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Original Article/Research

Thermal comfort in traditional buildings composed of local and modern construction materials

D.G. Leo Samuel [a,*], K. Dharmasastha [a], S.M. Shiva Nagendra [b], M. Prakash Maiya [a]

[a] Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Civil Engineering, Indian Institute of Technology Madras, Chennai 600036, India

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Abstract

In recent years, there is a renewed interest towards the passive cooling features of ancient building architectures, which are cost effective, eco-friendly and best suited for the local climate. On the other hand, the modern construction materials, such as cement and steel, are highly durable. Thermal comfort of eight vernacular buildings that use modern construction materials to improve the structural durability was monitored in July 2014. The buildings are located in Hyderabad, India. They have many passive cooling features that include air cavities in the structures to reduce heat transfer, high thermal mass to reduce temperature fluctuation and induced ventilation to remove heat from the indoor. All the passive cooling features investigated were found to have an appreciable influence on the thermal comfort of the indoor space. The ventilated air gaps in the roof reduced the average temperature of the roof interior surface by 1.2 °C. The diurnal temperature fluctuation of the indoor air reduced by 0.9 °C in a building with a higher thermal mass compared to a building with thin walls and roof. All the eight buildings were found to be comfortable most of the time with a slight discomfort during late night and morning hours. The maximum CO_2 recorded was 550 ppm. This indicates that the buildings were adequately ventilated.

Keywords: Thermal comfort; Traditional building; Passive cooling; Building architecture; Energy conservation

1. Introduction

1.1. Need for a blend between local and modern construction materials

Construction techniques have evolved continuously from cave dwellings to modern high-rise buildings. Traditionally, buildings are constructed with locally available materials like stone, wood, mud and lime. In recent years, modern construction materials such as cement and steel have replaced most of the local materials, due to the high durability, low maintenance, low likelihood of corrosion and decay, and ease of construction of the former. However, modern construction materials are energy intensive and eco-destructive. The cement industry accounts for 2% of the global energy consumption and 5% of the global anthropogenic CO_2 emission (Worrell, 2014). The embodied energy in the modern buildings is 10–20% of its lifetime energy consumption (Deepak et al., 2014). In addition, the higher cost of the modern construction materials increases

* Corresponding author.
E-mail address: dglsam@gmail.com (D.G. Leo Samuel).
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Nomenclature

t_n neutral temperature, °C
t_{rm} exponentially weighted running mean of outdoor temperature, °C
t_{od}^{-1} diurnal mean outdoor temperature of the previous day, °C
t_{od}^{-2} diurnal mean outdoor temperature of the day before and so on, °C
x constant for response speed (varies from 0 to 1, recommended value 0.8)

the capital cost of the buildings. Therefore, buildings constructed with a predominant use of the local materials and a judicious use of the modern construction materials would be not only cheap but also durable.

1.2. Thermal comfort in vernacular architecture

Another important factor to consider during the construction of a building is the thermal comfort of the indoor space. However, in the past few decades, the thermal performance of the building is not considered during the design and construction phase. This results in buildings with a poor thermal performance. After the building is constructed, the indoor thermal comfort is achieved using mechanical air-conditioning systems that are not only energy intensive but also eco-destructive. This was not the case before the advent of the modern air-conditioning systems. Thermal comfort was achieved by designing the building to suit the local climatic conditions. For example, in hot regions, buildings were constructed with low ventilation to prevent discomfort from the infiltration of the hot outdoor air. In dry regions, the temperature fluctuation of the outdoor air is high. Hence, the buildings were constructed with a high thermal mass to reduce the temperature fluctuation of the indoor space. In warm and humid tropical regions, the ventilation in the indoor space was maintained high with wide building openings (windows and doors) facing the predominant wind direction, whereas the thermal mass of the building was low to avoid evening discomfort from the stored heat. In solar-intensive regions, the dome structured roofs were used to reduce the solar heat gain, as they provide self-shading and reduce the surface area to volume ratio.

1.3. Local Need for cheap, comfortable and durable dwelling

Rapid urbanization in India has increased the housing need in cities. In urban locations, the government provides housing to the poor, particularly during relocation of slums, to facilitate infrastructure development. It is estimated that the Indian government has constructed a staggering 13,000,000 houses in rural and urban locations and still 15,000,000 are estimated to be homeless (Reddi and Joglekar, 2005). In general, the houses provided by the government are not only small due to the high cost of the modern construction materials but also thermally uncomfortable due to the undesirable thermal characteristics of the construction material. Hence, a switch to the traditional architecture styles that have passive cooling features (Hatamipour and Abedi, 2008) and are cost-effective is considered. The traditional architecture would also improve local employment, as it is labour intensive. This would provide employment to the migrant workforce. In addition, the use of locally available materials would strengthen the local economy and results in a milder impact on the environment. However, vernacular architecture with pure local construction materials is less durable. Hence, new architecture with a blend of vernacular architecture (for passive cooling), local materials (for cost reduction and local employment) and modern materials (for structural strength) is developed.

1.4. Literature review

Passive cooling features of vernacular architecture have been extensively researched in recent years. Passive cooling can be broadly classified into heat prevention, heat modulation and heat dissipation.

Shading, thermal insulation, building orientation and glazing are a few heat prevention/reduction strategies. Zaki et al. (2012) simulated a conventional terraced house and found that the house would require mechanical air-conditioning for 24 h on a hot summer day. However, incorporating passive architecture like insulating roof and walls, adding shading devices to windows and orienting the building and windows in the best direction would reduce the mechanical air-conditioning requirement to 8.5 h. The potential of shading devices to reduce cooling demand is reported to vary from 10% to 50% (Prieto et al., 2017). In general, lower savings are reported for the buildings with a lower window–wall ratio. Use of louvers in a fully glazed building in Santiago, Chile, reduced the cooling demand by 54% (Pino et al., 2012). A 30% reduction in the primary energy demand (cooling and lighting load) was achieved by optimizing the design of shading device using a genetic algorithm (Manzan, 2014). In a tropical climate, solar heat gain through the roof was reduced by 63% using hollow clay tiles with a provision for ambient air to flow through it (Vijaykumar et al., 2007). Use of light colour paints (Suehrcke et al., 2008) and deciduous creeper plants (Ip et al., 2010) to reduce the solar heat gain were also investigated.

Heat modulation strategies use the thermal mass of the building to achieve thermal comfort by storing heat and releasing it at different times of a day. Hazbei et al. (2015) investigated an underground shelter which utilizes the thermal mass of earth to improve thermal comfort. They found that the underground dwelling was comfortable with an indoor temperature of 25–26 °C even when the average temperature of the living space above the ground was 35 °C. Heat modulation could be coupled with heat dissipation techniques. Nighttime ventilation is a well-known example for coupling heat modulation and heat dissipation techniques. A study in the Mediterranean climate reported that the peak temperature of the indoor air was 0.6 °C lower than its outdoor counterpart if the space was ventilated at all times (Michael et al., 2017). The difference increased to 6.5 °C if the building was ventilated only at night time. Another study on nighttime ventilation reported a cooling energy reduction of 69–83%.

In passive heat dissipation systems, heat is transferred from the room to a lower temperature heat sink accessible at the site. Evaporative cooling, ventilation, geothermal cooling, nocturnal radiation and deep ocean/lake cooling are a few well-known heat dissipation techniques. Ventilation improves the indoor air quality (Sekhar and Goh, 2011), and in apt climatic conditions, it provides a better thermal comfort as well (Givoni, 1994). Removal of heat from the cavity in a double-skinned façade by ventilation air is reported to reduce the cooling demand by 17% (Radhi et al., 2013). The higher air movement caused by ventilation could offset the neutral temperature. For people adapted to the warm and humid climate, an air velocity of 1.6 m/s can increase the neutral temperature by 2.6 °C (Deb and Ramachandraiah, 2010). Nocturnal long-wave radiation cooling was reported to reduce the indoor temperature by 2.5–4 °C (Bagiorgas and Mihalakakou, 2008). Other heat dissipation techniques such as geothermal cooling (Li et al., 2014) and evaporative cooling (Ezzeldin and Rees, 2013) have also been investigated extensively.

1.5. Scope of this work

Even though there are numerous studies on thermal comfort of vernacular architecture, the buildings investigated in this study are different from the conventional vernacular buildings. The buildings investigated have used modern construction materials for load bearing elements to improve the durability of the structure. Investigation into thermal comfort of such buildings is reported scarcely in literature.

The thermal performance of eight buildings that were constructed predominantly with the local construction materials and used modern construction materials judiciously are investigated in this study. The influence of passive cooling features in these buildings is quantified in terms of the indoor air and surface temperatures. The thermal comfort achieved is examined using adaptive comfort standards. The buildings are monitored during the transient period between summer and monsoon (rainy) season, as a study during such a transient period is seldom done. Even though the structural strength of these buildings is not covered under the scope of this paper, the buildings have testified better durability till this point of their lifetime.

2. Methodology

2.1. Site description

The buildings investigated are in the Rural Technology Park at National Institute of Rural Development (NIRD), Hyderabad, India. Hyderabad experiences a hot semi-arid climate during summer, which peaks in the month of May, followed by the summer monsoon rains from June to September. In 2014, the monsoon was delayed. Some meteorologists attributed it to El Nino. The site received monsoon rain in the middle of July 2014. This reduced the average outdoor temperature from 31 to 24 °C within a span of 30 days (Weather Underground, 2015). The study had been planned during this period, to understand the performance of the buildings during a transient period. The investigation site is surrounded by greenery and located at a distance of 17 km from the city centre. Hence, the buildings are free from the pollution of the city.

2.2. Buildings description

India is a nation of pluralism, with diversity in language, culture and climate. The building architecture is not an exception. The traditional buildings vary widely, all through the country, based on the climate, availability of local materials and culture. In general, the traditional buildings are less durable with a relatively short lifespan and require frequent repairs compared to the buildings constructed with modern construction material. To overcome these limitations, the modern construction materials were used as load bearing elements of the building such as columns and beams and at other critical locations. In addition, a few features were incorporated to improve the longevity of the structure. An example of this is the use of non-erodible mud plaster and terracotta tiles on the external surfaces of the wall to prevent corrosion from rain water. In most of the buildings, the modern construction materials have no significant influence on the indoor thermal comfort because of their low quantity of usage compared to that of the traditional building materials. Table 1 lists the buildings monitored, their salient features and the preferred climatic regions of the buildings.

These buildings are preferred at different climatic regions based on their thermal characteristics. However, all the passive features considered in this study have a common purpose to reduce the average or peak temperature of the indoor. In the eight buildings investigated this purpose

Table 1
Traditional buildings investigated.

Sl. No.	Buildings	Salient features	Preferred climatic regions
1	Mud Block (MB)	i. Thick mud walls with high thermal mass reduce indoor temperature fluctuation ii. Air cavities in the roof (Wardha tumblers) and ceramic tiles over the roof reduce solar heat gain	Arid and semi-arid regions
2	Stabilized Mud Block (SMB)	i. Cooling by stack effect ii. Wooden carving below the roof reduces the radiative heat transfer from the roof	–
3	Rat Trap Bond (RT)	i. Rat trap bond in walls and filler material (Mangalore tiles) with air cavities reduce heat transfer and capital cost	Regions with extreme hot/cold climates
4	Jack Arch (JA)	i. Self-shading by arches reduces solar heat gain ii. Roof made of brick (low thermal conductivity than concrete) also reduces solar heat gain	Tropical regions
5	Stone Patti (SP)	i. Thick stone walls reduce the indoor temperature fluctuation ii. Central courtyard for adequate daylighting	Arid regions
6	Brick Dome (BD)	i. The dome shape of the roof provides self-shading ii. Rat trap bond walls reduce heat transfer	Tropical regions
7	Ferro Cement Channel (FCC)	i. FCC structures are eco-friendly, energy efficient and cheap compared to concrete roof	Regions with moderate climate
8	Filler Slab (FS)	i. Air flow (stack effect) through conical tiles at the bottom portion of roof reduces heat gain	Tropical regions

is achieved by removing the heat from indoor by cross or stack ventilation, by reducing the heat penetration with air cavities, low thermal conductive material or self-shading or by increasing the thermal mass of the structure. The objective of this study is to quantify the effect of these passive features. In order to understand the influence of these features and for a valid comparison of experimental data, the buildings located at a single location were investigated.

2.2.1. Mud block structure

Mud is the oldest and widely used construction material. According to the 2011 census of India, the walls of 23.7% households in India are constructed with mud (Devinfo, 2017). Mud structures are eco-friendly with a very low embodied energy, and use a low quantity of non-renewable materials, thus leading to sustainability (Walker, 2004). The thick mud walls have high thermal mass and reduce indoor temperature fluctuation. Hence, they are preferred in arid regions where the diurnal fluctuation of ambient temperature is high. In the investigated building, sun-dried mud blocks have been used to construct the walls. Mud blocks with one side terracotta tiles are used in the external walls to prevent water penetration and erosion from the rain water. The walls have fly ash brick columns to support the load. The roof is constructed using conical tiles “Wardha Tumblers” made of burnt clay (Fig. 1). The tumblers are inserted into one another in an arch fashion, and two series of arches make the roof. They reduce heat gain through the roof as the air entrapped inside the tumblers provides thermal insulation. The roof is waterproofed by plastering the external surface of the arches. Broken glazed ceramic tiles are stuck on the external surfaces of the roof to reflect the solar radiation and reduce the solar heat gain.

2.2.2. Stabilized mud block structure

Stabilization is the process of improving the compressive strength, volume stability, durability and permeability of the mud blocks using additives such as cement or lime (Nagaraj et al., 2014). The blocks are dried in sunlight, which reduces the CO_2 emission by 80% compared to that of the fired bricks (Heath et al., 2009). The structure, which was investigated, has a circular wall constructed with stabilized mud blocks (Fig. 2). The mud blocks were made by compressing a mixture of 5% cement, 5% rice husk ash, 33% quarry dust and 57% soil. A hexagonal pyramid roof was constructed above the walls with Mangalore tiles. Inclined roof and ventilation tiles cool the roof by enhancing air movement caused by stack effect. Transparent fibre tiles were used for adequate daylighting. A layer of wood carving present below the roof tiles also improves the thermal comfort by reducing the radiative heat transfer from the hot interior surface of Mangalore tiles. The structure has two openings of $0.46\ m \times 0.76\ m$ for windows and one opening of $1.14\ m \times 1.83\ m$ for a door.

2.2.3. Rat trap bond structure

A rat trap bond is a brick masonry bond in which the bricks are placed such that there are air cavities in the structure (Saileysh et al., 2012). It saves approximately 25% brick and 40% cement, and reduces the construction cost by 25%. In addition, the air cavities act as a thermal insulation and reduce heat penetration from the external sources. Hence, from a thermal comfort perspective, rat trap bonds are preferred in regions with extremely hot summer or extremely cold winter. The monitored rooms

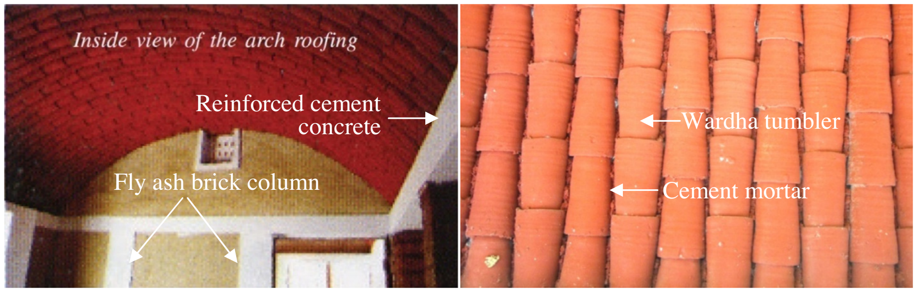

Fig. 1. Indoor view of roof made of fireclay tumbler (Reddi and Joglekar, 2005).

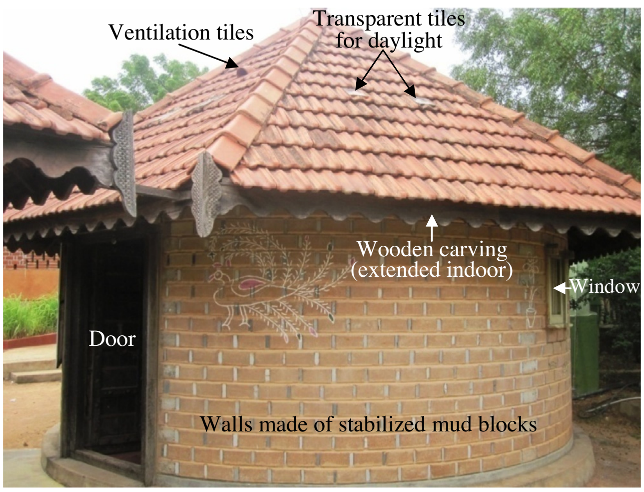

Fig. 2. Stabilized mud block structure.

(Fig. 3) have rat trap bond walls made of the conventional bricks. The rooms are hexagonal and well ventilated with five brick jally windows and one door. In the roof, Mangalore tiles are used as filler material. Two tiles are placed one over another to create air cavities. This reduces not only the solar heat gain but also the construction cost. The roof has transparent fibre tiles to provide adequate daylighting. The foundation is shaped like an arch to reduce the construction materials.

2.2.4. Jack arch structure

The Jack arch roof is cost effective and labour intensive, thus generates local employment. The structure is designed with the functionality of rural shops with a big door and no windows. The roof of the structure is made of four jack arches with each arch having a span, raise and thickness of 1.5, 0.25 and 0.1 m respectively. The arches are made of brick. This reduces the solar heat gain as the thermal conductivity of brick is lower than that of concrete, and the arches provide self-shading. Hence, Jack arch structures are preferred in solar-intensive tropical regions, where the Reinforced Cement Concrete (RCC) roof accounts for 40–75% of the total heat gain of a conventional building (Vijaykumar et al., 2007). The arches are supported by RCC columns. The roof is plastered on the external surface in order to eliminate moisture penetration. The walls are made of conventional bricks and plastered with non-erodible mud plaster. The structure is well shaded by adjacent trees.

2.2.5. Stone patti structure

The walls of the stone patti structure (Fig. 4) are constructed with dressed stones and reconstituted concrete blocks (concrete blocks with big stones to reduce cement usage). The structure is suitable for hot-arid regions like Rajasthan, which experiences high fluctuation of ambient air temperature, as thick stone walls, with a high thermal

Fig. 3. Salient features of rat-trap structure.

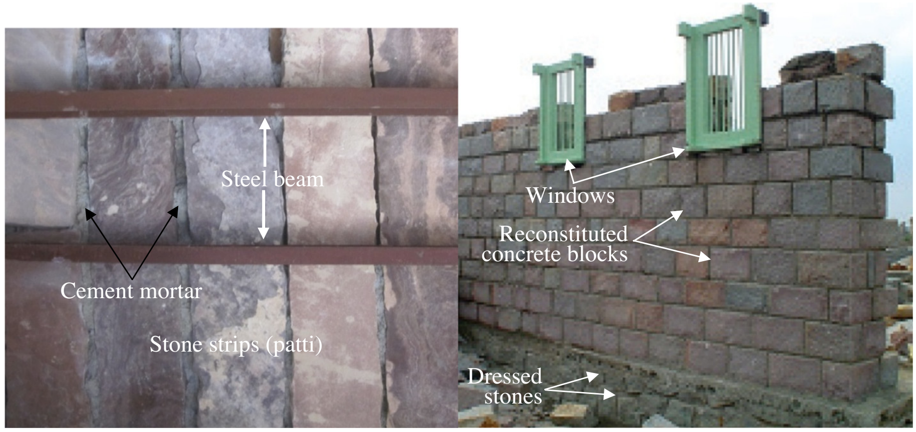

Fig. 4. Roof of stone patti structure (left) and dressed stone masonry (right) (Reddi and Joglekar, 2005).

mass, reduce the temperature fluctuation of the indoor air. The roof is made of stone strips (patti) placed over steel beams. The gaps between the stone strips are filled with cement mortar. The building has a central courtyard, which provides adequate daylighting. The building also has a provision for rainwater harvesting, as water is scarce in arid regions. The windows are very small as high ventilation is not desirable in hot and dry climatic conditions.

2.2.6. Brick dome structure

Dome structures are highly durable and strong. They reduce the heat interaction between the indoors and outdoors, as the surface area to volume ratio is low. They also reduce solar heat gain due to self-shading. A hemispherical roof receives 25–35% less solar radiation compared to a flat roof (Munoz et al., 2003). The investigated brick dome structure has a hexagonal centre hall and a corridor around it. It has rat trap bond walls and brick windows on all the walls that provide good ventilation. The roof of the centre hall, in the shape of a dome, has been constructed using bricks and concrete. The roof over the corridor has been made of ferro cement slabs in the shape of arches. A round glass has been placed at the centre of the brick dome for daylighting.

2.2.7. Ferro cement channel structure

The FCC is a thin concrete shell reinforced with closely spaced rebars and wire meshes (Richard, 2010). It is an energy efficient, eco-friendly and cost effective alternative to RCC. Compared to RCC, they have a high strength to weight ratio, reduced material usage, low construction cost and rapid construction. Though the FCC uses energy-intensive products, such as steel and rich cement proportion, they are energy efficient compared to the RCC due to the reduction in thickness, for uniform strength. The lower thickness of the FCC roof results in a higher heat transfer from the exterior. Hence, the FCC roofs are not preferable in solar-intensive tropical regions. They are suitable only for regions with a moderate climate. In the buildings investigated, the roof is constructed with FCCs placed adjacent to each other, with gaps not exceeding 7 mm, and the gaps are filled with cement mortar. FCCs are made at the site with earth–mortar mould, steel grill, chicken mesh and cement mortar of 1:3 (volume ratio of cement:sand). The roof is inclined towards the west. The walls are constructed with cement concrete blocks made at the site.

2.2.8. Filler slab structure

The filler is the material used to reduce the consumption of a more expensive material. Conical tiles called "Wardha Tumblers" are used in the lower part of the roof to reduce the consumption of concrete, with no appreciable impact on the slab's strength. This is because, concrete does not handle the tensile load in the lower part of the slab, which is caused by the slab's self-weight. The air gaps in the conical tiles reduce the solar heat gain. The roof is inclined, and the tiles are laid along the slope with openings at the lower and higher ends to facilitate air movement through the tiles caused by the stack effect. During daytime, the air movement removes the hot air inside the tiles, resulting in a reduced heat penetration and thus a relatively cold indoor space. The walls are constructed with fly ash bricks. The structure has one door and one bamboo mat paneled window in both east and west walls.

2.3. Monitoring protocol

The indoor air and interior surface temperatures have a greater bearing on thermal comfort. The temperature of the indoor and outdoor air, and the interior and exterior surfaces of the roof and walls are measured at an interval of one minute. T-type (copper – constantan) thermocouples, which work on the principle of Seebeck effect, are used for measuring temperatures. For measuring the surface temperatures, the thermocouples are placed in a small indentation on the surfaces and then pasted with a thin layer of white cement. A thermal conductive paste is used for better contact between the thermocouple and building fabrics.

The indoor CO_2 level is a good indicator of the indoor air quality, ventilation and prevalence of sick building syndrome (Gupta et al., 2007). The CO_2 concentration is measured at short intervals in all the buildings using an indoor air quality metre with an accuracy of ±3% of reading. A few of the buildings monitored have a good occupancy in the daytime, with the buildings being used as offices, whereas the other buildings are sparsely occupied with an occasional visit by the investigator and visitors. The average and maximum CO_2 levels monitored are 450 and 550 ppm. These indicate that the ventilation is adequate for the occupancy of the buildings.

2.4. Thermal comfort index

Thermal comfort indices are used to estimate the comfort level of a space. There are numerous such indices, of which Predicted Mean Vote (PMV) is widely used for conditioned spaces, whereas the adaptive neutral temperature model is apt for naturally ventilated buildings. Hence, the latter is used in this study. Neutral temperature is defined as the operative temperature at which the maximum number of people in a group feel neutral, i.e., neither cool nor warm. The neutral temperature is given by Fergus and Michael (2010),

$$t_n = 0.33t_{rm} + 18.8 \quad (1)$$

$$t_{rm} = (1 - x) \times (t_{od}^{-1} + x \times t_{od}^{-2} + x^2 \times t_{od}^{-3} + \ldots) \quad (2)$$

3. Results and discussion

The thermal parameters of eight buildings that have passive cooling features incorporated in them are investigated in three sets (Table 2). The surface temperatures of roof and walls are analysed to understand the influence of air cavity and thermal mass of the structure. The temperature of the indoor air is compared with neutral temperature and comfort limits to comprehend the comfort level in the buildings. Results obtained on the same days are compared. The outdoor conditions changed rapidly. Hence, a true comparison is not possible between different sets.

3.1. Mud block and stabilized mud block

The MB structure has air cavities in the roof to reduce solar heat gain. It also has thick walls with high thermal mass to reduce the temperature fluctuations. The SMB structure has ventilation tiles to facilitate air movement between the Mangalore tile roof and the wooden carving beneath it. The air movement is caused by stack effect, and it cools the structure.

Table 2
Experiment sets.

Sl. No.	Set	Buildings	Date
1	Set 1	MB and SMB	11th to 13th July 2014
2	Set 2	BD, FCC and FS	14th to 16th July 2014
3	Set 3	JA, RT and SP	08th to 10th July 2014

3.1.1. Roof temperature

Fig. 5 represents the diurnal temperature variation of the roof interior surface of both the MB and SMB structures and the exterior surface of the SMB structure. The temperature of both the interior and exterior surfaces reduces marginally during early morning hours. The temperature of the roof's exterior surface starts to increase at around 6:00, i.e., soon after sunrise, and continues to increase till it reaches the diurnal maximum. After which, the temperature of the roof's external surface reduces, due to the drop in solar intensity and ambient temperature. The maximum temperature of the roof's exterior surface of the SMB structure is reached at 11:20. This is earlier than normal, as on the day of the experiment the solar intensity reduced at around 11:00 and remained low for a couple of hours due to cloud cover. The change in the roof's exterior temperature influences its interior counterpart by heat conduction. However, the extrema of the interior surface lag behind that of the exterior surface due to the thermal mass of the roof.

The diurnal average temperature of the roof interior surface of the MB structure is 29.3 °C, which is almost the same as that of the SMB structure (29.4 °C). However, the diurnal fluctuation of roof interior surface is 1.9 °C lower in the former compared to the latter. Moreover, the peak temperature of the roof interior surface is attained at 15:00 in the former against 11:30 in the latter (Fig. 5). The roof of the MB structure is made of conical tiles and the gaps between the tiles are filled with cement mortar, whereas that of the SMB structure is made of Mangalore tiles and wooden carving. Hence, the thermal mass of the former is higher than that of the latter. This results in a lower temperature fluctuation and a delay in attaining the temperature extrema of the roof interior surface of the former compared to that of the latter. In the SMB structure, air movement beneath the roof and the low thermal mass of the roof results in a relatively fast temperature

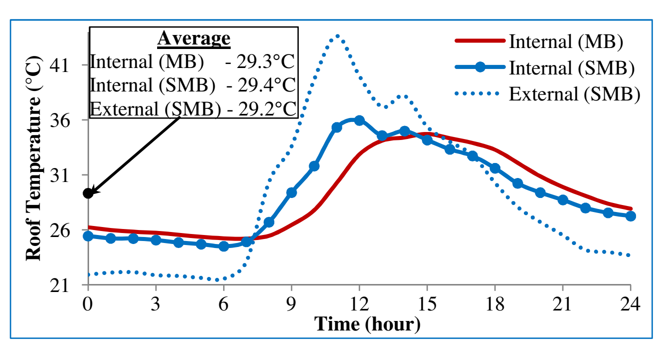

Fig. 5. Diurnal temperature variation of roof surfaces of MB and SMB structures.

drop of the roof interior surface, starting from early afternoon hours.

3.1.2. Wall temperature

The temperature of the wall exterior surfaces is measured on the north-facing surface of the MB structure and on the east- and west-facing surfaces of the SMB structure. The temperature of the walls is also measured at the nodes, where the normal passing through the exterior temperature nodes intersects the respective interior surface. The temperature fluctuation of the exterior surface of the MB structures is 9.1 °C, whereas that of the SMB structure is 7.3 °C (Fig. 6). The lower fluctuation in the latter is attributed to better shading by the adjacent buildings, trees and roof overhang. However, the temperature fluctuation of the interior surface is marginally lower in the former compared to that of the latter due to the high thermal mass of the thicker wall in the former. The diurnal average temperature difference between the interior and exterior surfaces of the wall is 2.7 °C for the MB structure, whereas that of the SMB structure is 1.6 °C. This is due to a lower thermal diffusivity and higher thickness of the walls of the MB structure. The average temperature of the wall interior surface is 28.3 and 27.9 °C in the MB and SMB structures respectively.

3.1.3. Indoor air temperature

Fig. 7 represents the diurnal temperature variation of the indoor air in the MB and SMB structures and comfort limits. The average temperature of the indoor air is almost the same in both the MB (28.4 °C) and SMB (28.2 °C) structures. However, the diurnal temperature fluctuation varies. For the former, the fluctuation is relatively less at 4.3 °C, due to a relatively high thermal mass, whereas for the latter it is 5.2 °C. The diurnal fluctuation of ambient temperature is found to be high at 9.5 °C. The average temperature of the outdoor air is 26.6 °C, which is at least 1.6 °C lower than the indoor air temperature of both the structures. The vertical temperature gradient is observed in the SMB structure from 10:00 to 18:00. The maximum difference in the indoor air temperature between 1 and 2 m height in the room is observed to be 1.1 °C.

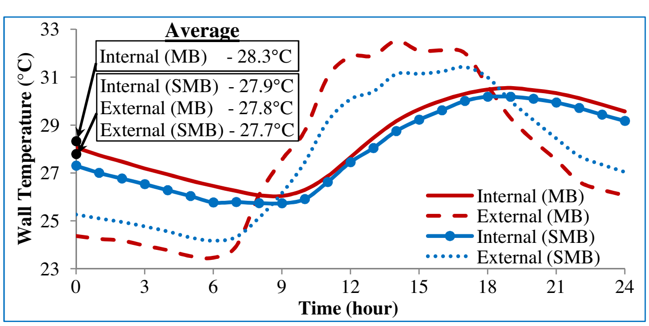

Fig. 6. Diurnal temperature variation of wall surfaces of MB and SMB structures.

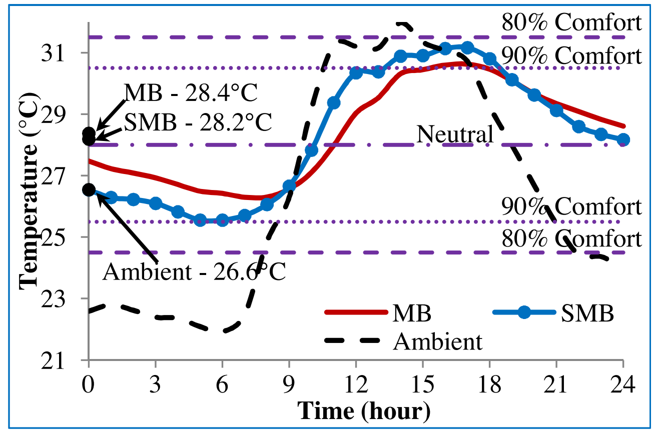

Fig. 7. Diurnal temperature variation of indoor air of MB and SMB structures and ambient air, and comfort limits.

Most of the rooms are small. Therefore, the view factor between the occupant and walls is high. Hence, the walls have a high influence on the mean radiant temperature. In addition, the temperature difference between the indoor air and the interior surfaces of the walls was low. Hence, the temperature of the indoor air was directly compared with the neutral temperature and comfort band to give an idea about the comfort achieved. The neutral temperature considering adaptive comfort is 28 °C. In both the structures, the temperature of the indoor air is within the 90% comfort limits (±2.5 °C) most of the time (Fig. 7) and within the 80% comfort limits (±3.5 °C) all through the day.

3.2. Brick dome, ferro cement channel and filler slab

The Brick Dome (BD) has a dome structure made of bricks. This reduces the solar heat gain of the structure due to self-shading and lower heat transfer as the thermal conductivity of brick is lower than that of the RCC. In addition, the air cavities in the walls reduce the heat transfer through the walls. In the Filler Slab (FS) structure, the air movement through the cavities in the roof caused by stack effect remove the heat from the roof. Thus, the solar heat gain is reduced significantly. The Ferro Cement Channel (FCC) structure has a high heat transfer through the roof due to its low thickness.

3.2.1. Roof temperature

The diurnal average temperatures of the roof interior and exterior surfaces of the FS structure are 24.9 and 25.3 °C respectively (Fig. 8), which are 1.2 and 1.9 °C lower than their FCC counterparts. This is because, heat is removed continuously from the roof of the FS structure by the ambient air flowing through the conical tiles embedded in the roof. The air movement is caused by stack effect. The air inside the conical tiles of the inclined roof is heated by solar radiation. The hot air moves up due to its low density and escapes out through the opening near the top of

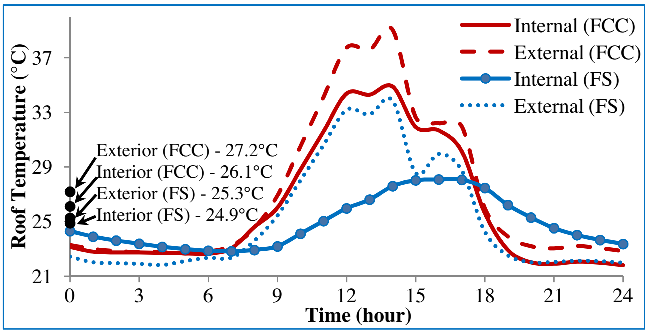

Fig. 8. Diurnal temperature variation of the roof interior and exterior surfaces of FCC and FS structures.

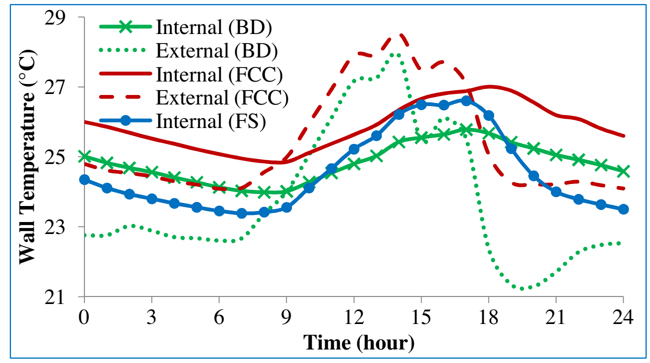

Fig. 9. Diurnal temperature variation of wall surfaces of BD, FCC and FS structures.

the inclined roof, whereas the ambient air which is at a relatively low temperature moves in through the opening at the bottom of the roof. The continuous heat removal in the FS structure during daytime results in a slower temperature rise of the roof exterior surfaces and a lower maximum value. Between 6:00 and 12:00, the temperature of the roof's exterior surface increases by 14.9 °C in the FCC structure, whereas in the FS structure the increase is only 10.8 °C. The maximum temperature of the roof's exterior surface of the FS structure is 5.2 °C lower compared to that of the FCC structure.

The diurnal average temperature of the roof interior surface is 1.2 °C lower for the FS structure compared to that of the FCC structure. This is also attributed to continuous heat removal from the roof. The difference between the diurnal average temperature of the interior and exterior surfaces of the roof is 0.4 and 1.1 °C in the FCC and FS structures respectively. The lower value of the former is due to the low thickness of the FCC roof. The diurnal temperature fluctuation of the roof interior surface is 13.1 °C in the FCC structure, whereas the fluctuation is just 5.3 °C in the FS structure. Moreover, it can be clearly observed that in the FCC structure, the temperature variation of the roof interior surface follows a similar trend as that of the exterior surface. The maximum temperature of the roof interior surface of the FCC structure is reached 2 h in advance compared to that of the FS structure as the thermal mass of the former is low due to the low thickness of the roof.

3.2.2. *Wall temperature*

In the BD structure, the temperature of the wall exterior surface is measured on the north-facing wall, whereas in the FCC structure, the temperature is measured on the exterior surface of both north- and south-facing walls and the average value is used for analysis. All the three locations, where the exterior surface temperature is measured, do not receive beam solar radiation due to the orientation of walls or shading by either adjacent structures or trees. For the BD structure, the diurnal average and fluctuation of the wall exterior surface temperature are 23.8 and 6.6 °C respectively, whereas in the FCC structures these are 25.1 and 4.7 °C respectively (Fig. 9). Higher fluctuation of temperature in the BD structure is due to higher resistance to heat transfer within the building fabric caused by the air cavities. At night, the ambient temperature is lower than that of the walls and hence the exterior surface of the wall loses heat by convection. However, due to the higher thermal resistance offered by air cavities in the BD structure, the external region of the wall receives less heat from the inner region; hence, the temperature of the external region drops faster. Thus, higher thermal resistance reduces the exterior surface temperature at night. Similarly, it increases the temperature during daytime. This results in a higher temperature fluctuation in the exterior surface of the structure with a good insulation.

The average temperatures of the wall interior surface in the BD, FCC and FS structures are 24.8, 25.7 and 24.6 °C respectively, and the temperature fluctuations of the surfaces in the three structures are 1.8, 2.4 and 3.2 °C respectively. Among the three, the temperature fluctuation of the interior surface is the highest in the FS structure due to the low thickness (1/2 brick wall) of its wall. The fluctuation is the lowest in the BD structure due to the higher thermal resistance offered by the air cavities in the walls. This is because, the air cavities reduce the penetration of external heat, which has a higher fluctuation. The average temperature is the highest in the FCC structure due to the high solar heat gain through the roof and the absence of ventilation.

3.2.3. *Indoor air temperature*

Fig. 10 represents the diurnal temperature variation of the indoor air in the BD, FCC and FS structures. The neutral temperature calculated using the adaptive comfort model and the lower limit of comfort band are also superimposed on the figure, whereas the upper limit of the comfort band is outside the vertical axis of the figure. The temperature difference of indoor air between the FS and BD structures is very small from 11:00 to 19:00, as both these structures are well ventilated. After 19:00, the temperature fall is slower in the BD structure compared to the FS structure due to the high thermal mass of the former and a

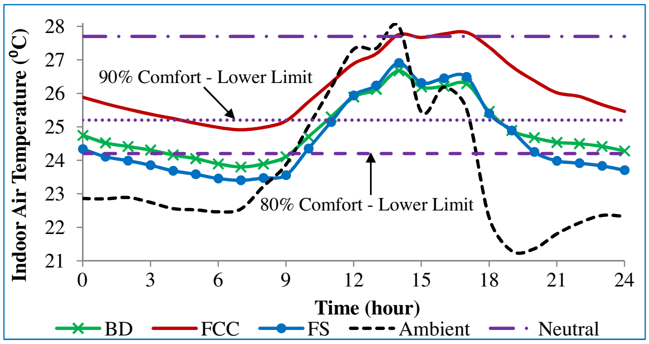

Fig. 10. Diurnal temperature variation of indoor air of BD, FCC and FS structures and ambient air, and neutral temperature and comfort bands.

reduction in the wind speed of the ambient air. The average temperature of the indoor air in the BD, FCC and FS structures is 24.9, 26.2 and 24.6 °C respectively. The temperature is higher in the FCC structure compared to the other two structures. This is due to the absence of ventilation and a relatively high solar heat penetration through the roof in the FCC structure. The average outdoor air temperature is 23.8 °C, which is lower than the average temperature of the indoor air in all the three structures. This is because of the fall in diurnal average temperature of the outdoor air due to the onset of the southwest monsoon and the accumulation of solar heat in the thermal mass of the building.

The diurnal temperature fluctuations of the indoor air in the BD, FCC and FS structures are 2.9, 2.8 and 3.5 °C respectively. The fluctuation is the lowest in the FCC structures, even though the temperature fluctuation of the interior surface of both the roof and the wall is the highest in this structure compared to the other two structures. This is due to the absence of ventilation in this structure. The neutral temperature on the day of the experiment is 27.7 °C. This is 3.9 °C higher compared to the diurnal average temperature of the outdoor air, as the temperature dropped faster over a period of a few days due to the onset of monsoon rain. In the FCC structure, the indoor air temperature is within the 90% comfort limit most of the time. Hence, the FCC structures are suitable for slightly colder regions with a good solar radiation; such climatic conditions are prevalent at higher altitudes in tropical regions. In both the BD and FS structures, the indoor air temperature is below the lower comfort limit most of the time, which would result in a thermal discomfort for the occupants. If 80% comfort limits are considered, then the space is uncomfortably cool from 4:00 to 9:00 in the BD structure and from 1:00 to 9:00 in the FS structure, and comfortable during the rest of the time.

3.3. Jack arch, rat trap bond and stone patti

The external heat penetration through the roof is low in the Jack Arch (JA) structure due to self-shading of arches and low thermal conductivity of bricks used in the roof compared to an RCC roof. In addition, the walls of the JA structure are well shaded by the trees. In the Rat Trap (RT) structure, the air cavities in roof and walls reduce the heat transfer. The Stone Patti (SP) structures have a very high thermal mass and are suitable for hot-arid regions.

3.3.1. Roof temperature

Fig. 11 represents the diurnal variation of the roof surfaces of the JA, RT and SP structures. The exterior surfaces of the RT structures are inclined and the surface which is monitored faces the southwest direction. Hence, this surface receives a higher solar radiation in the late afternoon compared to that of the horizontal roof in the SP structure. As a result, the temperature of the roof's exterior surface of the RT structure increases between 15:00 and 17:00 h, whereas that of the SP structure decreases during this period. Excluding this deviation, the temperature of the exterior surface of the SP and RT structures follows a trend similar to each other. Another notable difference is that the temperature of the RT structure increases more rapidly during the morning hours compared to that of the SP structure, even though the former receives a lower solar radiation in the morning due to its orientation. This is due to the thermal resistance offered by air cavities in the roof of the RT structure. The influence of air cavities on the temperature of the exterior surface is explained in Section 3.2.2. The average temperatures of the roof exterior surface in the RT and SP structures are 28.5 and 27.4 °C. The temperature of the roof's exterior surface of both the RT and SP structures is higher than that of the ambient air all through the day. The difference during daytime is due to heating of the roof by solar radiation, whereas that at night is due to the heat stored in the roof and lower nocturnal long-wave radiation cooling of the roof because of the cloud cover. On an average, the roof's exterior surface of the RT and SP structures is 2.8 and 1.7 °C hotter than the ambient air. The temperature drop in the exterior surface at around 14:00 is due to overcast sky and hazy weather at that time.

The average temperatures of the roof interior surface in the JA, RT and SP structures are 27.4, 27.8 and 27.9 °C respectively (Fig. 11), and the diurnal temperature fluctuations in these three structures are 4.1, 4.4 and 5.5 °C respectively. The absence of ventilation in the JA structure results

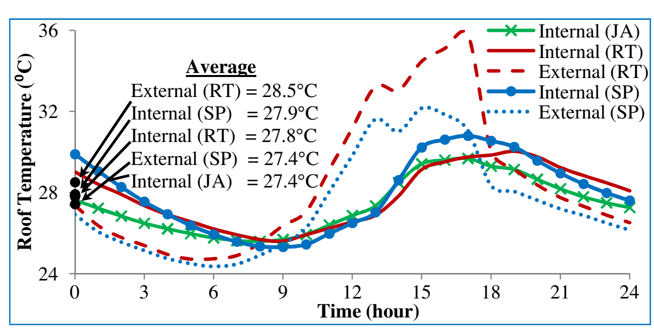

Fig. 11. Diurnal temperature variation of roof surfaces of JA, RT and SP structures.

in a low fluctuation of the indoor air temperature, which in turn reduces the temperature fluctuation of the roof interior surface with which it transferred heat by convection. Among the remaining two structures, the temperature fluctuation is higher in the SP structure due to a relatively high thermal conductivity of its roof.

The maximum temperature difference between the interior and exterior surfaces is 4.6 °C in the SP structure, whereas the difference is higher at 6.4 °C in the RT structure. This also points towards the thermal resistance offered by the air cavities in the RT structure. The temperatures of the roof's exterior and interior surfaces attain the peak at 15:00 and 17:00 respectively in the SP structure and at 17:00 and 19:00 respectively in the RT structure. The delay observed in the RT structure is mainly due to the inclination of its roof. In the SP structure, the average temperature of the roof's exterior surface is 0.5 °C lower than that of the interior surface due to relatively fast cooling of the exterior surface at night. In the RT structure, the former is 0.7 °C higher than that of the latter. This is due to the higher temperature difference between the interior and exterior surfaces during the daytime caused by the air cavities in the roof.

3.3.2. Wall temperature

The temperature of the wall exterior surface is measured on the north-facing wall of the RT structure and the southwest-facing wall of the SP structure that is shaded by the adjacent trees. The diurnal average temperatures of the wall exterior surface in the RT and SP structures are 27.5 and 26 °C respectively. From 8:00 to 17:00, the temperature of the wall exterior surface of the SP structure matches closely with the ambient air temperature (Fig. 12a). This is because the wall of the SP structure is well shaded by adjacent trees. Moreover, the predominant wind direction of west and west–northwest favoured the heat transfer between the wall and the ambient air. The temperature difference between the exterior wall surface of the SP structure and ambient air during the rest of the time is attributed to the fall in wind speed and the heat stored in the structure.

Fig. 12(b) represents the diurnal temperature variation of the interior surface of the JA, RT and SP structures. The diurnal average temperatures of the wall interior surface in the JA, RT and SP structures are 27.4, 28.9 and 27 °C respectively. The higher temperature of both interior and exterior surfaces of the RT structures is due to (i) higher solar heating, unlike the other two structures that are shaded by trees and (ii) higher internal load, as the structure is used as an office. The diurnal temperature fluctuations of the wall interior surface in the JA, RT and SP structures are 5.3, 2.8 and 2.0 °C respectively. Lower fluctuation in the JA structure is due to the absence of ventilation and shading of walls by adjacent trees.

3.3.3. Indoor air temperature

Fig. 13 depicts the diurnal temperature variation of the indoor air along with the neutral temperature and comfort limits. The diurnal temperature fluctuation of the indoor air in the SP structure is relatively high (5.1 °C) due to the presence of the courtyard, which permitted beam solar radiation to heat the indoor air. A sharp rise in the temperature of the indoor air of the SP structure between 10:00 and 13:00 is an evidence of the solar heating. In the SP structure, the temperature fluctuation of the indoor air observed between 13:00 and 18:00 is due to the fluctuation in solar radiation, as the weather is partly cloudy on the day of the experiment. In the JA and RT structures, the temperature fluctuations of the indoor air are 2.5 and 3.5 °C respectively. Low fluctuation in the former is due to the absence of ventilation, whereas the high fluctuation in the latter is partly due to the presence of ventilation and partly due to changes in internal load as the structure is used as office space during daytime.

The diurnal average temperatures of the indoor air are 27.8, 27.2 and 26.7 °C in the JA, RT and SP structures, which are higher than the average outdoor air temperature of 25.7 °C. Good ventilation in the RT and SP structures results in a lower temperature of indoor air in these structures compared to that of the JA structure, which is without ventilation. In the SP structure, the maximum temperature of the indoor air is reached at 13:00, just when

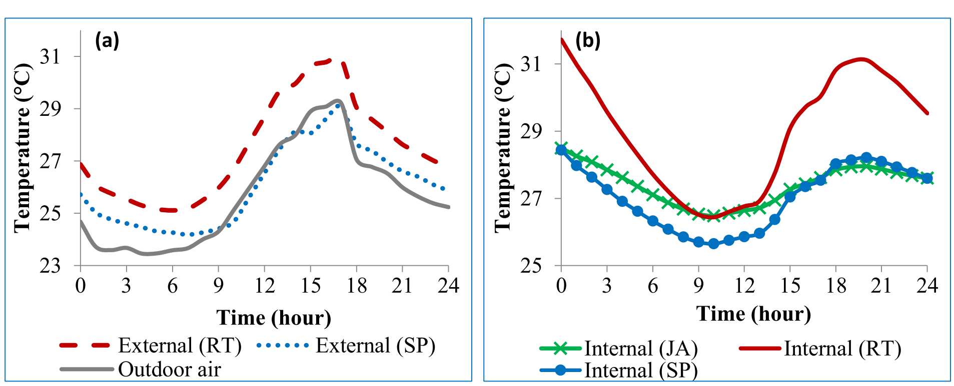

Fig. 12. Diurnal temperature variation of wall (a) exterior and (b) interior surfaces.

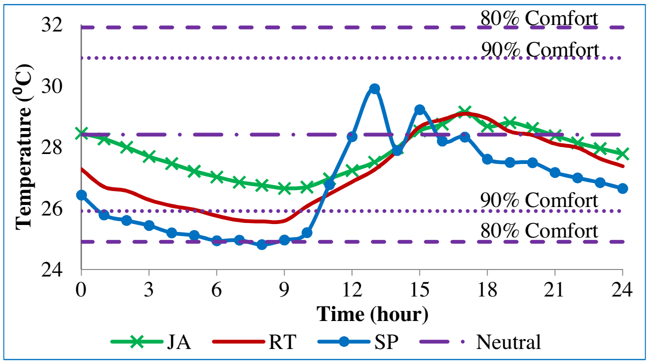

Fig. 13. Diurnal temperature variation of indoor air of JA, RT and SP structures and the comfort limits.

solar radiation is at its peak, due to direct heating of the indoor air by solar radiation. In the JA and RT structures, the peak temperature is reached at 17:00, due to the thermal storage of the building fabrics. The neutral temperature considering adaptive comfort is 28.4 °C. Considering 90% comfort band, the JA structure is comfortable at all times. The SP and RT structures are comfortable at all times if 80% comfort limits are considered.

4. Conclusions

Thermal performance of eight cost-effective, durable and eco-friendly structures, that have merged traditional architecture with modern materials, was investigated during the transition period between summer and monsoon seasons. Considering 80% adaptive comfort limits, the indoor spaces of six structures are comfortable all the time, and the remaining two structures are comfortable most of the time and slightly cold during the late evening and early morning hours. The use of filler materials in roofs and the presence of air cavity in the walls (rat trap bonding) are found to reduce the heat transfer through the structure significantly. The increase in the thermal mass of the structure reduces the temperature fluctuation and delays the time at which the temperature extrema are reached. The maximum temperature of the roof interior surface is reached 3 h 30 min later in the mud block structure (higher thermal mass) compared to that of the stabilized mud block structure. Induced ventilation caused by heating the roof is found to have an appreciable impact on the indoor temperatures. An inclined roof, with induced ventilation through conical tiles embedded in it, has 1.2 and 1.9 °C lower interior and exterior surface temperatures compared to that of a roof with no such provisions. Thus, passive architectural features in a building can provide thermal comfort if employed correctly.

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References

Bagiorgas, H.S., Mihalakakou, G., 2008. Experimental and theoretical investigation of a nocturnal radiator for space cooling. Renew. Energ. 33, 1220–1227.
Deb, C., Ramachandraiah, A., 2010. Evaluation of thermal comfort in a rail terminal location in India. Build. Environ. 45, 2571–2580.
Deepak, B., Ramkishore, S., Sawhney, R.L., 2014. Effect of construction materials on embodied energy and cost of buildings—A case study of residential houses in India up to 60 m^2 of plinth area. Energy Build. 69, 260–266.
Devinfo, India, Material of wall: Mud/Unburnt brick – Households – Percent http://www.devinfo.org/indiacensus2011/libraries/aspx/data-view.aspx 2017 accessed 09.02.17.
Ezzeldin, S., Rees, S.J., 2013. The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates. Energy Build. 65, 368–381.
Fergus, N., Michael, H., 2010. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Build. Environ. 45, 11–17.
Givoni, B., 1994. Passive and Low Energy Cooling of Buildings. Van Nostrand Reinhold, New York.
Gupta, S., Khare, M., Goyal, R., 2007. Sick building syndrome—A case study in a multistory centrally air-conditioned building in the Delhi City. Build. Environ. 42, 2797–2809.
Hatamipour, M.S., Abedi, A., 2008. Passive cooling systems in buildings: some useful experiences from ancient architecture for natural cooling in a hot and humid region. Energy Convers. Manage. 49 (8), 2317–2323.
Hazbei, M., Nematollahi, O., Behnia, M., Adib, Z., 2015. Reduction of energy consumption using passive architecture in hot and humid climates. Tunn. Undergr. Sp. Tech. 47, 16–27.
Heath, A., Walker, P., Fourie, C., Lawrence, M., 2009. Compressive strength of extruded unfired clay masonry units. Proc. Inst. Civil Eng. Constr. Mater. 162 (3), 105–112.
Ip, K., Lam, M., Mille, A., 2010. Shading performance of a vertical deciduous climbing plant canopy. Build. Environ. 45, 81–88.
Li, H., Yu, Y., Niu, F., Shafik, M., Chen, B., 2014. Performance of a coupled cooling system with earth-to-air heat exchanger and solar chimney. Renew. Energy 62, 468–477.
Manzan, M., 2014. Genetic optimization of external fixed shading devices. Energy Build. 72, 431–440.
Michael, A., Demosthenous, D., Philokyprou, M., 2017. Natural ventilation for cooling in mediterranean climate: A case study in vernacular architecture of Cyprus. Energy Build. 144, 333–345.
Munoz, V.M.G., Gandara, M.A.P., Heard, C., 2003. Solar performance of hemispherical vault roofs. Build Environ. 38, 1431–1438.
Nagaraj, H.B., Sravan, M.V., Arun, T.G., Jagadish, K.S., 2014. Role of lime with cement in long-term strength of Compressed Stabilized Earth Blocks. Int. J. Sust. Built Environ. 3 (1), 54–61.
Prieto, A., Knaack, U., Klein, T., Auer, T., 2017. 25 Years of cooling research in office buildings: review for the integration of cooling strategies into the building façade (1990–2014). Renew. Sust. Energ. Rev. 71, 89–102.
Pino, A., Bustamante, A., Escobar, R., Pino, F.E., 2012. Thermal and lighting behavior of office buildings in Santiago of Chile. Energy Build. 47, 441–449.
Radhi, H., Sharples, S., Fikiry, F., 2013. Will multi-facade systems reduce cooling energy in fully glazed buildings? A scoping study of UAE buildings. Energy Build. 56, 179–188.
Reddi, G.B., Joglekar, M.N., 2005. Blending the Traditional With The Modern: Cost Effective Rural Housing Technologies, first ed. National Institute of Rural Development, Ministry of Rural Development, Hyderabad.

Richard, P.C., 2010. Study of full-scale elements of a ferrocement roof system for Caribbean application. Constr. Build. Mater. 24 (3), 221–229.

Saileysh, S., Vijayakumar, S., Thandavamoorthy, T.S., Moses Aranganathan, S., Chinnaraju, K., 2012. Base shock excitation of rat-trap bond masonry with and without roof slab. Int. J. Earth Sci. Eng. 5 (1), 146–153.

Sekhar, S.C., Goh, S.E., 2011. Thermal comfort and IAQ characteristics of naturally/mechanically ventilated and air-conditioned bedrooms in a hot and humid climate. Build Environ. 46, 1905–1916.

Suehrcke, H., Peterson, E.L., Selby, N., 2008. Effect of roof solar reflectance on the building heat gain in a hot climate. Energy Build. 40, 2224–2235.

Vijaykumar, K.C.K., Srinivasan, P.S.S., Dhandapani, S., 2007. A performance of hollow clay tile (HCT) laid reinforced cement concrete (RCC) roof for tropical summer climates. Energy Build. 39, 886–892.

Walker, P., 2004. Strength and erosion characteristics of earth blocks and earth block masonry. J. Mater. Civ. Eng. 16 (5), 497–506.

Weather Underground Weather History http://www.wunderground.com 2015 accessed 23.02.15

Worrell, E., 2014. Cement and Energy. Ref. Module Earth Syst. Environ. Sci. 1, 307–315.

Zaki, W.R.M., Nawawi, A.H., Ahmad, S.S., 2012. Environmental prospective of passive architecture design strategies in terrace houses. Proc. Soc. Behav. Sci. 42, 300–310.