U.S.-India Joint

Center for Building Energy Research and Development

(CBERD)

Post occupancy analysis

Golconde

Afsanah

Luminosity

INTACH

Blessing House

Mukuduvidu

Solar Kitchen

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Doctor-Pingel, M., Sathyanarayanan, H., Vardhan, V., (2017). *Afsanah Guest House, Auroville Post Occupancy Analysis*. Centre for Scientific Research (CSR), Auroville. Submitted to the U.S.-India Joint Center for Building Energy Research and Development (CBERD)

Doctor-Pingel, M., Vardhan, V., (2017). *Luminosity Apartments: Post Occupancy Analysis*. Auroville, India: Centre for Scientific Research (CSR), Auroville. Submitted to the U.S.-India Joint Center for Building Energy Research and Development (CBERD)

Doctor-Pingel, M., Vardhan, V., (2017). *INTACH Office: Post Occupancy Analysis*. Auroville, India: Centre for Scientific Research (CSR), Auroville. Submitted to the U.S.-India Joint Center for Building Energy Research and Development (CBERD)

Doctor-Pingel, M., Vardhan, V., (2017). *Blessing House: Post Occupancy Analysis*. Auroville, India: Centre for Scientific Research (CSR), Auroville. Submitted to the U.S.-India Joint Center for Building Energy Research and Development (CBERD)

Doctor-Pingel, M., Vardhan, V., (2017). *Mukuduvidu: Post Occupancy Analysis*. Auroville, India: Centre for Scientific Research (CSR), Auroville. Submitted to the U.S.-India Joint Center for Building Energy Research and Development (CBERD)

Doctor-Pingel, M., Sathyanarayanan, H., Vardhan, V., (2017). *Solar Kitchen, Auroville: Impact of Solar Chimney*. Centre for Scientific Research (CSR), Auroville. Submitted to the U.S.-India Joint Center for Building Energy Research and Development (CBERD)

Centre for Scientific Research, Auroville

U.S. India Joint Centre for Building Energy Research and Development (CBERD)
Task 6.1: Climate Responsive Buildings

Post Occupancy Analysis
Compiled Report: 7 Buildings

November 2017

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1. CBERD Project

1.1 Introduction

Lawrence Berkeley National Laboratory, United States and CEPT University, India have collaborated to form the 'United States–India Joint Centre for Building Energy Research and Development', abbreviated as CBERD. CBERD is aimed at conducting collaborative research with a focus on commercial buildings - which significantly contributes to the society in measureable metrics of reductions in energy usage across the buildings in India and U.S. (CBERD, n.d.). The broad spectrum of R&D tasks in regard to Green Energy Technologies and Sustainable Buildings under the CBERD initiative are:

1. Simulation
2. Monitoring
3. Controls
4. Envelope/Passive Design (insulation, cool roofs)
5. Advanced technologies (HVAC, lighting)
6. Thermal comfort
7. Grid responsiveness
8. Renewable integration
9. Scientific collaboration

This outcome-based R&D will result in significant energy savings by driving development of cost-effective technologies and their implementation. In addition, this project will:

i. Contribute to enhanced ties between the U.S. and Indian Building Energy researchers and industry;
ii. Help in the development of integrated, proven, and marketable building technologies;
iii. Help establish a public-private collaboration to identify deployment pathways for a sustainable tomorrow;
iv. Involve leveraged research funding and ultimately result in improved capabilities for both the nations to ascend in the direction of development of energy efficient building technologies and markets.

1.2 Task 6.1 Climate Responsive Design

The task 6.1 – Climate Responsive Design, under the CBERD project focusses on the performance evaluation of buildings in the 5 climatic regions across India (Cold, Hot and Humid, Hot and Dry, Composite, and Moderate). The experimental research examined 15 buildings through 180 data loggers, 160 Sensors (Thermal, Humidity, Lux Level) with a research team of 50 people, and accounted for a cumulative data of over 1,32,000 hours across multiple seasons through the year (cberd.org).

1.3 Research Objective

The objective of the Task 6.1 is to ascertain the thermal performance of naturally ventilated buildings in the Hot and Humid climate of India. Naturally ventilated structures allow efficient ingress of natural air and greatly reduce the operational costs using numerous passive design strategies. This research aims at furthering the understanding of incorporating natural elements and passive design methods in rhyme with the building type, making it more sustainable and comfortable for the occupants.

2. Building Selection Criteria

2.1 Passive Design Strategies for India

India is the seventh-largest and the second-most populous country in the world. Its vast expanse stretches between 6.7° and 35.5° north in latitudes and 68.1° and 97.4° east in longitudes. In addition to being one of the most culturally vibrant and ancient civilisations, it has a generous abundance of geographical features – the mighty Himalayas in the north, the dry Thar Desert in the west, and the eastern-western ghats flanking the Deccan Plateau. India has a 5,423 km long coastline along the Arabian Sea in the south-west, Lakshadweep Sea in the south and the Bay of Bengal towards the south-east. Such varied geographical elements lend the country its multiple climatic zones.

Figure 1 shows the division of India on the basis of its different climatic zones (Bureau of Indian Standards, 2005). The northern and north eastern states like Jammu and Kashmir, Himachal Pradesh, Uttarakhand, the Seven Sister states, and a few hilly locales in the plateau experience a ‘Cold’ or ‘Temperate’ climate. The Thar makes portions of the western states of Rajasthan, Gujarat and Maharashtra ‘Dry and Hot’. The major part of the landmass experiences a ‘Warm/Hot and Humid’ or ‘Composite’ microclimate due to the flat river basins. Appendix A further discusses upon the characters of these climatic zones (Bansal & Minke, 1995; Krishan, 2001).

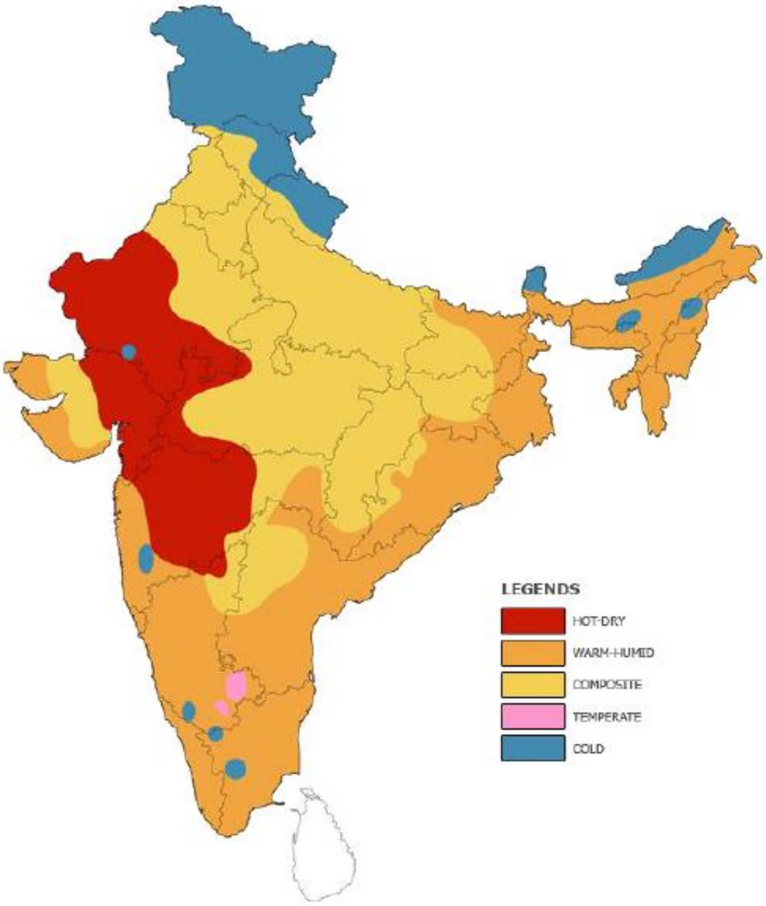


Figure 1 Climate zones of India

This research extends across the stretch of India, incorporating all the climatic zones. However, the buildings under study under AV CSR, Studio Naqshbandi fall under the ‘Warm/Hot Humid’ climate zone.

2.2 About Pondicherry and Auroville

Pondicherry (Puducherry) is defined by its unique confluence of the French and Tamil architecture and culture, owing to the fact that it was once a French colonial settlement until 1954. It is a Union Territory town with the state of Tamil Nadu to the southeast and the Bay of Bengal to the East. The town showcases different flavours of architecture on the basis of the dwelling ethnic groups in the immediate history. The streets are ornamented with bright-coloured colonial mansions, French styled fenestrations, and a contrast of pink and white bougainvillea vines. The kilometre long promenade to the east of the town serves as a leisurely spot for the commons – it also houses some of the most prominent buildings of the city, like the French Consulate, Chief Secretariat of the Government of Pondicherry and the biggest statue of Mahatma Gandhi in Asia.

The Golconde Dormitories lies towards the Eastern part of the town, on one of its most prominent roads – Ambour Salai, while INTACH office lies on the Mahatma Gandhi road, as can be seen in figure 2.

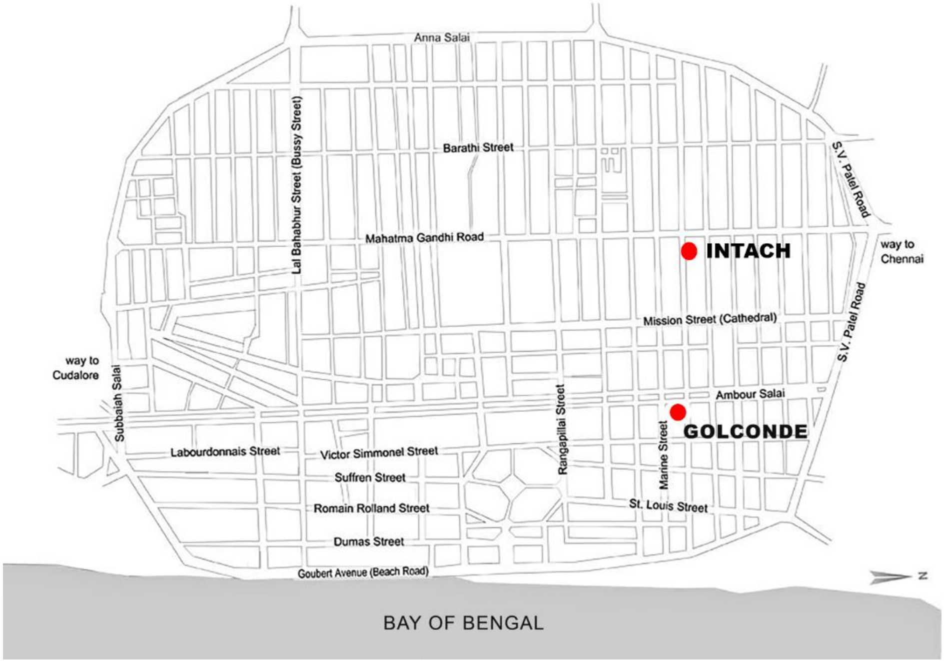


Figure 2 Location of Golconde and INTACH on the map of Pondicherry

Auroville is named after the great Indian philosopher, poet, and spiritual leader Sri Aurobindo. Conceptualised in February 1968, by the spiritual companion of Sri Aurobindo, Mirra Alfassa - known as ‘the Mother’, the town of Auroville has been fully encouraged and commended by the Indian Government and UNESCO as a project of importance to the future of humanity. The first of its kind township is planned in the form of a galaxy, with the iconic Matrimandir at its centre. The four – industrial, international, cultural, and residential zones spiral from the Matrimandir, and are enclosed by a Green Belt of moderate to dense natural foliage.

Figure 3 shows the plan of the Auroville Township with the buildings in question – Afsanah Guesthouse, Luminosity Apartments, Blessing House, Mukuduvidu, and the Solar Kitchen.

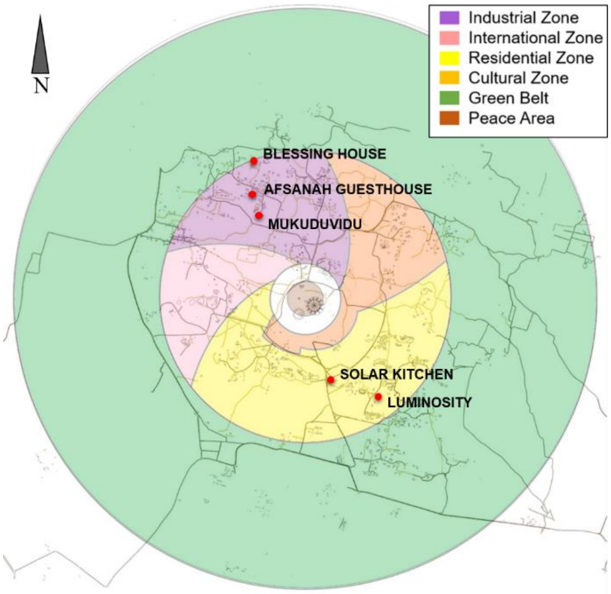


Figure 3 Location of the five buildings in the Auroville zones

2.3 AV CSR, Studio Naqshbandi

The Auroville Centre for Scientific Research is a novel scientific research hub, founded in 1984 with an aim to establish a strong scientific foundation for research in sustainable technologies that are locally and globally relevant. It has been involved in numerous projects intertwining the realms of society and technology - ranging from renewable energy systems, appropriate architecture & building technologies, to water and waste water management. Studio Naqshbandi is an Architectural Studio, which focusses on research in the field of Building Biology and stresses on the inclusion of bio-climatic design practices in all its projects.

Studio Naqshbandi, under the umbrella of The Auroville Centre for Scientific Research conducted post occupancy surveys and data acquisitions to analyse the temperatures, relative humidity levels, lux levels and wind speeds across the 7 buildings in the ‘Hot and Humid’ climes of Auroville and Pondicherry (Golconde Dormitories, Blessing House, Mukuduvidu, Afsanah Guest House, Luminosity Apartments, INTACH Office, and Solar Kitchen).

2.4 Selected Buildings

Under the Task 6.1 - Climate Responsive Design, 7 buildings were chosen for the hot and humid climate of Pondicherry and Auroville. The choice of these buildings was made on the basis of the varied passive design strategies employed and typologies. Table 1 mentions the buildings, their locations, and the incorporated passive design strategies. Two of these buildings, Golconde and Blessing House were chosen for a full building analysis and while the others were studied for specific passive design strategies.

Table 1 Buildings in question under the ‘Hot and Humid’ climate

Building	Location	Typology	Passive Design Strategy
Golconde Dormitories	Pondicherry	Collective Residential	Thermal Mass, Shading, Ventilation, Landscape, Orientation, Thermal Insulation.
Blessing House	Auroville	Individual Residence	Thermal Mass, Night Time Cooling, Shading, Thermal Insulation.
Mukuduvidu House (Doctor- Pingel et. al, 2014)	Auroville	Individual Residence	Thermal Mass, Shading, Ventilation, Landscape, Building Form – Domes and Vaults.
Afsanah Guest House	Auroville	Light Commercial	Thermal Mass, Shading, Landscape, Orientation.

Luminosity Apartments	Auroville	Collective Residential	Thermal Mass, Orientation, Ventilation, Thermal Insulation.
INTACH Office	Pondicherry	Office (Traditional Indian Building)	Thermal Mass, Ventilation, Shading.
Solar Kitchen	Auroville	Public Dining	Thermal Mass, Ventilation.

2.4.1 Golconde Dormitories

India's first and finest modernist building, the Golconde, was constructed during 1937 to 1942 in the heart of the city of Pondicherry by the eminent Czech Architect, Antonin Raymond, and American woodworker-architect, George Nakashima. It served as a spiritual retreat for the artists, *sadhaks* (practitioners of Integral Yoga), and the members of Sri Aurobindo Ashram. The building had been designed keeping in mind the nature of its occupants and their meditative state of mind – incorporating a multitude of natural elements and passive design strategies. (Gupta, P.V. et. al, Golconde – *the introduction of modernism in India*)

The building is draped with manually operable asbestos cement louvers on the northern and southern facades, allowing the ingress of natural air and illumination at convenience of the occupants. The landscape on the north and south, to the exterior of the building acts as a natural source for fresh, cool air, enhancing the thermal performance of the building. The southern garden is more densely vegetated than the northern garden, which leads to slight tem a natural pressure gradient, and the structure is oriented in a way to minimise the incidence of the sun during the hottest hours. One of the most interesting and novel approaches in Golconde, the ventilated double roof, acts as an efficient insulator and protects the top floor from the scorching heat afternoon sun. In addition to these passive design strategies, the appropriately placed corridors in the north double up as thermal buffers and stop the thermal radiation from the walls to reach the inhabitants in the rooms next to the corridors. (Bhatt, A., *Golconde: Architecture climate and comfort*)

Figure 4 Indoor and outdoor views of the Golconde

2.4.2 Afsanah Guest House

The Afsanah Guest House was designed by architect Poppo Pingel in 2003, and is located within the Auroville International Township. The building under study, dining hall of the guest house has a flat roof on the ground floor made of hollow terra cotta (hurdi) blocks and a state-of-the-art insulated manglore clay tile roof for the first floor guest room. The ground floor dining hall is fully naturally ventilated with wire mesh and grills with almost no walls and no glass. One enjoys the exterior-interior connection with the sand garden on one side and a largish pond integrated within the landscape on the other, which makes for an interesting study. This report focusses on multiple research questions the insulated roofing strategy, orientation, shading, lighting and cross ventilation with the help of plotted trends on monthly averaged, annual and instantaneous bases.

Figure 5 Afsanah guest house

2.4.3 Luminosity Apartments

The Luminosity apartments is a collective residential building, conceptualised and realised by the team of architects and planners led by David Nightingale and Ganesh Bala. The motivation behind the building was to create a 'temple of living' for the occupants and practitioners of the yogic way of life in Auroville. It is comprised of 12 small apartments, 8 offices, and community areas on the rooftop with two gardens, as can be inferred from the figure 6 below. The apartments are separated from each other and from the staircases with the help of cavity walls built of dense fly-ash blocks. The staircases are built as free-standing elements – separate from the main walls, and the north side of the structure is equipped with vertical acoustic louvres which can be closed to curb the rains or hot winds.

The building orientation allows the ingress of natural breeze in the summers, where sliding doors of mesh and glass can be opened to maximise the wind. In the morning and the evening hours the cavity walls to the east and west also minimise heat transfer from the sun, while the GI sheet enclosure on the roof reduces the direct solar heating. This report details on the thermal environment of the indoor zones and surfaces across the building.

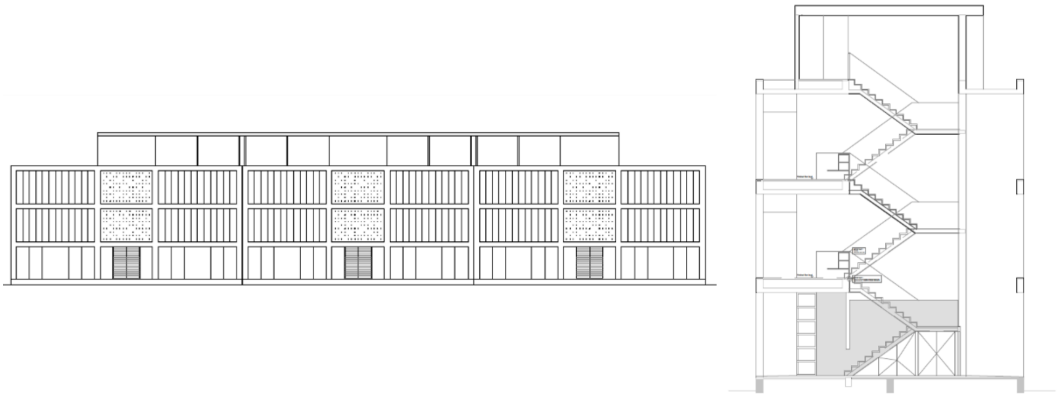


Figure 6 Front and side section view of Luminosity apartments

2.4.4 INTACH Office

INTACH - Indian National Trust for Art and Cultural Heritage, was set up in 1984 to preserve the varied architectural heritage of India. Pondicherry, being a city with a unique mix of the Tamil and French architectures, requires its eminent heritage buildings to be taken care of. INTACH undertook the task of listing, grading, and mapping the database of heritage buildings across the city and constantly appends on to the same list. This data is supplied to the Pondicherry Planning Authority (PPA), which ultimately formulates the norms and standards for the upkeep of the old buildings and the construction of the newer ones.

The INTACH office is set up in over a century old Franco-Tamil house in the heart of the city, restored in 2007. It includes trademark Tamil architectural elements like an open courtyard (shown in the figure 7 below) – wooden pillars surrounding it, terracotta roofing, etc. while including distinctive French elements like white pillars on the leading walls, ornate coloured glasswork in the transom windows, and the wooden doors and windows. The property still remains in the hands of the original owner's family, belonging to the Komati Chettu community. The family's ancestors were a part of the first Indian members of the Theosophical Society who were close associates of the British theosophist, Annie Besant.

Figure 7 INTACH office - central courtyard

2.4.5 Blessing House

The Blessing House is a two-story residential building located in Auroville, India, involving multiple passive design strategies in its construction. Designed by the Mr. Dhanya, with a conscious support of Dr. Chamanlal Gupta, the building focusses on using natural elements. Its walls consist of a composite wall assembly - compressed earth blocks on the internal side, Aerocon blocks on the exterior and a layer of cement plaster on both the sides. The building's ceiling/roof construction is an insulated assembly of white reflective ceramic tiles, Aerocon blocks, a layer of cement concrete, followed by *hurdi* terra cotta hollow blocks with reinforcement, and a layer of cement plaster. The building is fully solar powered and adds on to the sustainability with rainwater harvesting. The rainwater is collected into a swimming pool which is used throughout the year for leisure and watering the gardens. A solar water heater provides for hot water. Most windows (except in a small bedroom area) are single glazed float glass with aluminium frame. Entire house is grilled with metal sections with wire mesh to make it mosquito proof.

In addition to these passive design strategies, the Blessing House uses occupant controlled natural night ventilation to pre-cool the house - the occupants manually open their windows at night and close them in the morning at their own discretion. This report focusses on multiple research questions concerning the ventilation, thermal mass, shading, lighting and the occupant controlled phenomenon with the help of plotted trends on monthly averaged, annual and instantaneous bases.

Figure 8 The Blessing House. South façade to the left, North to the right

2.4.6 Mukuduvidu

Mukuduvidu is a residential two storied building, meticulously constructed by the architects Poppo Pingel and Mona Doctor-Pingel in the lush surroundings of Auroville. The building has north-south orientation with extensive usage of low fired country bricks, and lime mortar and plaster. It employs multiple passive design strategies such as: long overhangs on the north and south to curb the excessive incident radiation; wind exhausts for domes, high ceiling with vaults to facilitate ventilation and indoor air stratification; white reflective china mosaic on the dome surfaces for maximised albedo.

In addition to the above mentioned strategies, the thermal comfort in the building is further enhanced by larger openings in the south in comparison to the other directions – restricting the hot summer sun and the predominant rains. The structure has been draped by a generous amount of foliage – large trees on the north and west, natural self-maintained water bodies and the Zen sand garden to the south. Adding on to the sustainability, the building extensively incorporates the principles of building biology. It uses locally sourced natural materials, bio concrete with hand cut limestone aggregate, and indigenous plant species. It cuts down the energy consumption further by using treated waste water and Solar PV modules, in tandem with a solar water heater and cooker.

This report studies the temperature, humidity, and wind flow across the domes and vaults in particular.

Figure 9 Mukuduvidu

2.4.7 The Solar Kitchen

Designed by Architect Suhasini Ayer, the Solar Kitchen is a collective dining facility for Auroville completed in 1998. The most interesting feature of this building is a 15m diameter roof collector on the roof for creating steam used for cooking. The dining facility can house 1000 persons. The building is a load bearing construction made with cement stabilized earth blocks made on the site with large (10m) prefab ferrocement channels. The building has a solar chimney that is being monitored for the study.

Figure 10 Solar Kitchen

3. Methodology

3.1 Research Questions

Upon the selection of the building, the research team at Auroville, along with the CEPT team framed site-specific research questions. These research questions allowed the development of site-specific research framework (positioning of temperature, humidity and lux level sensors). The research questions for the respective buildings are mentioned as follows:

Golconde Dormitories:

1. How did the air temperature and relative humidity vary across the rooms on different floors? How did the comfort inside the rooms vary due to extremity of location?
2. How did the indoor conditions in rooms and passages vary diurnally and across the year?
3. How did the air temperature and relative humidity vary in the Northern passage compared to the rooms?
4. How did the air flow vary diurnally and across the year? What were the Air Flow patterns in the building?
5. What was the heat transmission through the double ventilated roof? What effect did the ventilated roof have on the rooms on the third floor?
6. What was the heat transmission through the north and south façades?
7. What was the heat transmission through the cavity wall? What was the surface temperature of the internal and external faces of the cavity wall?
8. Was the ceiling surface temperature different in the rooms in the west and east wings?
9. How did the ceiling surface temperature in the rooms on the third floor compare against the ceiling surface temperature in the room on the second?
10. Was the light intensity adequate with the used louvers type, overhangs on the both side and sunken level of semi-basement?
11. Was the light intensity adequate with the different window strategies at different floor levels and semi-basement?

Afsanah Guest House:

1. What is the thermal lag and heat conduction through the sloped terracotta Mangalore tiles roof with insulation? How does it vary diurnally and across the year?
2. What is the thermal lag and heat conduction through the flat roof with hollow blocks? How does it vary diurnally and across the year? Comparison of the performance of the two different roofing strategies.
3. What is the indoor condition in the dining room and how do these conditions vary over time (diurnally and across the seasons)?
4. How does the insulated flat and terracotta slope roof influence the indoor temperature and RH conditions?

5. How does the landscape influence the indoor temperature and RH conditions?

Luminosity Apartments:

1. How does the air temperature and relative humidity vary diurnally and across the seasons in the rooms on different floors and in different locations of the building?
2. What is the impact of the passage in the north side of the building on the indoor conditions of the rooms? How do these conditions vary diurnally and across the year?
3. What is the thermal time lag and heat conduction through the roof slab? How does it vary diurnally and across seasons?
4. What is the thermal time lag and heat conduction through the cavity wall and how does it impact the indoor space? How does it vary diurnally and across seasons?
5. What is the thermal time lag and heat conduction through the east and west walls? How does it vary diurnally and across seasons?

INTACH Office:

1. What is air temperature and relative humidity in the space adjacent to the courtyard?
2. How do the indoor conditions in naturally ventilated space vary diurnally and across the year?
3. How do the indoor conditions in mix-mode office vary diurnally and across the year?
4. How do indoor conditions differ in the naturally ventilated space from the condition of mixed mode office room?
5. What is the thermal time lag and heat transmission occurring through the madras roof covered with red terracotta tiles? How does it vary diurnally and across the year?

Blessing House:

1. How did the air temperature and relative humidity vary diurnally and across the seasons in different rooms across floors?
2. How did the strategy of ‘opening windows for night cooling and closing during the day’ wor
3. What was the heat transmission through the composite wall with Aerocon blocks? How did it vary diurnally and annually?
4. What was the heat transmission through the insulated terracotta roof? How did it vary diurnally and annually?
5. What was the impact of having double glass panes on the indoors?
6. What was the difference in thermal conditions of the rooms with glass windows and the balconies and verandas towards the north and south?
7. Was the indoor day lighting sufficient in the house?
8. What was the window opening and closing windows pattern of occupants?
9. How does behaviour of occupants change with change of seasons?

Mukuduvidu:

1. What is the daily and seasonal variation of air temperature, relative humidity and air velocity in the rooms with dome 1 and dome 2 respectively?
2. What is the variation due to different ventilation strategies used in both domes?
3. What is the stratification occurring at various heights in the rooms of both domes?
4. What is the thermal lag and heat conduction occurring in the domes due to material assemblies and thermal mass?
5. What is the thermal lag and heat conduction occurring in the vault due to material assemblies and thermal mass?
6. How does the thermal performance of domes compare against the thermal performance of vaults?

Solar Kitchen:

1. What is the air temperature inside the chimney and the room area below it?
2. What are the indoor conditions (air temperature, globe temperature and relative humidity) in the naturally ventilated (NV) space near the solar chimney?

3.2 Instrumentation

After a thorough market research in regard to the necessity of equipment, the following tools were finalised for usage. Long term monitoring of indoor air temperature and relative humidity was done using Onset HOBO data loggers. A HOBO data logger could log data for up to 3 years at regular intervals for temperature, humidity and lux. The measurement range for temperature was -20 to 70°C, for relative humidity was to 100% and light intensity was 1 to 3000 foot-candles. The accuracy of temperature measurement was ± 0.35°C (for a range of 0-50°C) and of relative humidity measurement was ±2.5% (for a range of 10-90%). The five kinds of loggers (A, B, C, D, and E) used for our study are shown in figure 11. Instantaneous air velocity measurements were taken using the hand-held Testo 405-V1 thermal anemometer (Figure 12). It measured air temperature, volumetric flow rate, and air velocity. It was capable of logging as well as taking instantaneous measurements for these parameters, with a 300mm telescopic extension. Measurement range for temperature was -20 to 50°C (±0.5°C), for volumetric flow rate it was 0 to 99990 m^3/h, and for air velocity 0 to 10m/s ±(0.1 m/s + 5% of mv – for 0-2 m/s), ±(0.3 m/s + 5% of mv – above 2 m/s) Testo. (n.d.).

Instantaneous measurements of air and globe temperature and relative humidity were taken using the Extech HT30 Heat Stress meter (Figure 12). Black globe temperature monitored the effect of direct solar radiation on an exposed surface. Its globe temperature measurement range was 0 to 80°C (±2°C accuracy), air temperature measurement range was 0 to 50°C (±1°C) and relative humidity measurement range was 0 to 100% (±3% at 25°C, 10 to 95% RH) Extech (n.d). The indoor instantaneous lux measurement was carried out using Testo 540 Lux Meter (Figure 12). It had a measuring range of 0 to 99999 Lux with an accuracy of ±3 lux and a resolution of 1 Lux. The measuring rate of the device was 0.5 seconds – Testo (n.d). The instantaneous surface temperature was measured using Fluke 561 IR Thermometer, which uses a single point laser sighting. The temperature measurement range was -40 to 550°C with a resolution of 0.1°C. It employs a K-type thermocouple for precise thermal measurement up to ±1% of the reading at the ambient temperature of 23°C – Fluke (n.d.).

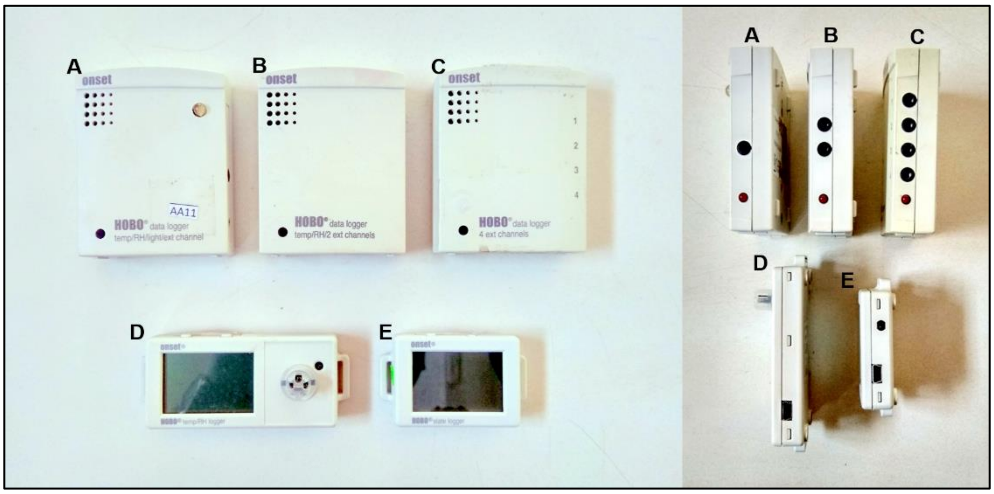


Figure 11 Permanent loggers A, B, C, D, and E with a side view showing the input/output channel slots

Figure 12 Handheld measurement instruments: Testo 405-V1 Anemometer, Extech HT30 Heat Stress Meter, Testo 540 Lux Meter, and Fluke 561 – IR Thermometer respectively

3.3 Monitoring Strategy

3.3.1 Long Term Monitoring

Data loggers were installed in multiple locations across the building. The sensors had to be placed in locations where they would not have affected the daily happenings, while gathering the most relevant data for our study. Tables 2 to 8 enlist the position, type, parameters monitored and name of each of the loggers placed across the seven buildings.

Table 2 Golconde loggers

Zone	Hobo. I.D.	Logger Name	Parameters	Height (mm)	Sensor Locations
I Floor, Eastern Room 9	B12	PDY_NV_GLCD_1E9_B12	Temperature, Relative Humidity	1750	South Façade External and Internal Surfaces
I Floor, Western Room 1	D10	PDY_NV_GLCD_1W1_D10	Temperature, Relative Humidity	1750	Inside the room on the cupboard
II Floor, Eastern Room 6	A8	PDY_NV_GLCD_2E6_A8	Temperature, Relative Humidity, Light Intensity	1750	Inside the room on the mirror
II Floor, Eastern Room 6	B11	PDY_NV_GLCD_2E6_COR_B11	Temperature, Relative Humidity	2050	Northern Wall Exterior & Internal Surface (Corridor)
II Floor, Western Room 6	D9	PDY_NV_GLCD_2W6_D9	Temperature, Relative Humidity	1750	Inside the room on the cupboard
II Floor, Western Room 6	B13	PDY_NV_GLCD_2W6_COR_B13	Temperature, Relative Humidity	2050	Northern Wall Exterior & Internal Surface
III Floor, Eastern Room 1	C5	PDY_NV_GLCD_3E1_C5	Temperature, Relative Humidity	1950	Ceiling Surface, East Wall Internal and External Surfaces

III Floor, Eastern Room 1	D11	PDY_NV_GLCD_3E1_D11	Temperature, Relative Humidity	1750	Inside the room on the cupboard
III Floor, Western Room 1	A7	PDY_NV_GLCD_3W1_A7	Temperature, Relative Humidity, Light Intensity	1750	Inside the room on the cupboard
III Floor, Western Room 1	C7	PDY_NV_GLCD_3W1_C7	Temperature, Relative Humidity	1950	Ceiling Surface, West Wall Internal and External Surfaces
Basement, Western Dining Room	A6	PDY_NV_GLCD_BAS_DR_A6	Temperature, Relative Humidity, Light Intensity	2050	Inside the dining room
Basement, Western Passage	D12	PDY_NV_GLCD_BAS_PAS_IN_D12	Temperature, Relative Humidity	1950	Inside the passage, under the tea place
Basement, Western Passage	B2	PDY_NV_GLCD_BAS_PAS_OUT_B2	Temperature, Relative Humidity	2050	On the beam of the corridor next to the passage
Rooftop	B10	PDY_NV_GLCD_RFT_B10	Temperature, Relative Humidity	0	Roof Shell Top Surface and Internal Surface
II Floor, Staircase	B17	PDY_NV_GLCD_STAIR_CAVW_B17	Temperature, Relative Humidity	1750	Cavity wall Internal & External Surface
III Floor, Eastern Room 1	A13	PDY_NV_GLCD_3E1_A13	Temperature, Relative Humidity	2050	On the East Wall
Basement, Northern Garden	B15	PDY_NV_GLCD_GARD_OUT_N_B15	Temperature, Relative Humidity	1750	Hanging on the tree
Basement, Southern Garden	B16	PDY_NV_GLCD_GARD_OUT_S_B16	Temperature, Relative Humidity	1750	Hanging on the tree

Table 3 Afsanah loggers

Zone	**Hobo. I.D.**	**Logger Name**	**Parameters**	**Height (mm)**	**Sensor Locations**
Ground floor dining hall	A4	AV_NV_AFG_DIN_GF_A4	Temperature, Relative Humidity	1900	Middle of hall
Ground floor-Zen Garden OUT	B14	AV_NV_AFG_ZENGD_OUT_B14	Temperature, Relative Humidity	1900	Outside
Ground floor-Pond Garden OUT	B25	AV_NV_AFG_PONGD_OUT_B25	Temperature, Relative Humidity	1900	Outside
First floor Balcony	C3	AV_NV_AFG_TER_FF_C3	Temperature, Relative Humidity	2300	Wall
Ground floor dining hall Pondside	D6	AV_NV_AFG_POND_IN_GF_D6	Temperature, Relative Humidity	1900	Wall
Ground floor dining hall Zen Garden side	D8	AV_NV_AFG_SANGD_IN_GF_D8	Temperature, Relative Humidity	2070	Wall
Sloping Roof		TMC-6 HE-6’ TMC-20 HD-20’	Surface temperature	6 feet 20 feet	Inside and outside the sloping roof
Flat roof		TMC-6 HE-6’ TMC-20 HD-20’	Surface temperature	6 feet 20 feet	Inside and outside the flat roof

Table 4 Luminosity loggers

Zone	Hobo. I.D.	Logger Name	Parameters	Height (mm)	Sensor Location
Ground Floor	D13	AV_NV_LUM_DAVOF_GF_D13	Temperature, Relative Humidity,	1900	Zone G1
Ground Floor	B19	AV_NV_LUM_JEFOF_GF_B19	Temperature, Relative Humidity	1830	Zone G2
Second Floor	A9	AV_NV_LUM_DAV_SF_A9	Temperature, Relative Humidity	1720	Zone S1, bedroom
Second Floor	B18	AV_NV_LUM_DAV_SF_B18	Temperature, Relative Humidity	2000	Zone S1, passage
Rooftop	B20	AV_NV_LUM_DAV_RFTOP_B20	Temperature, Relative Humidity	100	White tiled rooftop surface

Table 5 INTACH loggers

Zone	Hobo. I.D.	Logger Name	Parameters	Sensor Locations
Courtyard	B8	PDY_NV_INTACH_CRTYD_B8	Temperature, R.H.	Hanging on the west wall
Courtyard	A10	PDY_NV_INTACH_CRTYD_RM_A10	Temperature, R.H., Light Intensity	On the wooden pillar
Office	D14	PDY_NV_INTACH_OFC_D14	Temperature, R.H.	Middle of the pillar

Table 6 Blessing House loggers

Zone	Hobo. I.D.	Logger Name	Parameters	Height (mm)	Sensor Locations
Ground Floor Dining Hall	A5	AV_NV_BLH_DINR_GF_A5	Temperature, Relative Humidity, Light Intensity	1620	Kitchen Wall
Ground Floor Guest Room	B6	AV_NV_BLH_GR_GF_B6	Temperature, Relative Humidity	2000	East Wall
Ground Floor Veranda	D7	AV_NV_BLH_VER_GF_D7	Temperature, Relative Humidity	1630	East Wall
I Floor, Room 2	D3	AV_NV_BLH_SUR_FF_D3	Temperature, Relative Humidity	1680	West Wall
I Floor Room 1	D4	AV_NV_BLH_BAL_S_D4	Temperature, Relative Humidity	1680	West Wall
I Floor Room 1	A3	AV_NV_BLH_DHR_FF_A3	Temperature, Relative Humidity, Light Intensity	2360	East Wall
I Floor Bed Room	B4	AV_NV_BLH_BR_FF_B4	Temperature, Relative Humidity	1680	West Wall
I Floor Veranda	D5	AV_NV_BLH_VER_N_FF_D5	Temperature, Relative Humidity	1640	West Wall
I Floor Balcony	E2	AV_NV_BLH_DHR_FF_E2	Window Open/Close	1500	Next to the window

Mezzanine	C4	AV_NV_BLH_MEZ_WW_C4	Temperature	1670	West Wall
Outdoor	A13/ B7	AV_NV_BLH_OUT_B7	Temperature, Relative Humidity, Light Intensity	1670	South Garden

Table 7 Mukuduvidu loggers

Zone	**Hobo. I.D.**	**Logger Name**	**Parameters**	**Height (mm)**	**Sensor Locations**
Dome 1	A1	AV-NV-MV-DM1-FF-A1	Temperature, R.H., Light Intensity	1620	Western side of the dome
Dome 1	B9	AV-NV-MV-DM1-FF-B9	Temperature, R.H.	1770	Western side of the dome
Dome 1	C1	AV-NV-MV-DM1-FF-C1	Temperature, R.H.	1770	Exterior brick wall
Dome 1	D1	AV-NV-MV-DM1-FF-D1	Temperature, R.H.	1620	Hanging from the dome – central axis
Dome 1	A3*	AV-NV-MV-DM1-FF-A3	Temperature, R.H.	840	Hanging from the dome – central axis
Dome 1	A5*	AV-NV-MV-DM1-FF-A5	Temperature, R.H.	2170	Hanging from the dome – central axis
Dome 1	B6*	AV-NV-MV-DM1-FF-B6	Temperature, R.H.	3170	Hanging from the dome – central axis
Ground Floor Vault	B5	AV-NV-MV-VLT-GF-B5	Temperature, R.H.	1680	On the pillar
Dome 2	B1	AV-NV-MV-DM2-FF-B1	Temperature, R.H.	1580	Western side of the dome
Dome 2	C2	AV-NV-MV-DM2-FF-C2	Temperature	1580	Exterior brick wall
Dome 2	D2	AV-NV-MV-DM2-FF-D2	Temperature, R.H.	1450	Hanging from the dome – central axis
Dome 2	B3	AV-NV-MV-DM2-FF-B3	Temperature, R.H., Air Velocity	1830	Western side of the dome
Outdoor	AWS	-	Temperature, R.H.	-	Auroville Weather Station

Table 8 Solar Kitchen loggers

Zone	**Hobo. I.D.**	**Logger Name**	**Parameters**	**Height (mm)**	**Sensor Locations**
Dining Hall 1	B21	AV_NV_SK_DIN_DN_B21	Temperature, Relative Humidity	1770	Dining Hall
Dining Hall 2	B22	AV_NV_SK_DIN_DN_B22	Temperature, Relative Humidity	4000	Inside the Solar Chimney

The measurement involved usage of five kinds of loggers (A, B, C, D & E) depending on the number of channel inputs and parameters to be measured. Logger A was a single-channel logger which handled the data for temperature, relative humidity and the Lux Levels. Logger B, a two channel logger, reported the values of temperature and relative humidity. Logger C was a four channel logger, which reported the values of temperature and relative humidity. Logger D was a two channel logger with a display for instantaneous temperature and relative humidity. Logger E was a binary Open/Close logger which was used to indicate the open/close state of the window.

3.3.1.1 GOLCONDE LOGGER PLACEMENT

Figure 13 shows the position of the placement of loggers in the basement dining hall. Three loggers, A6, B2 and D12 were placed in the beam of the dining hall, the corridor next to the basement passage, and the semi open area/tea place in the passage respectively.

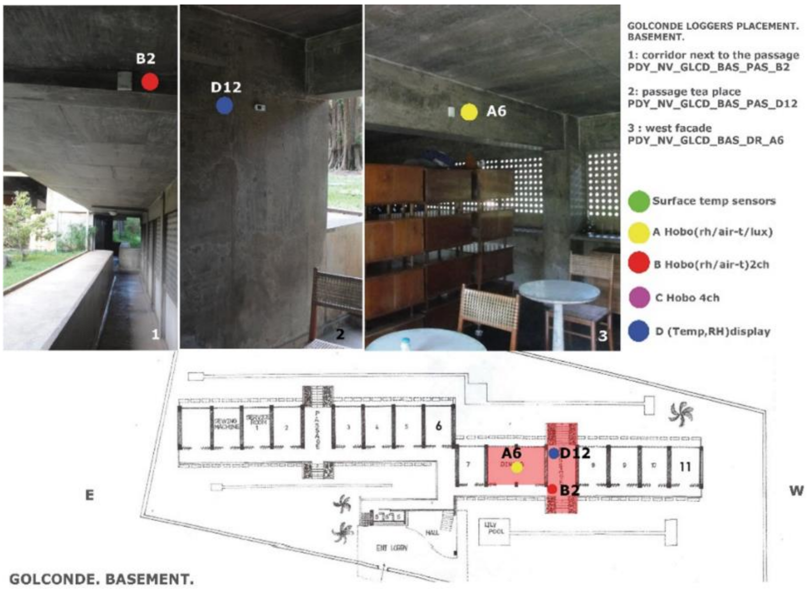


Figure 13 Placement of loggers in the basement

Figure 14 shows the placement of loggers on the first floor. Loggers B12 and D10 were placed in the 9th room in the east wing and 10th room in the west wing respectively.

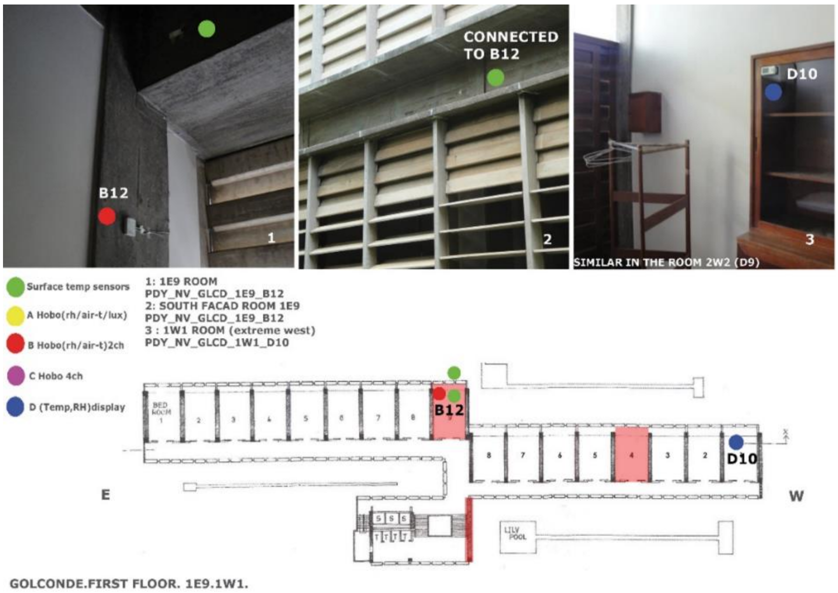


Figure 14 Placement of loggers on the first floor

Figures 15, 16 and 17 show the placement of loggers on the second floor. Loggers A8 and B11 were placed in the east wing, in the 6th room and the northern passage respectively. Loggers D9 and B13 were placed in the west wing, in the 6th room and the southern passage respectively.

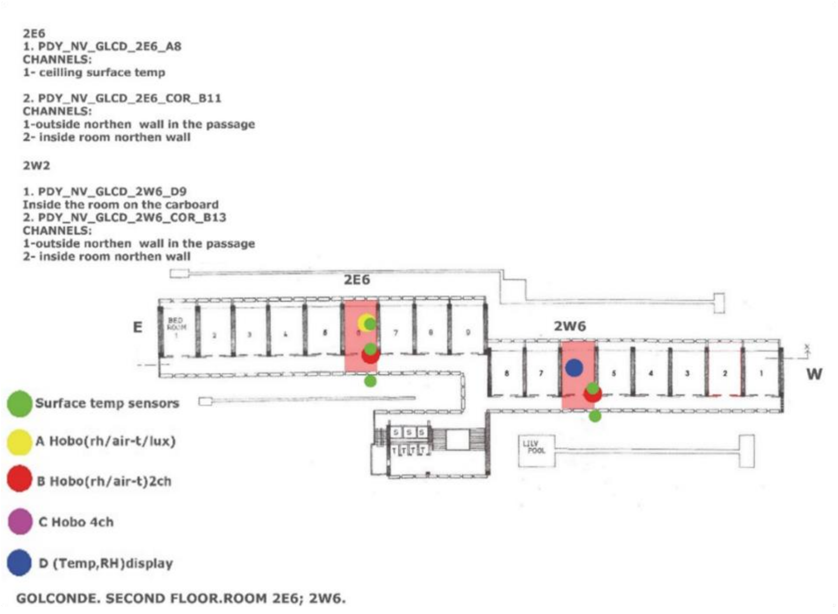


Figure 15 Placement of loggers on the Second Floor - Floor Plan.

Figure 16 Placement of loggers on the Second Floor – Inside the room

Figure 17 Placement of loggers on the Second Floor - East and West passages

Figures 18, 19 and 20 show the placement of loggers on the third floor. Loggers C5 and C7 were placed in the 1st room on the east wing and 1st floor on the west wing respectively.

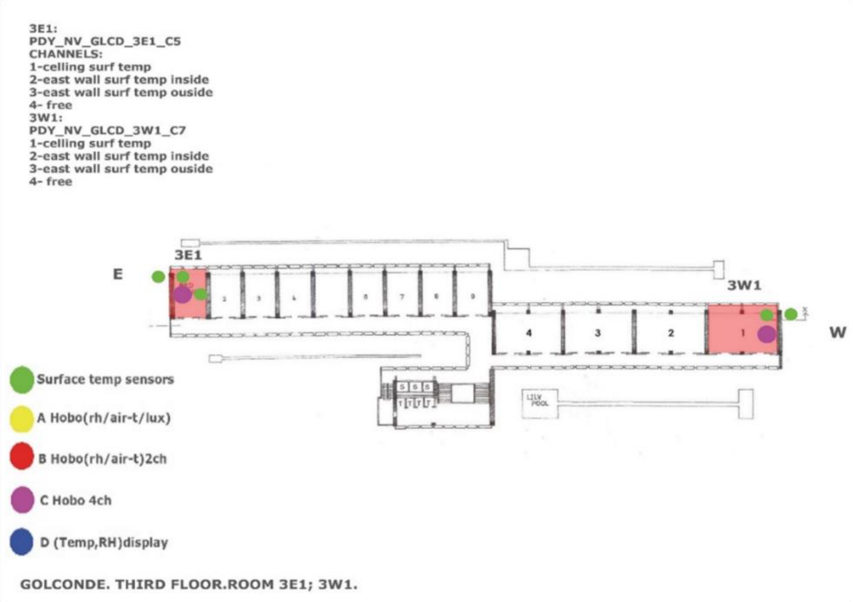


Figure 18 Placement of loggers on the Third Floor - Floor Plan

Figure 19 Placement of loggers on the Third Floor - Inside the room

Figure 20 Placement of loggers on the Third Floor - Inside the room

Figure 21 shows the placement of logger B10 on the rooftop. The logger was placed near the ventilated roof shell.

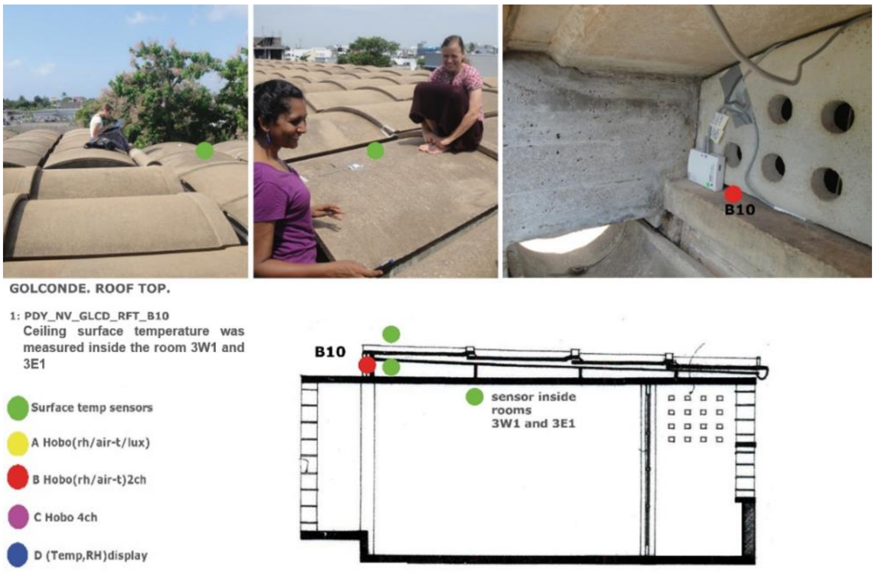


Figure 21 Placement of logger on the Rooftop

Figure 22 gives a representation of all the loggers placed in the Golconde – on all the floors.

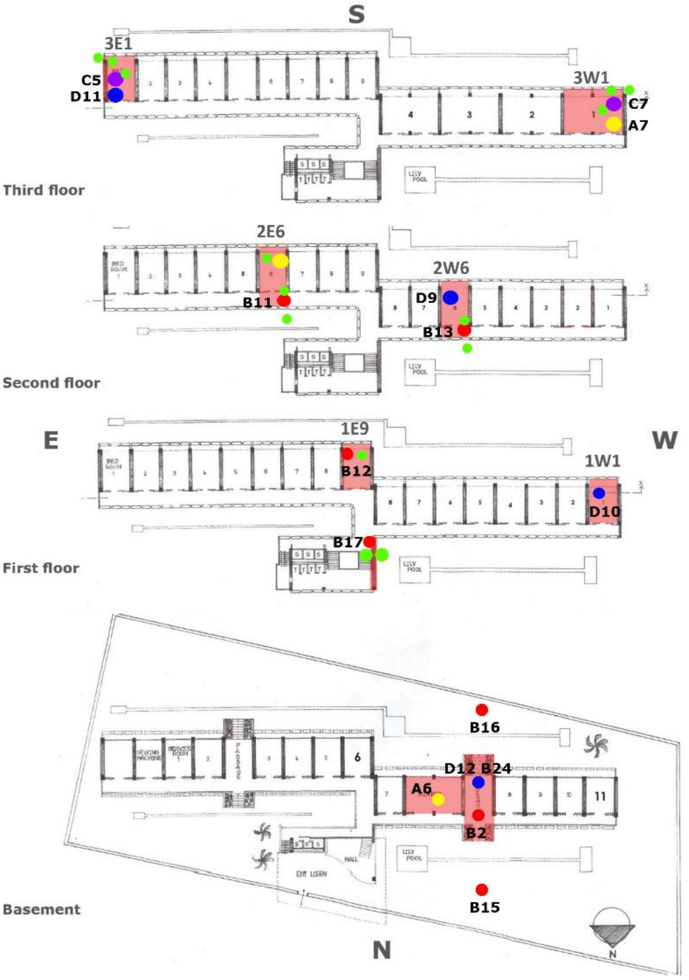


Figure 22 Placement of loggers across the building - cumulative representation of all floors

3.3.1.2 AFSANAH LOGGER PLACEMENT

Six loggers were placed in various locations across the building at different levels to measure the temperature, relative humidity, roof surface temperature and light intensity. Figure 23 shows the building under study, the Afsanah Guest House and the position of the placement of the loggers on the ground floor and first floor (indoor and outdoor).

The HOBO loggers were used for long term monitoring which started from August 29, 2013 and completed on November 4, 2014.

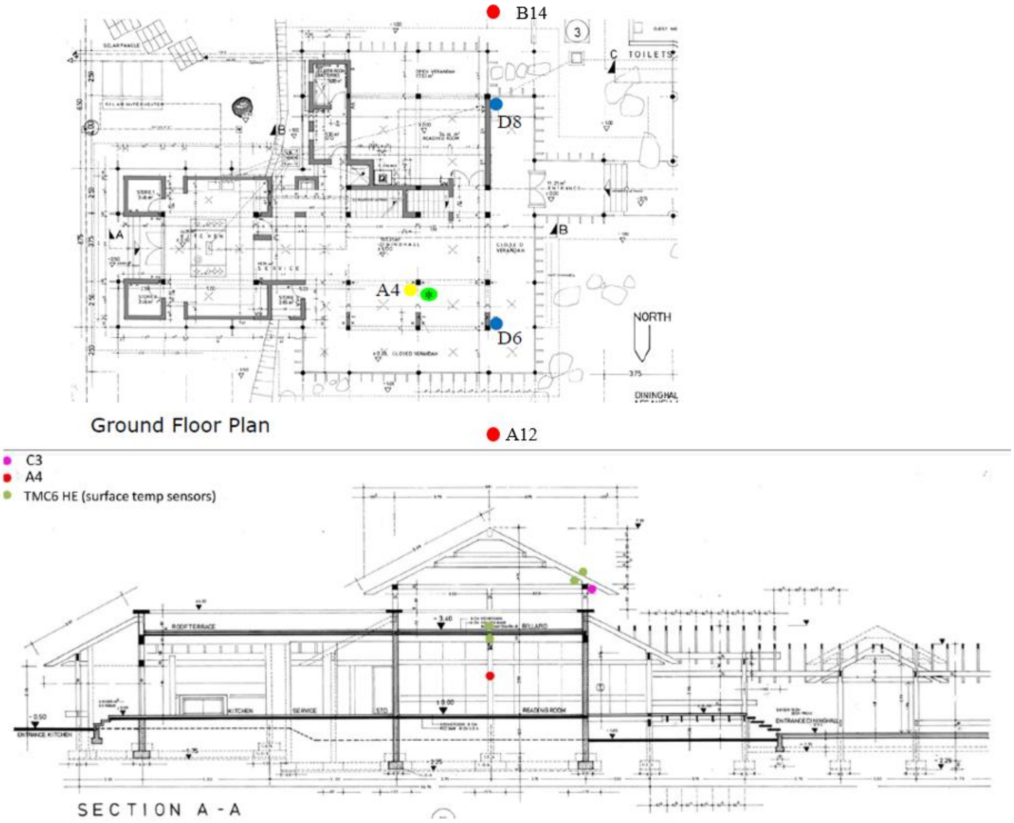


Figure 23 Afsanah – Floor plan and section through the entrance and dining hall indicating the logger locations

Figure 24 Installation of terracotta surface temperature sensor, logger C3

3.3.1.3 LUMINOSITY LOGGER PLACEMENT

Figure 25 Placement of loggers A9, B18, B20, and D13 in Luminosity

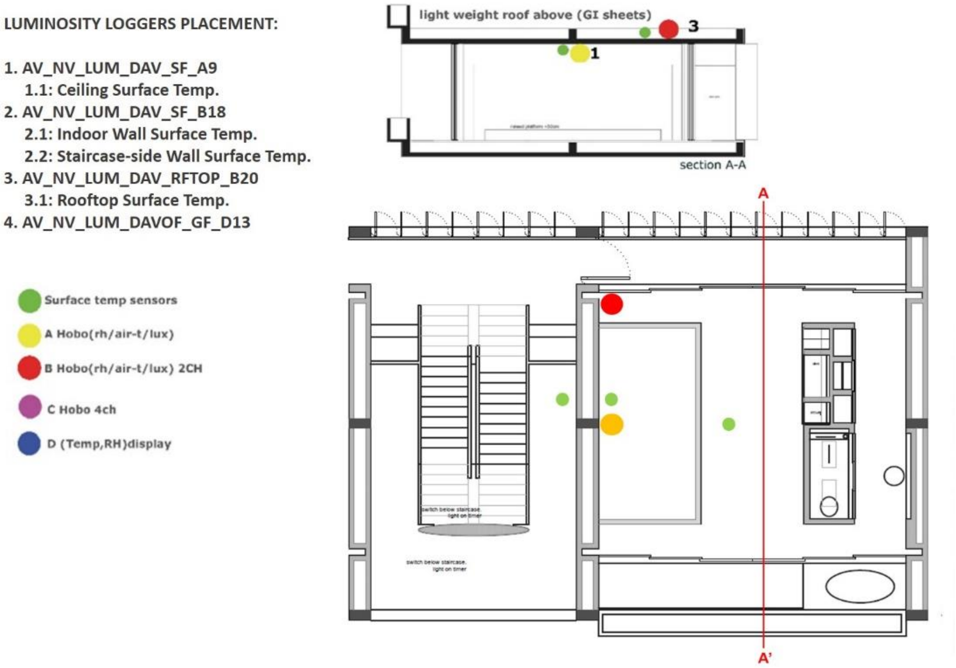


Figure 26 Position of loggers A9, B18, B20, and D13 in Luminosity

3.3.1.4 INTACH LOGGER PLACEMENT

Figures 27 and 28 show the locations for logger placement in the building with the on-site photographs and the building plan.

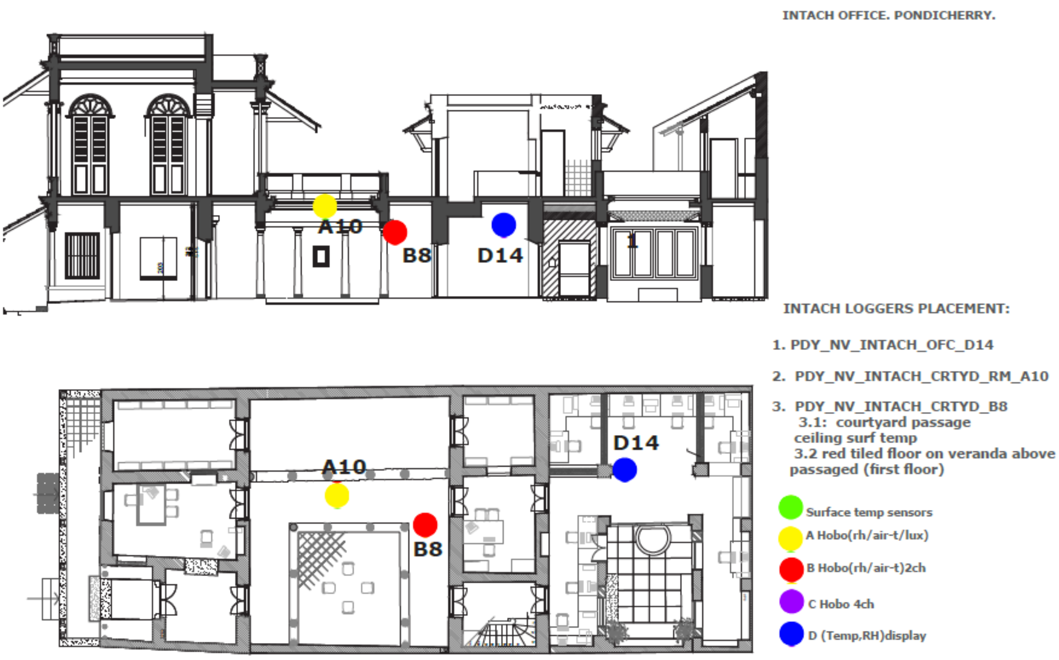


Figure 27 Placement of loggers in the INTACH office – building plan

Figure 28 Placement of loggers in INTACH office – site photos

3.3.1.5 BLESSING HOUSE LOGGER PLACEMENT

Figures 29 shows the position of the placement of loggers on the ground floor (indoor and outdoor). Loggers B6, A5 and D7 measure the internal parameters of the ground floor, while B7 measures the outdoor ambient conditions of the garden.

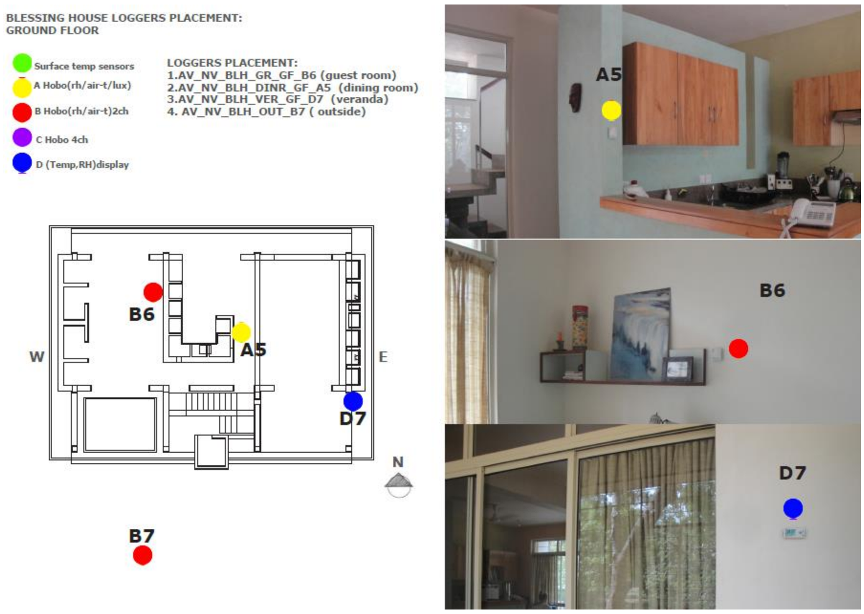


Figure 29 Placement of loggers on the ground floor

Figure 30 shows the placement of loggers on the first floor. Loggers A3, B4, D3, D4, and D5 measure the parameters for the first floor, while E2 logs the open/close state of the balcony window. Figure 31 measures the parameters on the mezzanine using logger C4.

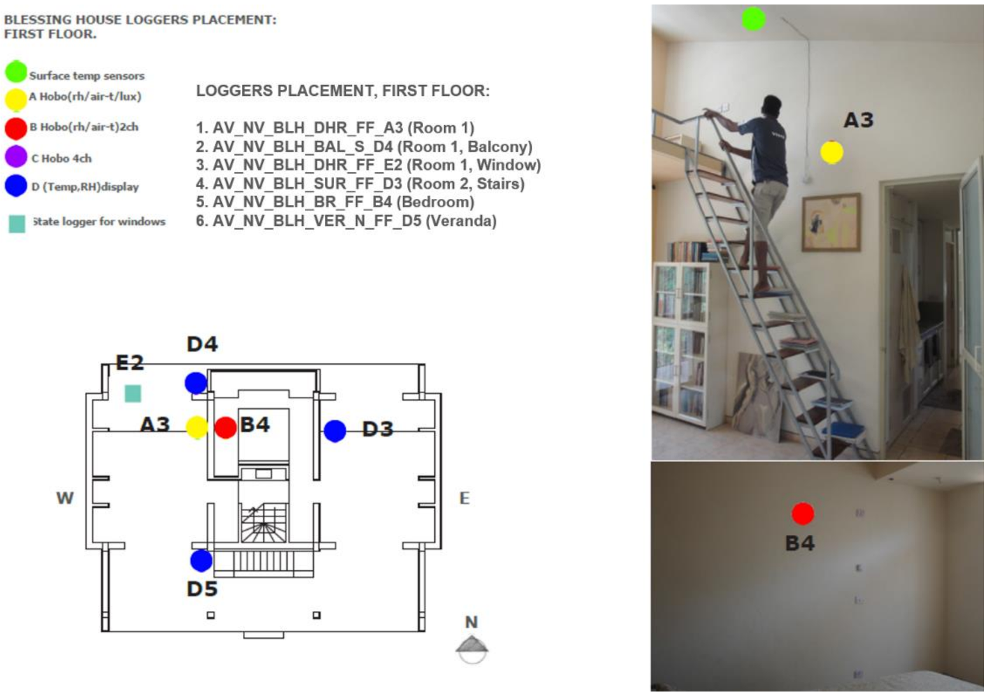


Figure 30 Placement of loggers on the first floor

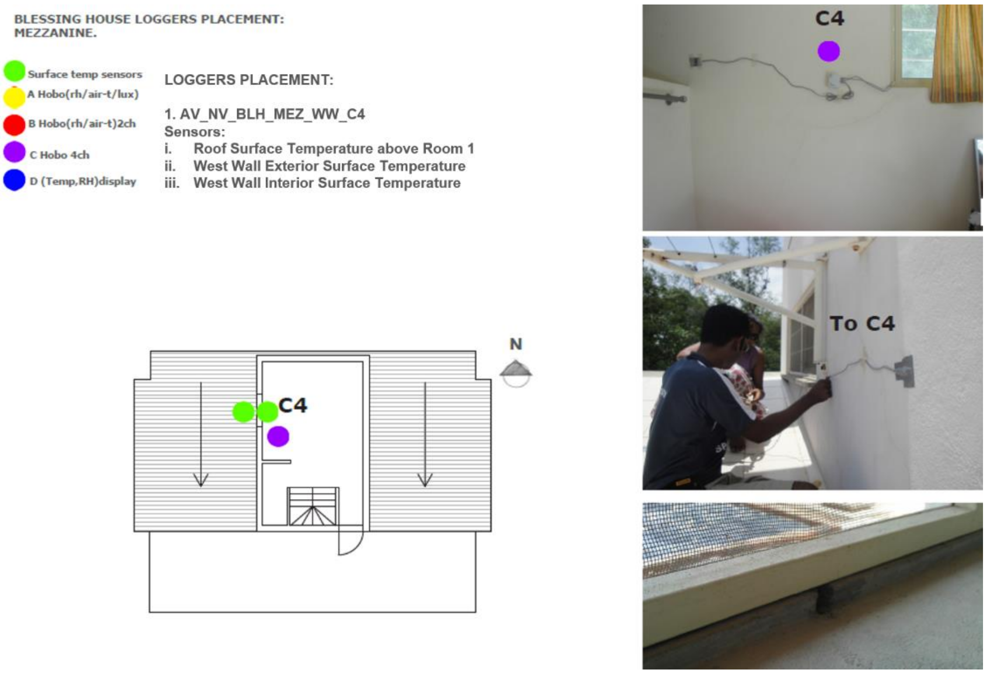


Figure 31 Placement of loggers on the mezzanine

3.3.1.6 MUKUDUVIDU LOGGER PLACEMENT

Figures 32, 33, and 34 show the locations for logger placement in the building with the on-site photographs and the building plan.

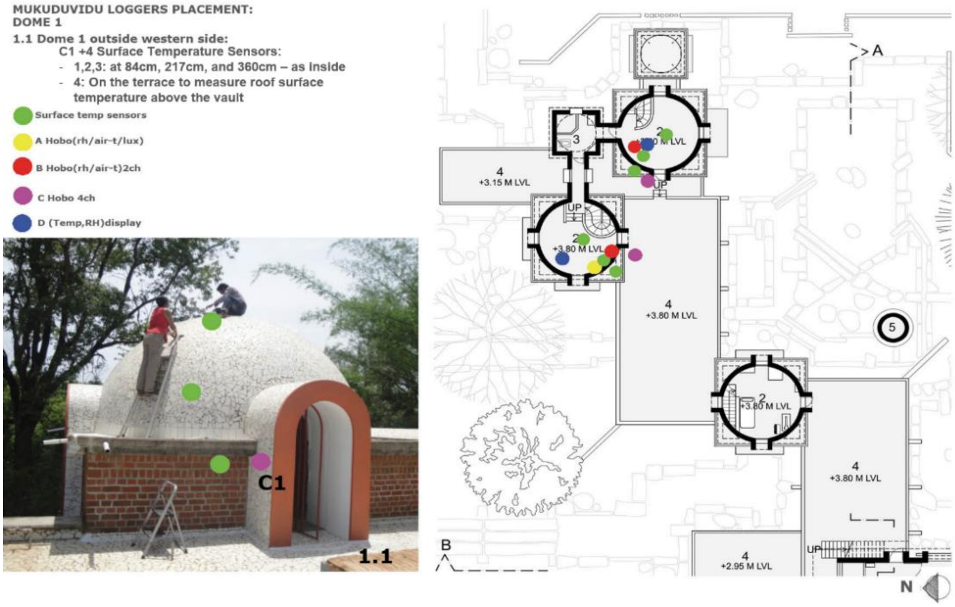
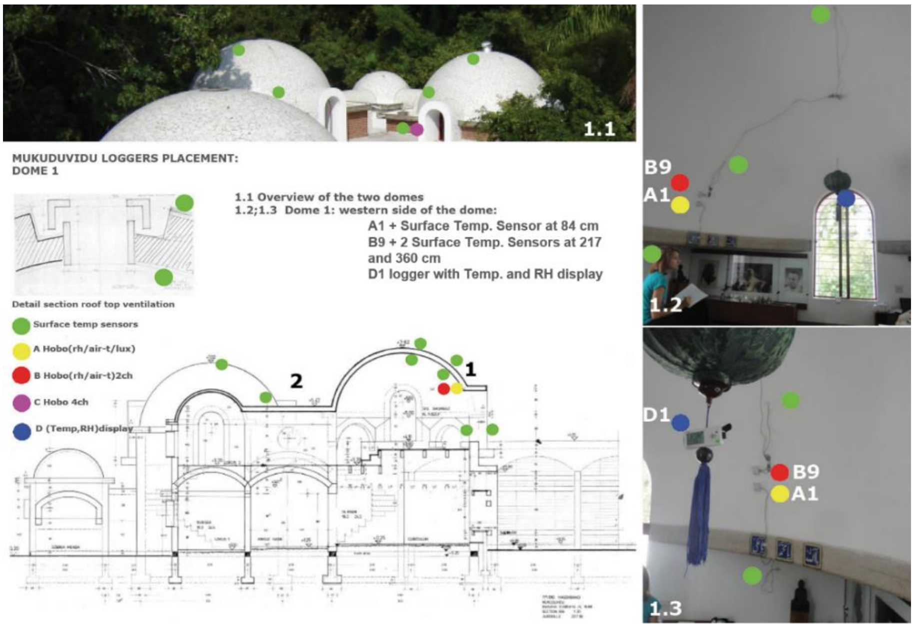
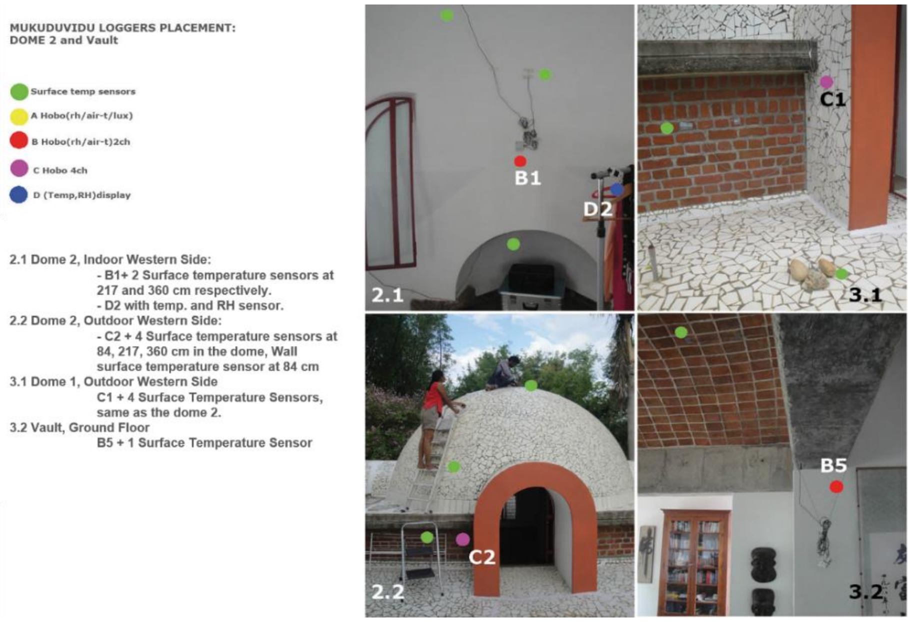


Figure 32 Placement of loggers on the first dome – top view


MUKUDUVIDU LOGGERS PLACEMENT:
DOME 1

1.1 Overview of the two domes
1.2;1.3 Dome 1: western side of the dome:
A1 + Surface Temp. Sensor at 84 cm
B9 + 2 Surface Temp. Sensors at 217 and 360 cm
D1 logger with Temp. and RH display

Figure 33 Placement of loggers on the first dome – side view


MUKUDUVIDU LOGGERS PLACEMENT:
DOME 2 and Vault

2.1 Dome 2, Indoor Western Side:
- B1+ 2 Surface temperature sensors at 217 and 360 cm respectively.
- D2 with temp. and RH sensor.

2.2 Dome 2, Outdoor Western Side:
- C2 + 4 Surface temperature sensors at 84, 217, 360 cm in the dome, Wall surface temperature sensor at 84 cm

3.1 Dome 1, Outdoor Western Side
C1 + 4 Surface Temperature Sensors, same as the dome 2.

3.2 Vault, Ground Floor
B5 + 1 Surface Temperature Sensor

Figure 34 Placement of loggers on the second dome and the vault

The two domes differ in the method of air extraction. Dome 1 uses natural convection while dome 2 employs forced convection of the indoor air through a wind driven mechanical extractor as can be seen in figure 35.

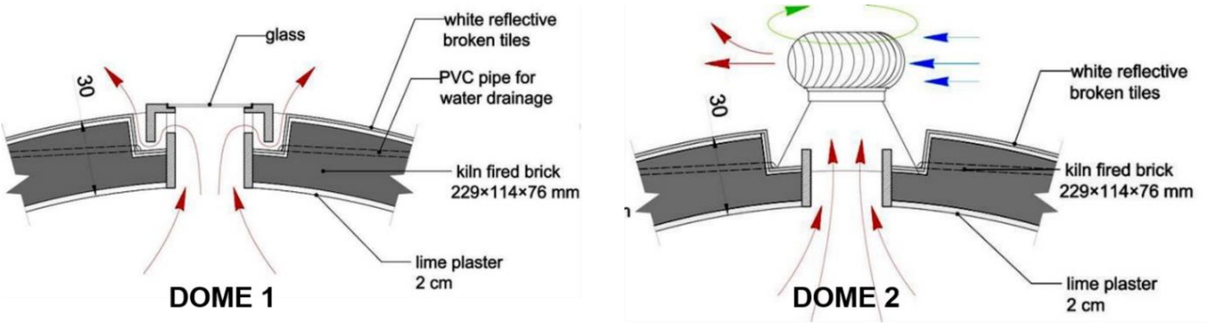


Figure 35 Schematics of the two domes

3.3.1.7 SOLAR KITCHEN LOGGER PLACEMENT

Following figures show the placement of loggers across the solar chimney and the dining hall.

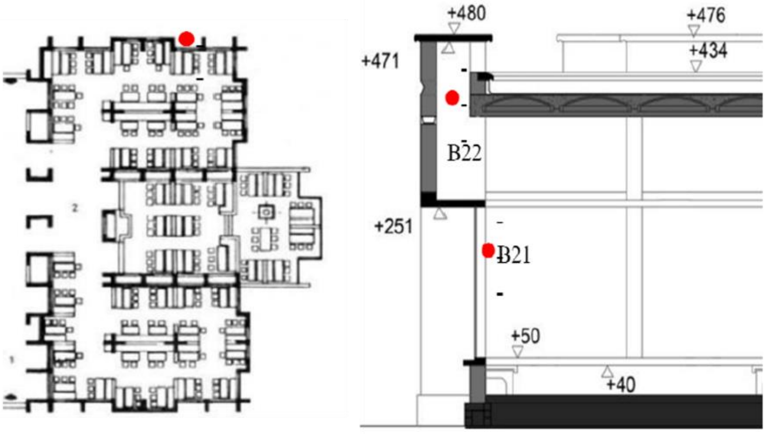


Figure 36 Solar Kitchen – floor plan and section through the exterior wall indicating the logger locations

Figure 37 Placement of loggers in the dining area

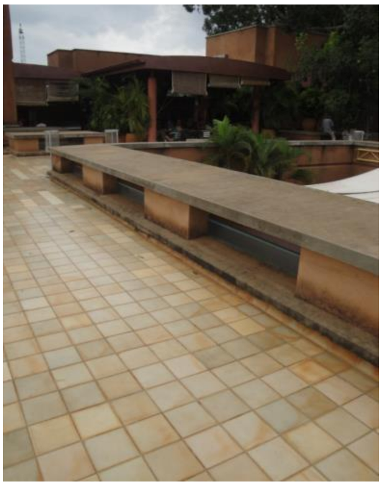


Figure 38 Solar chimney from terrace

3.3.2 Instantaneous Monitoring

In order to validate the readings indicated by the loggers, hand held readings were taken on a regular interval of three weeks and analysed for consistency. The validated readings were considered for further data analysis. The following figures mention the locations for handheld readings across five of the buildings under study.

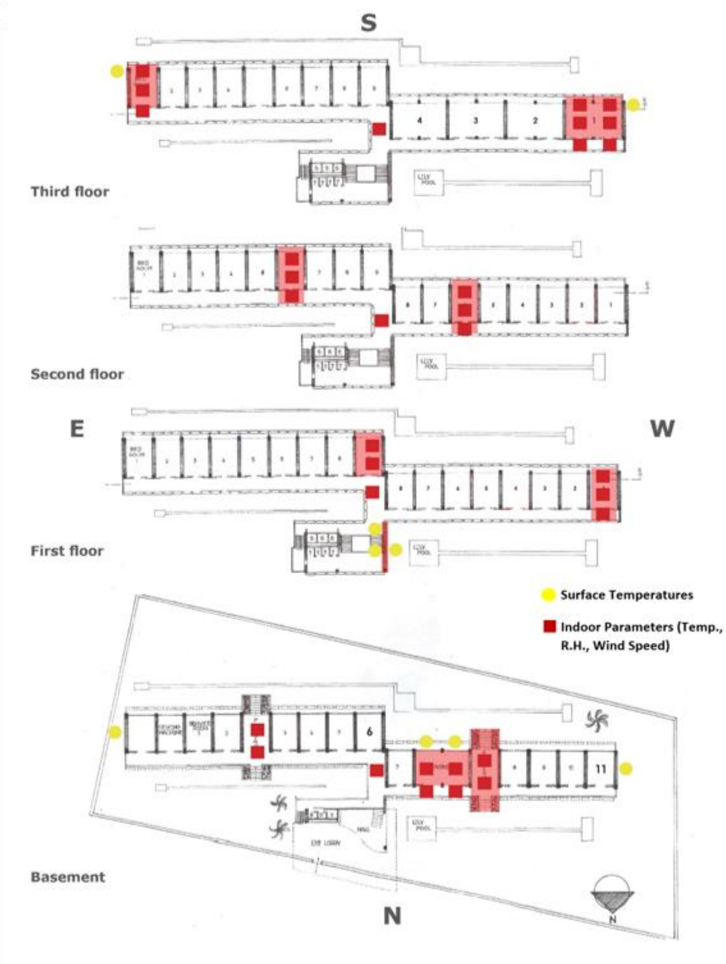


Figure 39 Golconde: Points of handheld data measurement

Figure 40 Luminosity: Points of handheld data measurement

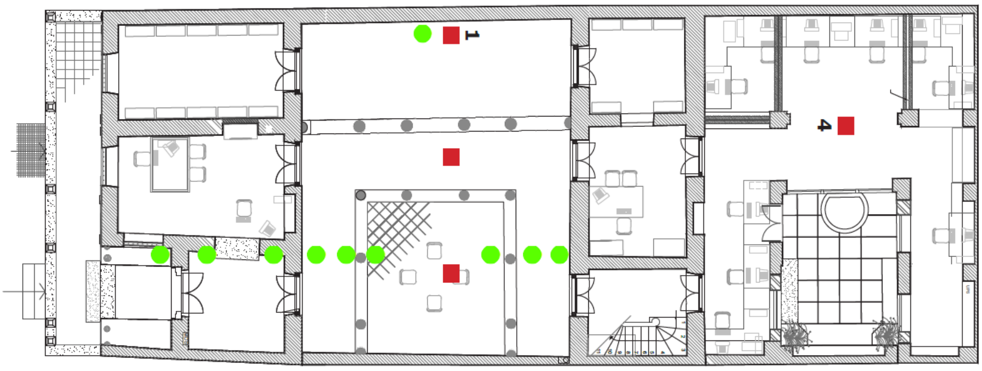


Figure 41 INTACH: Points of handheld data measurement

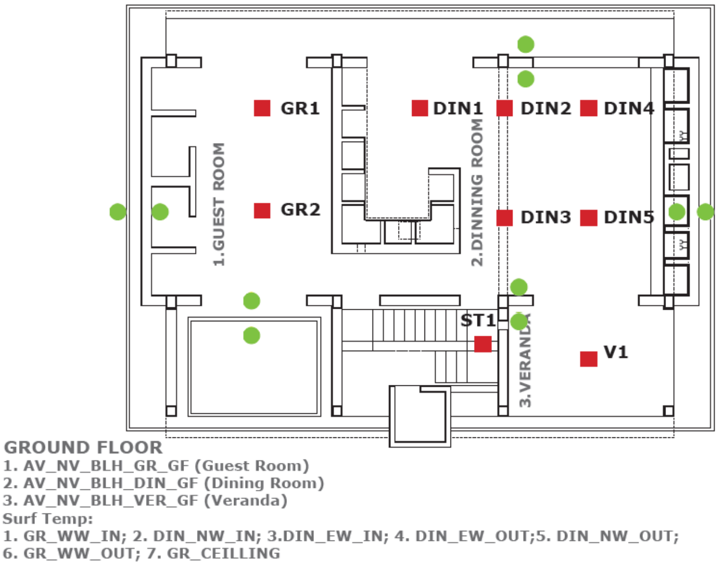
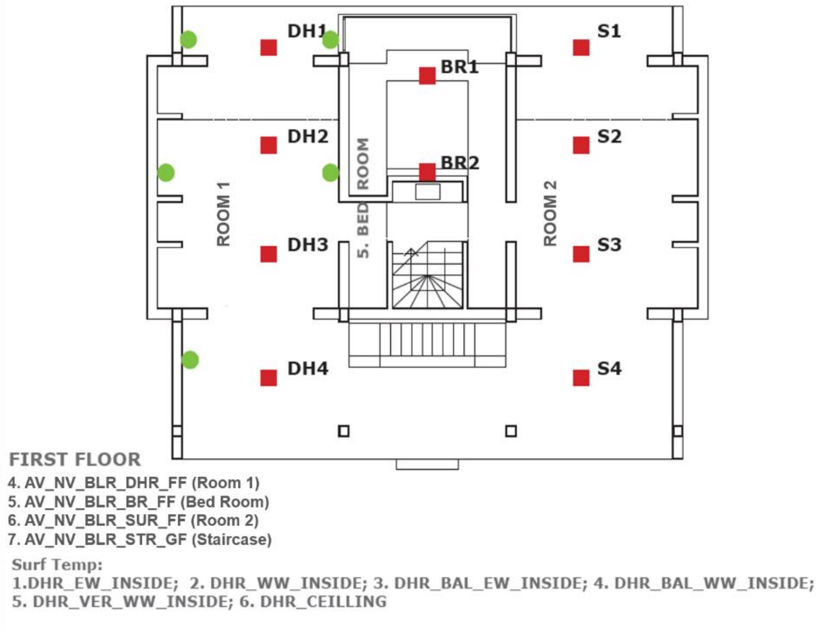
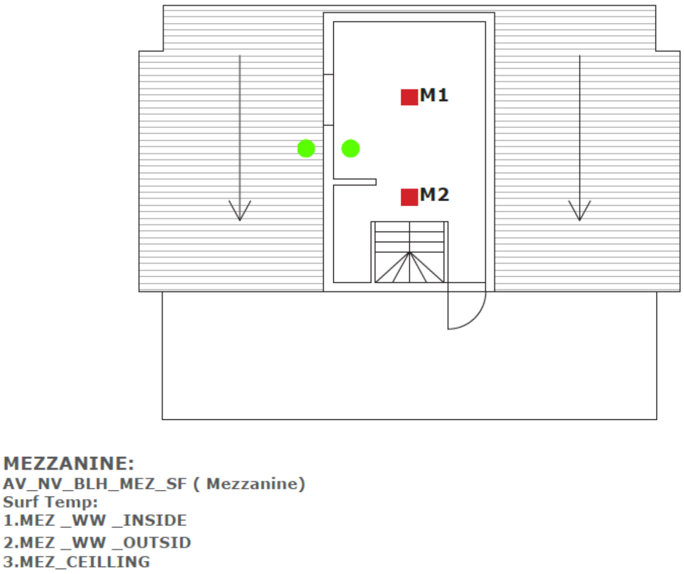


Figure 42 Blessing House: Points of handheld data measurement – ground floor



FIRST FLOOR
4. AV_NV_BLR_DHR_FF (Room 1)
5. AV_NV_BLR_BR_FF (Bed Room)
6. AV_NV_BLR_SUR_FF (Room 2)
7. AV_NV_BLR_STR_GF (Staircase)
Surf Temp:
1.DHR_EW_INSIDE; 2. DHR_WW_INSIDE; 3. DHR_BAL_EW_INSIDE; 4. DHR_BAL_WW_INSIDE;
5. DHR_VER_WW_INSIDE; 6. DHR_CEILLING

Figure 43 Blessing House: Points of handheld data measurement – first floor



MEZZANINE:
AV_NV_BLH_MEZ_SF (Mezzanine)
Surf Temp:
1.MEZ _WW _INSIDE
2.MEZ _WW _OUTSID
3.MEZ_CEILLING

Figure 44 Blessing House: Points of handheld data measurement – mezzanine

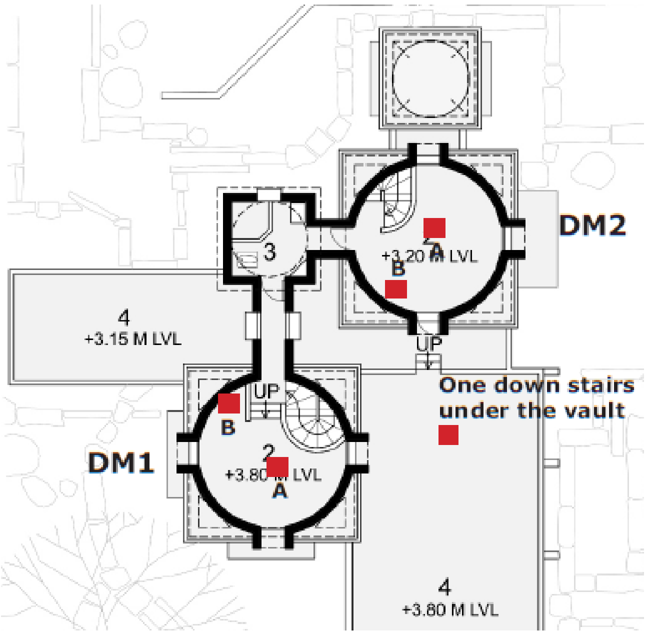


Figure 45 Mukuduvidu: Points of handheld data measurement

Tables 9 to 16 show typical logger readings against handheld readings for all the buildings.

Table 9 Golconde: Comparison of embedded and handheld logger readings

Building Element	Zone	Measurement Tool	Date and Time	Temperature (°C)
Ceiling Surface	3W1	Handheld	30/11/2013 10:41	27.3
		Embedded	30/11/2013 10:00	27.0
			30/11/2013 11:00	27.2
	3E1	Handheld	30/11/2013 10:01	27.0
		Embedded	30/11/2013 10:00	27.0

Table 10 Afsanah: Comparison of embedded and handheld logger readings

Building Element	Measurement Tool	Date and Time	Temperature (°C)
Ceiling Surface Temperature	Handheld	20/05/2014 10:50	31.4
	Embedded	20/05/2014 11:00	31.7
Indoor Air Temperature	Handheld	20/05/2014 10:50	32.4
	Embedded	20/05/2014 11:00	32.4
Terracotta Roof	Handheld	12/08/2014 10.32	36.1
	Embedded	12/08/2014 11:00	36.1

Table 11 Comparison of embedded and handheld logger readings

Building Element	Measurement Tool	Date and Time	Temperature (°C)
Second Floor, Zone 1 (S1)	Handheld	15/01/2014 14:20	26.5
	Embedded	15/01/2014 14:00	26.5
Ground Floor, Zone 2 (G2)	Handheld	15/01/2014 14:51	27.3
	Embedded	15/01/2014 15:00	27.3

Table 12 INTACH: Comparison of embedded and handheld logger readings

Building Element	Method	Date and Time	Temperature (°C)
Courtyard	Handheld	5/3/2014 11:12	29.20
	Embedded	5/3/2014 11:00	29.16
		5/3/2014 12:00	29.31
Office	Handheld	5/3/2014 11:20	30.40
	Embedded	5/3/2014 11:00	31.03
		5/3/2014 12:00	31.10

Table 13 Blessing House: Comparison of embedded and handheld logger readings

Building Element	Measurement Tool	Date and Time	Temperature (°C)
Rooftop Surface	Handheld	22/10/2013 10:14	29.8
	Embedded	22/10/2013 10:00	28.8
		22/10/2013 11:00	31.0
Ceiling Surface	Handheld	22/10/2013 10:52	26.0
	Embedded	22/10/2013 11:00	25.8

Table 14 Mukuduvidu: Comparison of embedded and handheld logger readings

Building Element	Method	Date and Time	Temperature (°C)
Dome 1 (2170 mm)	Handheld	2/4/2014 15:21	31.3
	Logger (B9)	2/4/2014 15:00	30.5
		2/4/2014 16:00	31.2
Dome 2 (2170 mm)	Handheld	2/4/2014 15:21	30.9
	Logger (B1)	2/4/2014 15:00	30.5
		2/4/2014 16:00	30.8

Table 15 Solar Kitchen: Comparison of embedded and handheld logger readings

Building Element	Zone	Measurement Tool	Date and Time	Temperature (°C)
Solar Chimney	B21	Handheld	29/12/2014 15:05	26.9
		Embedded	29/12/2014 15:00	26.82
	B22	Handheld	14/05/2014 13:47	34.7
		Embedded	14/05/2014 14:00	34.67

3.3.3 Quality Assurance

Due to tampering or malfunctioning of the loggers, a few sets of data were either missing or deemed erroneous. A simple quality assurance of the data was done to identify instances of missing and erroneous data points. To do this, all the data was merged in one MS Excel sheet and '*' was used as an identifier for missing data. Details of missing and erroneous data are provided in Appendix C. All the data, for each of the respective parameter was deemed erroneous if it exceeded the following limit:

- Air temperature: 0 to 60°C
- Surface temperature: 0 to 60°C
- Relative humidity: 5 to 100%
- Light levels: 0 to 1100 lux

Thereafter, the cleaned data was used for further analysis.

4. Data Analysis and Discussion

Pondicherry/Auroville experiences a hot and humid climate throughout the year, owing its vicinity to the Arabian Sea. The sea and land breeze moderates the temperature and humidity – the highest avg. monthly temperature of the city lies under 32°C, which is comfortable as per Indian comfort, but is marred by the high humidity levels throughout the year. Figures 46 and 47 show the yearly temperature and relative humidity variation for the city.

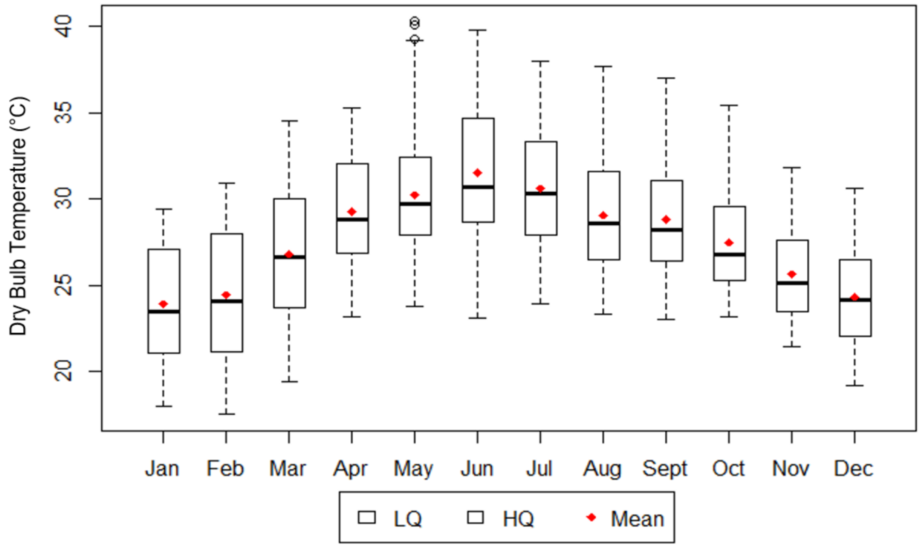


Figure 46 Annual temperature trends for Pondicherry/Auroville

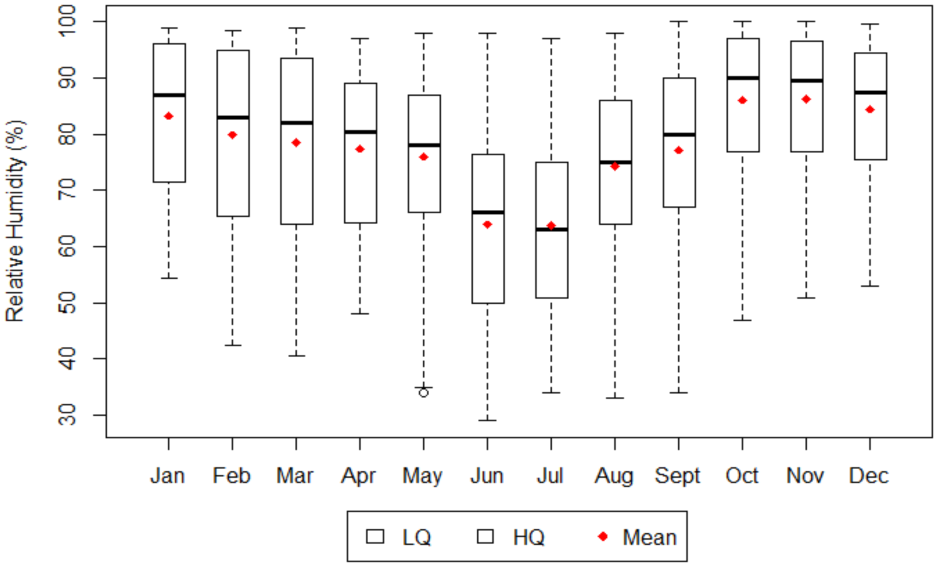


Figure 47 Annual relative humidity trends for Pondicherry/Auroville

June was chosen for month-specific analysis and hourly averaged parameter results as the average outdoor temperature was the highest during the same. Deeper analysis further proved the fact that the indoor temperatures across the buildings reached their maximum during the month of June too.

4.1 GOLCONDE

4.1.1 Ventilation

Ventilation is the key to indoor thermal comfort – adequate air changes per hours, uniform stratification of air and the position of the neutral layer, all play a major role in reducing the energy costs and making the building more comfortable. As Golconde is a naturally ventilated building, it does not have mechanically driven ventilation systems, instead, it uses passive design methods like the thermal buffer of corridors, ventilated double roof, optimized orientation and positioning of fenestrations for air ingress, and incorporation of louvers instead of glass paned windows. These strategies make the Golconde a well ventilated structure, as can be seen in this section.

Figure 48 shows the hourly averaged values of air temperature and relative humidity for the month of June across all the floors of Golconde. The outdoor temperature varies from 28.5 to 35.5 degrees between the dawn and the noon respectively. Temperatures on all the floors follow the same curve as the outdoor temperature but with a time-lag of 2 hours between their peak values, due to the thermal mass of the building fabric. The coolest portion of the building during the hottest hours (11:00 – 17:00) of the day was the first floor. The basement, first and second floor temperature profiles were quite similar to one another due to similar thermal masses above and below them. The third floor was warmer than the rest of the floors by over 1 degree, however, it still was more moderated than the outdoors by over 2 degrees. The topmost floor of any building was most likely to have the hottest temperatures due to the vicinity to the rooftop – solar radiation heated up the rooftop and the heat was conducted through the ceiling to the topmost floor, wherein, indoor convection currents distributed the heat to the entire room, maintaining the thermal equilibrium.

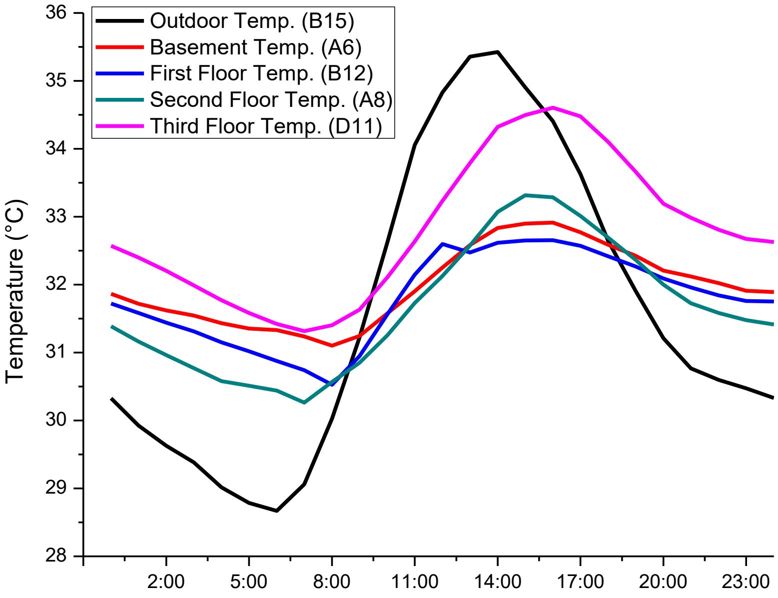


Figure 48 Variation of Hourly Avg. Temp. across floors, June 2014

Figures 49 shows the hourly averaged values of relative humidity for the month of June across all the floors of Golconde. The outdoor R.H. varied from 56% to 76% between the noon and the night respectively. Similar to the case of temperature, R.H. curves of the indoors trace the same trend as the outdoors. However, unlike temperature, R.H. profiles do not have a time-lag.

To understand this, we must understand the way humidity is transported to the structure – through convective transfer (air movement). As Golconde was a naturally ventilated building with very efficient indoor ventilation, the humidity changes in the outdoors are almost immediately reflected in the indoors. However, due to the difference in temperature of the floors and rooms, and filtration of air thorough vents and louvers, the humidity is reduced fractionally. It must also be noted that with the rise in temperature, the humidity reduced – high temperature evaporated the moisture present in the air and dried it. This phenomenon can be observed from the undulating R.H. curve below – the colder hours of the day experienced a higher R.H. level than the warmer hours, also, the third floor is the least humid floor as it had the highest temperature in comparison to the other floors.

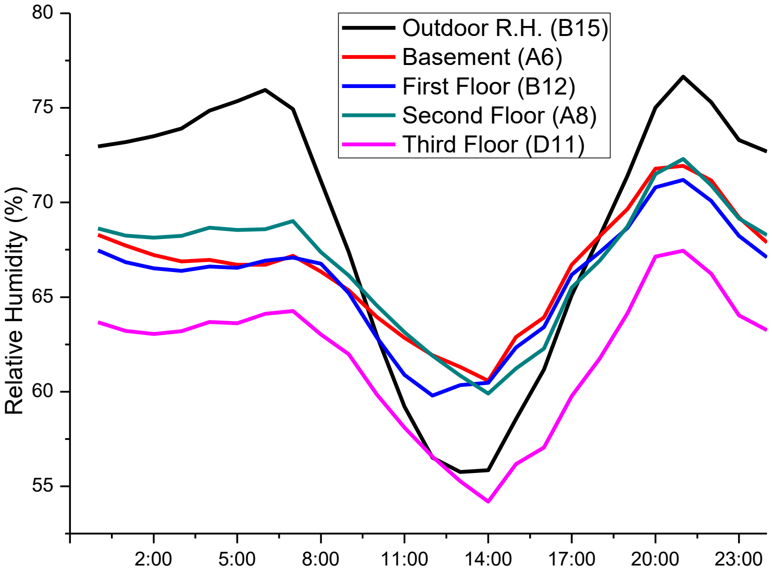


Figure 49 Variation of Hourly Avg. R.H. across floors, June 2014

The temperature in Golconde is moderated through the various passive design strategies and the building fabric, however, to ascertain if the naturally ventilated building is comfortable enough for the occupants or not, 90% IMAC (India Model for Adaptive Comfort) temperature limits for naturally ventilated buildings were referred and compared against the temperatures for all the floors, as shown in Figure 50. The ‘90%’ implies that at least 90% of the occupants in the zone feel thermally comfortable.

Generally, thermal comfort was maintained across all floors except for the third, during the moderate months of the year while the upper comfort limit was breached during the hot months of June and July. The third floor, being next to the rooftop was significantly warmer than the other floors and exceeded the upper comfort limit throughout the year, except January and portions of November and December.

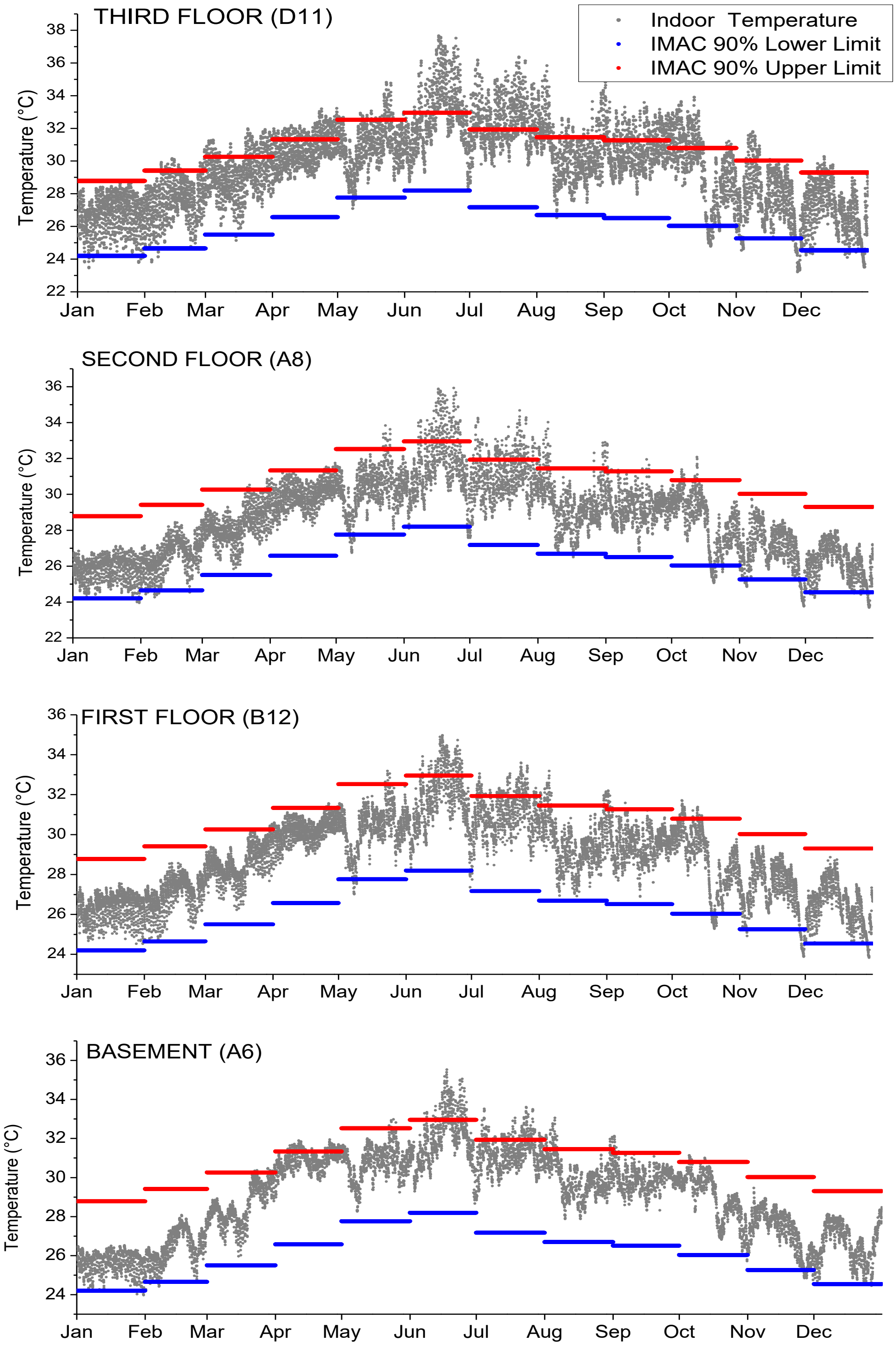


Figure 50 Instantaneous Temp. across floors, in comparison to the 90% IMAC comfort limits for Naturally Ventilated Buildings

The third floor was found to be the most uncomfortable floor with the highest air temperatures, as it fell immediately below the rooftop, followed by the second floor – most of the portions of June and July were above the upper comfort limit. The first floor and the basement were the most comfortable. Figures 51 and 52 compare the temperatures and R.H. of the third floor in different seasonal conditions (January, June, and October – winter, monsoon, and summer respectively).

Time lag for the three seasons remained around three hours. For all three cases, the building fabric was able to moderate the indoor air temperature effectively, keeping it between 25-28, 31-35, and 28-31 degrees for each of the cases respectively. The R.H. curves indicate that the humidity on the third floor remained constantly lower than the outdoors (except for the noon hours in January) – allowing a more comfortable living environment.

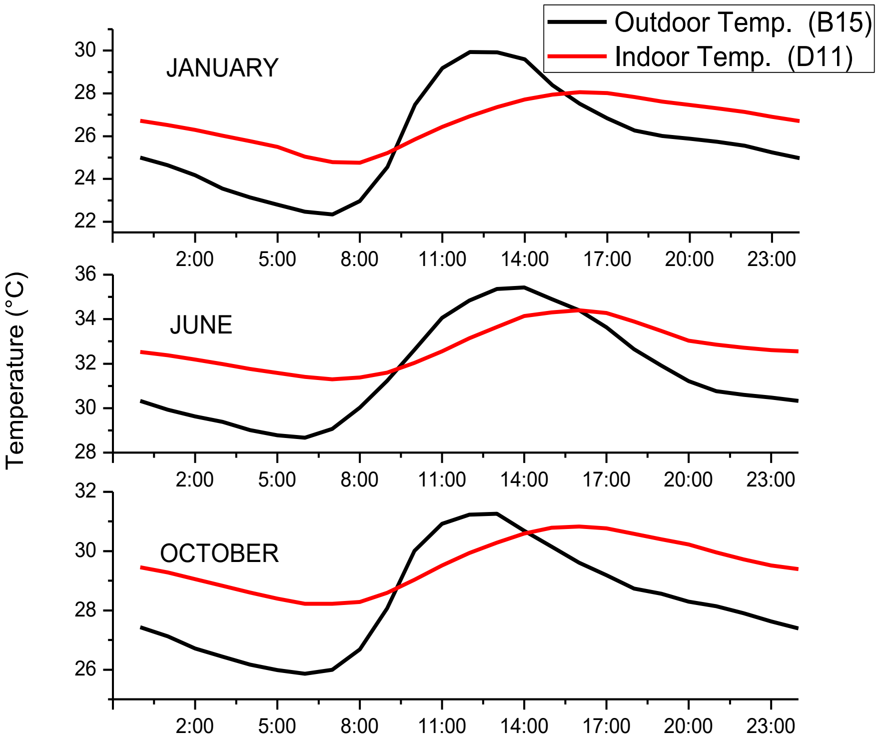


Figure 51 Variation of Hourly Avg. Temp. for April, September and December for the Third floor

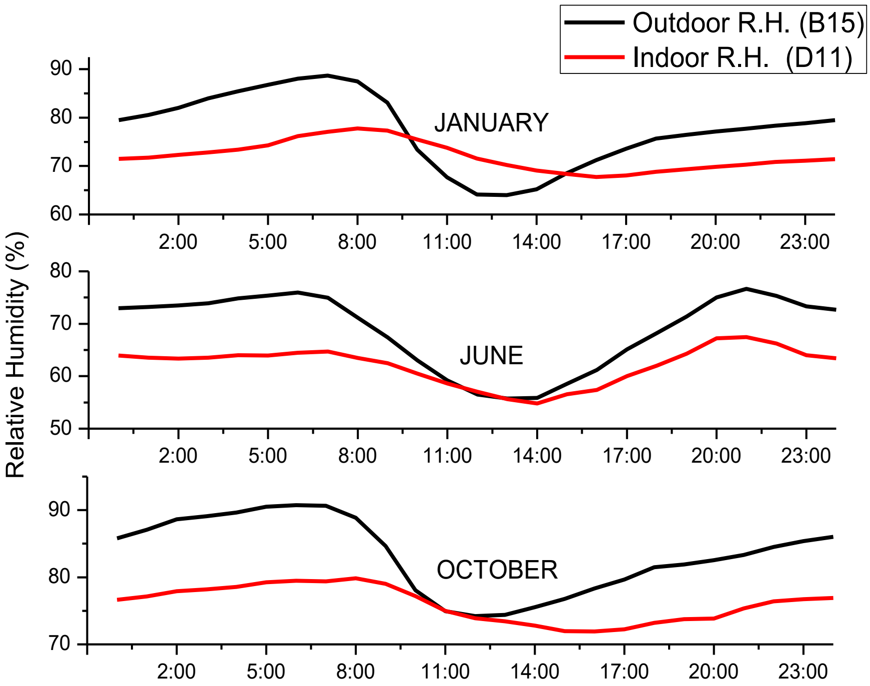


Figure 52 Variation of Hourly Avg. R.H. for April, September and December for Third floor

The above curves present average monthly data for a general representation but to account for daily occurrences like precipitation, instantaneous data must be visualised. Figure 53 and 54 show the variation of instantaneous temperature and R. H. across all the floors.

The temperature profile showed a sudden dip on the night of 2nd June due to rains and had an impact on the peak temperature of the next day (3rd June). This anomaly was indicated in the R.H. profile of 2nd June too – the outdoor R.H. peaked up to 95%, indicating excessively high moisture content in the air. During the rains, all the fenestrations were closed to avoid the water from entering and the air exchange with the environment would have reduced – this can explain the low humidity values of the indoors despite high outdoor humidity.

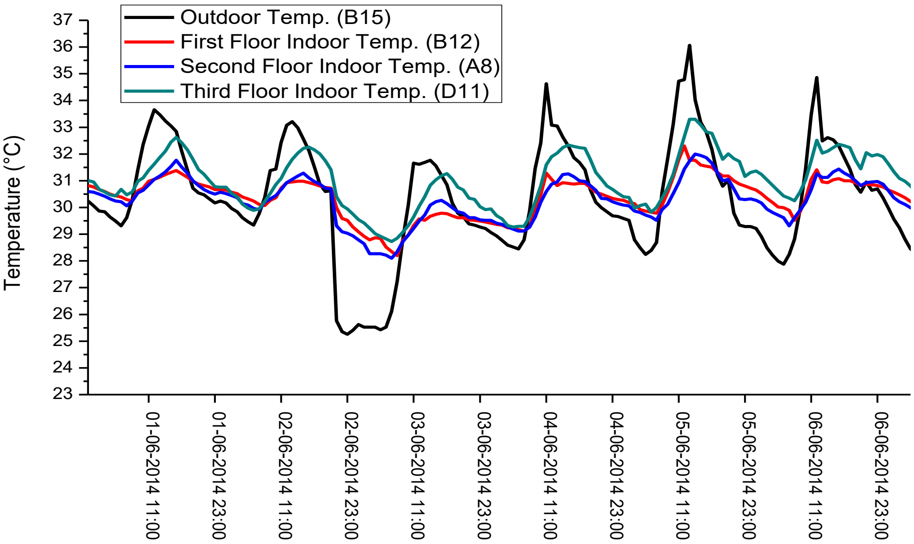


Figure 53 Variation of Instantaneous Temperature, 1st - 6th June 2014

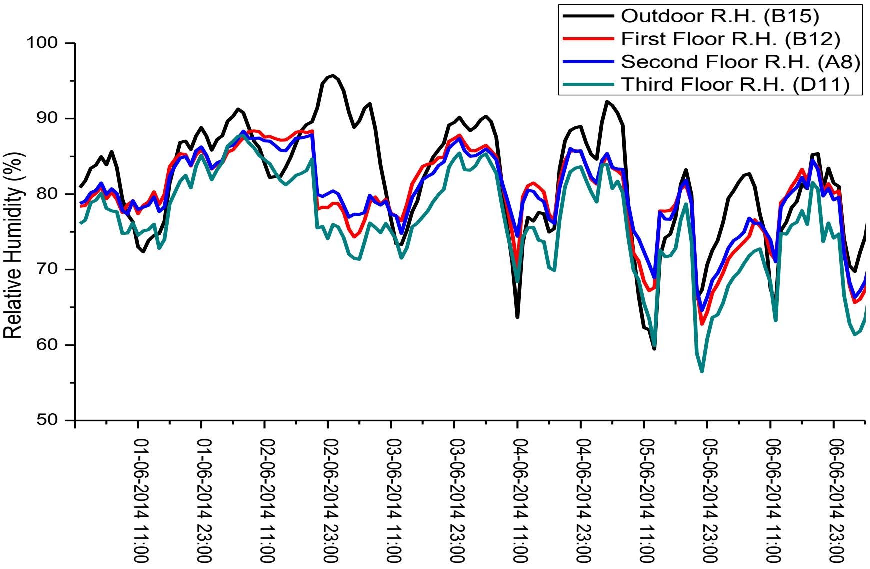


Figure 54 Variation of Instantaneous Relative Humidity, 1st – 6th June 2014

Movement of air through the corridors served as an effective passive design strategy. Figure 55 shows the comparison of hourly averaged air temperatures and R.H. for the north corridor and the room insides for the second floor. The thermal buffer of the corridor was continually warmer than the Indoors. Due to a warmer temperature, the humidity levels in the corridor were lower than that of the room.

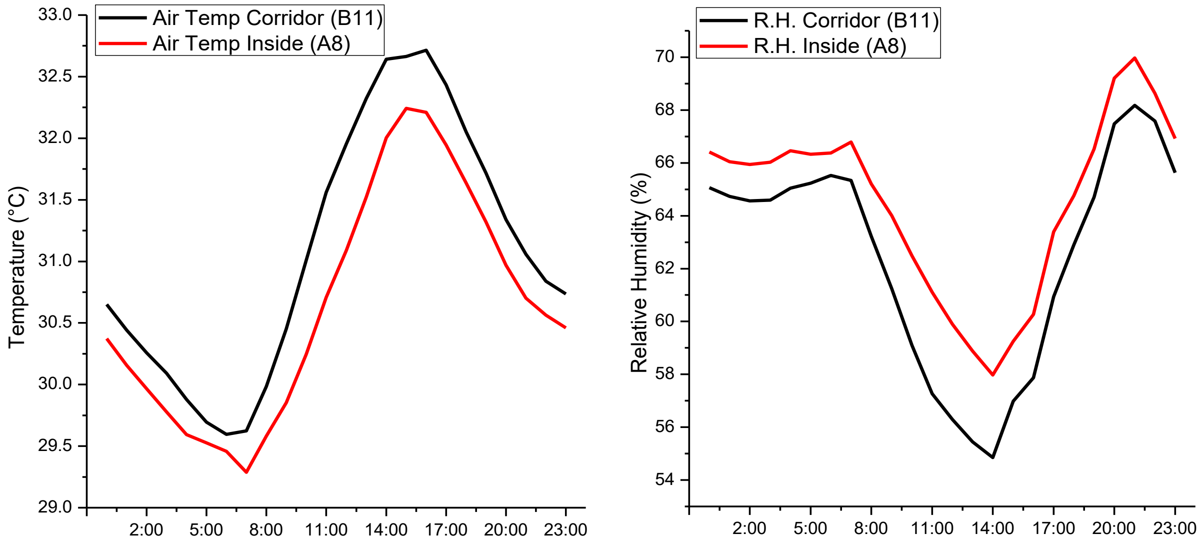


Figure 55 Comparison of Hourly Avg. Temperature and R.H. between the North Corridor and Room Indoors, June 2014

Air exchange with the environment is critical for any naturally ventilated building. Wind currents around the building maintained and moderated the indoor conditions. Figure 56 showcases typical wind speeds recorded by hand-held anemometer in the basement of Golconde. As there were no wind speed sensors coupled with the loggers, there was no data available for wind speeds across the building for a continuous time scale. On the basis of discontinuous data, no trends or conclusions could be drawn.

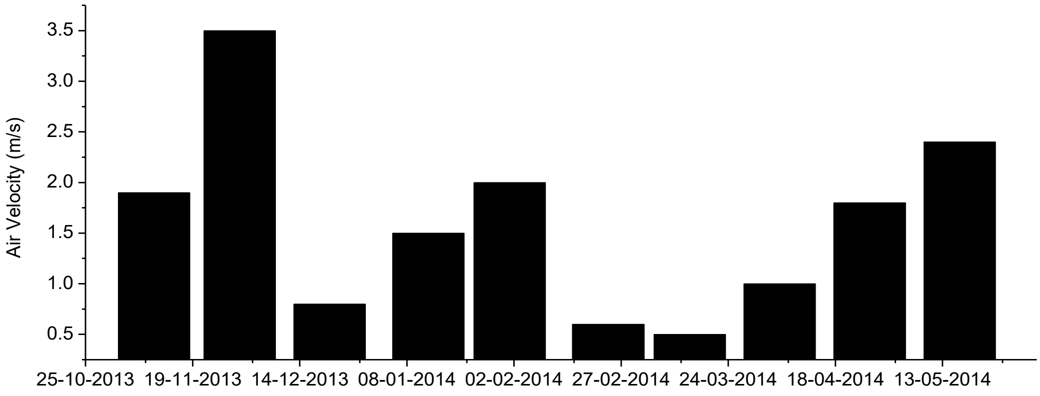


Figure 56 Instantaneous handheld measured values of Air Velocity through the Basement Dining Room

4.1.2 Thermal Mass

Thermal mass can be explained as the physical property of the building fabric which allows it to store the heat in itself. The higher the thermal mass, the more time it will take for the heat to reach from the outdoors to the indoors - this difference in time is called as ‘time lag’.

Figure 57 compares the temperatures across the doubly ventilated roof. The structure included multiple air vents which allowed the ingress of cool atmospheric air, lowering the U-Value of the entire structure. The roof shielded the third floor from the direct solar radiation as can be seen in the figure. The outermost layer of the roof heated up to over 50 degrees but the air cavities inside the roof prevented that heat from being transmitted to the ceiling, creating a high temperature gradient of over 15 degrees and a time lag of 3 hours between the exterior shell and the indoor ceiling of the third floor.

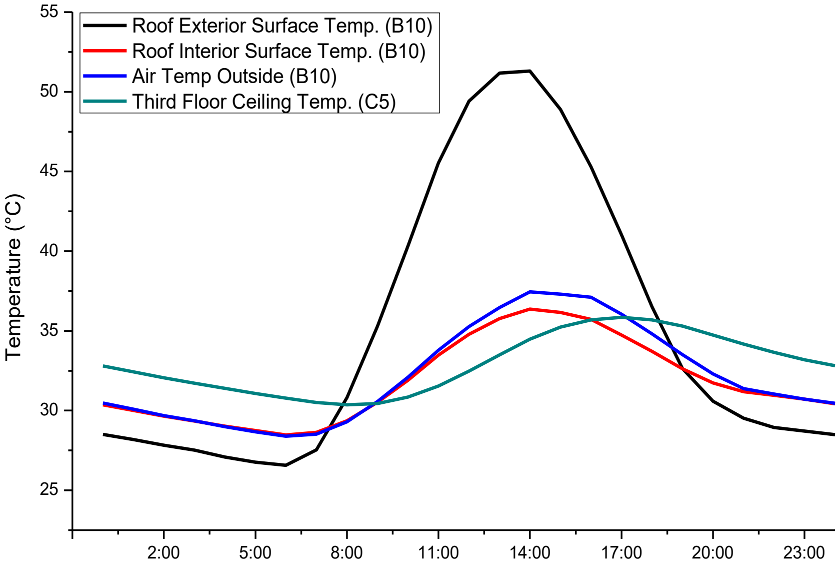


Figure 57 Variation of Hourly Avg. Temp. across the double-ventilated roof, June 2014

In addition to the thermally efficient double ventilated roof, the north and south facades shielded the building from the impinging solar radiation, however, as their orientation was parallel to the radiation during the hottest hours, their peak temperatures were far lesser than that of the rooftop. Figures 58 and 59 showcase the variation of temperatures across the north and south facades. Figure 58 further investigates into the variation of temperature across the east and west wings on the north façade, as discussed earlier – there was negligible difference between the east and west wings and could be treated equally.

However, the only instance of variation between the east and west wings was the case of exterior surface temperatures – western north façade was warmer than the eastern north façade by over 4 degrees. This difference arose as the western façade had already heated up to a certain extent by the noon, and the sun started to impinge on it thereafter. This excessive exposure to the sun elevated its temperature, while the eastern north façade rested in shadow. Despite having a high external surface temperature difference, the internal temperatures of the eastern and western wings were almost the same – signifying the effective thermal insulation of the façade.

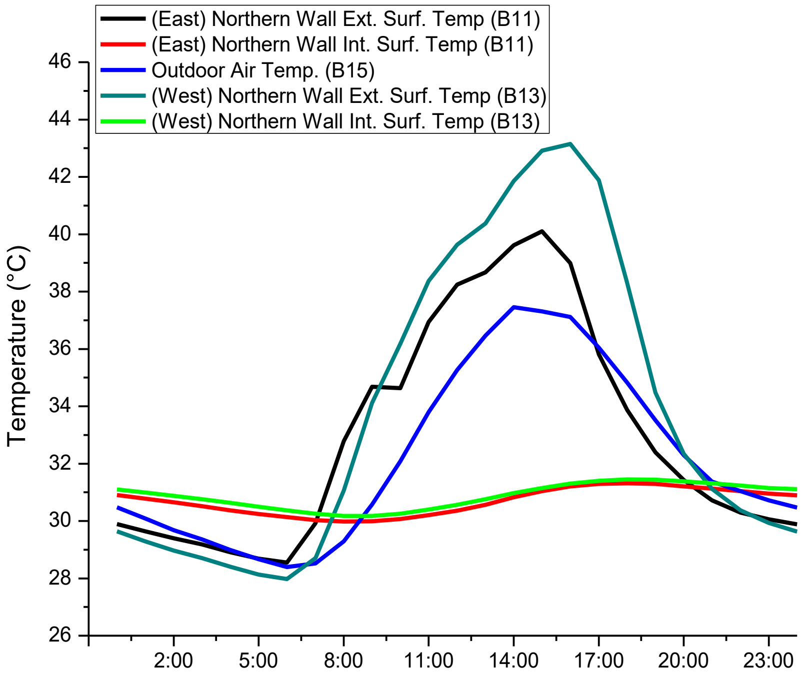


Figure 58 Variation of Hourly Avg. Temp. across the North Facade, June 2014

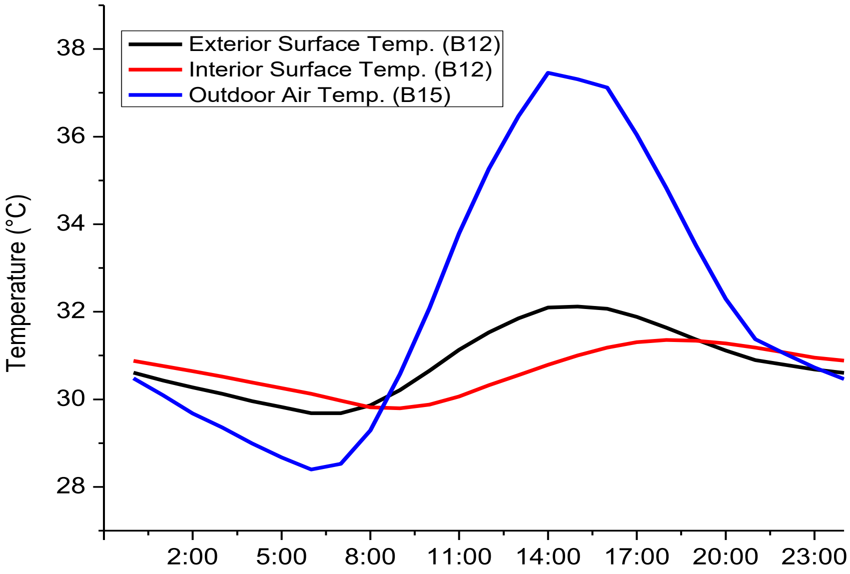


Figure 59 Variation of Hourly Avg. Temp. across the South Facade, June 2014

Another important element of the Golconde, the cavity wall insulated the staircase area along the northern façade. Figure 60 shows the thermal distribution around the cavity wall – the exterior surface temperatures reached as high as 40 degrees while maintaining the internal temperature below 32 degrees. Low U-value of the wall allowed it to create gradients as high as 8 degrees. This portion of building experienced low temperatures on the outside due to the natural shade of the building, the foliage, and the open plan of the stairwell. The outdoor air temperatures by logger B17 are thus lower than that of B15.

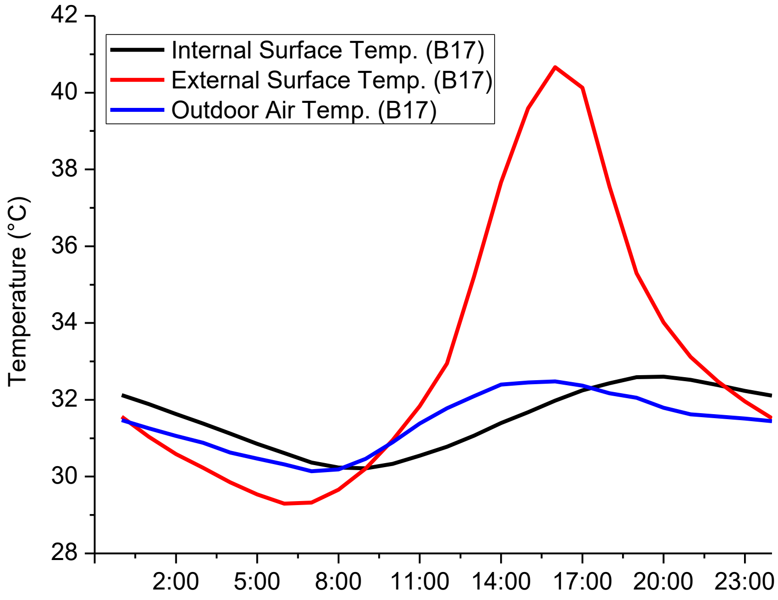


Figure 60 Variation of Hourly Avg. Temp. across the Cavity Wall, June 2014

Figure 61 compares the ceiling surface temperatures on the second and third floors and the east and west rooms on the third floor. It is evident from the above discussions and this figure that the second floor ceiling temperatures were lower than the third floor ceiling temperatures – as the third floor had the rooftop right above the ceiling and the second floor ceiling experienced a natural thermal mass of an entire floor above it.

Similar to the discussions above, the east and west interior ceiling surface temperatures did not show a lot of variation – the entire floor experienced similar ceiling Temperatures.

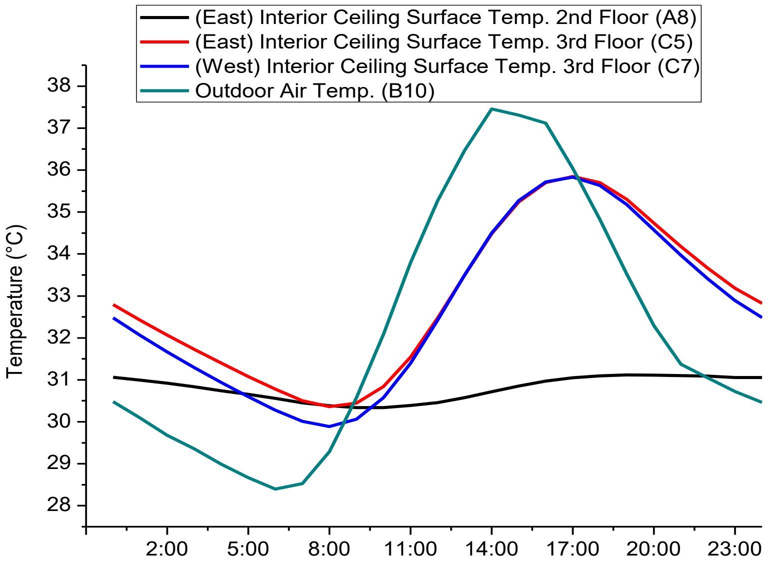


Figure 61 Variation of Hourly Avg. Ceiling Surface Temp., July 2014

4.1.3 Light Intensity

In addition to temperature and relative humidity, the Golconde was studied for the light intensity in the basement, and the rooms on the second and third floors. Figure 62 shows the distribution of intensity of natural light (lux) against hours of day, hourly averaged for the month of June. The basement started to experience natural light by the morning and gradually increased till the noon and decreased thereafter as the evening neared. Light intensity on the second floor increased in the morning with the incident sun till the louvers were lowered to stop the heating of the room – reducing the lux levels. Sudden peaks around 13:00 to 15:00 hours on the second floor could be due to the opening of louvers for cleaning. Lux levels on the third floor did not show much variation – this was expected as the room under study was unoccupied and had its louvers down permanently.

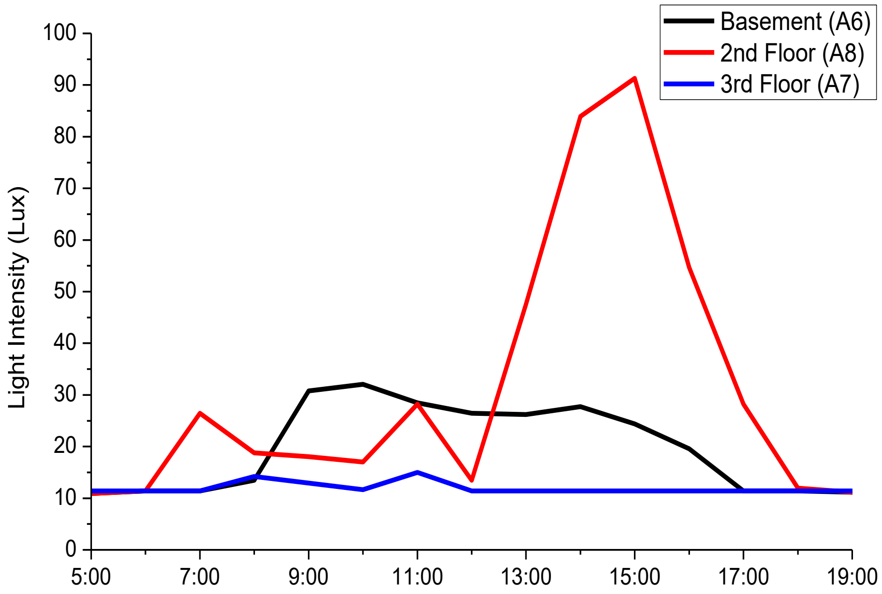


Figure 62 Variation of Hourly Avg. Natural Light Intensity across floors, June 2014

4.2 AFSANAH

The monthly average of the outdoor air temperature is below 30°C throughout the year. In the months of July to October, there is a slightly smaller spread of the outdoor air temperature, and a slightly lower maximum values of outdoor air temperature. June was chosen for the month-specific analysis and hourly averaged parameter results as the average outdoor temperature was the highest during the same. Deeper analysis further proved the fact that the indoor temperatures reached their maximum during the month of June too. For a seasonal representation, the months of January, June, and October have been chosen – they correspond to the minimum temperature, maximum temperature and the maximum humidity respectively. Figure 63 shows the large diurnal swings seen in this climate, with some instances as large as 20°C in amplitude.

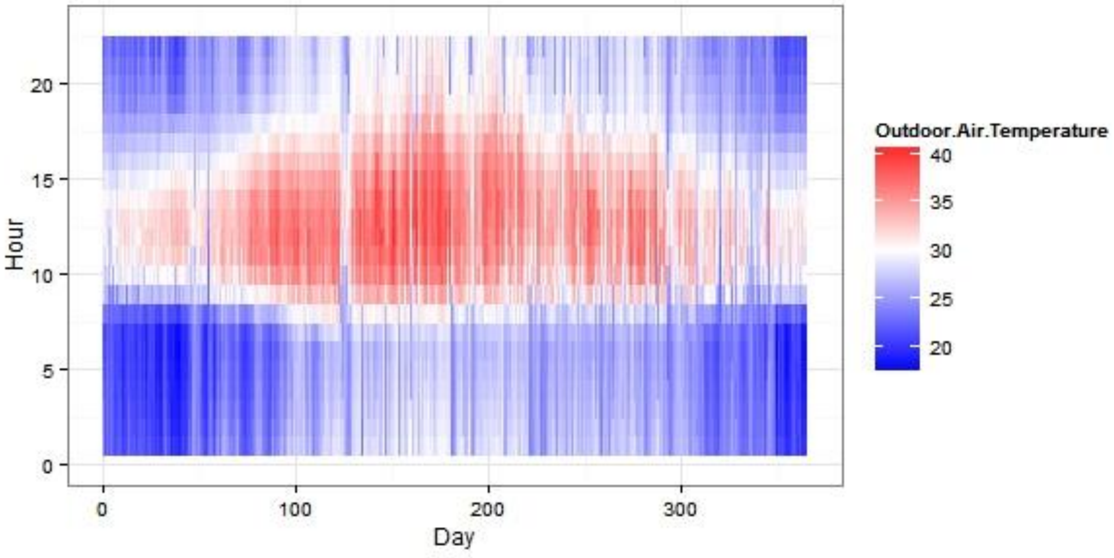


Figure 63 Hourly outdoor air temperature from September 2013 to September 2014

4.2.1 Thermal Lag and Heat Conduction of hollow block and terracotta

4.2.1.1 Sloped terracotta Mangalore tile roof

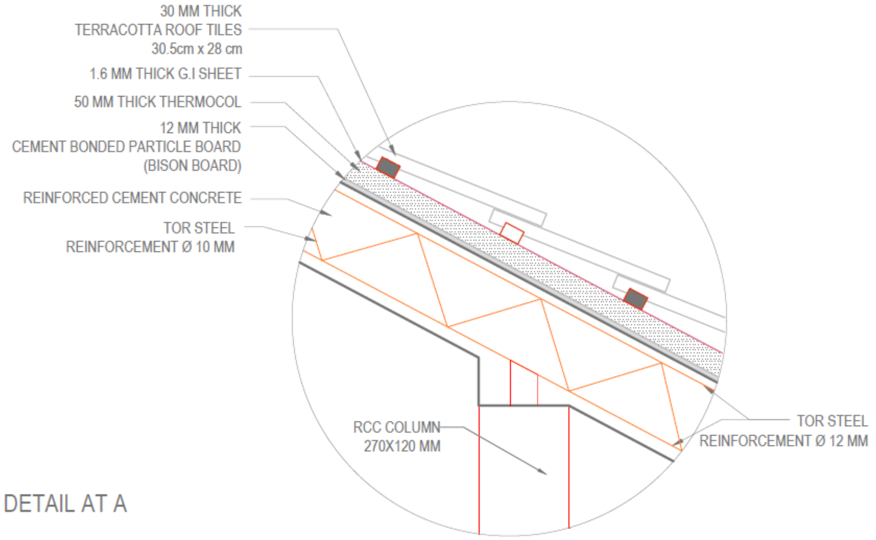


Figure 64 Sloped terracotta tile roofing detail

Figure 64 shows the detail of the sloped terracotta Mangalore tile roofing detail analysed for performance. The air and surface temperatures during three days in June were taken to be representative for the whole year, and is shown in Figure 65. In this three-day period, the outdoor air had a damping of 7°C, indoor air temperature a damping of 11.6°C, outdoor surface temperature a damping of 35°C, and indoor surface temperature a damping of 9.8°C. The indoor air temperature is seen to have a lesser fluctuation than the outdoor air temperature; and air is seen to have a lesser fluctuation than the terracotta.

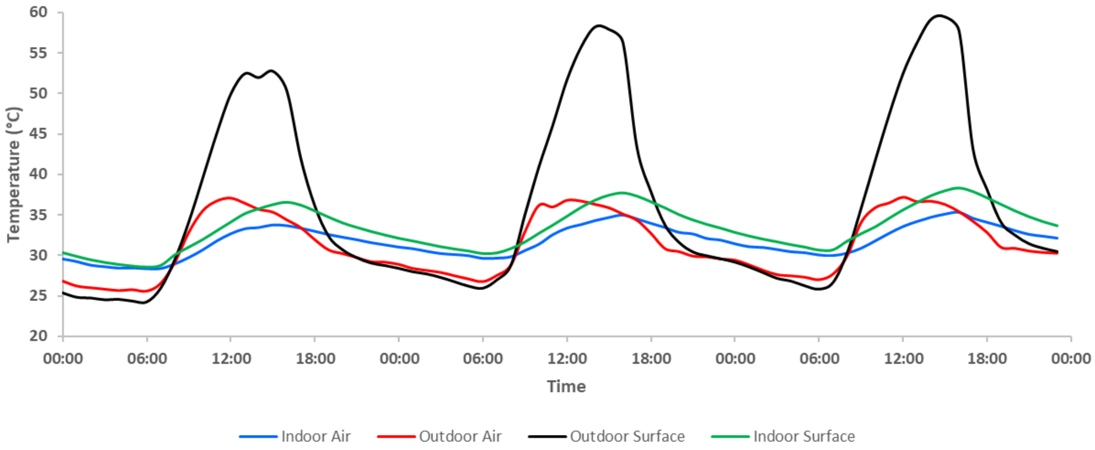


Figure 65 Hourly average of the air and terracotta temperature over a three-day period in June 2014

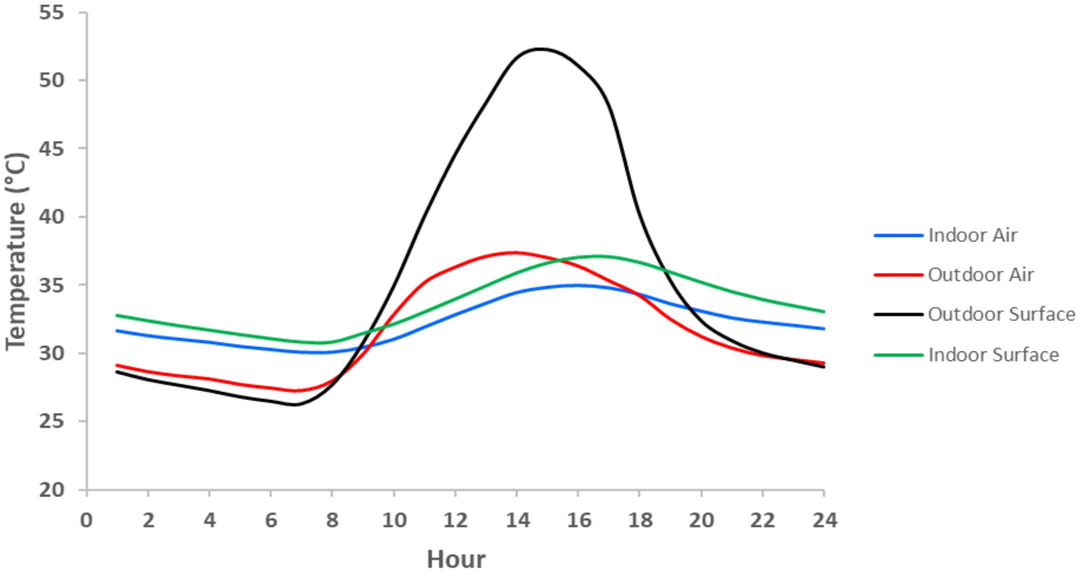


Figure 66 Hourly average of the air and terracotta temperature in June 2014

The analysis of the hourly average temperatures of the air and terracotta surface is shown in Figure 66. The terracotta sees an average maximum damping of 15°C at 2pm, and an average daily time lag of 2 hours. The indoor and outdoor surface temperatures reach their peaks at the same time as the air temperature. The larger maximum damping (by about 12.5°C) indicates that heat conduction through the terracotta is stronger than through air. This also means that terracotta is successful in reducing the indoor operative temperature.

4.2.1.2 Flat roof with hollow blocks

Figure 67 shows the detail of the flat hollow block roofing detail analysed for performance. The air and surface temperatures during three days in June were taken to be representative for the whole year, and is shown in Figure 68. In this three-day period, the outdoor air had a damping of 7°C, indoor air temperature a damping of 11.6°C, outdoor surface temperature a damping of 23°C, and indoor surface temperature a damping of 8.7°C. The indoor air temperature is seen to have a lesser fluctuation than the outdoor air temperature; and air is seen to have a lesser fluctuation than the hollow block.

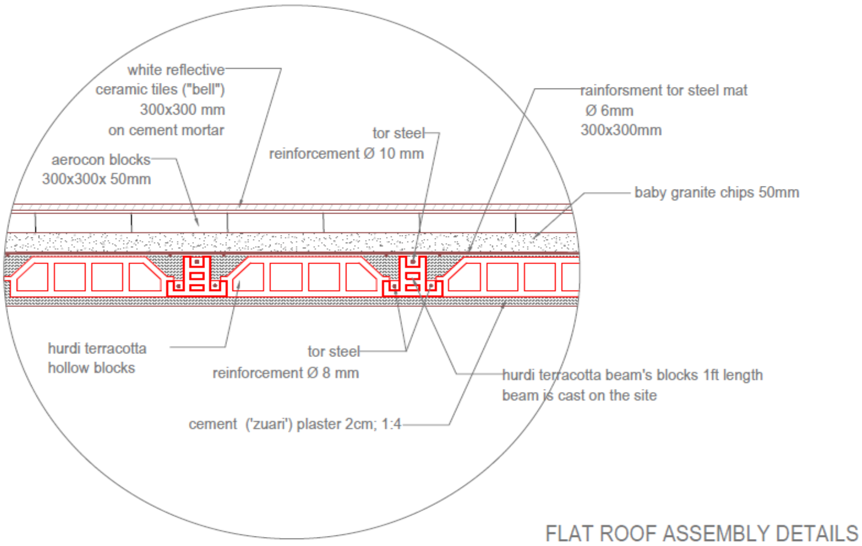


Figure 67 Flat hollow block roofing detail

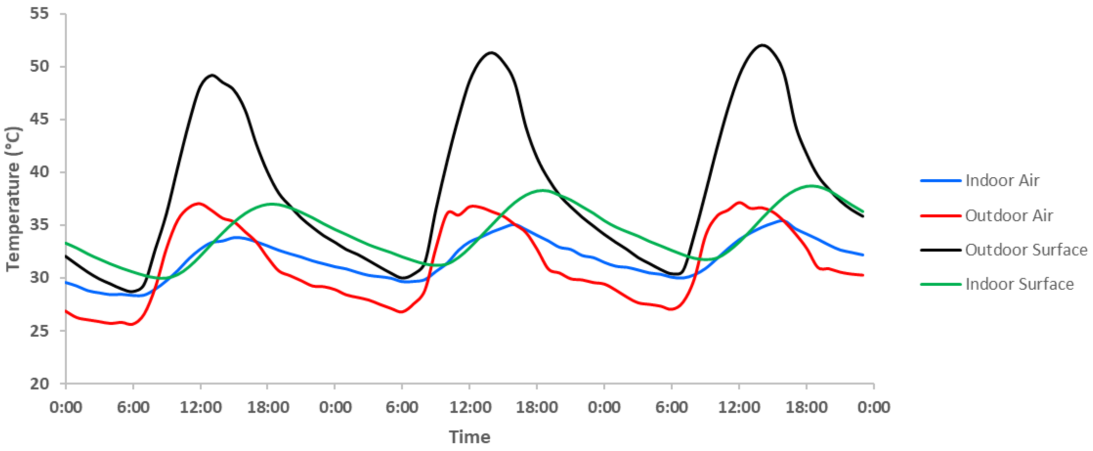


Figure 68 Hourly average of the air and hollow block temperature over a three-day period in June 2014

The analysis of the hourly average temperatures of the air and terracotta surface is shown in Figure 69. The air sees an average maximum damping of 2.5°C, hollow block sees an average maximum damping of 10°C at 2pm, and an average daily time lag of 4 hours. The outdoor air and surface temperatures reach their peaks at 2pm while the indoor surface temperature reaches its peak at 6pm. The larger daily time lag (by 2 hours) indicate that heat conduction through the hollow block is much slower than through air. This means the hollow block is successfully slowing down the heating of the interior space.

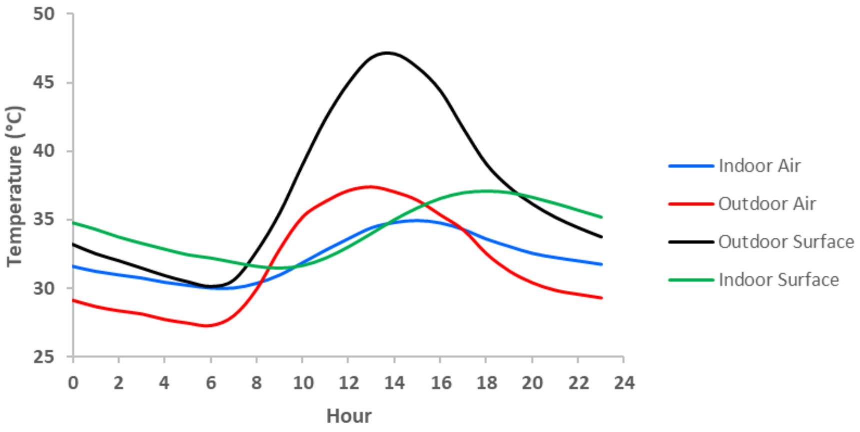


Figure 69 Hourly average of the air and hollow block temperature in June 2014

A comparison of the performance of the terracotta tile roofing and the hollow block roofing show that the hollow block has a significantly larger outdoor surface temperature damping than that of the terracotta roofing, but their indoor surface temperature amplitudes are different only by 1°C.

Figures 70 and 71 analyse the hourly average temperature profiles of the three materials based on the outdoor and indoor temperatures. The outdoor air temperature and hollow block surface temperature have a difference in peak temperature of 10°C and a difference in amplitude of almost 10°C; outdoor air temperature and terra cotta surface temperature have a difference in peak temperature of almost 15°C and a difference in amplitude of almost 16°C. The indoor air temperature and hollow block surface temperature has a difference in peak temperature of 2.20°C and a difference in amplitude of 0.7°C; indoor air temperature and terra cotta surface temperature have a difference in peak temperature of 2°C and a difference in amplitude of almost 1.4°C.

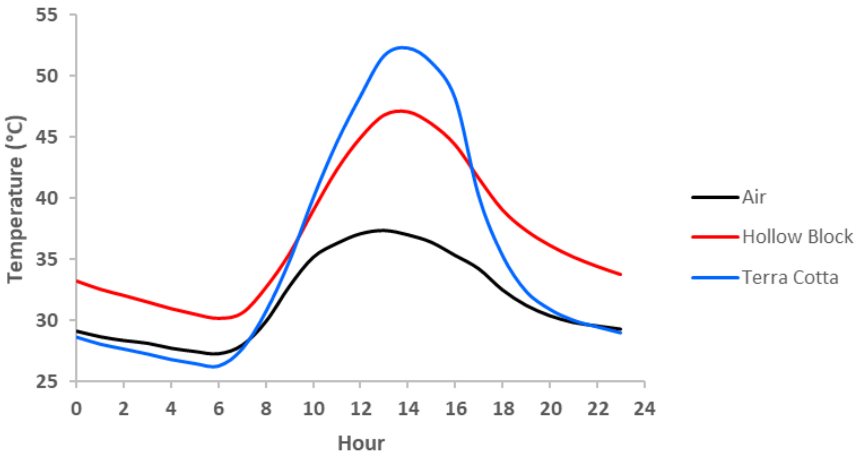


Figure 70 Hourly average of the outdoor temperature in June 2014

It is interesting to note that although the difference in outdoor surface temperature peak and outdoor air temperature peak is over 10°C for each material, they are both less than 3°C for the difference in indoor temperature peaks. It should also be noted that the difference between outdoor surface temperature peak and outdoor air temperature peak is roughly 5°C larger for terra cotta, and the difference between outdoor surface temperature damping and outdoor air temperature damping is roughly 9°C larger for terra cotta. Although there is a significant dissimilarity for outdoor values of the two materials, the indoor values for the two materials are closer.

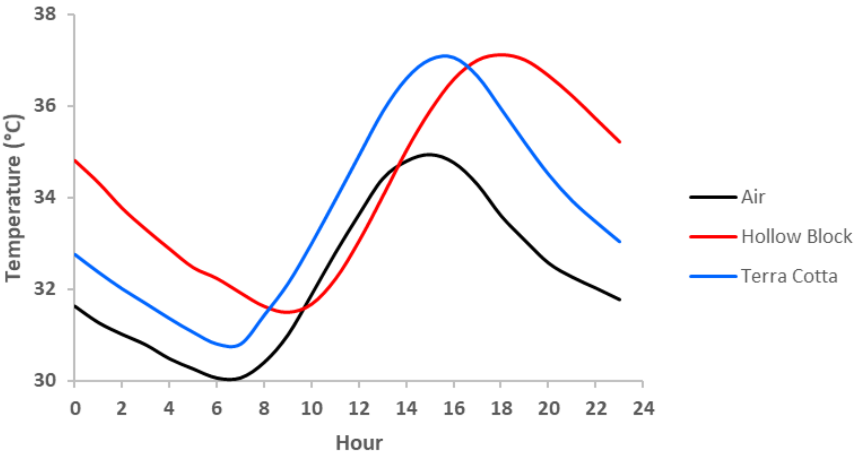


Figure 71 Hourly average of the indoor temperature in June 2014

4.2.1.3 Annual Temperature

Although analysing individual days and specific months can be useful to see specifically how the thermal mass strategy is working, it does not take advantage of a full year's worth of data, requiring other visualization techniques for analysing the complete set of data. It should be noted that due to some errors in the data loggers, there are numerous days in the month of May that are missing data resulting in gaps in the following visualizations, due to the missing data.

Figures 72, 73 and 74 were developed to look for general patterns present across the year for indoor and outdoor air and surface temperatures. The results show that much of the observations taken on temperature variation in the month of June would be applicable throughout the year. These include less indoor temperature fluctuation than outdoor temperature fluctuation, less outdoor air temperature fluctuation than outdoor mass temperature fluctuation, and roughly the same indoor air and mass fluctuation. It was then decided to take a further consider annual variation, and separating the temperatures by month.

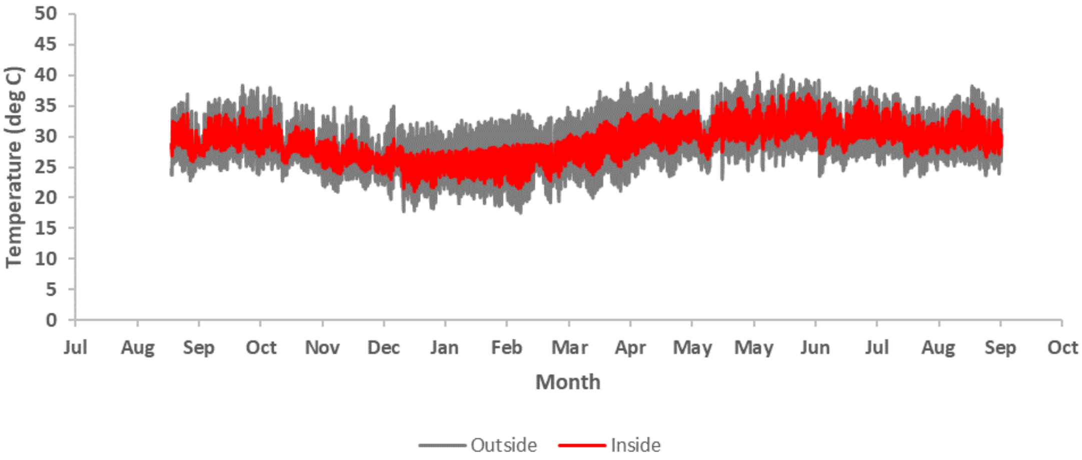


Figure 72 Hourly indoor and outdoor temperature from September 2013 to September 2014

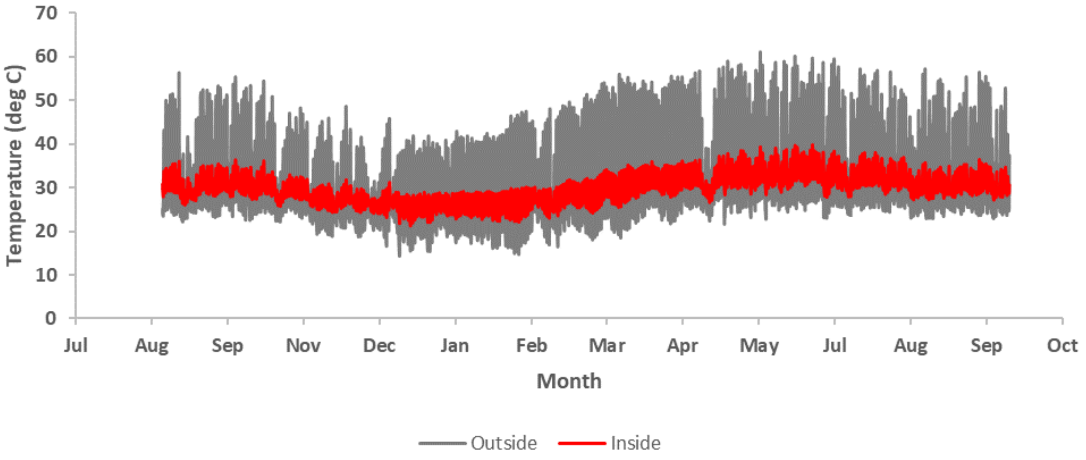


Figure 73 Hourly indoor and outdoor terracotta surface temperature from September 2013 to September 2014

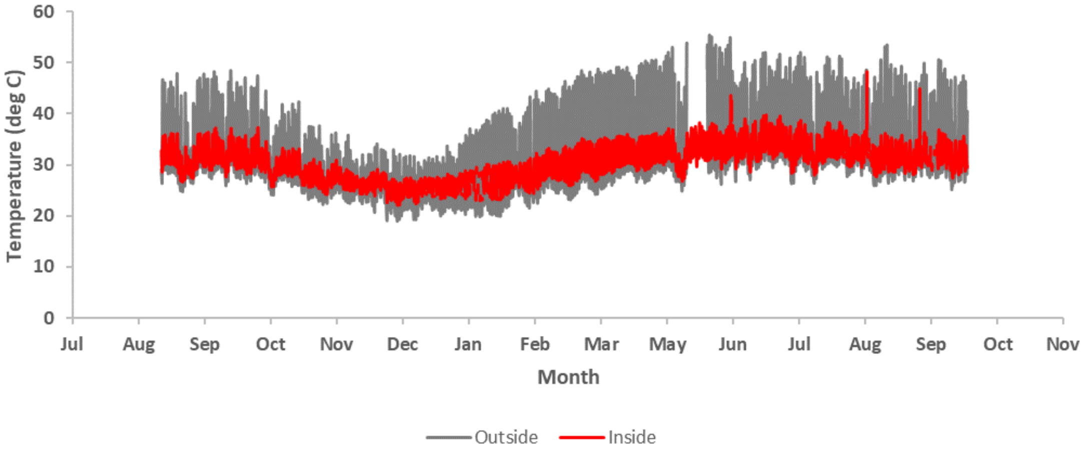


Figure 74 Hourly indoor and outdoor hollow block surface temperature from September 2013 to September 2014

Figures 75 and 76 show that the monthly average temperature, both indoor and outdoor, generally increase from January to June, reaching a peak in June, and decreasing from June to December. Monthly average indoor and outdoor air temperature also seem to be similar for every month. Although the monthly average indoor and outdoor mass surface temp is roughly the same from November through February, the outdoor surface temperature is higher than indoor surface temperature from March through October. Finally, it was noted that monthly average indoor mass temperature is higher than monthly average indoor air temperature for every month. After analysing the monthly average temperature, temperature peak throughout the year was analysed.

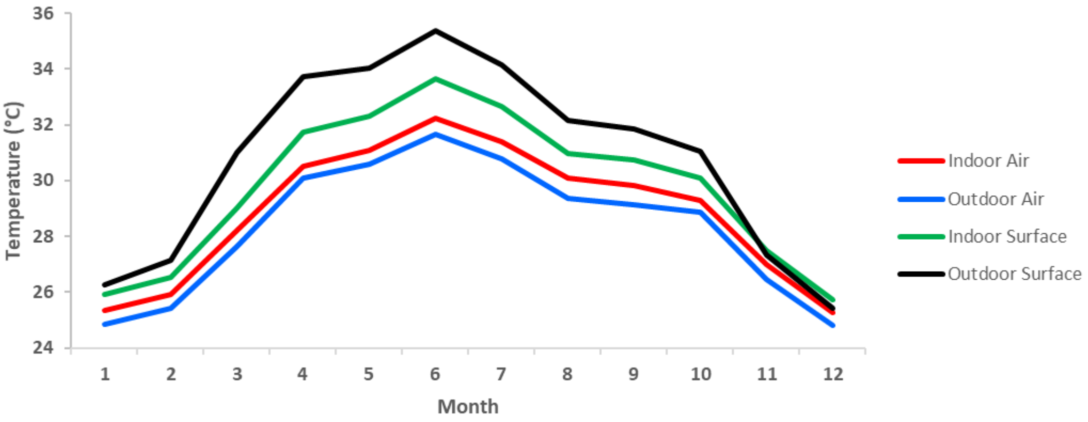


Figure 75 Monthly average air and terracotta temperature

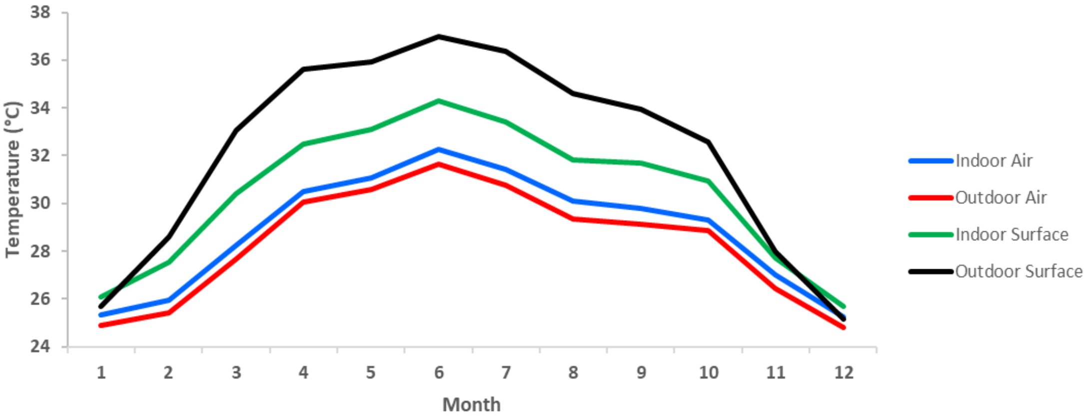


Figure 76 Monthly average air and hollow block temperature

4.2.1.4 Peak Temperature

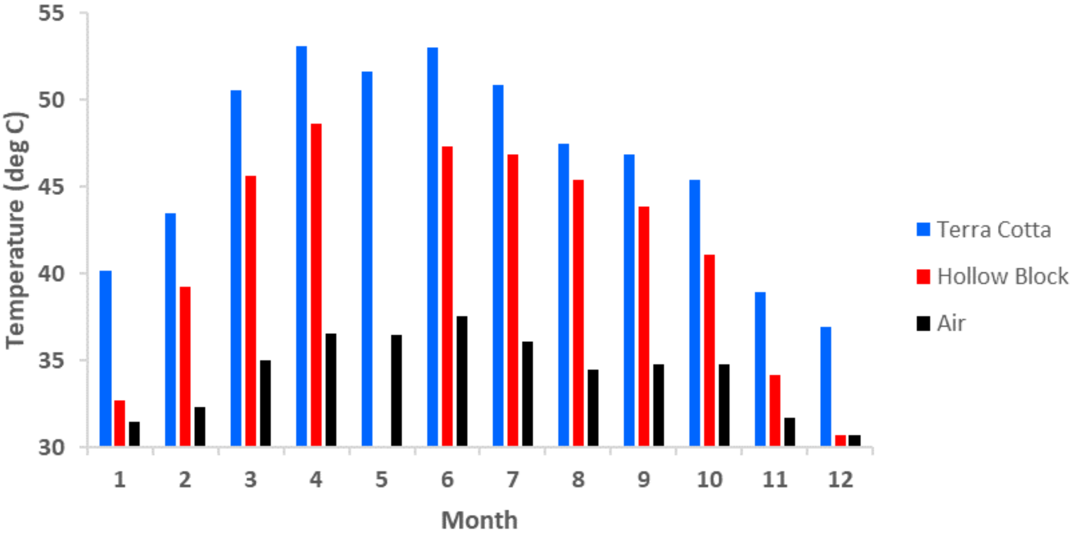


Figure 77 Monthly average of outdoor air, terracotta and hollow block temperature peak

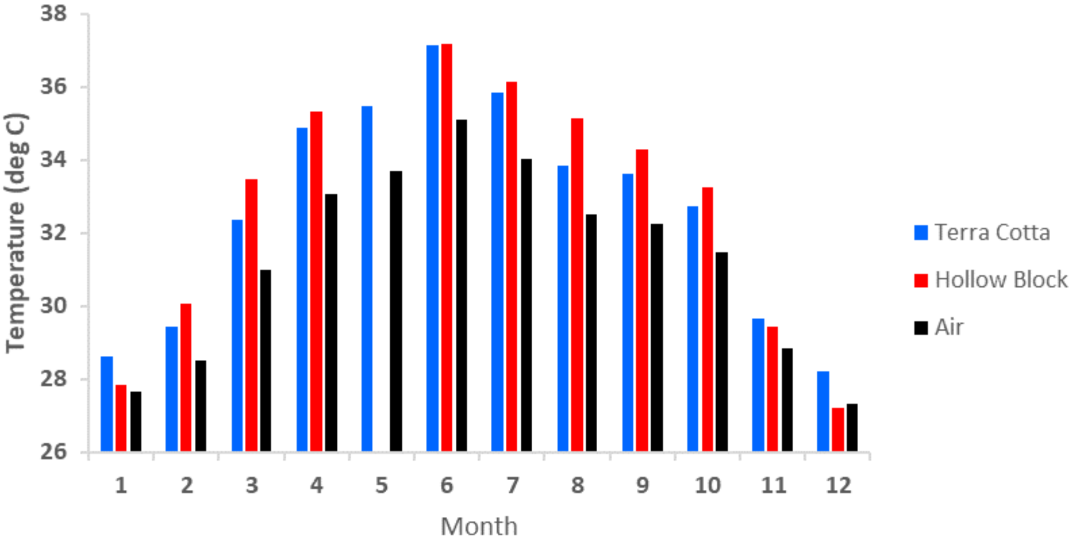


Figure 78 Monthly average of indoor air, terracotta and hollow block temperature peak

Figures 77 and 78 show the monthly average temperature peak to have a similar trend to monthly average temperature, reaching its highest value in June and lowest value in December. In all the months, the average outdoor terra cotta surface temperature peak is higher than that of hollow block and air. In addition, average indoor terra cotta surface temperature peak and average indoor hollow block surface temperature peak is approximately the same for every month. In the months of November through January, monthly average indoor air temperature peak is approximately the same as average indoor mass temperature peaks, but lower than indoor mass temperature peaks for all other months. The most commonly occurring indoor temperatures fall between 29°C and 30°C while the most commonly occurring outdoor temperatures fall between 37°C and 38°C. The distribution of indoor air temperature is almost identical to the distribution of outdoor air temperature, shifted down by about 8°C.

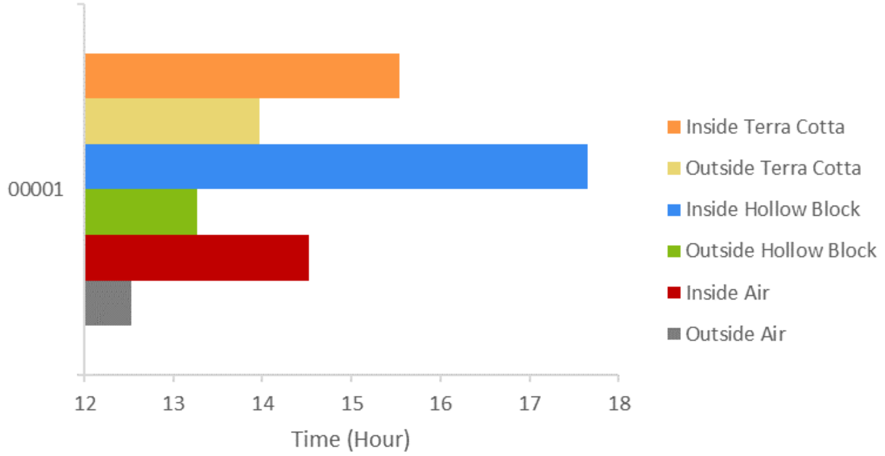


Figure 79 Annual average of time of the temperature peak

Figure 79 shows the annual average time of the peak temperatures. The outdoor air temperature peak occurs at about 12:30pm, indoor air temperature peak occurs at about 2:30pm, outdoor hollow block surface temperature peak occurs at about 1:30pm, indoor hollow block surface temperature peak occurs at 5:30pm, outdoor terra cotta surface temperature peak occurs at 2:00pm, and indoor terra cotta surface temperature peak occurs at 3:30pm. This indicates that the annual average time lag of air is 2 hours, hollow block is 4 hours, and terra cotta is 1.5 hours. It should also be noted that the time of outdoor temperature peaks is earliest for air and latest for terra cotta, while the time of indoor temperature peaks is earliest for air and latest for hollow block. A closer look shoes that the indoor temperature peak takes place from 10am to 3pm, occurring most frequently at 12pm, while the outdoor temperature peak takes place from 12pm to 5pm, occurring most frequently at 3pm.

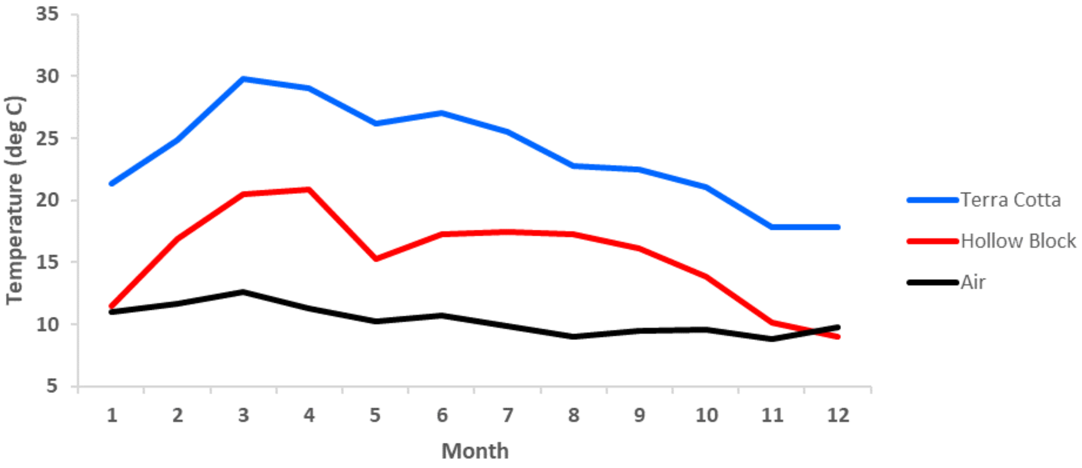


Figure 80 Monthly average of time of the outdoor temperature amplitude

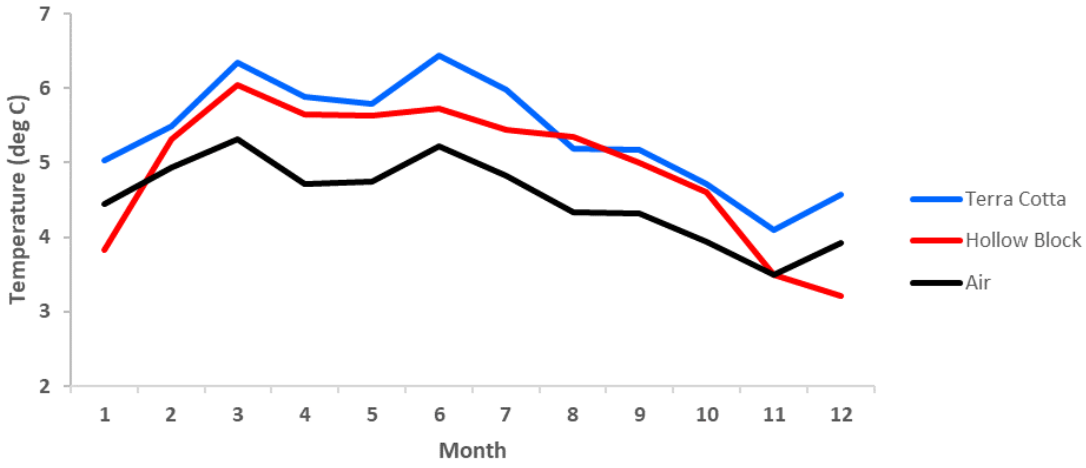


Figure 81 Monthly average of time of the indoor temperature amplitude

Figure 80 shows that, like outdoor temperature peak, outdoor temperature amplitude is widest for terra cotta and narrowest for air. However, unlike outdoor temperature peak, monthly average outdoor temperature amplitude reaches its maximum value in March. Figure 81 indicates that average monthly indoor temperature amplitudes are roughly the same for all materials and months, falling within a range of 3°C. After analyzing the difference in indoor and outdoor average temperature, temperature peak, and temperature amplitude, further analysis was conducted on the instantaneous difference between indoor and outdoor temperature, also known as instantaneous hourly damping.

4.2.1.5 Instantaneous hourly damping

As seen in Figure 82, the path of annual average instantaneous hourly damping looks very similar to that of daily temperature. The path remains flat at night (8pm to 5am) and rapidly increases until the afternoon, after which it rapidly decreases. The path for instantaneous damping is slightly different for each material.

- Air instantaneous damping is about -4°C at night, implying that indoor air temperature is greater than outdoor air temperature,
- hollow block and terra cotta night-time instantaneous damping is about 0°C,
- air instantaneous damping reaches its peak of about 3.65°C at 11am, while
- hollow block instantaneous damping reaches its peak of about 10.82°C at 1PM, and
- terra cotta instantaneous damping reaches its peak of about 13.37°C at 2PM.

Terra cotta instantaneous damping has the largest range of values, while air instantaneous damping has the smallest range.

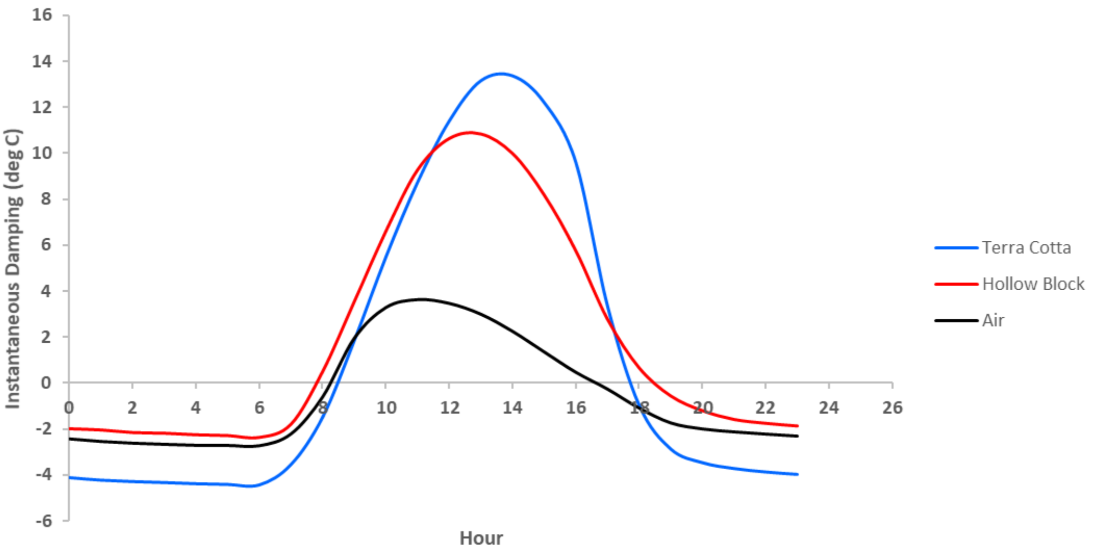


Figure 82 Annual average of instantaneous hourly damping

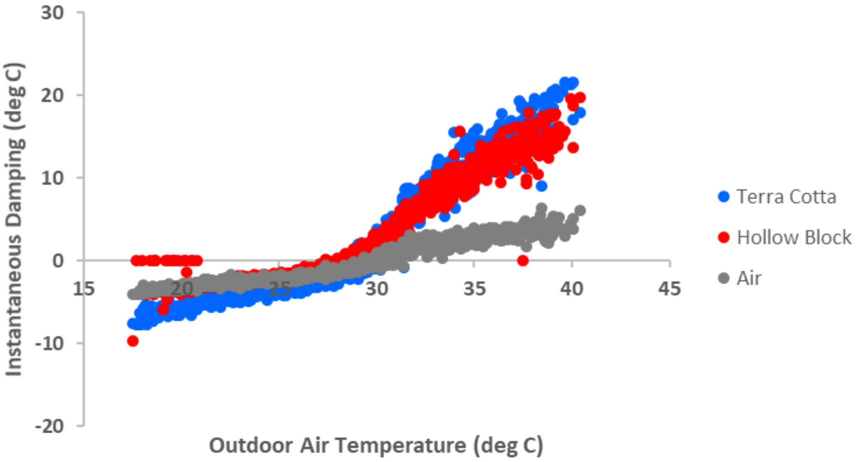


Figure 83 Instantaneous hourly damping by outdoor air temperature

Hollow block, terra cotta, and air all appear to have a linear relationship with outdoor air temperature, as seen in Figure 83. Although the daily profile for terra cotta and hollow block instantaneous damping is quite different in peak and time of peak, their relationship with outdoor air temperature appears to be similar. Hollow block instantaneous damping increases by approximately 0.99°C for every 1°C increase in outdoor air temperature while terra cotta instantaneous damping increases by about 1.26°C and air instantaneous damping increases by about 0.41°C. Air instantaneous damping noticeably increases at a significantly slower rate.

Visualizing instantaneous damping through box plots in Figure 84 shows the spread in each month. Both hollow block and terra cotta have the largest spread of instantaneous damping in January through March, and the narrowest spread of instantaneous damping in July through September. This spread is like that of outdoor air temperature. For further analysis into the trends of instantaneous damping, it was chosen to explore maximum damping, the difference in temperature between the indoor and outdoor temperature peaks.

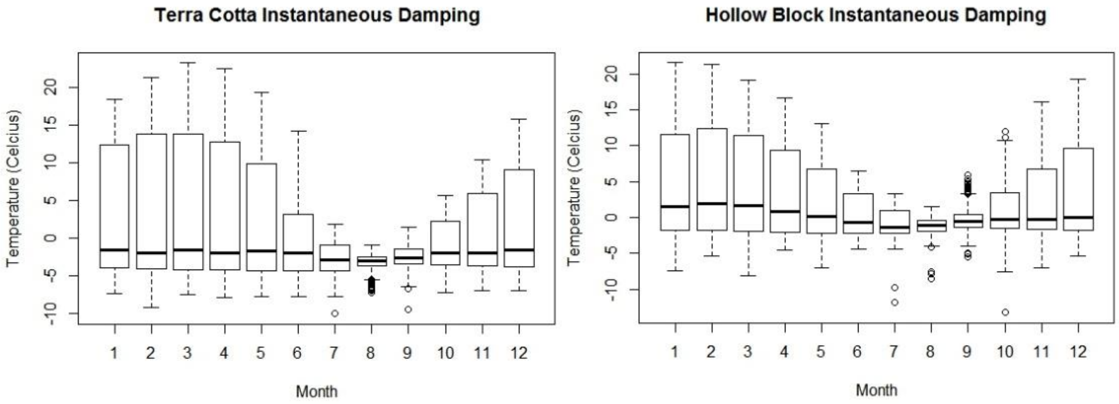


Figure 84 Monthly spread of instantaneous damping

4.2.1.6 Maximum damping

Maximum damping is the most commonly used metric for assessing performance of thermal mass. From the monthly average of maximum damping seen in Figure 85, the annual profile is similar to that of daily outdoor temperature amplitude, decreasing from March to December. The spread for air maximum damping is much narrower than the spread of mass maximum damping, and that the values of air maximum damping are much lower than most of the values for mass maximum damping. After analysing the maximum damping, the daily time lag, the second most common metric for assessing performance of thermal mass was analysed.

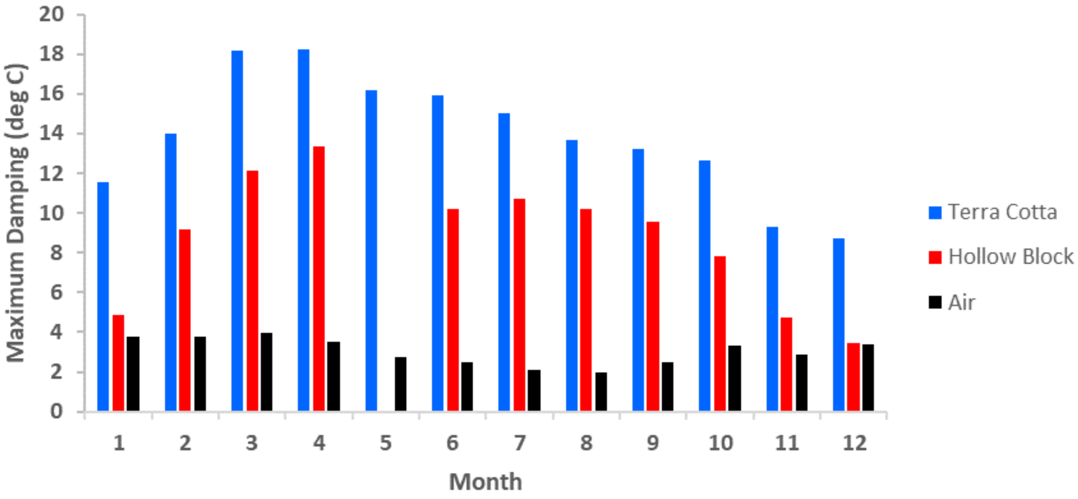


Figure 85 Monthly average of maximum damping

4.2.1.7 Daily time lag

Although there is a clear trend in maximum damping throughout the year, Figure 86 shows that there is no obvious annual trend in monthly average daily time lag. However, both Figures 86 and 87 indicates that daily time lag is significant higher for hollow block than for air or terra cotta. This is surprising as terra cotta was higher in maximum damping than terra cotta throughout the entire year. One would expect a material high in maximum damping to also be high in daily time lag. To confirm this relationship, maximum damping was normalized by daily temperature amplitude and daily time lag was normalized by daily temperature period. After normalization, the same results were produced. This discrepancy is probably due to the orientation or angle of the roofs. An additional takeaway from this analysis was the relationship between daily time lag and hour of outdoor temperature peak. As outdoor temperature peak occurs later, the daily time lag decreases. This could be attributed to the fact that outdoor air temperature is lower at later hours, and therefore the outdoor temperature peak is lower.

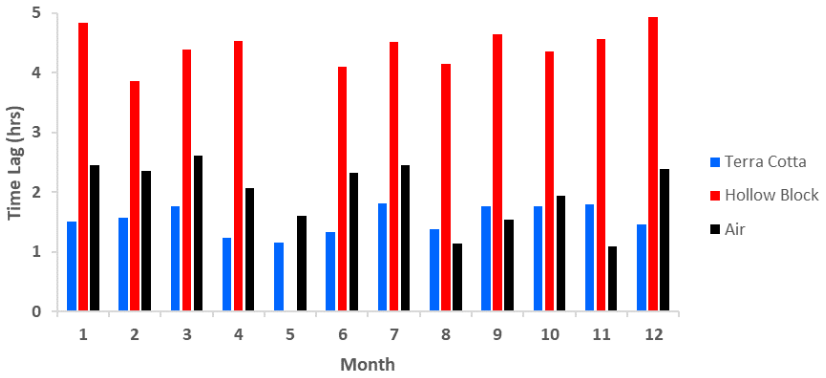


Figure 86 Monthly average of daily time lag

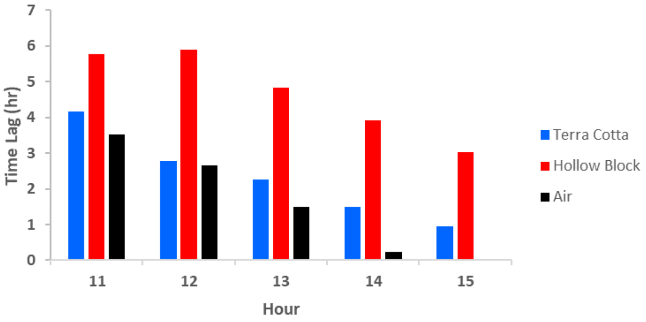


Figure 87 Annual average of daily time lag by hour of outdoor temperature peak

4.2.2 Ventilation and indoor thermal comfort

Ventilation is the key to indoor thermal comfort – adequate air changes per hours, uniform stratification of air and the position of the neutral layer, all play a major role in reducing the energy costs and making the building more sustainable. The Afsanah Guest House has well placed fenestrations and verandas to facilitate ventilation, and the same can be observed in the following discussions.

Figure 88 presents the variation of monthly average temperatures indoor and outdoor through the day for all the spaces monitored. Figure 89 presents the hourly averaged temperature and relative humidity of the monitored spaces for the months of January, June, and October, respectively for the seasons of winter, summer, and monsoon. The temperature across all the zones is sufficiently moderated and remains in the range of 23-25.5°C, 31-32.5°C, and 27.5-29.5°C degrees. The relative humidity is inversely proportional to the temperature of the zone, with the humidity of the internal zones varying between 76-84%, 64-68%, and 76-83% for the respective months.

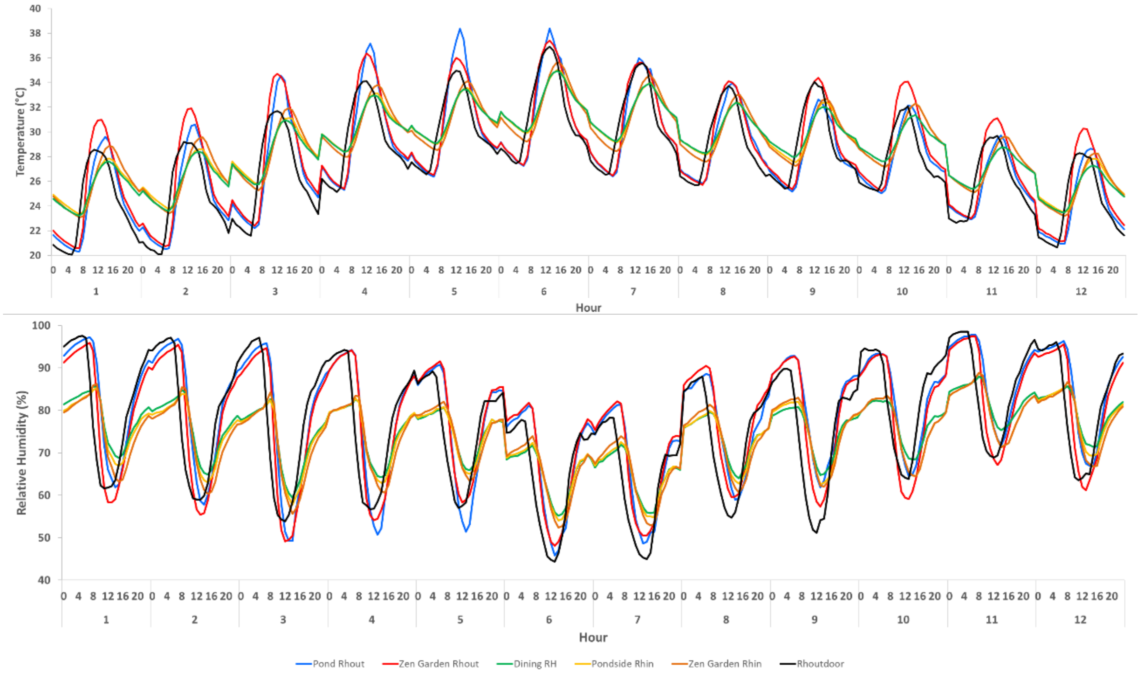


Figure 88 Variation of monthly average temperatures indoor and outdoor through the day

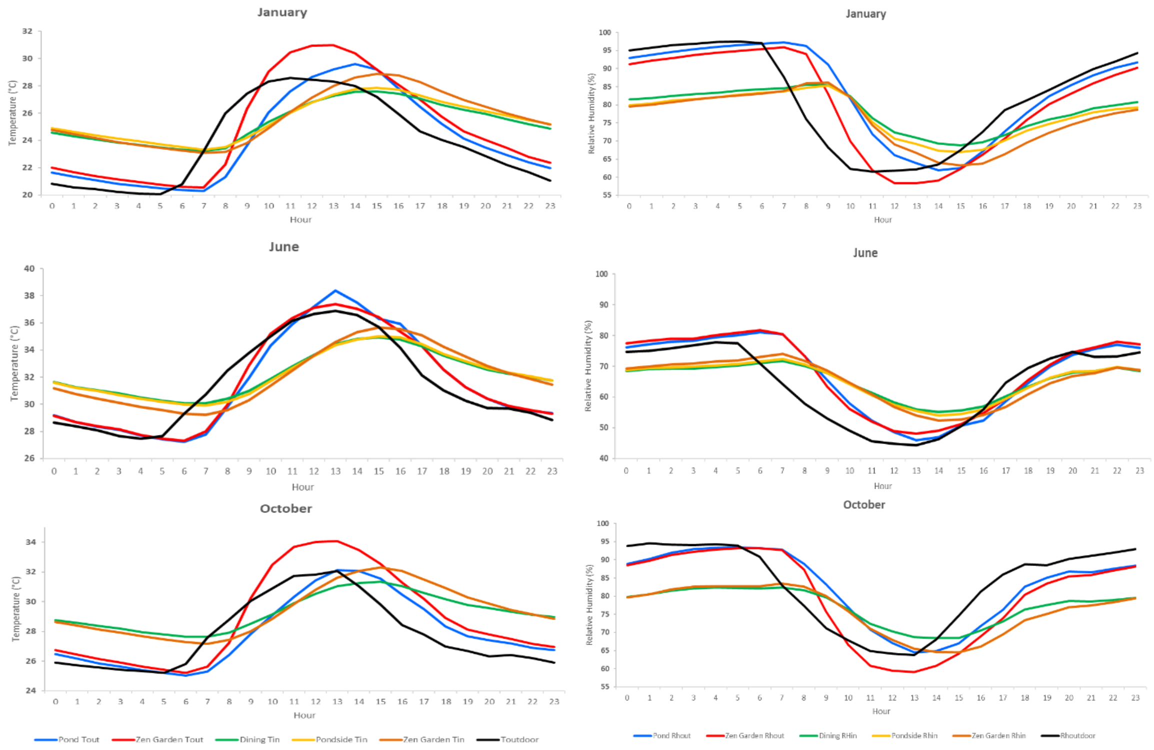


Figure 89 Variation of hourly average temperature and relative humidity for January, June, October 2014

The analysis is done based on the three measurements taken outdoors and three measurements taken indoors to study the effect of the outdoor environmental conditions on the indoors. The outdoor gardens demonstrate the higher temperatures, with the Zen garden having the higher temperatures in January and October (winter and monsoon), and the pond garden the higher temperature in June (summer). In the indoors, the dining hall shows the lowest temperatures. The Zen garden side indoor shows a slightly higher temperature in comparison to the indoor pond garden side. This could be attributed to some cooling provided by the pond.

The analysis of the relative humidity shows that in the outdoor, the Zen garden has the lowest humidity levels throughout the year, and the pond garden the highest humidity levels. This could be attributed to the effect of presence of water. In the indoor, the dining hall shows the highest humidity levels, and the Zen garden side the lowest. The influence of the pond on both the temperature and the relative humidity of the spaces is clearly seen.

4.2.2.1 IMAC adaptive comfort model

To understand the annual variation of temperature, the instantaneous air temperatures across the dining hall were plotted against the 80% and 90% IMAC temperature limits for thermal comfort in Figure 4-30. There are many points outside the IMAC adaptive comfort limits for 80% and 90% acceptability range, especially in the period between March to September. These are the months in the summer and monsoon seasons, where it is critical to achieve indoor temperatures for thermal comfort. The winter seems to be more acceptable with most of the measured temperatures within the comfort band, with some exceedances from November to February in the lower limits of acceptability. However, most of the low temperatures were experienced during the early hours (0:00 – 7:00) while the occupants are likely not using the space.

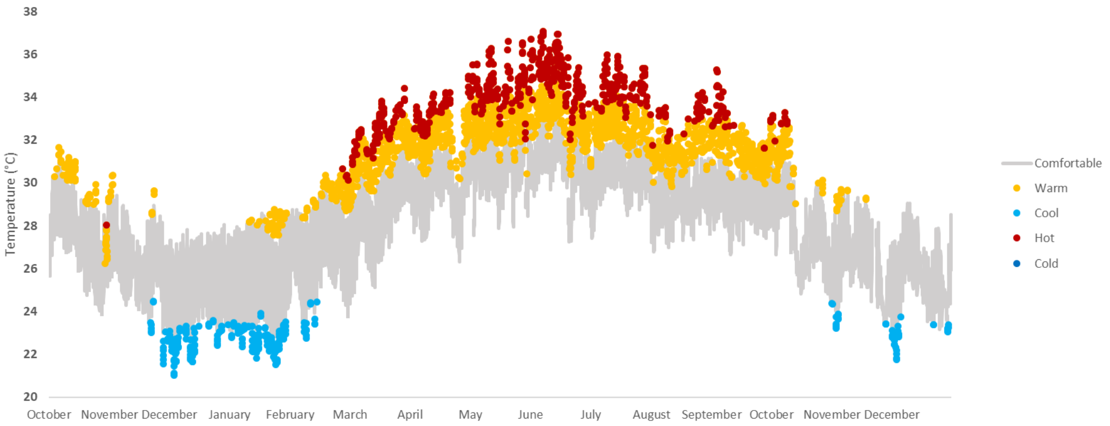


Figure 90 Evaluation of monthly indoor temperatures based on the IMAC adaptive model for the thermal comfort for 90% and 80% acceptability range

4.2.3 Lighting

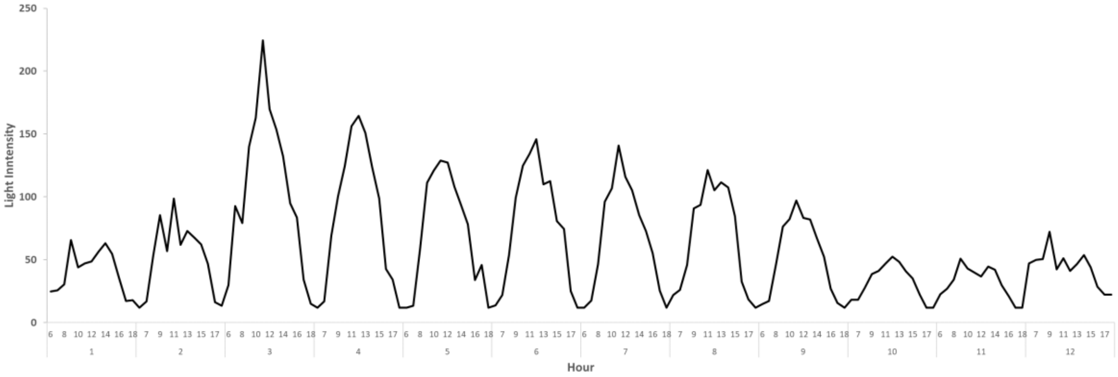


Figure 91 Variation of the hourly averaged daylighting intensity in the dining hall throughout the year 2014

The Afsanah Guest House dining hall was monitored for the daylight intensity throughout the year. The Figure 91 shows the variation of the lighting intensity in the dining hall from 6am to 6pm throughout the year. The lux profiles show a large variation through the seasons with maximum lux levels in March and lux levels above 100lux from March to September during the midday. The hall has low lighting levels in the winter around 50lux.

4.3 LUMINOSITY

4.3.1 Ventilation

Ventilation is the key to indoor thermal comfort in a hot-humid climate – adequate air changes per hours, uniform stratification of air and the position of the neutral layer, all play a major role in reducing the energy costs and making the building more comfortable and sustainable.

Figure 92 shows the variation of temperature and humidity across the various building zones for the three months of January, June, and October to account for winter, summer, and monsoon respectively. For the three months, the mean outdoor temperature ranged between 19.5-27.5, 26.5-35, and 23-31 degrees respectively. The mean indoor temperatures across all the zones except the passage remained between 23.5-27 degrees for the winter, 29-32.5 degrees for the summer, and 26-29 degrees for the monsoon. The temperature profile of zone G1 at ground floor was found to be higher than that of the other zones, while the zone S1, on second floor was the coolest of all by one degree. However, for all the cases, the indoor temperature remained lower than the outdoor temperature during the hottest hours of the day and higher than the outdoor temperature during the comparatively cooler hours. The avg. temperature of the passage was closest to the outdoors due to its vicinity to the atmosphere and lied between 21-26, 29-33, and 25.5-29 degrees.

The relative humidity profiles of the three months were the inverse of the temperature profiles, with mean outdoor humidity levels between 60-95%, 43-75%, and 55-90% for the respective months. Higher temperatures resulted in lower humidity due to evaporation – thus, the humidity for June was the lowest, while low temperatures and monsoon respectively resulted in the high humidity levels for the months of January and October. The indoor humidity levels for the respective months for all the zones except the passage lied in the range of 63-80%, 57-68%, and 66-78% respectively. Due to the lowest temperature profile, the humidity across the zone G1 on the ground floor was lowest for all the seasons, S1 the most humid zone. Similar to the case of temperature, the relative humidity profile of the passage was most similar to the outdoor conditions with a range of 68-90%, 54-66%, and 67-79% for the respective months.

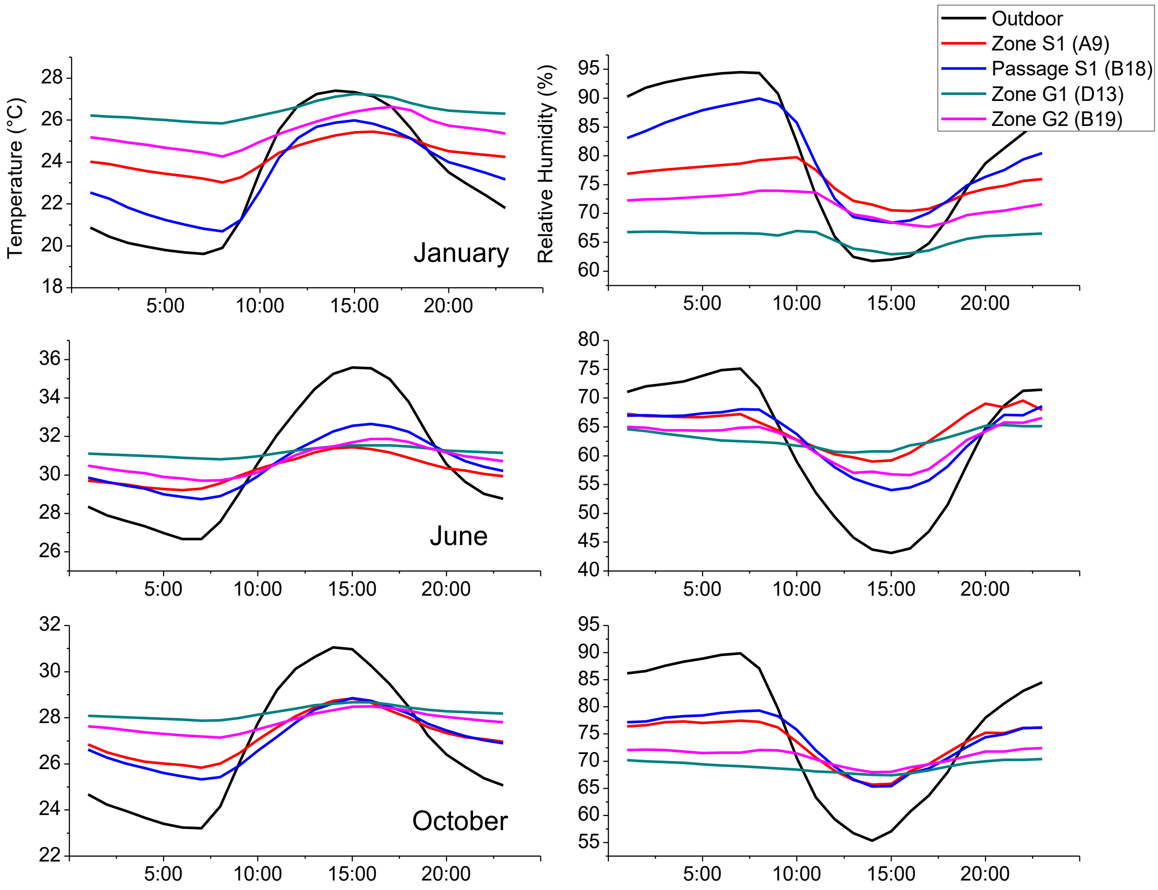


Figure 92 Variation of hourly averaged air temperatures and relative humidity across various building zones for three seasons/months, 2014

The passage remains in the closest contact with the outdoors and can be seen almost overlapping certain portions of curve in the year, as can be seen in figure 93. The cooler months of November – February experience moderated and overlapping temperatures. However, during the extreme months of April – August, the excessive heat of the outdoors peaks is not reflected in the passage temperatures.

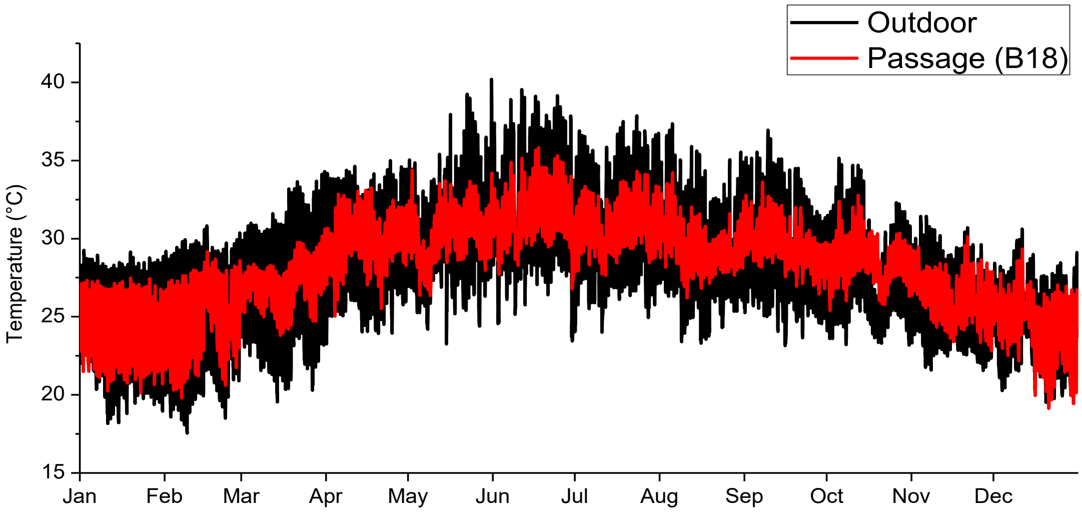


Figure 93 Annual variation of instantaneous temperature of the passage against the outdoor temperature, October 2013 - October 2014

The instantaneous temperature data points were compared against the 90% IMAC (Indian Model for Adaptive Comfort) temperature limits for naturally ventilated buildings, as shown in Figure 94. The '90%' indicates that at least 90% of the occupants were thermally comfortable. The indoor temperatures remained well moderated across all the building zones with occupants. However, the upper comfort limit was breached a few times during the summers and the lower limit was breached for the extreme winter months. As per the IMAC limits, Zone G1 on the ground floor was the most comfortable.

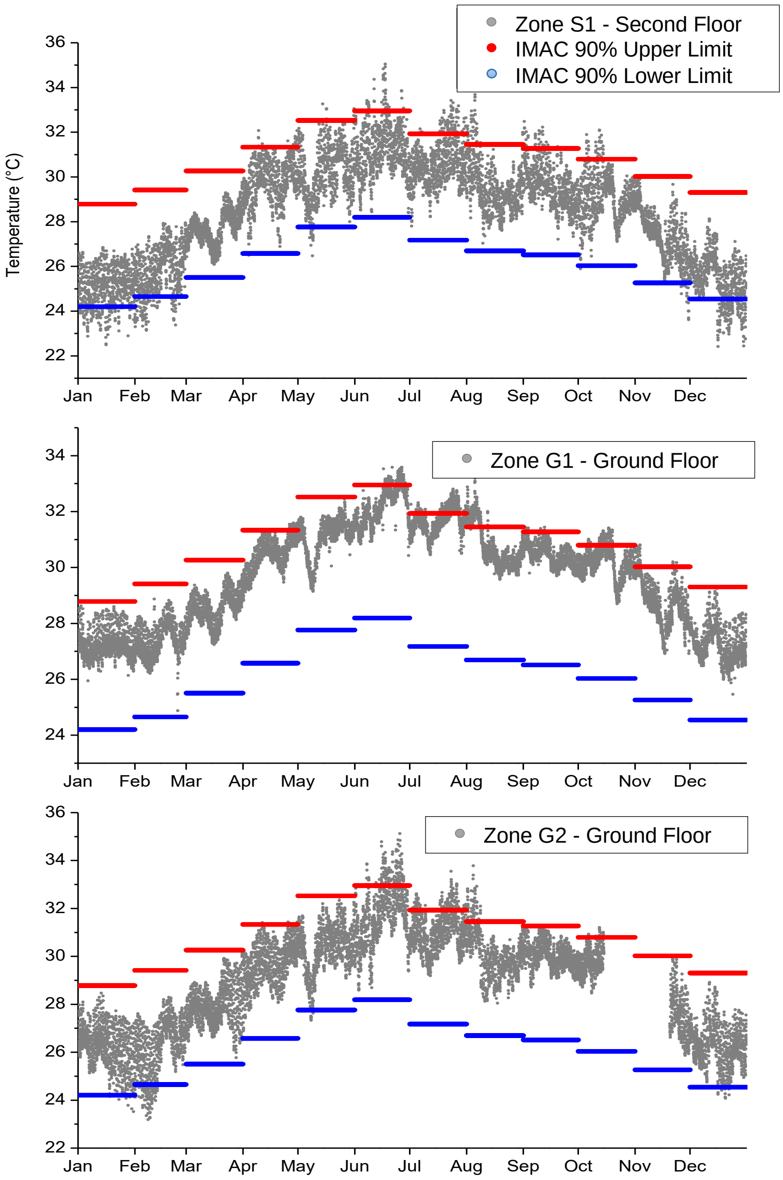


Figure 94 Comparison of instantaneous air temperatures across various building zones against the 90% IMAC limits, October 2013 - October 2014

4.3.2 Thermal Mass

Thermal mass can be explained as the physical property of the building fabric which allows it to store the heat in itself. The higher the thermal mass, the more time it will take for the heat to reach from the outdoors to the indoors - this difference in time is called as 'time lag'. For our case, in hot and humid climate, a high time lag was preferable, as it shielded the indoors from the extreme noon sun and gradually dissipated the heat by the evening through natural ventilation, when it was comparatively cooler.

Figure 95 shows the variation of hourly averaged surface temperatures across the rooftop. Intuitively, the rooftop surface should have reached a temperature above the outdoor air temperature by the hottest hours of the day, but in this case, the mean rooftop temperature ranged between 22-25, 29-33, and 26.5-30 degrees for the months of January, June, and October respectively. Such low top surface temperatures can be credited to the fact that the roof is covered with another light weight G.I. sheet roof, which shields the surface from direct solar radiation. Thus, the mode of heat transfer between the atmosphere and the rooftop is reduced from radiation and convection to merely convection. Due to the same, we can also observe that there is no time lag between the outdoor air temperature and the exterior ceiling surface temperature. The indoor ceiling surface temperature is further moderated by the thermal mass of the roof and remains between 23.5-24.5, 29.8-30.8, and 27.6-28.9 degrees. There is a marginal time lag of 0-1 hours between the exterior and ceiling surface temperatures, as air is the medium of heat transfer and the thermal inertia of the roof does not play a major part. However, the thermal gradient between the two surfaces is 0.5, 2, and 1.5 degrees for the respective months – highest for the summer, lowest for the winters.

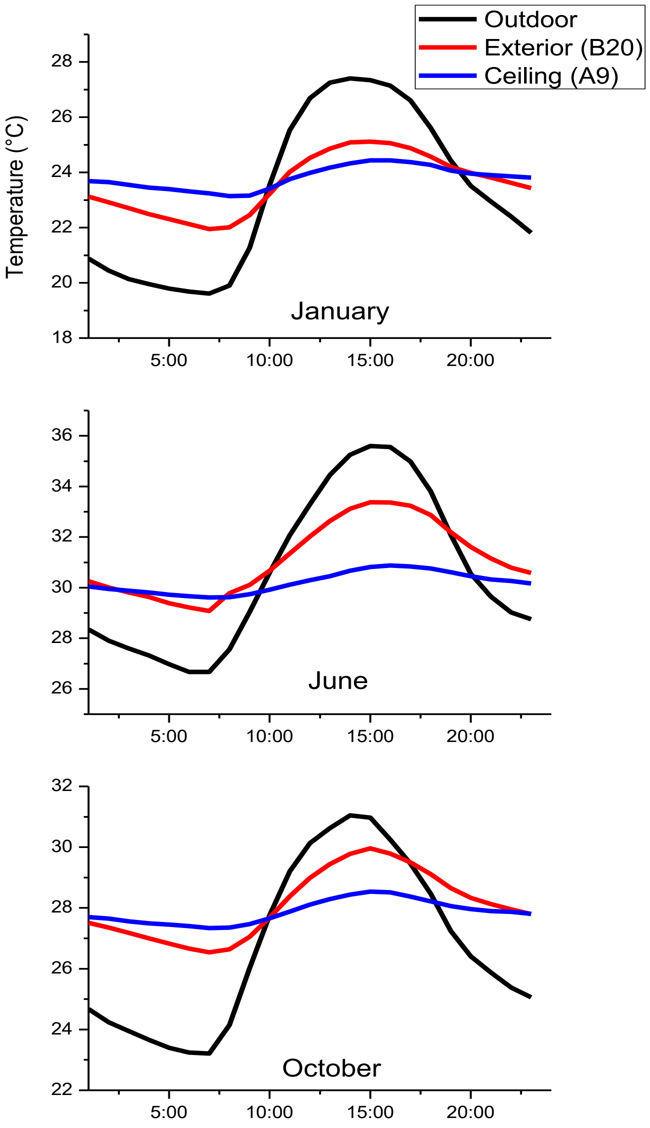


Figure 95 Variation of hourly averaged surface temperatures across the rooftop for three months/seasons, 2014

Figure 96 shows the variation of hourly averaged surface temperature across the indoor cavity wall next to the staircase. As both the surfaces are indoors, they are sufficiently moderated in the range of 23.5-25, 28.3-29.5, and 27-29 degrees for the respective months. The surface of the wall closer to the staircase is warmer than the room temperature by 0.5, 0.2, and 1 degrees for the respective months. This difference was most prominent during the early morning hours and least prominent during the evening hours.

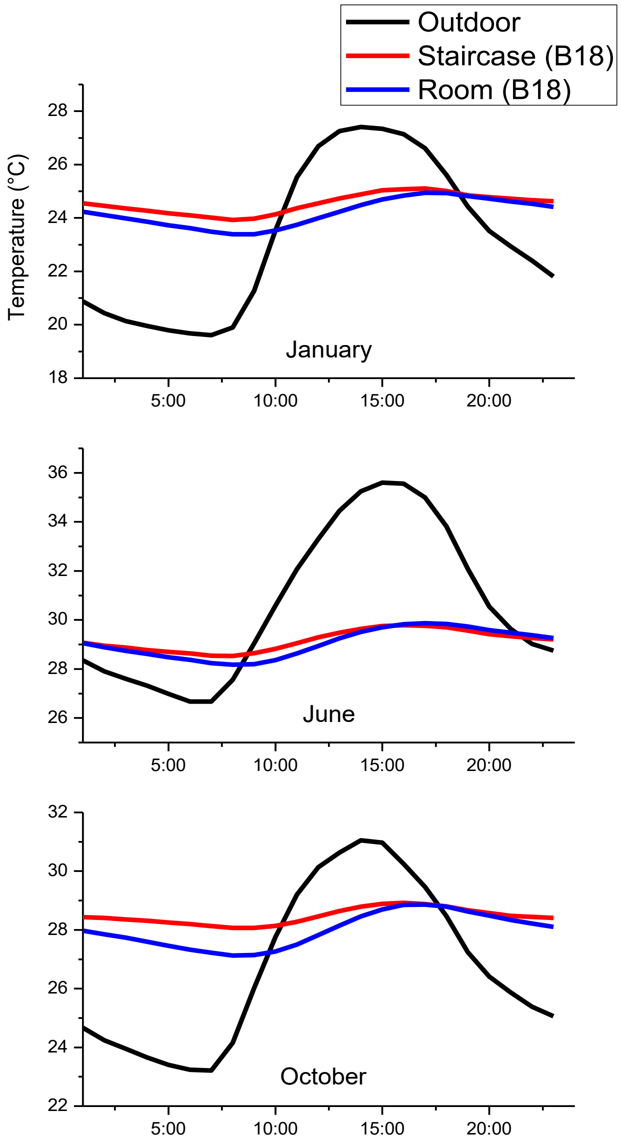


Figure 96 Variation of hourly averaged surface temperatures across the indoor cavity wall for three months/seasons, 2014

The east wall of the building was exposed to the morning sun and its seasonal variation of hourly averaged temperatures can be seen in figure 97. We observe a thermal lag of 6 hours across all the seasons between the exterior and interior surfaces of the wall. The avg. exterior surface of the east wall experiences a maximum of 28.3, 36.3, and 30.9 degrees for January, June, and October. The avg. internal surface temperatures remain moderated under 26, 31, and 28.5 degrees respectively and undergo a fluctuation of 1-1.5 degrees. During the hottest hours of the day for the east wall, there was a temperature gradient of 4, 5, and 3 degrees for the respective months.

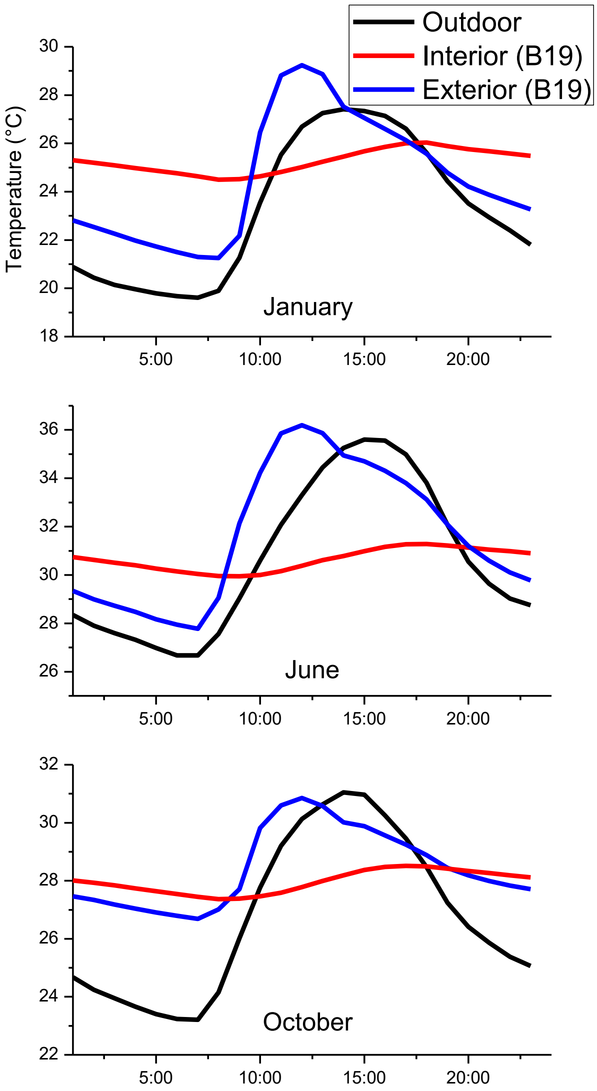


Figure 97 Variation of hourly averaged surface temperatures across the East wall for three months/seasons, 2014

4.3.3 Light Intensity

Buildings in the hot and humid climates are typically designed to keep the summer solar radiation away, and allow the sun in the colder months. Figure 98 shows the hourly averaged lux values for the second floor bedroom for January, June, and October. It can be seen that the lux levels are the lowest during the hottest month of June, and distinctly higher in the coldest month of January. The maximum lux level for respective months is 832, 428, and 984 lux respectively.

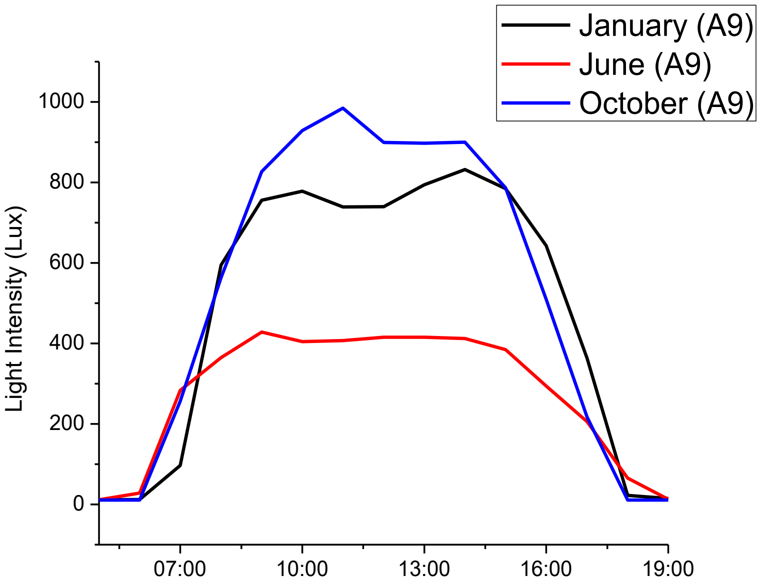


Figure 98 Variation of hourly averaged lux levels on the second floor bedroom - across the seasons/months

4.4 INTACH

4.4.1 Ventilation

Ventilation is the key to indoor thermal comfort – adequate air changes per hours, uniform stratification of air and the position of the neutral layer, all play a major role in reducing the energy costs and making the building more sustainable. The INTACH office includes a naturally ventilated courtyard and a mixed mode ventilated office.

Figure 99 shows the variation of temperature and humidity across two positions in the courtyard and the office for the months of January, June, and October to account for winter, summer, and monsoon respectively. For the three months, the outdoor temperature ranged between 19.5-27.5, 26.5-35, and 23-31 degrees respectively. The indoor temperatures across both the positions of the courtyard remained between 24.5-26.5 degrees for the winter, 31-33 degrees for the summer, and 28-30 degrees for the monsoon. However, the temperature profile of the mixed-mode office was found to be almost constant throughout a particular season without much diurnal variation. The temperature remained between 27.3-27.8, 29.9.-30.9, and 29.5-30 degrees for the three respective seasons.

The relative humidity profiles of the three months were the inverse of the temperature profiles, with outdoor humidity levels of 60-95%, 43-75%, and 55-90% for the respective order of months. Higher temperatures result in lower humidity due to evaporation – thus, the humidity for June was the lowest, while low temperatures and monsoon resulted in the high humidity levels for the months of January and October. For the courtyard, the indoor humidity levels for the respective months lied in the range of 67.7-73.4%, 55.5-65.6%, and 66.5-71.3% for the respective months. Similar to the temperature, the humidity levels of the office did not vary much and remained in the ranges of 65-68.5%, 51.3-63.6%, and 62.5-66.9% for the respective months.

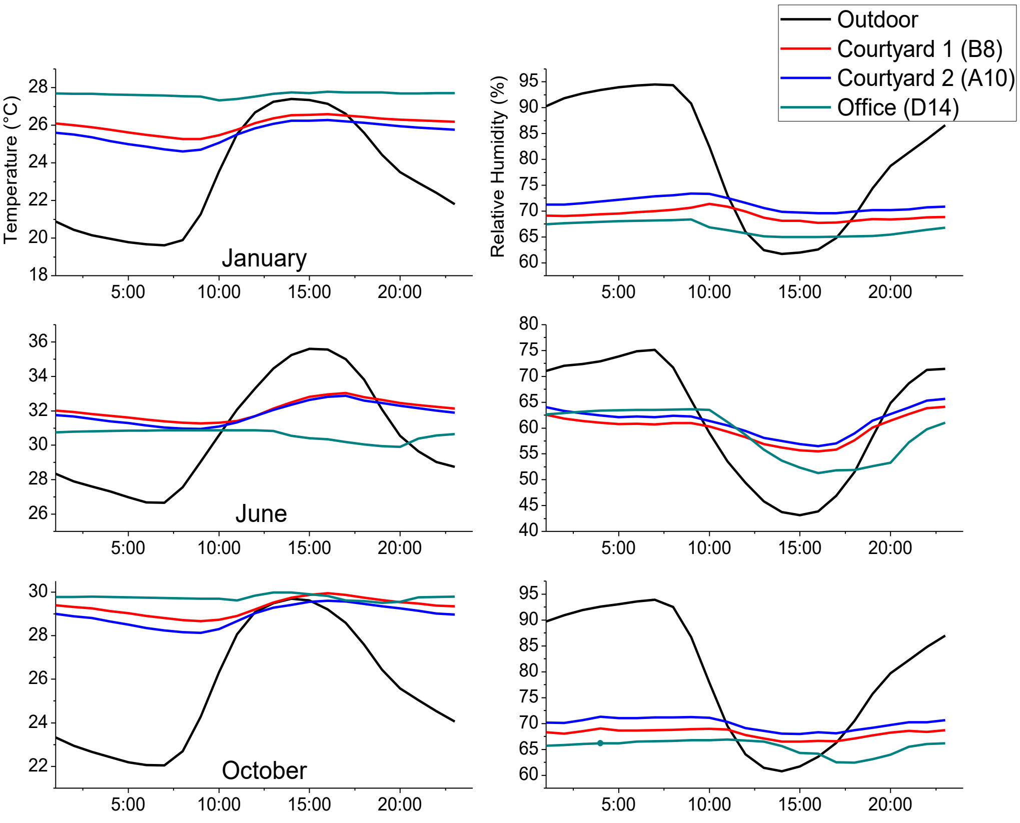


Figure 99 Variation of hourly averaged temperature and humidity across three months/seasons for the two points in courtyard and the office, 2014

In order to compare the indoor air temperatures across the two zones (courtyard and office), the instantaneous temperature data points were compared against the 90% IMAC (Indian Model for Adaptive Comfort) temperature limits for naturally ventilated buildings – for the courtyard and the 90% IMAC limits for mixed mode buildings – for the case of the office, as shown in figure 100. The '90%' indicates that at least 90% of the occupants were thermally comfortable. The indoor temperatures across the courtyard remained moderated in the comfortable limit for the cool months of November-February. However, the upper comfort limit was breached almost constantly throughout the remaining months. The office did not experience a prominent diurnal temperature variation thus remained warmer than the courtyard throughout the year except for some isolated instances of December and early mornings in the summers.

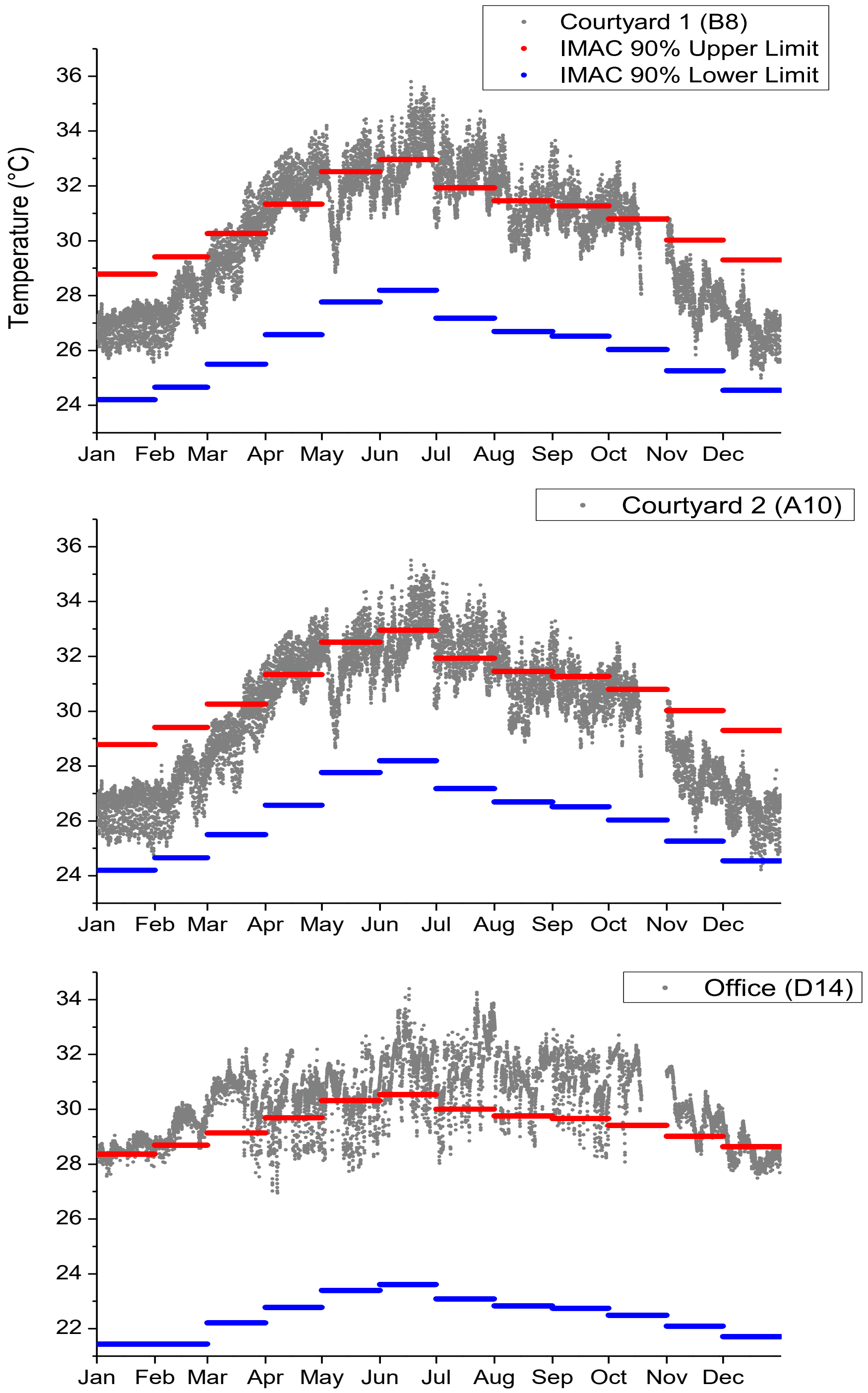


Figure 100 Variation of instantaneous indoor air temperatures for two positions in the corridor, and the office, against the IMAC 90% comfort limits for naturally ventilated buildings (for the courtyard) and mixed mode buildings (for the office) - year 2014

4.4.2 Thermal Mass

Thermal mass can be explained as the physical property of the building fabric which allows it to store the heat in itself. The higher the thermal mass, the more time it will take for the heat to reach from the outdoors to the indoors - this difference in time is called as ‘time lag’. For our case, in hot and humid climate, a high time lag was preferable, as it shielded the indoors from the extreme noon sun and gradually dissipated the heat by the evening, when it was comparatively cooler through the natural ventilation.

Figure 101 shows the seasonal variation of hourly averaged surface temperatures of the external rooftop and indoor ceiling. For winter, summer and monsoon, the exterior terracotta surface heated up to 41.5, 49.5, and 41.7 respectively, while the indoor ceiling surface temperature remained constantly moderated with the highest of 23.5, 29.5, and 26.5 degrees - the thermal gradient at the hottest time of the day was 15, 16.9 and 11.5 degrees respectively. The indoor ceiling remains cooler than the external surface during the hottest hours of the day and there exists a thermal time lag of around 8 hours throughout the year.

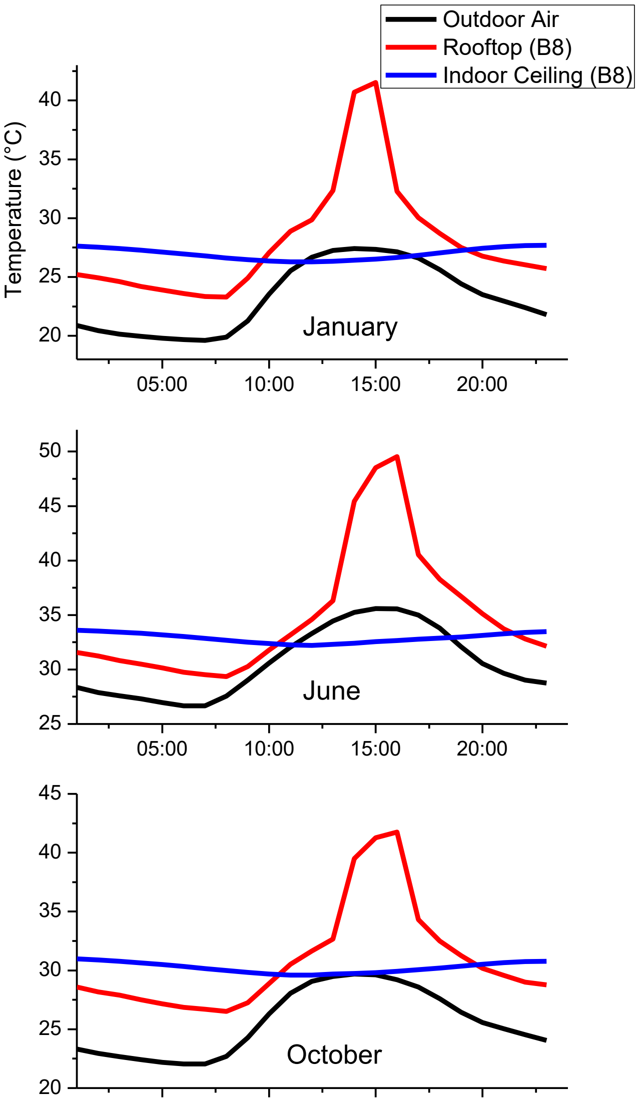


Figure 101 Variation of hourly averaged rooftop surface temperatures for three seasons, 2014

4.4.3 Light Intensity

Figure 102 shows the hourly averaged indoor lux levels for January, June, and October. The lux levels indicate the amount of incident solar radiation for visual as well as thermal comfort. The figure indicates that the lux levels were maximum during the month of June (summer), and lowest during the month of October (monsoon). With the lower limits at 11.4 lux, the upper limits for the respective months were 89.3, 555.6, and 73.8 lux. The ingress of the summer sun would have caused excessive heating of the indoors and risen the temperature above the comfort limit, as indicated by the IMAC plots in the previous section.

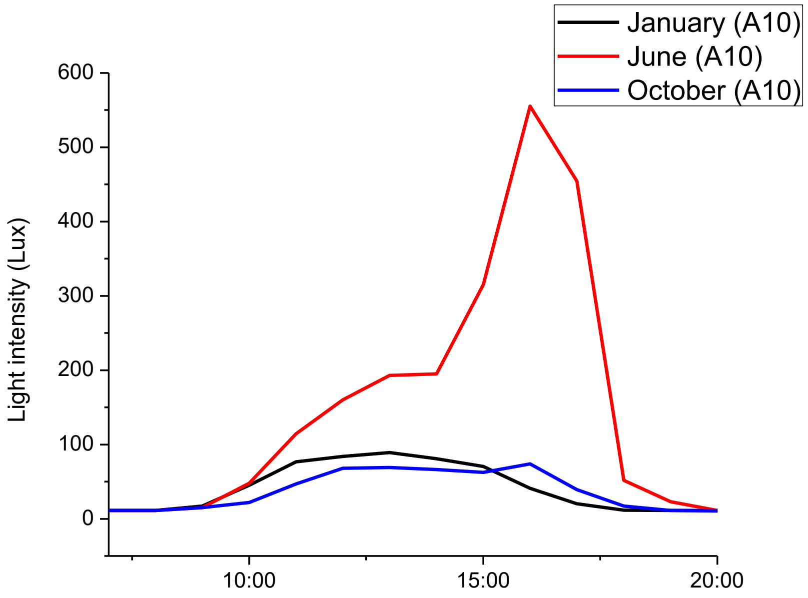


Figure 102 Variation of hourly averaged indoor lux levels for three months/seasons, 2014

4.5 BLESSING HOUSE

4.5.1 Ventilation

Ventilation is the key to indoor thermal comfort – adequate air changes per hours, uniform stratification of air and the position of the neutral layer, all play a major role in reducing the energy costs and making the building more sustainable. The Blessing House has well placed fenestrations and verandas to facilitate ventilation, and the same can be observed in the following discussions.

Figure 103 presents the hourly averaged temperature and relative humidity of the building zones for the months of January, June, and October for the respective seasons of winter, summer, and monsoon. The temperature across all the zones is sufficiently moderated and remains in the range of 22-25, 28-30.5, and 27-29.5 degrees. The Veranda acts as a bridge between the outdoors and the indoors – therefore experiences a temperature closer to the atmosphere, while out of rest of the rooms, Room 2 was found to be the warmest and the dining room the coolest during the hottest hours of the day. The relative humidity is inversely proportional to the temperature of the zone – high temperature leads to the evaporation of water vapour and decreases the moisture content. The humidity of the internal zones varies between 87-75%, 75-65%, and 78-68% for the respective months. Humidity of the veranda, similar to the temperature, is closest to the atmosphere. The Dining room is the most humid, while Room 2 is the least across all the seasons.

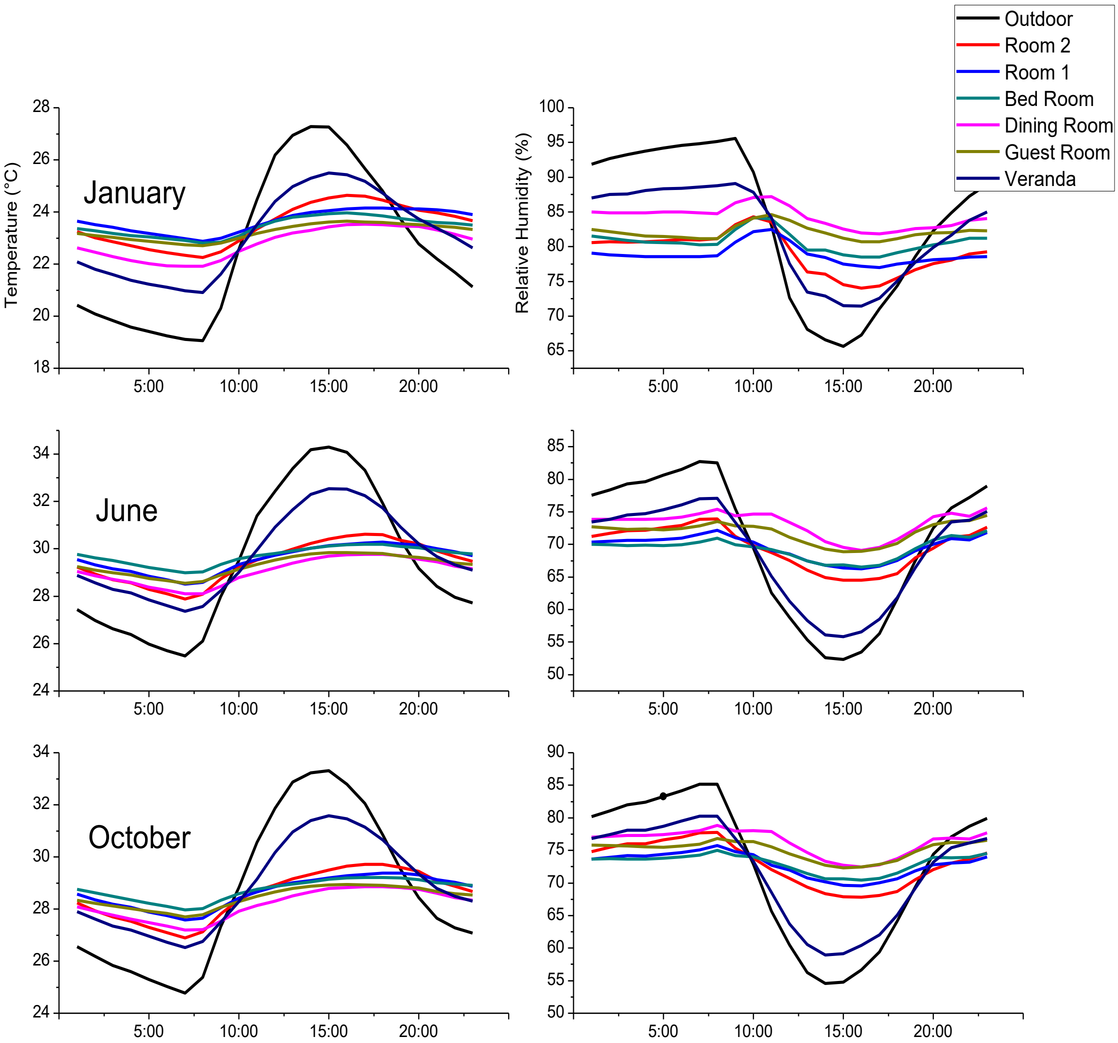


Figure 103 Seasonal variation of hourly averaged temperature and relative humidity across building zones

In order to understand the annual variation of temperature across various zones of the structure, the instantaneous air temperatures across first floor (Rooms 1 and 2) and the ground floor (Guest room, Dining room) are plotted against the 90% IMAC (India Model for Adaptive Comfort) temperature limits for thermal comfort of naturally ventilated buildings in Figure 104. The ‘90%’ implies that at least 90% of the occupants in the building zone were thermally comfortable. As can be seen, the building did not breach the upper comfort limit throughout the year – which is significant for any building lying in the ‘Hot and Humid’ climatic zone. However, the indoor air temperatures did go below the lower IMAC limit, mostly during the months of December to March. The ground floor dining room was the most uncomfortable zone with most of the data points lying below the comfortable temperature, while Room 1 on the first floor performed marginally better than the others. However, most of the low temperatures were experienced during the early hours (0:00 – 7:00) while the occupants were sleeping. Usage of an ordinary blanket could have accommodated for this lower limit breach.

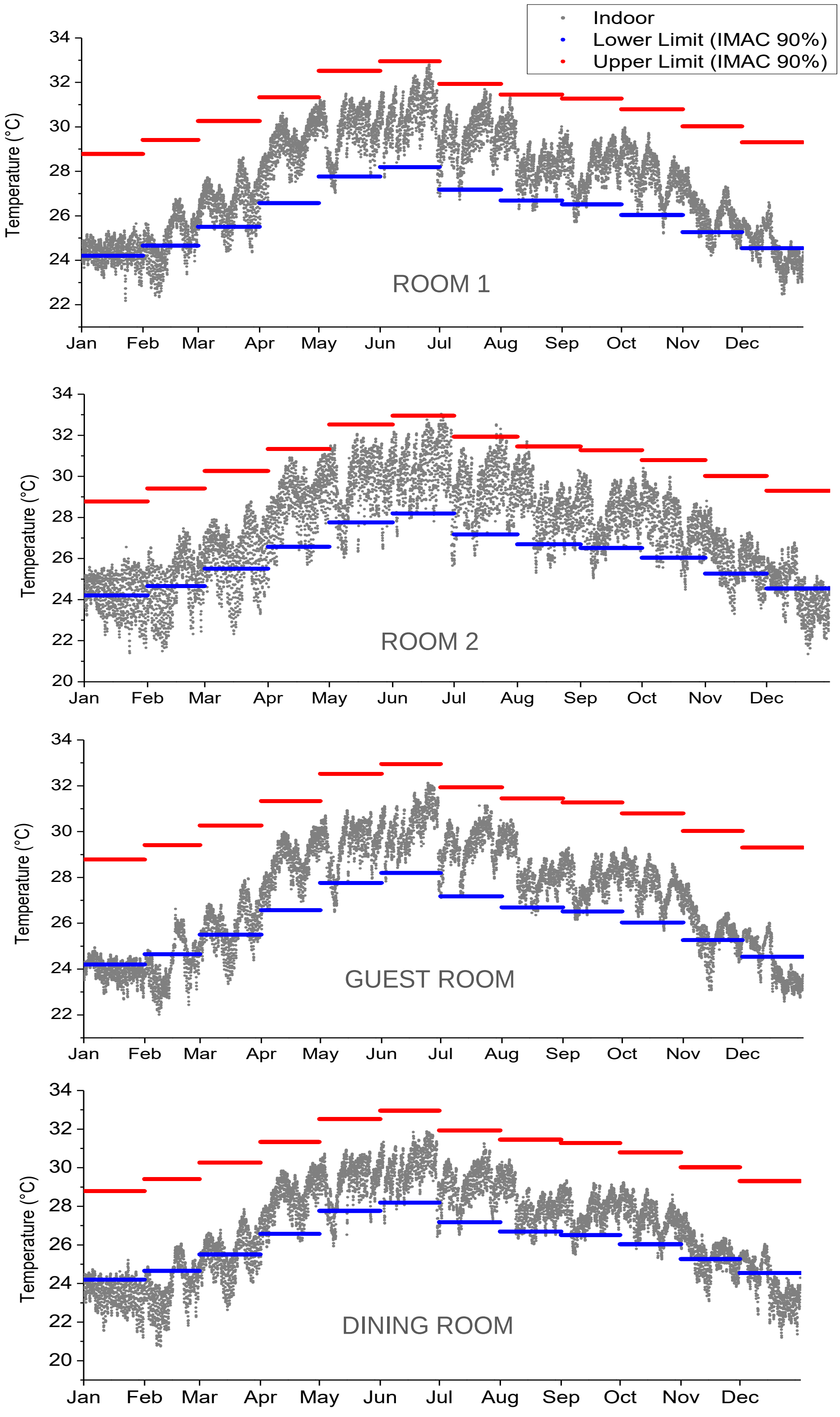


Figure 104 Instantaneous Temp. across building zones, in comparison to the 90% IMAC comfort limits for Naturally Ventilated Buildings

One of the reasons for the indoor temperature not breaching the upper limit was the employment of 'night flushing'. The windows were opened by the occupants when the outdoor temperature was lower than the indoor temperature at a yearly average of 19:19 hours. The warm indoor air rushed out from the windows to be displaced by the cool atmospheric air. Figure 105 shows the instantaneous variation of the outdoor, balcony and the indoor air temperatures with the opening/closing period of the windows. During the hotter hours of the day, the air in the balcony went on to be marginally hotter than the atmospheric air – had the windows been open during this period, the indoors would have been adversely affected by the influx of the hot balcony air. Whereas in the evenings, as the temperatures dropped, the balcony temperature moderated the indoors with the outdoors – air from the outdoors, through the balcony, cooled the indoors. This is why the balcony temperature was closer to the outdoor temperature during the hotter hours, and to the indoor temperature during the cooler hours of the day, resulting in an efficient flushing out of the warm air during the evenings.

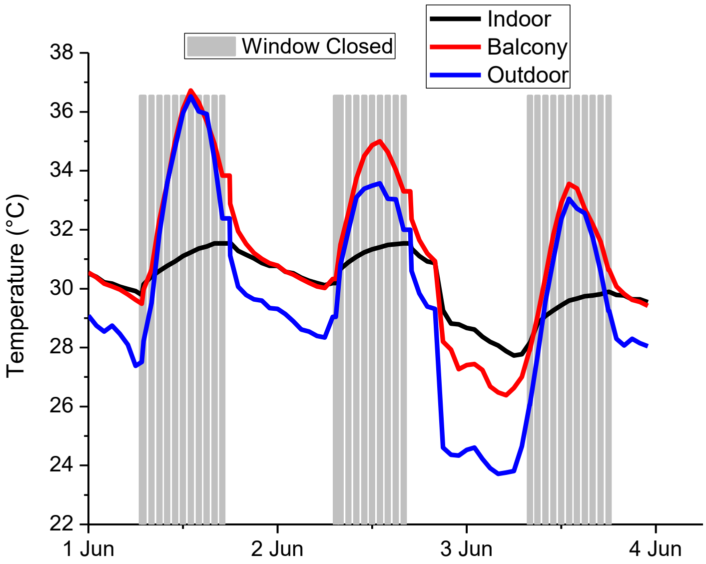


Figure 105 Impact of opening/closing of windows on the indoor temperatures

4.5.2 Thermal Mass

Thermal mass can be explained as the physical property of the building fabric which allows it to store the heat in itself. The higher the thermal mass, the more time it will take for the heat to reach from the outdoors to the indoors - this difference in time is called as ‘time lag’. For our case, in hot and humid climate, a high time lag was preferable, as it shielded the indoors from the extreme noon sun and gradually dissipated the heat by the evening, when it was comparatively cooler through the natural ventilation.

Figures 106 and 107 show the variation of outdoor and indoor surfaces of the mezzanine on an hourly averaged basis for June and annual basis for 2014. For the first figure, the mezzanine wall, made up of compressed earth and Aerocon blocks was able to shield and moderate the indoors from exterior surface temperatures of 42 degrees. The indoors were constantly moderated between 30-32 degrees throughout the day and experienced a time lag of 8 and 9 hours between the peak values of the exterior surface and the outdoor air. The exterior surface had a time lag of about 1 hour in comparison to the outdoor air. As per the annual thermal profile, the exterior temperature peaks till 49 degrees during the summer months but the internal surface temperature is well maintained in the range of 25-35 degrees throughout the year.

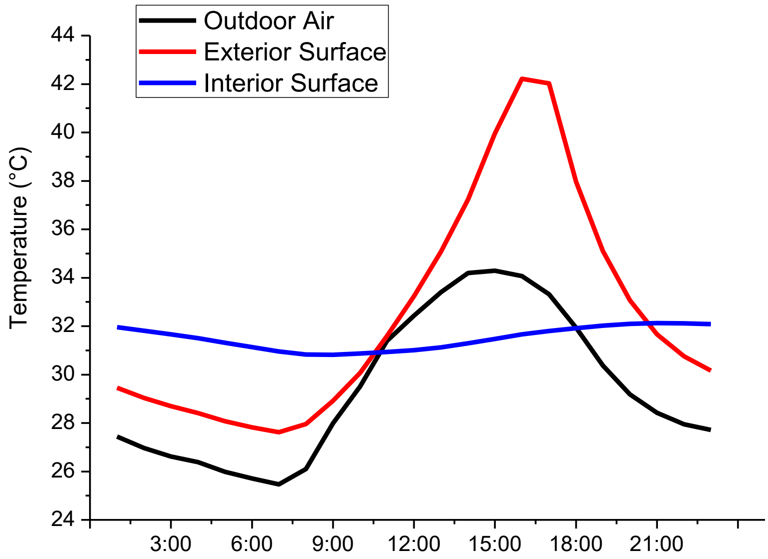


Figure 106 Variation of hourly averaged surface temperature for the mezzanine, June 2014

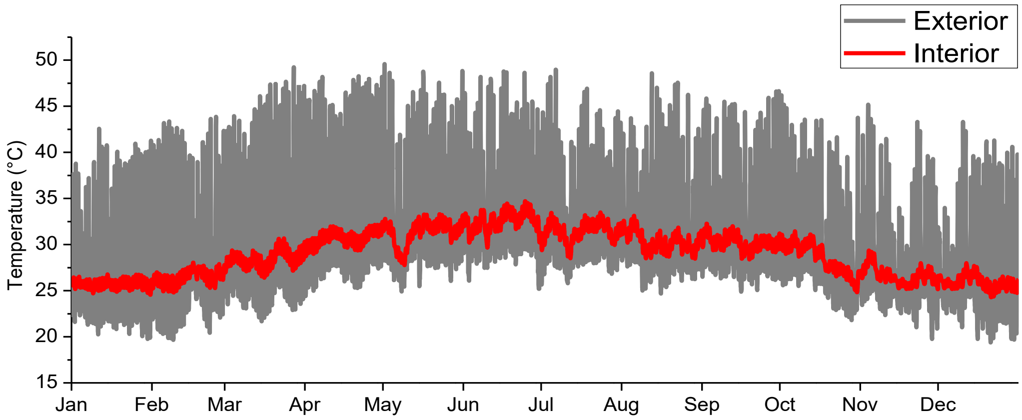


Figure 107 Annual variation of instantaneous surface temperatures for the mezzanine, 2014

The insulated terracotta roof with a combination of white reflective tiles and Aerocon blocks, acts as an efficient moderator for the ceiling. Figures 108 and 109 show the variation of hourly averaged surface temperatures for the terracotta rooftop and the indoor ceiling surface for the hottest month of June and the instantaneous temperatures for the year 2014 respectively. For the monthly average of June, the roof offers a thermal gradient of 14 degrees and time lag of 6 hours between the exterior and interior ceiling. There is no time lag between the exterior surface temperatures and the outdoor air temperatures. Due to the insulation of the roof, the indoor ceiling surface temperature is moderated between 29-31 degrees. Interestingly, the ceiling surface reaches its maxima at 21:00 hours due to the high thermal mass of the terracotta assembly. For the annual profile, the rooftop surface temperatures can be seen around 50 degrees for the hot months of June, while the internal surface remains under 33 degrees throughout the year. This explains the thermal efficacy of the insulated roof.

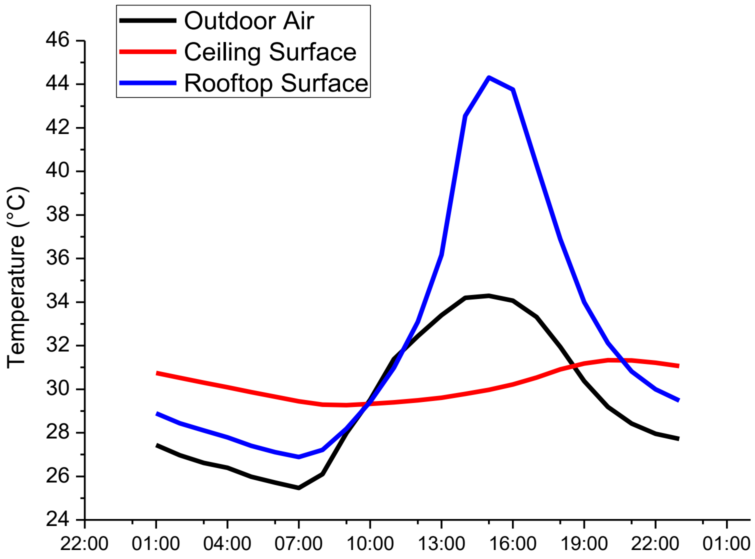


Figure 108 Variation of hourly averaged surface temperature across rooftop, June 2014

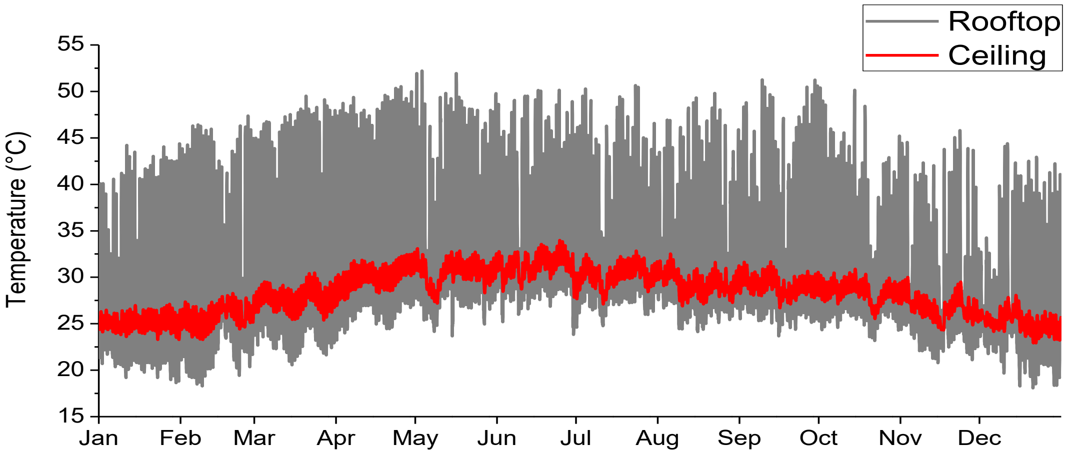


Figure 109 Annual variation of instantaneous surface temperatures across rooftop, 2014

4.5.3 Light Intensity and Shading

The Blessing house incorporated the usage of double paned glass windows for most of its rooms, followed by a veranda or balcony, linking the indoor and outdoor spaces. The temperature difference between these spaces and the indoor spaces can be seen in Figure 110. It compares the hourly averaged values for the month of June, for the ground floor (Veranda, Dining Room) and the first floor (Veranda, Bedroom). As reflected in the above discussions, the ground floor was found to be cooler than the first floor by about 1 degree due to the thermal mass of the entire first floor above it. The verandas of both the ground and the first floors are in vicinity to the atmosphere with minimal shading and thermal barriers, thus experience less moderated temperatures. For the ground floor, the veranda is hotter than the indoors by 3 degrees, which is similar to the thermal gradient of the first floor. The time lag between the outdoors and the veranda is less than 1 hour, while for lag between outdoors and the indoors is around 4 hours for both the cases.

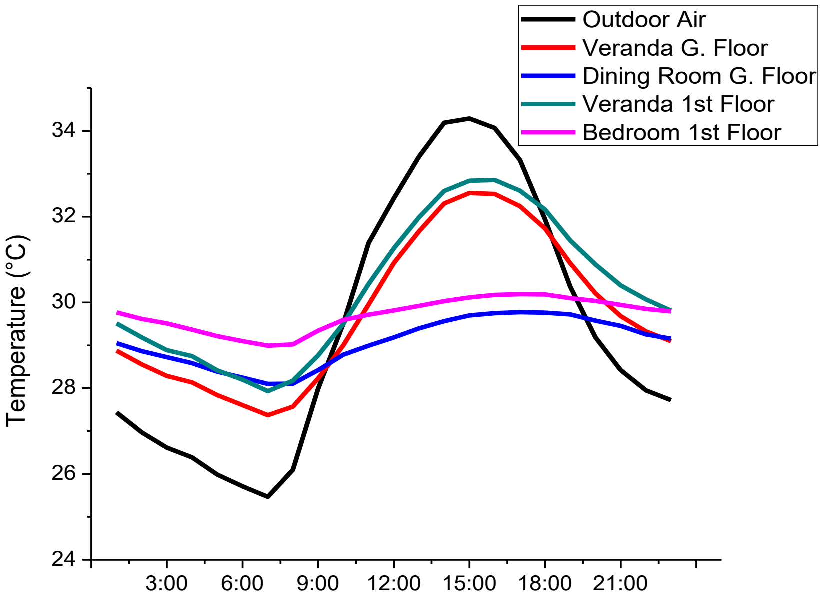


Figure 110 Variation of hourly averaged temperatures across the ground and the first floor - veranda vs indoors

The Blessing House is an adequately lit structure with ample fenestrations, allowing the ingress of air and natural sunlight. Figure 111 shows the variation of hourly averaged light intensity across the Dining room on the ground floor and Room 1 on the first floor. The lux profiles of both the zones are similar, except for the fact that the first floor received the natural sunlight before the ground floor – the low height foliage around the structure could be a contributing cause for this excessive shade. The peak values, however, are almost the same – between 175-180 lux, with the lower limits at around 10 lux.

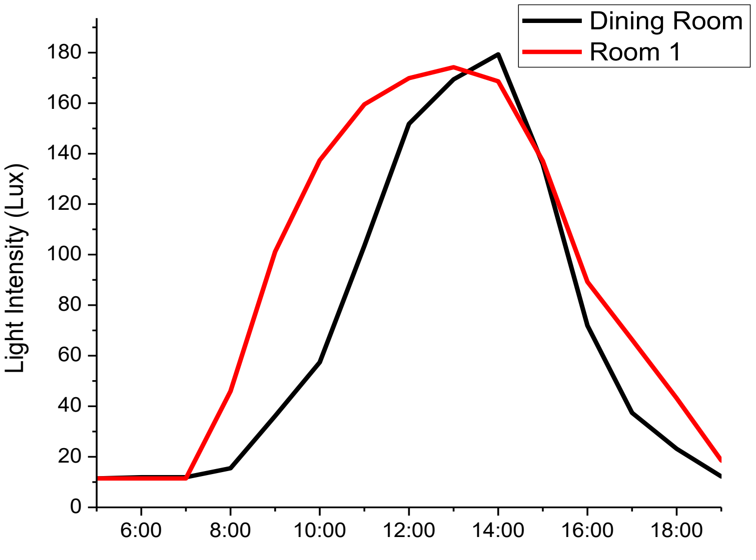


Figure 111 Variation of hourly averaged natural light intensity across the two floors, June 2014

4.5.4 Occupants

In addition to the structural passive design strategies, the role of occupants in maintaining the thermal comfort in the Blessing House was found to be crucial. The occupants controlled the phenomenon of 'night flushing' as explained by Figure 112. To study the varying trends of occupant behaviour, the opening and closing pattern of one of the windows on the first floor has been shown below. Annually averaged window opening and closing times were 8:57 and 19:19 hours, respectively. As can be seen in the figure, the opening and closing times for the window for the three seasons and months (January – Winter, June – Summer, and October – Monsoon) mostly varies around 7:00-9:00 hours and 19:00-21:00 hours respectively. This shows a clear pattern in the closing and closing of the window. This pattern in the occupant behaviour could be due to a working schedule starting between 8:30 – 9:00 AM. When comparing between months, June indicates the most orderly operation of the window as the outdoor temperatures were the highest during the same period. High outdoor temperatures would have forced the occupants to close the windows to curb the ingress of hot air. However, during the cool month of January, this operational pattern is irregular – as the outdoor air does not bear the capacity to heat the indoors (periods: 1-4 Jan, 13-18 Jan, etc. were irregular).

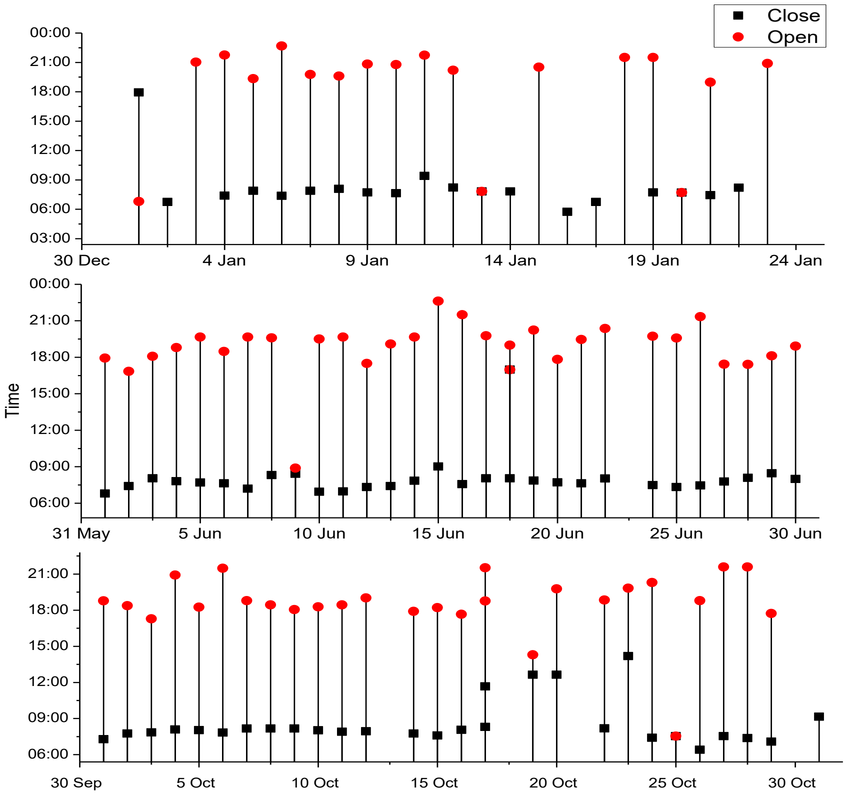


Figure 112 Window opening and closing patterns for the months of January, June, and October

4.6 MUKUDUVIDU

4.6.1 Ventilation

Ventilation is the key to indoor thermal comfort – adequate air changes per hours, uniform stratification of air and the position of the neutral layer, all play a major role in reducing the energy costs and making the building more sustainable. As Mukuduvidu was a naturally ventilated building, it did not have mechanically driven ventilation systems, instead, it used the aforementioned passive design strategies to suffice for the comfort.

Figure 113 shows the variation of temperature and humidity across the domes and the vault for the three months of January, June, and October to account for winter, summer, and monsoon respectively. For the three months, the outdoor temperature ranged between 19.5-27.5, 26.5-35, and 23-31 degrees respectively. The indoor temperatures across both the domes and the vault remained between 23-26 degrees for the winter, 29-33 degrees for the summer, and 26.5-29.5 degrees for the monsoon. The temperature profile of the vault was found to be marginally lower than that of the domes, while dome 1 was the warmest by a small margin. However, for all the cases, the indoor temperature remained lower than the outdoor temperature during the hottest hours of the day and higher than the outdoor temperature during the comparatively cooler hours.

The relative humidity profiles of the three months were the inverse of the temperature profiles, with outdoor humidity levels of 60-95%, 43-75%, and 55-90% for the respective order of months. Higher temperatures result in lower humidity due to evaporation – thus, the humidity for June was the lowest, while low temperatures and monsoon resulted in the high humidity levels for the months of January and October. The indoor humidity levels for the respective months lie in the range of 63-83%, 53-73%, and 65-72%. Due to the lowest temperature profile, the humidity across the vault was the highest for all the seasons, while the two domes performed similar in terms of humidity.

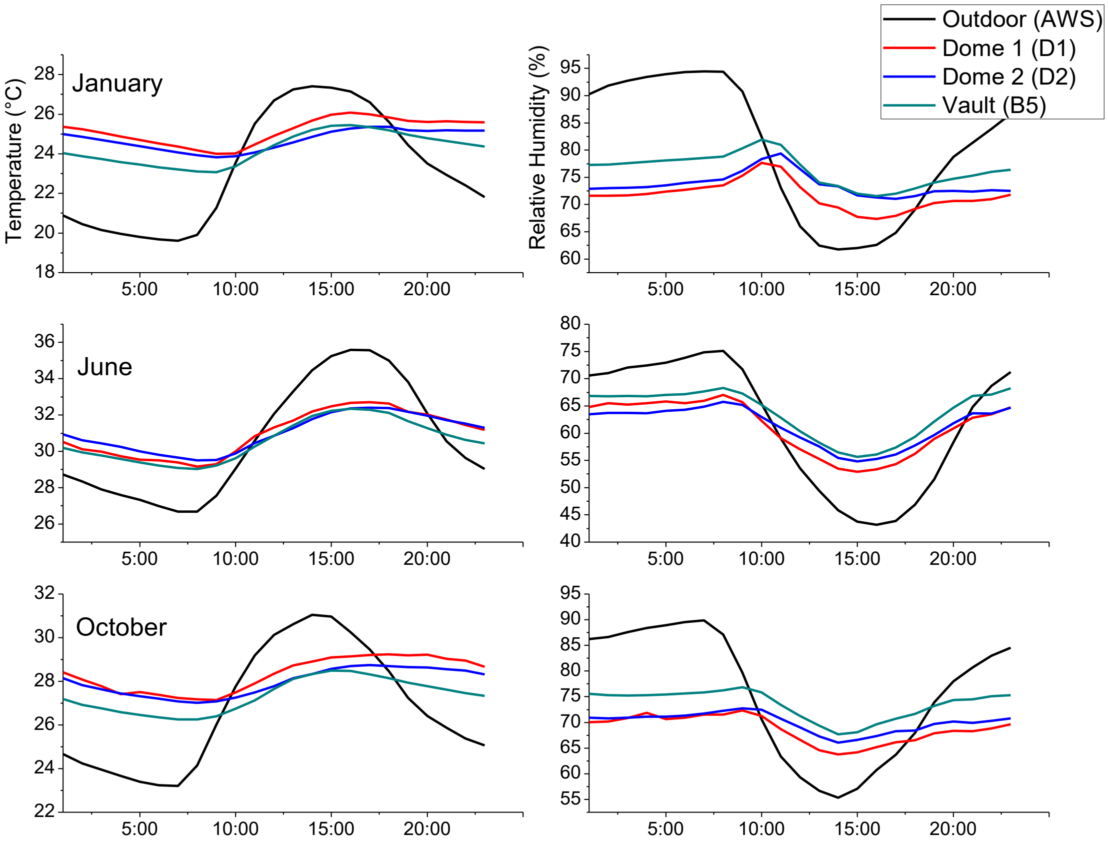


Figure 113 Variation of hourly averaged temperature and humidity across three months/seasons for the domes and vault, 2014

Contrary to the smooth temperature and humidity profiles, the monthly averaged wind velocity profile shows abrupt variation. The indoor wind velocities ranged from 0.20-0.48, 0.28-0.55, and 0.33-0.60 m/s for the three respective months. The wind velocities for June turned out to be the highest, while for October they turned out to be the lowest. For all the months, a general pattern is observed: speeds remain constant till early afternoon, higher temperatures force the air out in the afternoon and the wind speed reduces till the evening, as the night progresses, the air circulation is re-established and the velocities rise.

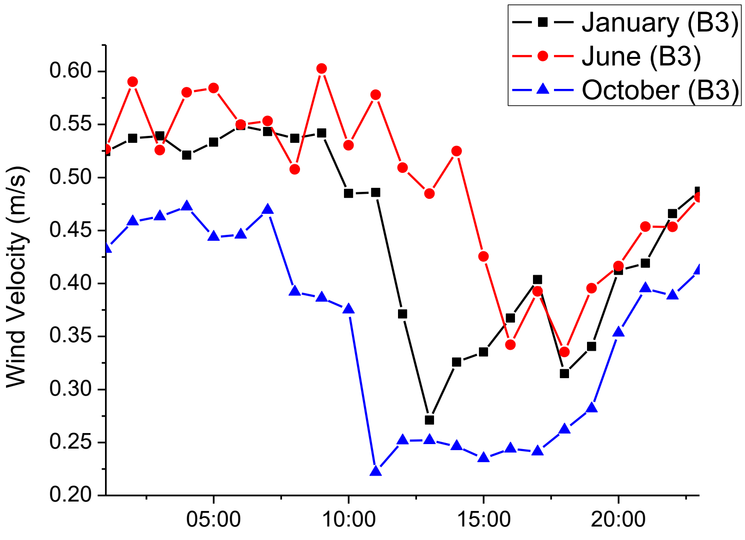


Figure 114 Variation of hourly averaged wind speeds across dome 2 for three seasons/months, 2014

In order to compare the indoor air temperatures across the two domes and the vault, the instantaneous temperature data points were compared against the 90% IMAC (Indian Model for Adaptive Comfort) temperature limits for naturally ventilated buildings, as shown in Figure 115. The '90%' indicates that at least 90% of the occupants were thermally comfortable. The upper limit is breached across all the three building elements during the hottest months. However, the vault temperatures fell in the comfortable zone for major portions of March and April. The lower limit was breached at times during the coldest months of November to February – most prominently for the vault.

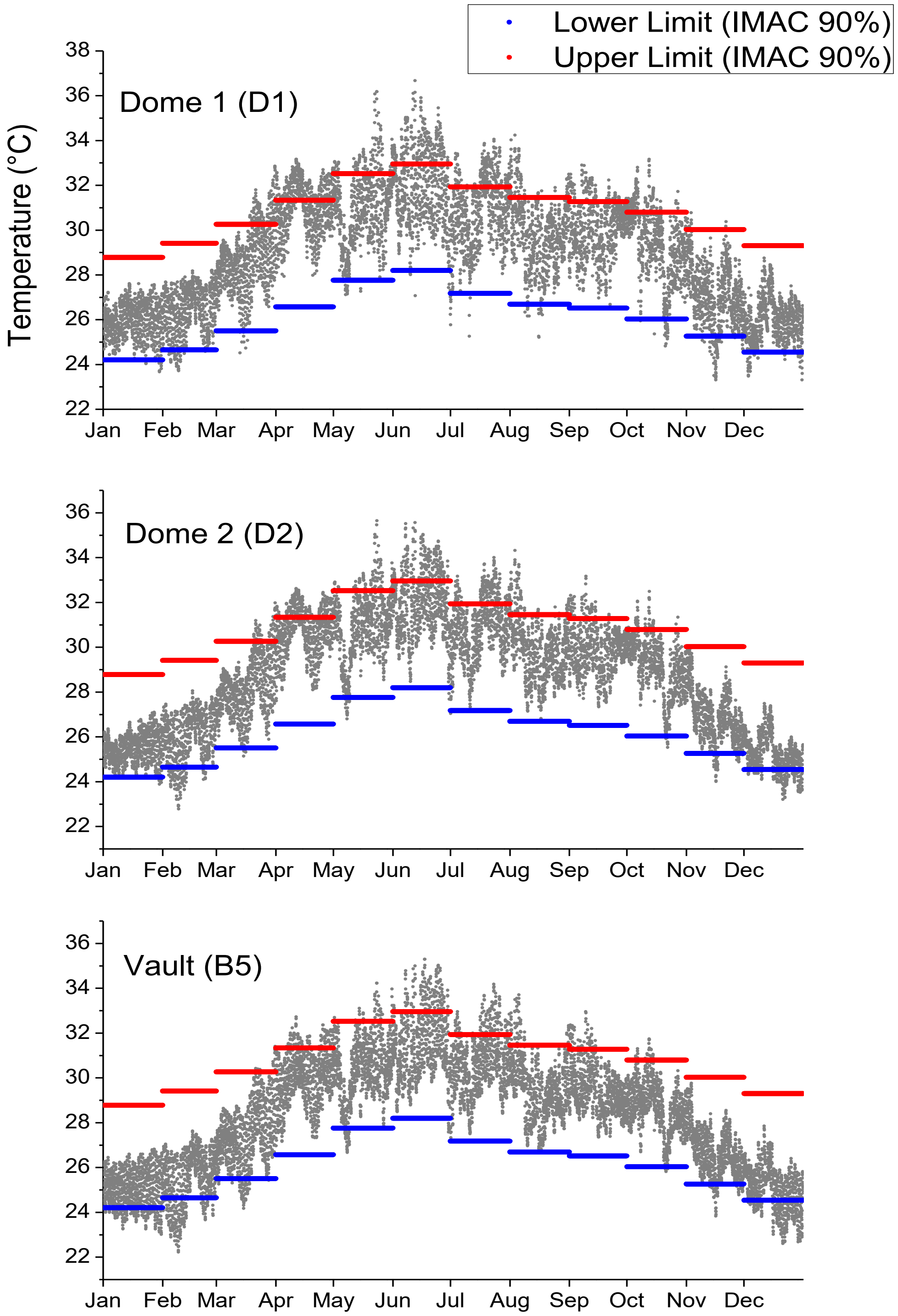


Figure 115 Variation of instantaneous indoor air temperatures of the domes and the vault against the IMAC 90% comfort limits, for the year 2014

For the case of the domes, there is a variation in air temperature with varying height – characterised as stratification of air. Warm air is less dense and consequently tries to move above the heavier parcels of cooler air – this creates a distinct hot-cold separation of air inside any closed space. Figure 116 shows the temperature of layers of air at different heights in the dome 1. The upward movement of hot air is observed as there is a gradient of about 1.25 degrees between the top and bottom layers. It must be noted that the air temperatures were measured along the central axis of the dome and are not be confused with surface temperatures. However, a similar trend is observed in the surface temperatures too as they are the contributing cause to stratification.

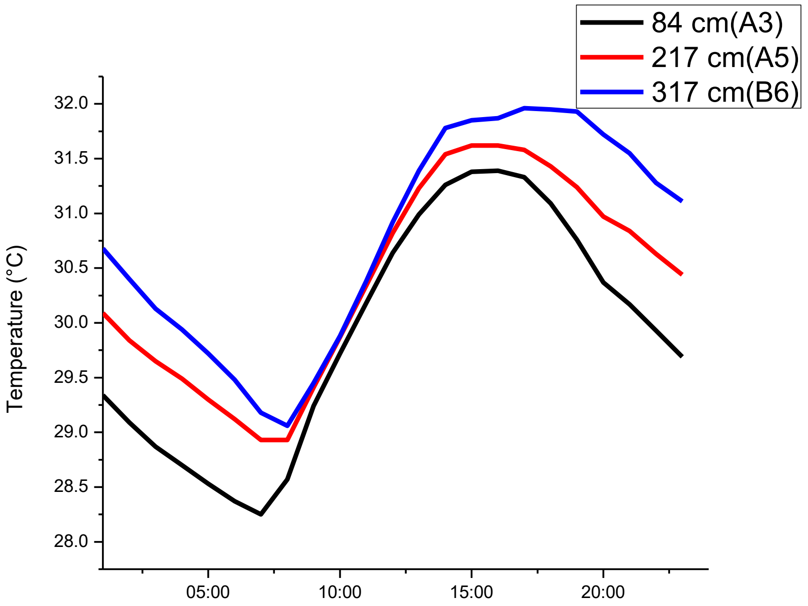


Figure 116 Variation of hourly averaged air temperature at different heights for Dome 1, June 2015

4.6.2 Thermal Mass

Thermal mass can be explained as the physical property of the building fabric which allows it to store the heat in itself. The higher the thermal mass, the more time it will take for the heat to reach from the outdoors to the indoors - this difference in time is called as ‘time lag’. For our case, in hot and humid climate, a high time lag was preferable, as it shielded the indoors from the extreme noon sun and gradually dissipated the heat by the evening, when it was comparatively cooler through the natural ventilation.

Figure 117 shows the distribution of surface temperature at different heights for the two domes, hourly averaged for the month of June. The dome 1 includes an air vent with a glass top, while the dome 2 is capped with a wind driven mechanical extractor. A clear distinction of surface temperatures could be observed for varying heights for both the cases, with a thermal time lag of about 5 hours. The surface temperature at 360 cm was more than that of 217 cm by over 1.5 and 1 degrees for domes 1 and 2 respectively. The temperature at 84 cm constantly remained between 31-32 degrees for the first dome; there was no sensor placed at 84 cm for the second dome. For both the domes, it can be observed that the exterior temperatures were further facilitating this upward movement of warm air – exterior temperatures for 360 cm were higher by over 7 and 4 degrees for domes 1 and 2 respectively. The higher exterior temperatures for the second dome can be attributed to the fact that dome 1 was positioned closer to the foliage and experienced partial shade of the trees, which the second dome didn’t.

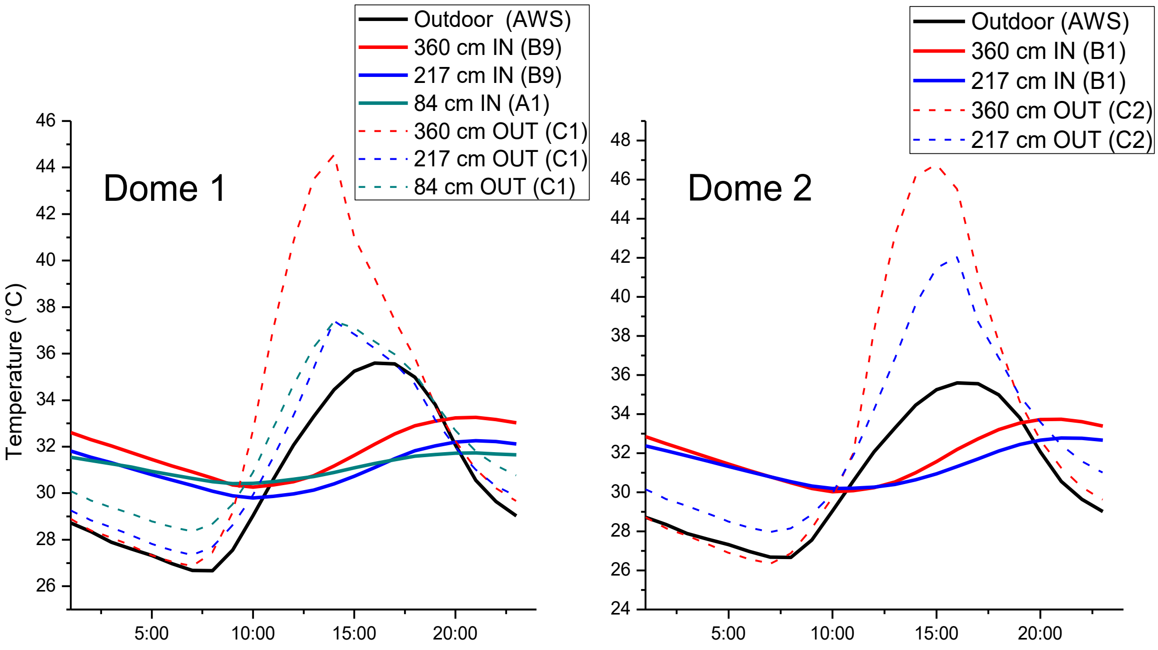


Figure 117 Variation of hourly averaged surface temperatures for the two domes at different heights – accounting for the stratification, June 2014

For the case of vault, the average exterior roof surface temperature reaches as high as 42 degrees for the month of June, as indicated by figure 118. The interior vault ceiling temperature remains constantly moderated around 31.5 degrees throughout the day. The temperature of the exterior surface is reflected in the ceiling maxima after a lag of 4 hours.

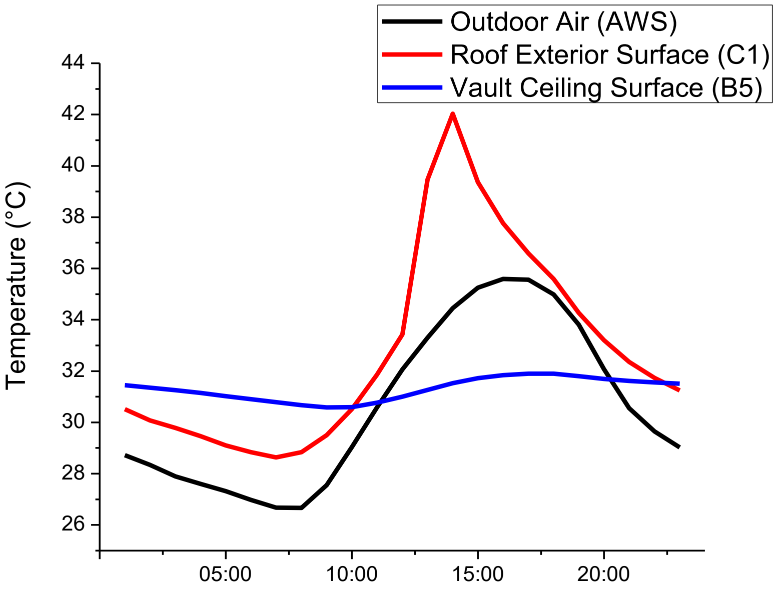


Figure 118 Variation of hourly averaged temperature across the vault, June 2014

The two prominent roofing methods – domes and vaults used in Mukuduvidu performed differently across seasons. Figure 119 shows the instantaneous temperature difference across the domes and the vault for a week of each of the peak seasons (January, June, and October). The temperature difference, $T_{outdoor} - T_{zone}$ mostly remained in the negative quadrant for all the zones, implying that the indoor air temperature was warmer than outdoor temperature. However, for the hottest hours of the day, the indoor temperature was moderated and stopped from reaching extremes, as indicated by the peaks in the positive quadrants. For June, the air temperature across the domes reached went far higher than that of the vaults – indicated by the low troughs in the negative quadrant. This can help us deduce that vaults kept the insides cooler than the two domes.

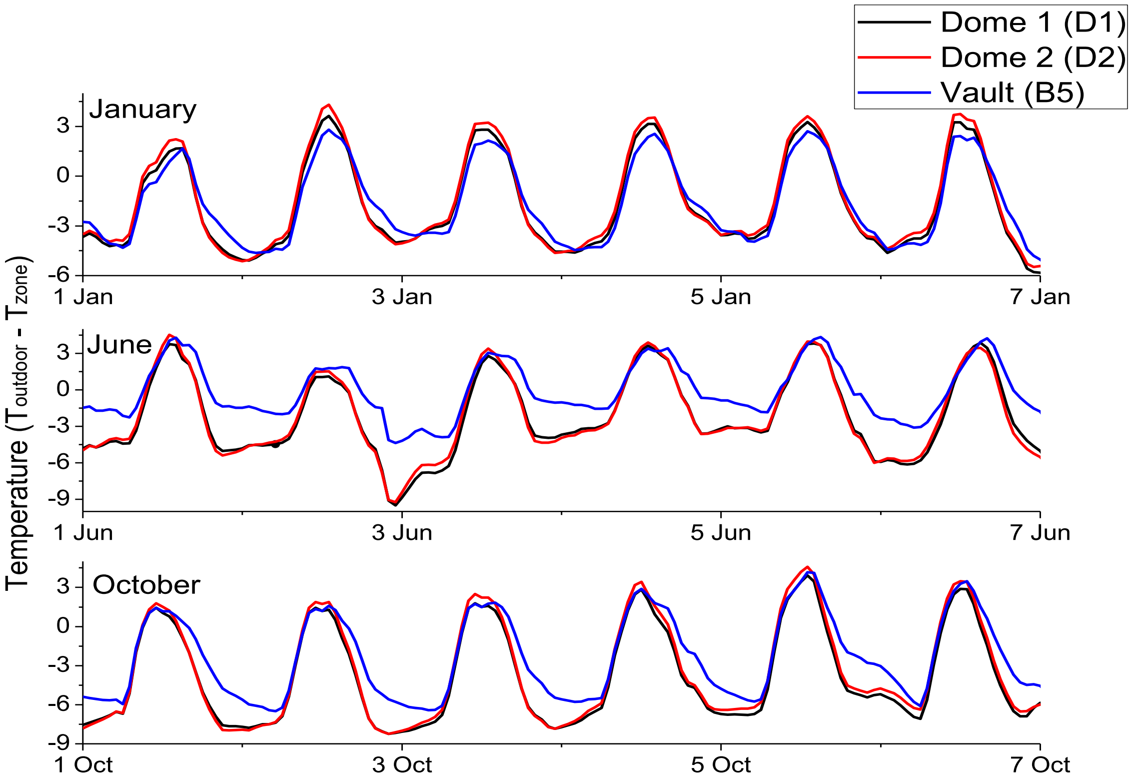


Figure 119 Variation of instantaneous temperature difference across the domes and vault for a week of each season, 2014

4.6.3 Light Intensity

Figure 120 shows the hourly averaged indoor lux levels for January, June, and October. The lux levels indicate the amount of incident solar radiation for visual as well as thermal comfort. Mukuduvidu was designed to keep the sunlight away during the summer and allow the winter sunlight. The figure indicates that the lux levels were maximum during the month of January (winter), and lowest during the month of June (summer). With the lower limits at 11 lux, the upper limits for the respective months were below 325, 220, 270 lux.

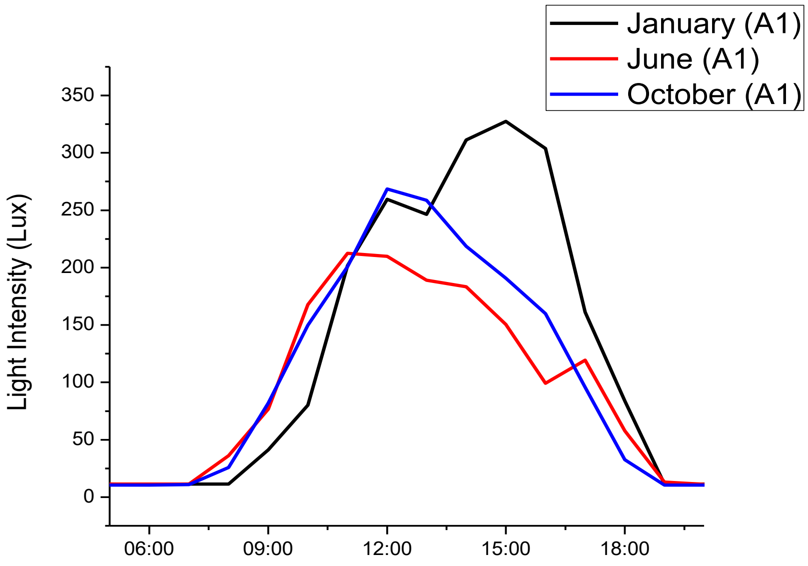


Figure 120 Variation of hourly averaged indoor lux levels for three months/seasons, June 2014

4.7 SOLAR KITCHEN

4.7.1 Stack Ventilation

Ventilation is critical to indoor thermal comfort – adequate air changes per hours, uniform stratification of air and the position of the neutral layer, all play a major role in reducing the energy costs and making the building more sustainable. The solar kitchen was a naturally ventilated building and used passive design methods such as the provision of the solar chimney, to create stack ventilation.

Figure 121 shows the hourly daily average, maximum and minimum outdoor temperature for Auroville from January 2014 to March 2015. The recorded maximum temperature was 40.3°C on May 31, 2014 at 2.30pm, and the recorded minimum temperature was 16.2°C on February 9, 2014 at 5.00am. Since Auroville is a hot and humid location, the study included seasonal variations in temperature based on monsoon, winter and summer seasons. A warm and cool month was identified based on the daily temperature profiles, for further analysis. These periods are highlighted in grey bands. Figure 122 similarly plots the daily average, maximum and minimum relative humidity for Auroville, and Figure 123 plots the annual temperature profile of the solar chimney during the measurement period along with the outdoor temperature.

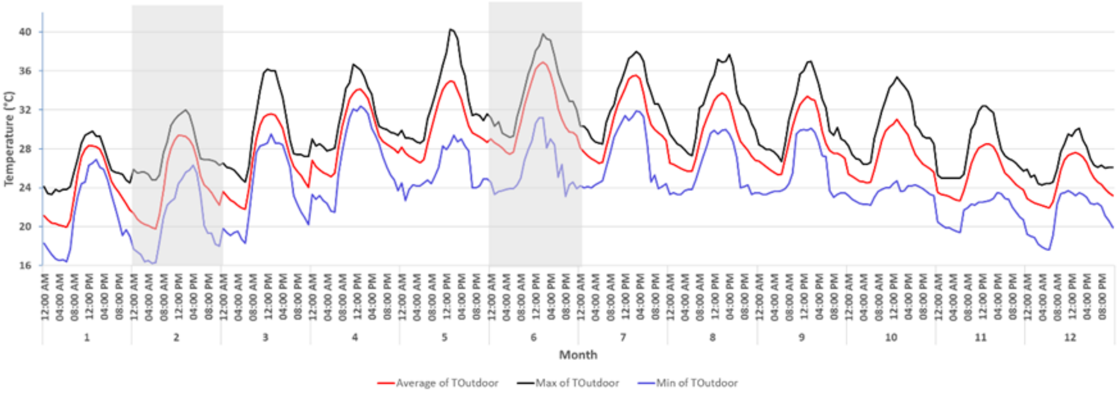


Figure 121 Daily outdoor temperature profiles across the year: Jan 2014 – Mar 2015

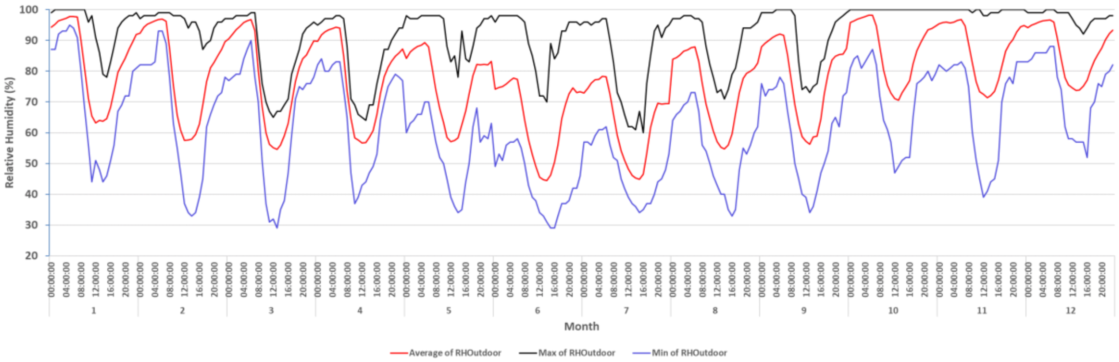


Figure 122 Daily outdoor humidity profiles across the year: Jan 2014 – Mar 2015

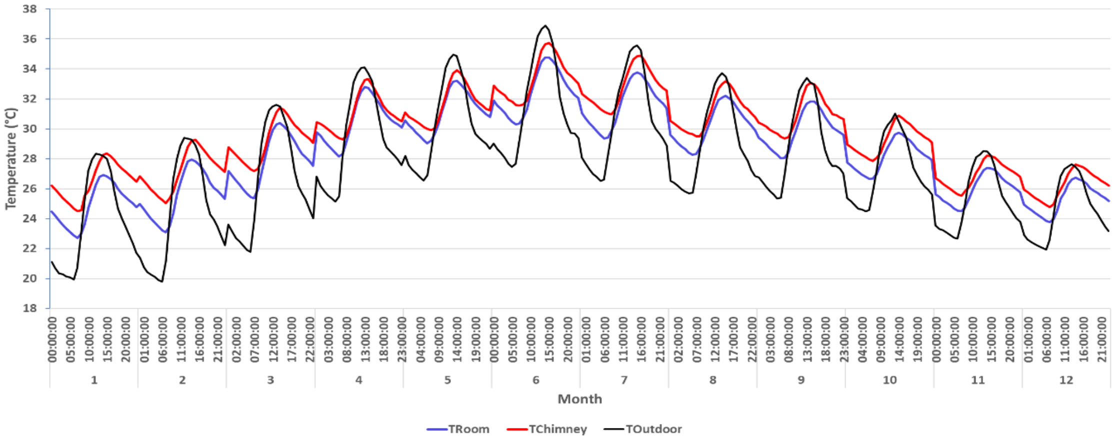


Figure 123 Annual profile of Temperature in Solar Chimney: Jan 2014 – Mar 2015

Figure 124 shows the monthly average, maximum and minimum temperatures of the room, chimney and outdoor based on the seasonal variations for the year. Further analysis has been conducted for the warm and cool months to establish the effectiveness of the chimney for stack ventilation through different seasons.

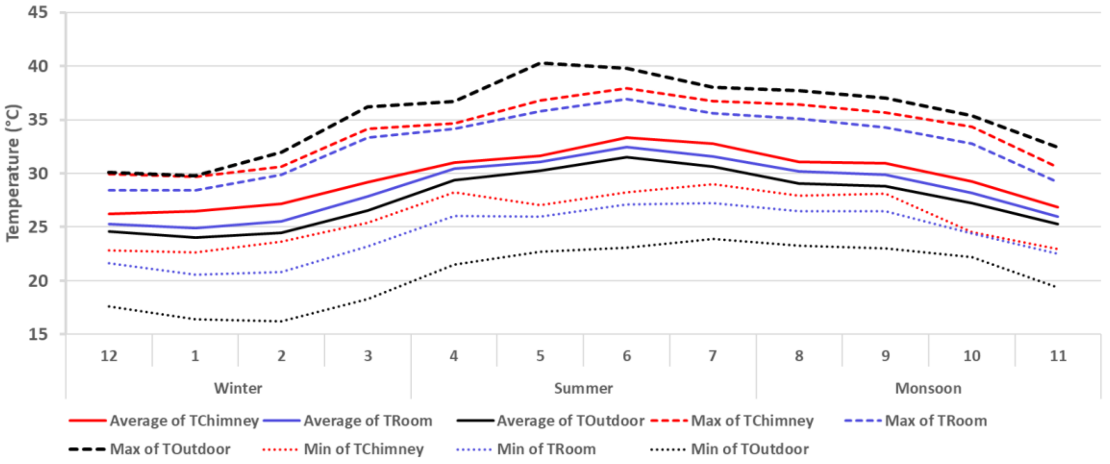


Figure 124 Seasonal profile of Temperatures in Solar Chimney: Jan 2014 – Mar 2015

Figure 125 shows hourly averaged values of air temperature for the warm month of 'June 2014' during the monitoring period for the dining hall and the solar chimney. The peak outdoor temperature occurs at 3pm with a diurnal range of 7-8.4°C. The temperatures in the chimney and room are lower with a variation in the temperature of the chimney from 3.5-4.2°C and the temperature of the room from 3.2–3.9°C. The figure also shows the hourly averaged values of relative humidity for the month of June. The outdoor R.H. varied from 44% to 78% between noon and night respectively. The R.H. curves of the indoors trace the same trend as the outdoors, similar to the temperature. However, unlike temperature, R.H. profiles do not have a time-lag.

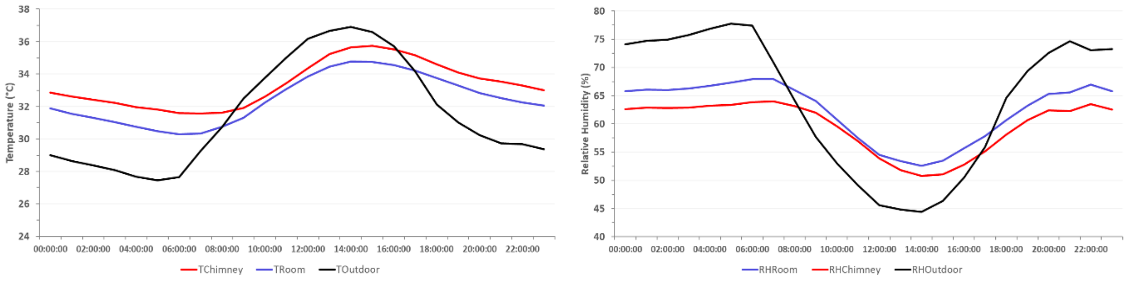


Figure 125 Variation of hourly average temperature and relative humidity for the 'warm month': June 2014

It must also be noted that with the rise in temperature, the humidity reduced – high temperature evaporated the moisture present in the air and dried it. This phenomenon can be observed from the undulating R.H. curve below – the colder hours of the day experienced a higher R.H. level than the warmer hours

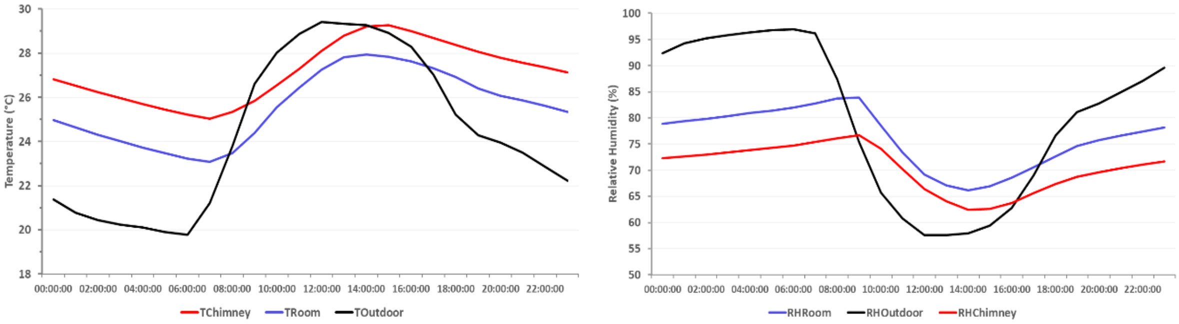


Figure 126 Variation of hourly average temperature and relative humidity for the 'cool month': February 2014

Figure 126 similarly shows the hourly averaged values of air temperature for the cool month of 'February 2014' during the monitoring period for the dining hall and the solar chimney. The lowest outdoor temperature occurs at 6am, and we see a diurnal range of about 7-12.3°C. The figure also shows the hourly averaged values of relative humidity for the month of February. The outdoor R.H. varied from 58% to 96% between noon and the night respectively. Like the case of temperature, R.H. curves of the indoors trace the same trend as the outdoors.

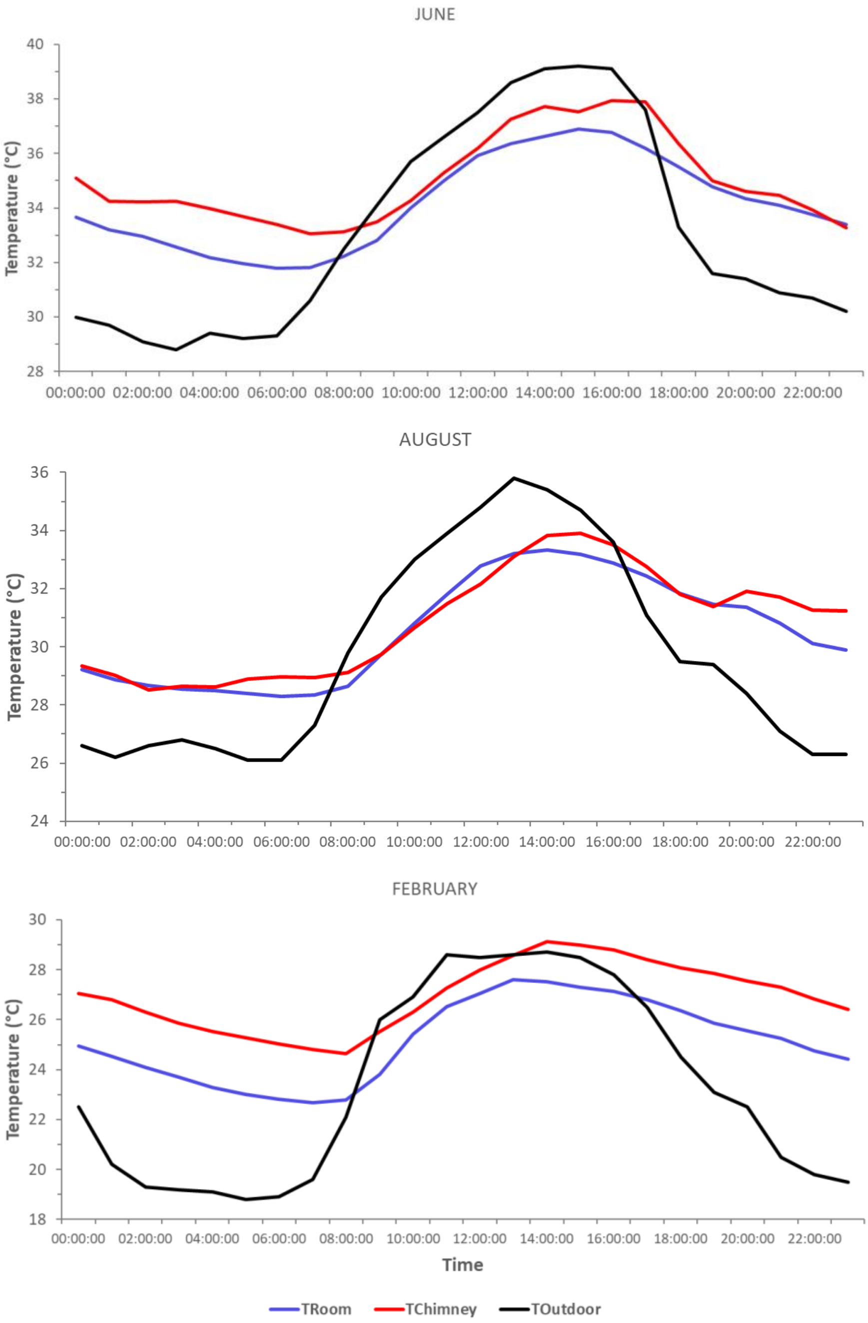


Figure 127 Variation of hourly average temperature for June, August, February 2016

Figure 127 compares the temperature profile for the ‘warmest day’ in June 2014 to the ‘coolest day’ in February and 2014 and the day during the monsoon where we see the least effective performance of the solar chimney. We see a maximum damping of 1.7°C at 5pm in June, with the outdoor peak at 3pm. The temperature profile for the ‘coolest day’ shows a maximum damping of 2.5°C at 9am, with the outdoor peak at 1pm. The temperature during August (monsoon) is inverse with the room temperature being slightly higher than the chimney at in the early part of the day, with the lowest annual damping of -0.6°C at 12pm. This clearly shows the effectiveness of the solar chimney in creating a stack effect for better natural ventilation in winter and summer compared to the monsoon, when humidity is high and there is lesser thermal stratification in the solar chimney. The highest temperature differential in the solar chimney of 3.14°C was achieved on 9 Feb 2014 at 6am and it tallies with the coolest recorded day during the monitored period. The lowest temperature differential was 0.6°C on 14 Aug 2014 at 12pm.

The temperatures in the Solar Kitchen were moderated through the various passive design strategies and the building fabric, however, to ascertain if the naturally ventilated building was comfortable enough for the occupants or not, the IMAC (India Model for Adaptive Comfort) (Manu, Shukla, Rawal, de Dear, & Thomas, 2014) temperature limits for naturally ventilated buildings were referred and compared against the indoor temperatures. Neutral operative temperatures for each set of measurements were calculated and plotted in figure 128 as scatter points. The acceptability limits were calculated from the neutral operative temperatures and mean monthly outdoor air temperatures. For most instances, the temperatures were within the IMAC 80% acceptability limits, the portion indicated in green are the points within the 'comfortable' range.

There are many points outside the IMAC adaptive comfort limits for 80% and 90% acceptability range, especially in the period between March to October. These are the months in the summer and monsoon seasons, where it is critical to achieve indoor temperatures for thermal comfort. The winter seems to be more acceptable with most of the measured temperatures within the comfort band, with some exceedances from November to February in the lower limits of acceptability. The graph clearly shows that both in the summer and winter months the dining hall is likely to get uncomfortable when the upper and lower limits are exceeded. From the earlier analysis we see this is likely to occur from 2pm to 5pm when the dining hall is likely to be occupied and functional.

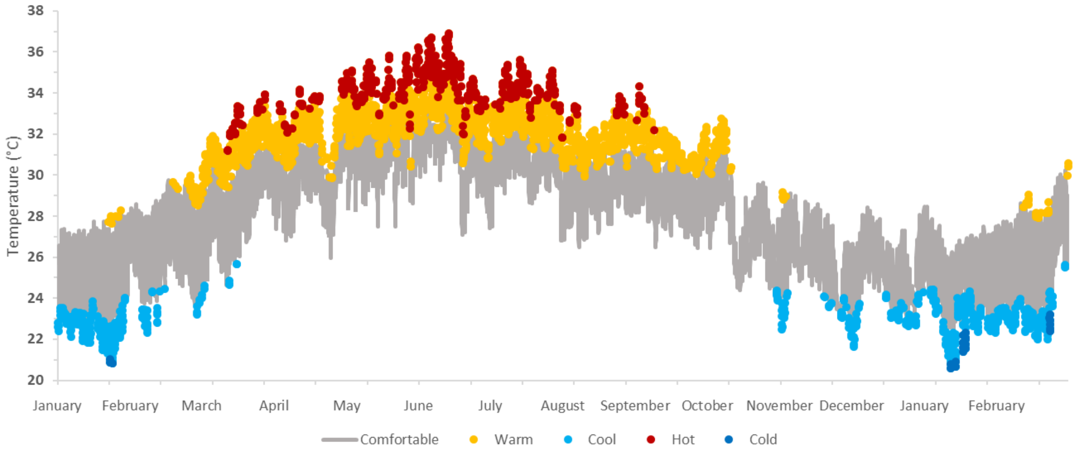


Figure 128 Evaluation of monthly indoor temperatures based on the IMAC adaptive model for the thermal comfort for 90% and 80% acceptability range

Instantaneous measurements were recorded for air and globe temperature and relative humidity in dining room near the chimney at 16 instances during the monitoring period. Figure 129 plots the air and surface temperatures inside the solar chimney. We cannot see much difference between the red and blue lines, the locations for surface temperature measurements on the lower and top part of the chimney where the loggers were placed during the monitoring period. The maximum difference in temperature is only 1.2°C measured in October 2014. The measured third point, which is the highest point reachable (refer to methodology for instantaneous measurements), shows a much higher temperature difference ranging from 9.9 °C from the lower measured point, and 10.4°C from the measured point at the top respectively, in June and Dec 2014. This indicates that the solar chimney design sees a considerable degree of stratification leading to effective stack ventilation. From the chart and the temperature differential, we can see that the solar chimney is more effective during the summer and winter months when it is desirable to have increased ventilation; with lower effectiveness in the monsoon period.

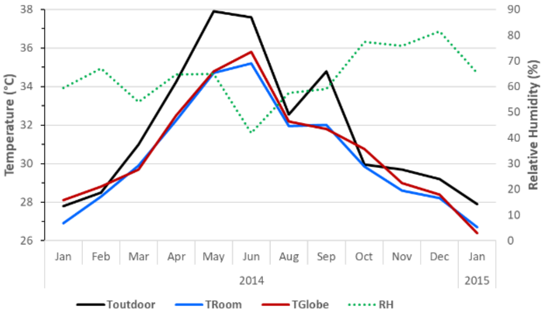


Figure 129 Plots of monthly instantaneous monitoring – indoor & outdoor temperature, relative humidity and globe temperature

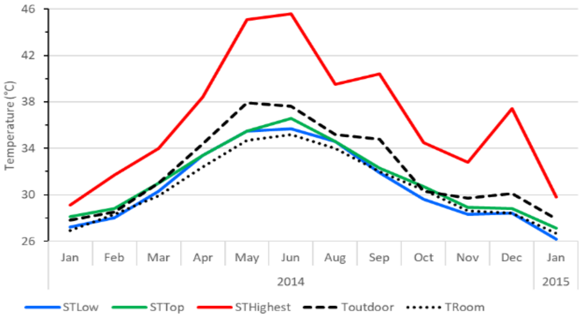


Figure 130 Plots of monthly instantaneous monitoring - surface temperature profile

5. Conclusion

5.1 GOLCONDE

- The air temperature for the third floor was found to be the highest and the first floor was the coolest during the peak hours for the month of June, 2014 and had a lag of 2 hours.
- The R.H. was lowest for the third floor and similar for the basement, first and second floor with no time lag.
- Most of the portions of the building were comfortable throughout the year, except for the third floor and the peak summer months and June and July. Based on the IMAC 90% limits for naturally ventilated buildings, the third floor was the most uncomfortable and the basement was the most comfortable for a year round analysis.
- Seasonal variation of temperature yielded a time lag of about 3 hours for summer, monsoon and winter alike, while the temperature was moderated between 25-28, 31-35, and 28-31 degrees for each of the seasons respectively.
- Seasonal R.H. profile showed that the indoor R.H. remained lower than the outdoors except for some portions of January.
- Instantaneous temperature and humidity profiles indicated the trends during the first week of June, with the third floor being the warmest and the second floor the coolest – while the third floor being the least humid in comparison to rest of the building. It also indicated an event of precipitation on the 2nd night.
- The thermal buffer of the northern corridors was able to keep the indoors cooler by 0.5 degrees and offered a relatively higher humidity indoors.
- Despite the absence of wind velocity sensors, the handheld readings for the same were plotted and found to be in the healthy range of 0.5-3.5 m/s in the basement.
- The double ventilated roof was able to shield the ceiling by creating a thermal gradient of over 15 degrees and a thermal lag of 3 hours between the external shell and the internal ceiling.

- The northern and southern facades kept the building from horizontal solar radiation, with the internal surface temperatures in the range of 30-32 degrees while the external temperatures remained as high as 40 and 44 degrees for the eastern and western wings of the north façade respectively.
- The southern façade showed relatively lower exterior temperatures (32 degrees) due to shading and kept the interiors cooler by 1 degree.
- The cavity wall towards the north of the building experienced exterior surface temperatures of over 40 degrees, while maintaining the indoor staircase surface in the range of 30-32 degrees.
- The ceiling surface temperatures for second floor were lower than the third floor's temperatures and remained almost constant at 31 degrees throughout the day. The east and west wings of the third floor had identical ceiling surface temperatures.
- The lux levels on the basement, second and third floors were found to be in the range of 10-35, 10-100, and 10-12 lux respectively on a monthly averaged basis. Being an occupied building, a specific analysis with louvers opened/closed for an entire day could not be performed and cannot be commented upon. However, since the louvers were opaque, the rooms will necessarily remain dark during the instances of rain or high outdoor temperature.

5.2 AFSANAH

- The terracotta roofing and the hollow block roofing atretegies are seen to reduce the indoor air and surface temperatures.
- Indoor surface temperature peak of the terracotta and hollow block roofing are roughly the same.
- Instantaneous damping of the terracotta and hollow block are seen to have a similar linear relationship with the outdoor air temperature.
- Maximum damping performance of the terracotta roofing is better than the hollow block roofing.
- Daily time lag performance of the hollow block roofing is better than the terracotta roofing.
- The discrepancy in maximum damping and daily lag performance between the terracotta and hollow block is probably due to the orientation or angle of the roofs, as we expect the same material to perform well in damping and daily time lag.
- The daily time lag decreases as outdoor air temperature peak occurs later in the day. This could be attributed to the fact that outdoor air temperature is lower at later hours, and therefore the outdoor temperature peak is lower.
- Hollow block instantaneous damping increases by approximately 0.99°C for every 1°C increase in outdoor air temperature while terra cotta instantaneous damping increases by about 1.26°C and air instantaneous damping increases by about 0.41°C.
- Terracotta sees an average maximum damping of 15°C at 2pm, and an average daily time lag of 2 hours.
- Hollow block sees an average maximum damping of 10°C at 2pm, and an average daily time lag of 4 hours.
- The indoor temperature peak takes place from 10am to 3pm, occurring most frequently at 12pm, while the outdoor temperature peak takes place from 12pm to 5pm, occurring most frequently at 3pm.
- The air temperature across all the zones is in the range of 23-25.5°C, 31-32.5°C, and 27.5-29.5°C degrees and the relative humidity is between 76-84%, 64-68%, and 76-83% for the respective months of January, June and October.
- The IMAC adaptive comfort used to calculate comfort exceedance for 80% and 90% acceptability limits, shows a lot of exceedances both in the summer and monsoon seasons.
- Effect of the garden on the temperature
- The gardens influence on both the temperature and relative humidity. The pond provides cooling and increased humidity in comparison to the Zen garden that shows higher temperature and lower humidity outdoor.
- This translates to a marginal effect in the indoors. The pond side and Zen garden side walls in the dining hall that shows a similar trend in temperature and humidity with lower temperatures and higher humidity on the pond side wall of the dining hall in comparison to the Zen garden side wall.
- The lux levels in the dining hall range from 10-220lux. There is a large variation in the hourly lux levels through the seasons with low lux levels in the winter in comparison to the summer. This could be attributed to the landscaping on the site, the shading from the verandas and the climatic conditions.

5.3 LUMINOSITY

- The average air temperature across all the building zones was found to be in the range of 23.5-27, 29-32.5, and 26-29 degrees and average R.H. in the range of 63-80%, 57-68%, and 66-78% for the respective months of January, June, and October.
- Zone G1 on the ground floor was found to be the warmest and the least humid, while the bedroom on the second floor in the zone S1 was found to be the coolest and most humid.
- The 'passage' acted as a bridge between the outdoors and the indoors and had their parameters in close proximity to the atmospheric parameters. Average temperature and relative humidity remained in the range of 21-26, 29-33, and 25.5-29 degrees and 68-90%, 54-66%, and 67-79% for the respective months of January, June, and October.
- Based on the IMAC 90% temperature limit for naturally ventilated buildings, the indoors were well moderated, with minor transgressions from the upper/lower limits in the extreme months of May-July, and December-February.
- The avg. rooftop surface temperature ranged between 22-25, 29-33, and 26.5-30 degrees while the avg. ceiling surface temperature ranged between 23.5-24.5, 29.8-30.8, and 27.6-28.9 degrees for the three months respectively, with a thermal time lag of 0-1 hours and thermal gradient of 0.5, 2, and 1.5 degrees respectively.
- Avg. temperature of both the surfaces of the cavity wall falls in the range of 23.5-25, 28.3-29.5, and 27-29 degrees and there is a gradient of 0.5, 0.2, and 1 degrees, with the staircase side wall being warmer for the respective months.
- The east wall exterior avg. surface temperature has a maximum of 28.3, 36.3, and 30.9 while the internal surface remained moderated under 26, 31, and 28.5 degrees.
- The lux levels on the ground and second floor remain almost the same in terms of the upper and lower limit (180-10 lux), with the second floor receiving the solar radiation slightly earlier than the ground floor due to the shade of the trees around.
- In addition, the double paned windows were able to moderate the indoor temperatures in the range of 28-30 degrees while keeping the verandas in the range of 27.5-33 degrees.

5.4 INTACH

- The outdoor temperature ranged between 19.5-27.5, 26.5-35, and 23-31 degrees for January, June, and October respectively.
- The indoor temperature for the two points in the courtyard ranged between 24.5-26.5, 31-33, and 28-30 degrees for January, June, and October respectively.
- The indoor temperature for the mixed mode ventilated office did not show significant variation and ranged between 27.3-27.8, 29.9.-30.9, and 29.5-30 degrees for January, June, and October respectively.
- The outdoor relative humidity ranged between 60-95%, 43-75%, and 55-90% for January, June, and October respectively.
- The relative humidity for the two points in the courtyard ranged between 67.7-73.4%, 55.5-65.6%, and 66.5-71.3% for January, June, and October respectively.
- The relative humidity for the mixed mode ventilated office ranged between 65-68.5%, 51.3-63.6%, and 62.5-66.9% for January, June, and October respectively.
- The indoor temperatures across both the points in the courtyard breached the IMAC 90% upper limit during the hottest months (March – October).
- The indoor temperature for the office breached the IMAC 90% upper limit throughout the year, except some isolated instances during December and early summer mornings.
- The courtyard is thermally more comfortable in comparison to the office indoors.
- The rooftop surface temperature had a maxima of 41.5, 49.5, and 41.7 degrees for January, June, and October respectively.
- The indoor ceiling surface temperature had a maxima of 23.5, 29.5, and 26.5 degrees for January, June, and October respectively.
- There was a gradient of 15, 16.9 and 11.5 degrees across the roof section, for January, June, and October respectively.
- The terracotta roof assembly offered a thermal time lag of about 8 hours throughout the year.
- The highest indoor lux levels for January, June, and October were 89.3, 555.6, and 73.8 lux respectively.

- The high indoor lux during the summers added on to the high temperature and had a negative impact on the thermal comfort.

5.5 BLESSING HOUSE

- The air temperature across all the building zones was found to be in the range of 22-25, 28-30.5, and 27-29.5 degrees and the R.H. in the range of 87-75%, 75-65%, and 78-68% for the respective months of January, June, and October.
- Room 2 was found to be the warmest and the least humid, while the dining room was found to be the coolest and most humid.
- Verandas acted as a bridge between the outdoors and the indoors and had their parameters in close proximity to the atmospheric parameters.
- The building did not overshoot the IMAC 90% upper limit at any instance during the year 2014. However, the IMAC 90% lower limit was breached during the cooler months (December – March).
- Based on the IMAC results, the ground floor dining room was the most uncomfortable while Room 1 on the first floor was the most comfortable (based on IMAC 90% lower limit).
- 'Night flushing' proved to be an effective way to passively cool the indoors during the cooler hours of the night.
- The compressed earth-Aerocon made mezzanine wall was able to maintain a thermal gradient of 10 degrees and a time lag of 8 hours between the exterior and interior surfaces during the month of June.
- Annually, the exterior temperature peaked till 49 degrees during the summers while maintaining the indoor temperature of 25-35 degrees throughout the year.
- The insulated terracotta roof shielded the ceiling by maintaining a thermal gradient of 14 degrees and a time lag of 6 hours, moderating the indoor ceiling surface between 29-31 degrees for the month of June.
- Annually, the rooftop surfaces reached as high as 50 degrees for the hottest times in summer, while maintaining the indoor temperatures between 22-33 degrees throughout the year.
- The double paned windows were able to moderate the indoor temperatures in the range of 28-30 degrees while keeping the verandas in the range of 27.5-33 degrees.
- The lux levels on the ground and first floor remain almost the same in terms of the upper and lower limit (180-10 lux), with the first floor receiving the solar radiation slightly earlier than the ground floor due to the shade of the trees around.
- There was a distinct pattern observed in the window operation pattern of the occupants, with the annually averaged window opening and closing times as 8:57 and 19:19 hours.
- For a seasonal variation across January, June, and October – the window operation is most regular in the month of June due to high temperatures, and least regular during the coolest month of January.

5.6 MUKUDUVIDU

- The outdoor temperature ranged between 19.5-27.5, 26.5-35, and 23-31 degrees for January, June, and October respectively.
- The indoor temperature ranged between 23-26, 29-33, and 26.5-29.5 degrees for January, June, and October respectively.
- Throughout the year, the indoor temperature was lower than the outdoor temperature during the hottest hours of the day (10:00 – 16:00) and higher than the outdoor temperature during the cooler hours.
- The outdoor relative humidity ranged between 60-95%, 43-75%, and 55-90% for January, June, and October respectively.
- The indoor relative humidity ranged between 63-83%, 53-73%, and 65-72% for January, June, and October respectively.
- Throughout the year, the indoor humidity was lower than the outdoor temperature during the hottest hours of the day (10:00 – 16:00) and higher than the outdoor temperature during the cooler hours.
- Throughout the year, the indoor humidity was higher than the outdoor humidity during the hottest hours of the day (10:00 – 16:00) and lower than the outdoor humidity during the cooler hours.
- The indoor wind velocities ranged between 0.20-0.48, 0.28-0.55, and 0.33-0.60 m/s for January, June, and October respectively.
- The indoor temperatures across both the domes and the vault breached the IMAC 90% upper limit during the hottest months (March, April).

- The indoor temperatures across the vault occasionally breached the IMAC 90% lower limit during the coolest months (November - February), but can be regarded as the most comfortable zone out of the three zones under study.
- Due to air stratification, the air temperature in the upper portion (317 cm) of dome 1 was higher than the air temperature in the lower portion (84 cm).
- There was a thermal time lag of 5 hours in case of both the domes and 4 hours in the case of the vault, for the hottest month - June.
- The surface temperature for domes 1 and 2 at 360 cm was higher than that at 217 cm by 1.5 and 1 degrees.
- Exterior surface temperatures for 360 cm were higher by over 7 and 4 degrees for domes 1 and 2 respectively for the month of June.
- Dome 2 experienced a warmer exterior environment due to the lack foliage and shade.
- The interior ceiling temperature for the vault remained moderated between 31-32 degrees for June.
- The indoor air temperatures for vaults remained lower than that of the domes.
- The difference in the indoor temperatures for both the zones was most prominent in the hottest month of June, and least prominent during the winters - January.
- The highest indoor lux levels for January, June, and October were 325, 220, and 270 lux respectively.
- The building was designed in a way to not allow the summer sun while allowing the winter sun, as indicated by the respective lux levels.

5.7 SOLAR KITCHEN

- The results of the temperature differential across the stack was less than expected, with a top-to-bottom gradient of 3.4°C from the long term monitored data.
- The IMAC adaptive comfort used to calculate comfort exceedance for 80% and 90% acceptability limits, shows a lot of exceedances in the summer and monsoon.
- The results of the instantaneous measurements taken at peak outdoor temperature conditions are seen to achieve a gradient of 9.9 °C from the lower measured point, and 10.4°C from the measured point at the top respectively, in June and Dec 2014. This indicates that the solar chimney design sees a considerable degree of stratification leading to effective stack ventilation especially during the summer and winter months when it is desirable to have increased ventilation.
- The solar chimney does not seem to be as effective in achieving a powerful stack ventilation, although it does provide some stratification for ventilation. Had the top portion of the chimney been painted black, it would have resulted in a greater thermal gradient and more efficient stratification of air.

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7. Appendix

7.1 Climatic Zones of India

		Temperature (°C)							
Climate Zone	**Description**	**Summer Midday (High)**	**Summer Night (Low)**	**Winter Midday (High)**	**Winter Night (Low)**	**Diurnal Variation**	**Mean Relative Humidity**	**Annual Rainfall**	**Sky Condition**
Hot and Dry	High Temperature | Low humidity and rainfall | Intense solar radiation and a generally clear sky | Hot winds during the day and cool winds at night | Sandy or rocky ground with little vegetation | Low underground water table and few sources of surface water	40-50	20-30	5-25	0-10	15-20	Very Low, 25-40%	Low, < 500mm/yr	Cloudless skies with high solar radiation, causing glare
Warm and Humid	Temperature is moderately high during day and night | Very high humidity and rainfall | Diffused solar radiation if cloud cover is high and intense if sky is clear | Calm to very high winds from prevailing wind directions | Abundant vegetation | Provision for drainage of water is required	30-35	25-30	25-30	20-25	5-8	High, 70 to 90%	High, > 1200 mm/yr	Overcast (cloud cover ranging between 40 and 80%), causing unpleasant glare

Temperate (Moderate)	Moderate Temperature | Moderate humidity and rainfall | Solar radiation same throughout the year and sky is generally clear | High winds during summer depending on topography | Hilly or high plateau region with abundant vegetation	30-34	17-24	27-33	16-18	8-13	High, 60 to 85%	High, > 1000 mm/yr	Mainly clear, occasionally overcast with dense low clouds in Summer
Cold (Sunny/ Cloudy)	Moderate summer Temperatures and very low in winter | Low humidity in cold/sunny and high humidity in cold/ cloudy | Low precipitation in cold/ sunny and high in cold/cloudy | High solar radiation in cold/sunny and low in cold/cloudy | Cold winds in winter | Very little vegetation in cold/sunny and abundant vegetation in cold/cloudy	17-24/ 20-30	4-11/ 17-21	(-7)-8/ 4-8	(-14)-0/(-3)-4	25 to 25/ 5 to 15	Low, 10-50%/ High,70-80%	Low, <200 mm/yr / Moderate, 1000mm /yr	Clear with cloud cover < 50% Overcast for most of the year
Composite	This applies when 6 months or more do not fall within any of the above categories | High temperature in Summer and cold in winter | Low humidity in summer and high in monsoons | High direct solar radiation in all seasons except monsoons high diffused radiation | Occasional hazy sky Hot winds in summer, cold winds in winter and strong wind in monsoons | Variable landscape and seasonal vegetation	32-43	27-32	10-25	4-10	35-22	Variable Dry Periods= 20-50% Wet Periods= 50-95%	Variable 500-1300 mm/yr, during monsoon reaching 250 mm in the wettest month	Variable, overcast and dull in the monsoon

7.2 Abbreviations

CBERD	Centre for Building Energy Research and Development
AV CSR	Auroville Centre for Scientific Research
Temp.	Temperature (°C)
R.H.	Relative Humidity (%)
QA	Quality Assurance
IMAC	India Model for Adaptive Comfort

7.3 Missing/Errored Data

7.3.1 GOLCONDE

Zone	HOBO I.D.	Parameter	From	To	Type
2nd Floor, Eastern Room 6	B11	Indoor Air Temp	01-09-2013 0:00	24-09-2013 10:00	Errored Values
2nd Floor, Western Room 6	D9	Indoor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Indoor R.H.	01-09-2013 0:00	07-09-2013 11:00	Missing Values
	B13	Corridor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Northern Wall Outside Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Northern Wall Indoor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
3rd Floor, Eastern Room 1	D11	Indoor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Indoor R.H.	01-09-2013 0:00	07-09-2013 11:00	Missing Values
3rd Floor, Western Room 1	A7	Indoor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Indoor R.H.	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Indoor Light Intensity	01-09-2013 0:00	07-09-2013 11:00	Missing Values
Basement	A6	Indoor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Indoor R.H.	01-09-2013 0:00	07-09-2013 11:00	Missing Values

		Indoor Light Intensity	01-09-2013 0:00	07-09-2013 11:00	Missing Values
	B24	Indoor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Indoor R.H.	01-09-2013 0:00	07-09-2013 11:00	Missing Values
	B2	Outdoor Air Temp	01-09-2013 0:00	07-09-2013 11:00	Missing Values
		Outdoor R.H.	01-09-2013 0:00	07-09-2013 11:00	Missing Values
South Garden	B16	Outdoor Air Temp	01-09-2013 0:00	21-09-2013 11:00	Missing Values
		Outdoor R.H.	01-09-2013 0:00	21-09-2013 11:00	Missing Values
North Garden	B15	Outdoor Air Temp	01-09-2013 0:00	21-09-2013 11:00	Missing Values
		Outdoor R.H.	01-09-2013 0:00	21-09-2013 11:00	Missing Values
2nd Floor, Western Room 6	B13	Northern Wall Outdoor Temp	09-09-2013 12:00	21-09-2013 11:00	Errored Values
2nd Floor Staircase	B17	Outdoor Air Temp	01-09-2013 0:00	21-09-2013 11:00	Missing Values
		Outdoor R.H.	01-09-2013 0:00	21-09-2013 11:00	Missing Values
		Cavity wall Internal Surface Temp	01-09-2013 0:00	21-09-2013 11:00	Missing Values
		Cavity wall External Surface Temp	01-09-2013 0:00	21-09-2013 11:00	Missing Values
Basement	B24	Indoor Air Temp	20-12-2013 22:00	21-12-2013 11:00	Missing Values
		Indoor R.H.	20-12-2013 22:00	21-12-2013 11:00	Missing Values
Basement	B24	Indoor R.H.	29-01-2014 4:00	01-02-2014 10:00	Errored Values
Basement	B24	Indoor Air Temp	01-02-2014 11:00	07-02-2014 9:00	Missing Values
		Indoor R.H.	01-02-2014 11:00	07-02-2014 9:00	Missing Values
Garden North	B15	Outdoor Air Temp	26-07-2014 12:00	19-08-2014 13:00	Missing Values

		Outdoor R.H.	26-07-2014 12:00	19-08-2014 13:00	Missing Values
Garden South	B16	Outdoor Air Temp	08-08-2014 18:00	09-08-2014 11:00	Missing Values
		Outdoor R.H.	08-08-2014 18:00	09-08-2014 11:00	Missing Values
Garden South	B16	Outdoor Air Temp	17-09-2014 3:00	22-09-2014 10:00	Missing Values
		Outdoor R.H.	17-09-2014 3:00	22-09-2014 10:00	Missing Values
Basement	A6	Indoor R.H.	22-09-2014 1:00	22-09-2014 10:00	Errored Values

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7.3.2 AFSANAH

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7.3.3 LUMINOSITY

Zone	HOBO I.D.	Parameter	From	To	Type
Rooftop	B20	Air Temperature	28-09-2013 0:00	17-10-2013 23:00	Missing
		Relative Humidity	28-09-2013 0:00	17-10-2013 23:00	Missing
		Light Intensity	28-09-2013 0:00	03-06-2014 12:00	Missing
		Roof Surface Temperature	28-09-2013 0:00	17-10-2013 23:00	Missing
		Relative Humidity	16-11-2013 8:00	10-03-2014 1:00	Error
		Roof Surface Temperature	31-12-2013 21:00	31-12-2013 23:00	Error
			21-01-2014 2:00	27-01-2014 1:00	Error
			17-02-2014 3:00	20-02-2014 2:00	Error
			20-02-2014 9:00	05-03-2014 1:00	Error
			05-03-2014 10:00	10-03-2014 1:00	Error
		Air Temperature	10-03-2014 2:00	18-03-2014 17:00	Missing
		Relative Humidity	10-03-2014 2:00	03-06-2014 12:00	Missing
		Roof Surface Temperature	10-03-2014 2:00	18-03-2014 17:00	Missing
Zone G2	B19	Air Temperature	28-09-2013 0:00	19-11-2013 23:00	Missing

		Relative Humidity	28-09-2013 0:00	19-11-2013 23:00	Missing
		East Wall Interior Temperature	28-09-2013 0:00	19-11-2013 23:00	Missing
			28-09-2013 0:00	19-11-2013 23:00	Missing
			06-08-2014 15:00	17-09-2014 14:00	Error

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7.3.4 INTACH

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7.3.5 BLESSING HOUSE

Zone	HOBO I.D.	Parameter	From	To	Type
Veranda Middle	D5	Indoor Air Temp	19-11-2013 11:00	19-11-2013 12:00	Missing Values
		Indoor R.H.	19-11-2013 11:00	19-11-2013 12:00	Missing Values
		Indoor Air Temp	4-2-2014 10:00	4-2-2014 11:00	Missing Values
		Indoor R.H.	4-2-2014 10:00	4-2-2014 11:00	Missing Values
		Indoor Air Temp	7-5-2014 15:00	20-5-2014 10:00	Missing Values
		Indoor R.H.	7-5-2014 15:00	20-5-2014 10:00	Missing Values
Outdoor Garden	B7	Outdoor Air Temp	10-08-2014 8:00	31-08-2014 23:00	Missing Values
		Outdoor R.H.	10-08-2014 8:00	31-08-2014 23:00	Missing Values

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7.3.6 MUKUDUVIDU

Zone	HOBO I.D.	Parameter	From	To	Type
Dome 1, Exterior 84cm	C1	Surface Temperature	19-11-2013 11:00:00	19-11-2013 12:00:00	Missing Data
Dome 1, Roof above vault	C1	Surface Temperature	19-11-2013 11:00:00	19-11-2013 12:00:00	Missing Data

Dome 2, Exterior 217cm	C2	Surface Temperature	19-11-2013 11:00:00	19-11-2013 12:00:00	Missing Data
Dome 2, Interior 84cm	C2	Surface Temperature	19-11-2013 11:00:00	19-11-2013 12:00:00	Missing Data
Vault, Internal Ceiling	B5	Surface Temperature	19-11-2013 11:00:00	19-11-2013 12:00:00	Missing Data

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7.3.7 SOLAR KITCHEN

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