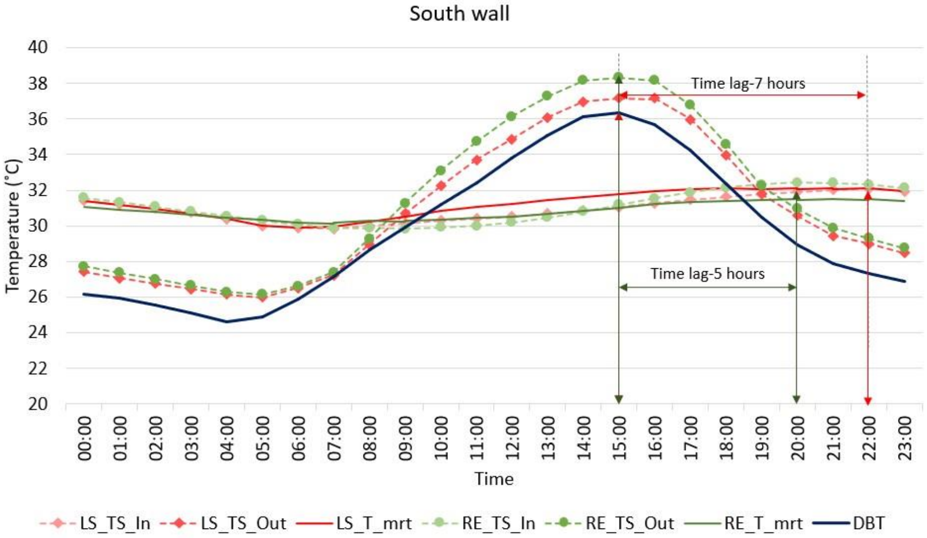


Figure 14: Simulated data for peak summer day (May)

In Figure 14, we can observe that the peak TS_out was attained at 15:00 hours in both cases. The peak TS_in for rammed earth was attained at 20:00 hours, whereas for laterite stone, it was attained at 22:00 hours. The time lag for rammed earth is 5 hours, and for laterite stone, it is 7 hours. The decrement factor for both walls remains the same at 0.85, as both walls have the same thickness. As the walls held the heat longer due to their high specific heat capacity, the laterite wall remained warmer, and the stored heat was dissipated into the room volume. Hence, the Tmrt for laterite stone was higher compared to rammed earth. Comparatively, rammed earth, due to its lower specific heat capacity and density, reaches peak surface temperature 2 hours earlier, giving the wall time to cool faster. Thus, we observe a lower Tmrt for rammed earth during the day-time hours. The high fluctuation in TS_in compared to laterite was due to the thermal conductivity and specific heat capacity of rammed earth.

Conclusion

As the properties of the wall influence the amount of heat conducted into the room, it is essential to understand the thermal properties and how they directly influence the indoor conditions. In this study, an experimental take on the thermal performance of two materials rammed earth and laterite stone, was conducted in its built environment. The study was done with hand-held devices measuring the surface temperature, indoor temperature, and humidity conditions at intervals for 1 hour for 9 hours in the day.

The study observed that laterite stone walls showed a mean inner surface temperature range of 29.3°C to 30°C on all the walls oriented along different directions. The lowest inner surface temperature was observed on the north wall and the maximum on the south wall due to its exposure to the sun. The outer surface temperature depends on its exposure to the sun and ranges from a mean of 30.6°C on the north wall to 35.4°C on the west. The indoor air temperature was observed to have a mean of 30.8°C, whereas the indoor globe temperature, a measure of the radiant impact of the surfaces, had a mean of 31°C. The small increase in the globe temperature compared to the air temperature showed that the walls are radiating heat to indoors.

In the rammed earth residence, the mean inner surface temperature was the lowest for the north wall at 27.3°C and highest for the south wall at 28.4°C. The mean outer surface temperature ranged from 29.4°C on the north wall to 34.1°C on the south wall. A consistent increase in outer surface temperature on the west wall was not observed due to the presence of trees facing the wall. The presence of trees and other shading elements can help reduce the high surface temperatures. The large difference between the outer surface temperature and inner surface temperature of the rammed earth wall can be attributed to the higher thermal conductivity of the wall. The indoor air temperature was observed to have a mean of

30.7°C, whereas the indoor globe temperature had a mean of 30.2°C. Lower globe temperature compared to the air temperature showed that the walls provide a cooling effect for the indoor spaces.

As the building designs are not identical, an attempt was made to analyze spaces with similar exposure and adjacency to have a preliminary understanding of the difference between the two materials. The distribution pattern of the surface temperatures of the east wall showed that 45% of the inner surface temperature for rammed earth and 97% of the inner surface temperature for laterite stone points are more than 28°C. Hence, the rammed earth wall, due to its thermal properties, has an overall 2°C lower surface temperature for both walls compared to the laterite stone wall. Comparing the indoor air temperature and relative humidity levels, it was observed that 76% of the data for rammed earth observed a temperature less than 31°C while the relative humidity was less than 68% compared to laterite stone. The 1°C lower mean WBGT shows that the indoor spaces in rammed earth residences have lower heat stress compared to laterite stone and hence provide a higher degree of comfort. To understand the impact on the built environment, a thermal simulation study was conducted considering the thermal properties obtained from other studies and compared with the measured data. This study showed that rammed earth had a thermal conductivity of 0.6 W/mK, and for laterite stone, it was 0.55 W/mK. Evaluating the thermal properties of a single residence, it was found that with the use of rammed earth, the cooling load for a space can be reduced by 10%. Additionally, the rammed earth wall had a lower time lag of 5 hours compared to laterite stone of 7 hours, which showed that the walls cool faster due to its higher thermal conductivity, which helps naturally ventilated buildings to lose heat faster and cool, leading to higher comfort levels.

Limitations and Future scope of work

As the study was conducted for a period of 3.5 months, the data from peak summer months couldn't be measured. The actual thermal properties of the walls are not measured or calculated, and properties from other studies are relied on to understand the material performance. Since thermal properties are taken from other studies and variations of weather data (TMY) with actual climatic conditions, the simulation results will not match the exact on-site conditions. Additionally, the measurements are conducted using hand-held instruments due to the unavailability of digital data loggers and are conducted hourly from 10 am to 6 pm; hence, the measured data will show the thermal response for the daytime hours and not the night-time hours.

Although preliminary comparisons are made by identifying similar living spaces, identical rooms, or spaces, there is uncertainty due to the design, presence of other buildings and trees, elevation, etc. These uncertainties can cause discrepancies in understanding the thermal performance of the materials. The study can be further tuned by using identical building cells with data loggers, which can be built in the same location and have the same surroundings, thereby reducing the design and locational discrepancies for the study. Additionally, testing of the material used for its thermal properties will help better evaluate and understand the nature and heat transfer abilities of the material.

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