Data driven investigation of thermal comfort in an informal settlement – a case of Mumbai

Abstract

Large pockets of informal settlements are a common sight, especially in emerging economies like India. The built environment of these informal settlements remains an area less explored. This research therefore aimed to investigate thermal comfort in typical urban informal settlements. Real time onsite monitoring of environmental parameters affecting thermal comfort for 2 houses in a selected settlement of Mumbai was done which led to an inference that roof element of the house receives maximum solar radiation. The two cases were then further simulated in Design Builder to understand the effect of solar radiation and heat gain through the roof which is exposed the most. The research further expanded to studying mitigation strategies by adopting multiple roof assemblies as retrofit solutions for these houses. These assemblies were studied keeping thermal conductance, ease of installation, strength and over workability and maintenance into consideration. The research reveals how an overall study of thermal comfort through a data-driven approach can assist stakeholders and authorities to develop design-guidelines and strategies for thermal comfort in informal settlements.

Key Innovations

- Field studies conducted to understand the thermal comfort in informal settlements.
- Retrofitting solutions for roof sections tested for thermal performance as well as its affordability and maintenance.

Practical Implications

Through this research, yearly data was analysed through simulation to determine that most of the months in the warm and humid conditions of Mumbai fall out of the comfort zone. The results of modelling various retrofit options over the roof, where most of the solar radiation is gained, revealed which option enhances the thermal comfort within an informal dwelling. The field study actually gave an insight into how the spaces in these settlements are not comfortable to carry out daily activities with ease. The alterations suggested therefore will help the owners of these houses themselves retrofit and maintain these roofing solutions for comfortable indoors.

Introduction

In earlier times, most people around the world lived in small communities. Over the past few centuries, especially in recent decades, there has been a mass migration of populations from rural to urban areas. By 2017, 4.1 billion people were living in urban areas, which means more than half of the world (55%) live in urban areas. Quality of life in urban centres is of course an important measure of well-being. One measure of living standards is the proportion of the urban population living in slum households. Slums are defined as a group of people living under one roof without one or more of the following conditions: access to improved water, access to improved sanitation, adequate living space and sustainable housing.

In India, 33.60% of the population lives in urban areas as seen in Figure 1. (UN World Urbanization Prospects: 2018). As per the Census of India 2011, Maharashtra houses the highest number of slum households (Census of India, 2011). Greater Mumbai sees the highest proportion of the slum households to the total urban household. The gap between Mumbai and the second highest metro-city i.e. Kolkata is 11.7% (Census of India, 2011). Individuals and households in low-income communities and slums are exposed to heat indoor. Thermal well-being is important for the efficient functioning of living beings which remains a neglected area of focus in slum settlements A WHO, Europe review of housing and energy policies shows that affordable energy used to maintain thermal comfort is generally not considered a health concern, although it is particularly relevant for households with lower income levels. Indoor thermal comfort affects humans psychologically and physiologically. It positively impacts health and productivity and improves the sense of wellbeing (Shaikh et al., 2014). For these reasons, thermal comfort for all should become an important goal for all developing countries. Most of the housing structures in the slums are inferior in quality and do not comply with local building codes and good construction practices. Often slum dwellers have no legal title to the house in which they reside or any other form of secure property. Furthermore, public institutions do not usually consider slums as part of the city's housing infrastructure. This is one of the reasons why there is very little data on slum settlements in many countries and especially their housing comfort conditions.

Background

The human body uses natural mechanisms to maintain a consistent body temperature, such as reducing and increasing blood flow to the body's outer surface, shivering, and increased sweat. However, in extreme conditions as extremely cold temperatures (below 0°C), extremely high temperatures (above 40°C), or a hot and humid atmosphere, these natural precautions taken by the human body are insufficient to keep oneself comfortable. To deal with such scenarios and to make one's living space more comfortable, heating, cooling, or ventilating has been used to change the living area's environment. (ASHRAE Fundamentals, 2009). High temperatures and/or humidity in the summer might disrupt the body's thermal homeostasis equilibrium, resulting in discomfort. Humans achieve thermal comfort in hot weather by wearing lighter clothing, lowering activity, opening windows for improved natural ventilation and air movement when the outside temperature is suitable, and employing space cooling equipment such as fans and air conditioners. It has a good impact on one's health and productivity, as well as one's sense of well-being (Shaikh et al., 2014).

However, houses in slums are frequently not designed and built in a sustainable manner. With more than 60% of the population living in informal settlements heat stress experienced by the occupants is ignored by at large. In India, it is also typical for rural residents to relocate to cities in search of better economic prospects, resulting in congested and increasingly unsustainable infrastructure that supports this housing. The comparatively affluent parts of society, with greater expendable income and desires for a better life, use active air-conditioning and other cooling systems to combat the urban heat island effect and increased thermal discomfort in typical modern residences. (Shakti Sustainable Energy Foundation). This scenario gets aggravated due to the power outrage and non-accessibility to basic comfort medium of fan as well increasing the uncomfortable conditions indoor. the only option we have is to give people This extreme bifurcation and overlooking of this marginalised community needs to be addressed through data driven approach and retrofitting solutions. Increased urbanization, which causes urban temperatures to be several degrees hotter than surrounding rural temperatures, has the potential to worsen heat exposure (Oke, 1982). Larger surface area from new structures, increased heat absorption from man-made materials, and decreased evapotranspiration by eradicating plants and vegetated areas are all factors that contribute to the urban heat island effect (Kleerekoper et al., 2012). Urban regions, on the other hand, are neither monolithic nor homogeneous. Temperature readings can fluctuate by several degrees due to different microclimates, implying that a resident's heat exposure can vary by neighbourhood or even inside conditions. (Oke et. al., 2012) and is a chosen method in this research to understand thermal comfort of occupants.

Today in most parts of the country, corrugated iron sheeting is used to cover the roofs of millions of low-income homes, resulting in severely uncomfortable indoor temperatures in summers and winters. Because these populations have the lowest, if any, significant earnings, the solutions to address this issue over heating and cooling must be addressed through exceedingly low-cost solutions. With these roofing materials used extensively due to its easy installation and availability, roof temperatures are seen crossing more than 50ºC when the air temperatures are between 40-43ºC. This makes indoors very uncomfortable to carry out basic daily activities. Retrofitting solutions has received much interest as a means of making buildings more energy efficient and sustainable. This can help reduce carbon emissions, make buildings cheaper and easier to maintain, and help overcome poor ventilation and damp issues, so enhancing occupant health. It can also improve the adaptability, durability, and resiliency of a structure. Passive, or non-mechanized, solutions are a priority in this case since they eliminate the need for fossil fuels or other purchased energy. A well-designed, climate-adaptive structure can reduce the requirement for additional technologies to a minimum. Passive solutions are also less expensive and because they are not mechanical systems, they are more reliable in terms of users, operation, and maintenance.

Methodology

The research carried out looked at two quantitative methods of data collection. The 1st part was to collect onsite data in a slum community in Mumbai. Two data loggers were stationed in two houses for 10 days in April 2021. The onsite data collected was for thermal parameters of air temperature, humidity Measurements of operative temperature, Outdoor Air Temperature and Air Velocity were taken on site while observing the clothing and activity pattern of the residents. Readings for air speed and radiant temperature were taken on one day with the help of an anemometer and globe thermometer respectively. Since a data logger couldn’t be installed outdoors, readings were recorded of the nearest Automatic Weather Station for 10 days outdoor weather data from SAFAR, India) web portal. ASHRAE 55 – Adaptive Comfort Index was used to determine indoor comfort for all the days with the help of CBE Berkeley Thermal Comfort Tool. Further the 2nd part of the research looked at various roof solutions and how they performed with respect to the heat ingress. Since the data logging was carried out only for the month of April being peak summer month, one could not establish the performance of the house’s year long. Thus, simulation studies were performed to examine each month’s discomfort hours and to identify which seasons faces high thermal stress. Next step involved looking at retrofit solutions for these houses to create comfortable indoor spaces. For this, current ongoing data under the Fair conditioning Programme by cBalance Solutions Pvt. Ltd. as part of their project ThermIC is considered on which the authors are also a part. As part of this project, 7 innovative retrofit roofing solutions were to be installed and tested for their thermal performance. These roof options were considered by the author for retrofitting solutions for simulation purpose. These above options were modelled and simulated in Design Builder and compared across for their impact on indoor thermal comfort.

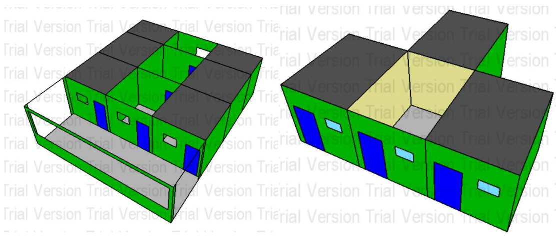

Figure 1: House 1 and House 2 modelled on Design Builder software

Project Location

According to the 2011 census, the population of Mumbai was 12,478,447. In 2016, an estimated 55 percent of Mumbai's population lived in slums. Density of population at Bhandup beats Asia's largest slum of Dharavi in Mumbai. The extended suburb of Mumbai is high density having 87% slums in the area (Accommodation Times, 2015). Bhandup is on the eastern side of Mumbai. Bhandup lies in S-ward of Mumbai

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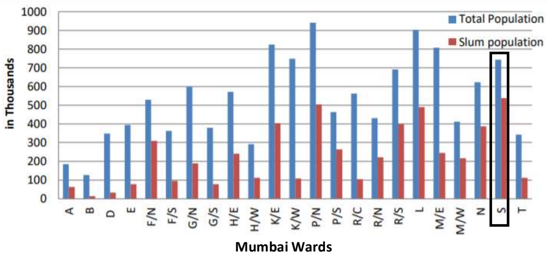


Figure 2- Mumbai Ward wise Slum vs total population

The site is in Shivnagar, Bhandup West. There are nearly 150-200 houses in this settlement. It is surrounded by high-rise buildings from all sides. The two houses were selected at random and keeping in mind the access to install the data loggers.

Figure 3: Site Location in Bhandup, Mumbai

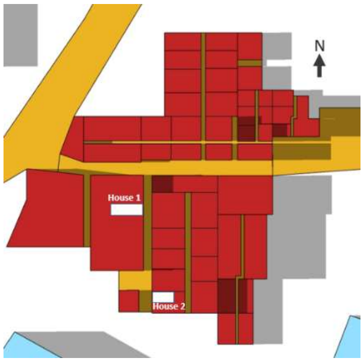


Figure 4: Location of the houses

House 1:

This house is situated in a two storeyed chawl on the G+1 floor. The occupants are a family of 4 members. The female of the house is the 24 hours occupant of the house. The husband goes to work from 8 AM to 6 PM. The children attend school and tuitions from 8AM to 6PM as well.

Figure 5: Photographs of House 1

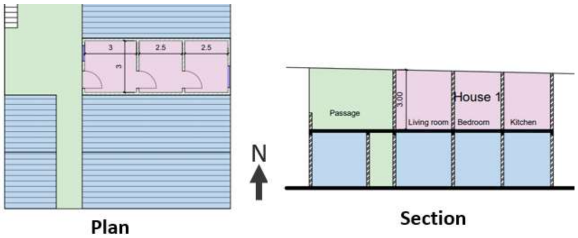


Table 1: House Description

	House 1	*House 2*
Type	*Semi- Pucca*	*Semi- Pucca*
Height	*G+1 (6m)*	*G (3m)*
Area	*24 sqm.*	*12 sqm.*
Roof	*Tin roof (corrugated sheet)*	*Tin roof (corrugated sheet)*
Wall	*Brick with plaster and yellow paint*	*Brick with plaster and green paint*
Family members	*4*	*4*

House 2-

Figure 6: Photographs of House-2

Plan

Section

Discussions and Findings

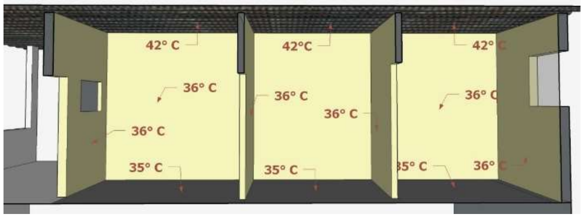


Figure 7: House-1 Surface Temperatures

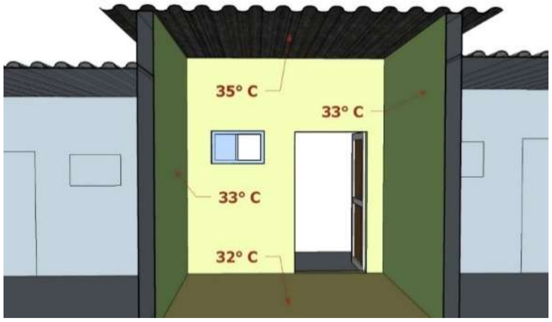


Figure 8: House-2 Surface Temperatures

The surface temperatures for House 1 are show in Figure 10 and 11. All the recordings were taken around 4:00 – 4:30 PM. The highest temperature recorded was from the roof being 46 ⁰C and 42 ⁰C. The floor in passage and inside the house were lowest, 32⁰C and 35⁰C compared to other materials and heat gain locations. With the recorded data, it was found that all the days were falling into the discomfort range according to the Adaptive Comfort Model.

The space geometry of House 1 was built on model interface of the software. Inputs for Activity schedules, Occupancy, Construction Details and Ventilation were applied accordingly to the house. The model was simulated for the whole year and monthly data was noted. A base case was developed which would be helpful in next section of comparison in retrofit solutions.

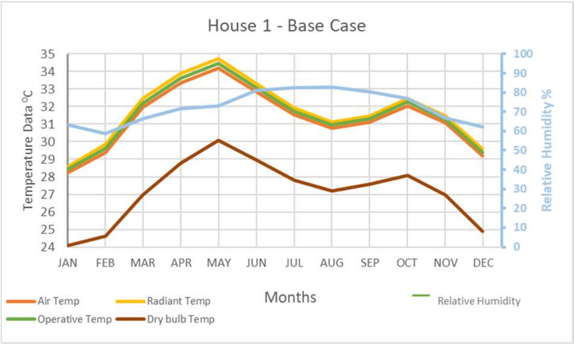


Figure 9: Simulation result of Basecase for House-1

The monthly averages of Operative Temperature and Outside Dry Bulb Temperature were plotted on the CBE Berkely Adaptive Comfort Model to see which month falls in the comfort range. December and January were the only months falling into the comfort band. February lies just outside the comfort band, while rest of the months all fall into uncomfortable (too warm) range.

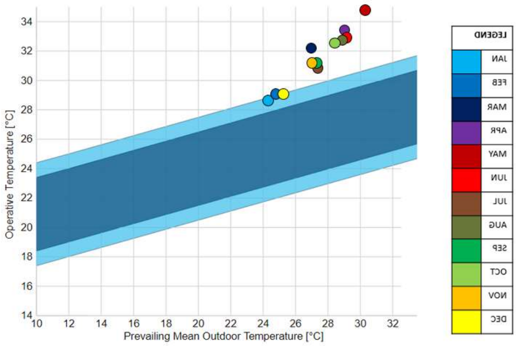


Figure 10: House-1 Adaptive Chart

Similar steps as mentioned above for House 1 were taken for the House 2 for the inputs in the software. The two houses differ in their carpet area size, occupancy density, occupancy schedules, elevation, and surroundings.

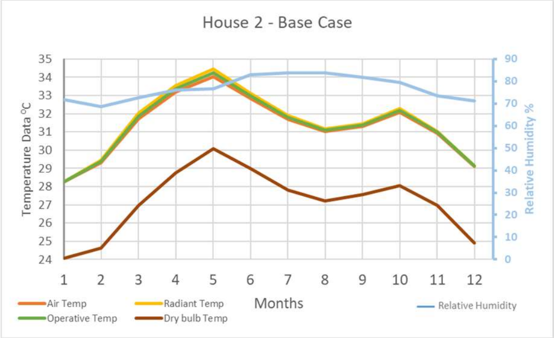


Figure 11: Simulation result of Base case of House-2

January, February, and December were the months falling into the comfort band. November, March, July, August and September lie outside the comfort range but the next nearest to the acceptability limits. Rest of the months all fall into uncomfortable (too warm) range.

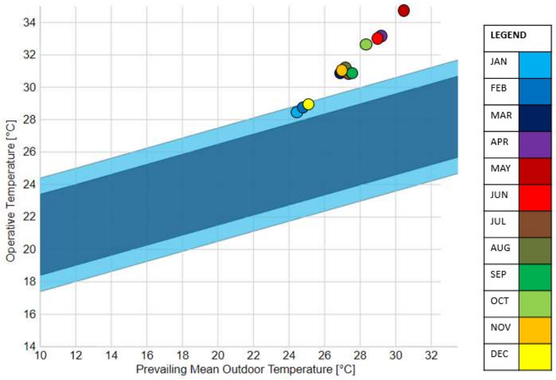


Figure 12: House-2 Adaptive Chart

The retrofit solutions as mentioned in the Background were considered for implementation over these two houses' base models. Through previous field data surface temperature and simulation results, it was observed that roof in these houses gains the maximum heat since the walls are most of the time shared thus not actively contributing to heat gain.

Retrofit Solutions

As mentioned above 7 roof solutions were considered for retrofitting options and simulated for. The roofing solutions tested for and considered as part of this research were-

(a) Alufoil (Crosslinked Polyethylene Aluminium foam)/ Bubble Wrap

(b) Modular Roofing Panels (80% recycled paper and coconut husk coated entirely with an insulation)

(c) Green Roof System

(d) Water-filled PET-bottles

(e) Dormer Window

(f) Fiberglass Insulation

(g) Reprocessed Tetra-Pak Roofing Sheets

(h) Ecoboard (Corrugated roofing sheet made of recycled tetrapak).

These seven retrofit solutions were considered according to their science principles of insulation, radiation control, conductive and convective heat transfer, and ventilation.

In case of House 1, Fibreglass reduces the operative temperature by 1.25 ºC. It works on the principle of thermal insulation. Alu-foil reduces the Operative Temperature by 1.20 ºC; it works on the principle of radiation and insulations. After these solutions Reprocessed Tetrapak Sheets (Science principle-radiation) shows reduction of 1.01 ºC. Least reduction is seen in Dormer Window (difference of 0.03ºC) (Table 3 and Figure 17)

House	House 1							
Sr No.		1	2	3	4	5	6	7
Material	**Base Case**	Alufoil	Reprocessed TetraPak Roofing Sheets	Rooftop Urban Gardening	Water-filled PET-bottles	Dormer Window	Fiberglass Insulation	Modular Roofing Panels
Location	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai
U- value			2.05 W/m2K	1.78 W/m2K	3.09 W/M2.k	4.7 W/M2.k		
R value		2.98 m2K/W					11 m2K/W	1 m2·K/W
Thickness		4mm	6mm	150mm	60mm	3mm	89mm	50mm
JAN	28.41	28.22	27.88	28.29	28.41	28.38	28.33	28.46
FEB	29.62	28.9	28.77	29.2	29.41	29.57	28.97	29.36
MAR	32.21	30.68	30.91	31.32	31.66	32.17	30.63	31.52
APR	33.62	31.61	32.12	32.5	32.92	33.57	31.48	32.65
MAY	34.46	32.3	32.97	33.32	33.77	34.41	32.09	33.44
JUN	33.07	31.45	31.95	32.28	32.64	33.04	31.29	32.47
JUL	31.74	30.45	30.8	31.13	31.44	31.71	30.35	31.27
AUG	30.95	29.92	30.17	30.5	30.77	30.93	29.84	30.64
SEP	31.29	30.17	30.36	30.7	30.97	31.26	30.12	30.84
OCT	32.25	30.72	31.05	31.42	31.75	32.22	30.64	31.55
NOV	31.26	30.32	30.34	30.73	30.96	31.22	30.34	30.93
DEC	29.4	29.07	28.77	29.19	29.34	29.37	29.18	29.43
Mean	31.52	30.32	30.51	30.88	31.17	31.49	30.27	31.05

Table 2: Retrofit Simulation results of House-1

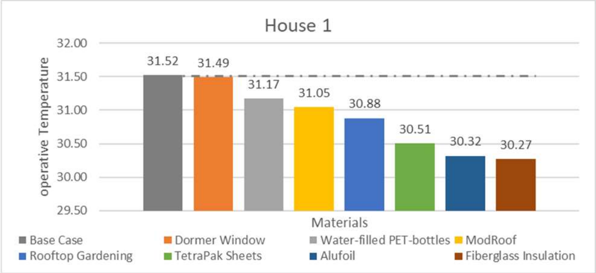
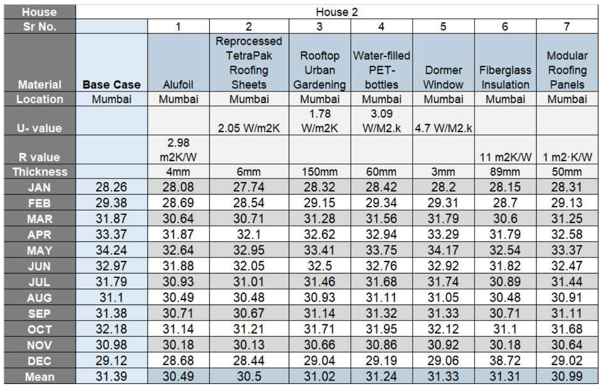


Figure 13: Graphical representation of Operative Temperature at House-1

In case of House 2, Alufoil and Tetapak roofing sheets have similar results. They reduce the Operative Temperature by ~1ºC. Least reduction is seen in Dormer Window (difference of 0.19ºC). Here fiberglass insulation does not show much reduction as seen in House 1 results. (Table 4 and Figure 18). Rooftop Urban gardening, Modroof, Water filled PET bottles, and Tetrapak sheet showed reduction in summer month and increase in operative temperature in winter months. According to the price PET bottle, Alufoil, Reprocessed Tetrapak sheets, are the cheaper options. Modroof and Urban Rooftop gardening are the costly solutions. The weight of Urban gardening and Water filled PET bottles are too heavy for the structural system. This solution would also use water, while rooftop garden would use electricity for pumping as well. In case of any calamity, they can harm human life if the structure collapses. Rooftop gardening will also require space for water pump in the living area to supply water to the rooftop. Almost all solutions have good life span, but it can't be predicted for Water filled PET bottle since the water may remain stagnant if no technology is used to filter water (which might lead to electricity consumption). The fungal and bacterial growth inside the water may harm the plastic and would require frequent replacing.



House	House 2							
Sr No.		1	2	3	4	5	6	7
Material	**Base Case**	Alufoil	Reprocessed TetraPak Roofing Sheets	Rooftop Urban Gardening	Water-filled PET-bottles	Dormer Window	Fiberglass Insulation	Modular Roofing Panels
Location	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai	Mumbai
U- value			2.05 W/m2K	1.78 W/m2K	3.09 W/M2.k	4.7 W/M2.k		
R value		2.98 m2K/W					11 m2K/W	1 m2·K/W
Thickness		4mm	6mm	150mm	60mm	3mm	89mm	50mm
JAN	28.26	28.08	27.74	28.32	28.42	28.2	28.15	28.31
FEB	29.38	28.69	28.54	29.15	29.34	29.31	28.7	29.13
MAR	31.87	30.64	30.71	31.28	31.56	31.79	30.6	31.25
APR	33.37	31.87	32.1	32.62	32.94	33.29	31.79	32.58
MAY	34.24	32.64	32.95	33.41	33.75	34.17	32.54	33.37
JUN	32.97	31.88	32.05	32.5	32.76	32.92	31.82	32.47
JUL	31.79	30.93	31.01	31.46	31.68	31.74	30.89	31.44
AUG	31.1	30.49	30.48	30.93	31.11	31.05	30.48	30.91
SEP	31.38	30.71	30.67	31.14	31.32	31.33	30.71	31.11
OCT	32.18	31.14	31.21	31.71	31.95	32.12	31.1	31.68
NOV	30.98	30.18	30.13	30.66	30.86	30.92	30.18	30.64
DEC	29.12	28.68	28.44	29.04	29.19	29.06	38.72	29.02
Mean	31.39	30.49	30.5	31.02	31.24	31.33	31.31	30.99

Table 3: Retrofit Simulation results of House-2

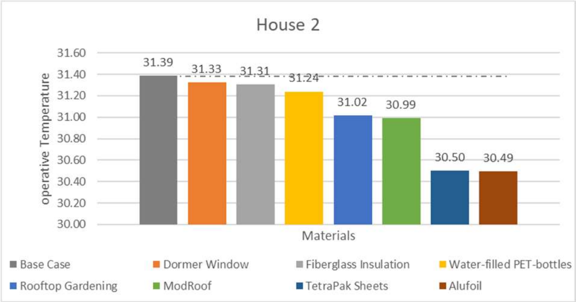


Figure 14: Graphical representation of Operative Temperature at House-2

The most uncomfortable hours for the residents were 10AM to 4PM as mentioned by them in person. Through the CBE Berkeley Adaptive Comfort Model tool, all days were identified as uncomfortable. This arose the question of checking whether all months are comfortable or not for the residents. The models were developed on Design builder to check every month's thermal comfort. As the dry bulb temperature rose, it was also observed that the internal air temperature, MRT and operative temperature has risen in the month of May. May is one of the hottest summer months according to the climatic data of Mumbai. After May as the Relative humidity increases in Mumbai the temperatures during Monsoon decreased. A smaller peak in temperature was observed in October. This may be due to the post-monsoon, pre-winter rise in temperatures across the country is referred to as October heat. However, as the monsoon fades, the temperature increases, and the humidity drops once again. The temperature dips in November and December. Monthly averages of all months except January, February and December were found to be uncomfortable in the base case according to the Adaptive Comfort Model. Month with highest level of discomfort was May for both the houses. Alufoil, Fiberglass insulation and Reprocessed Tetrapak sheets seem the better options for application according to their price, performance, and maintenance prospects out of all the other options.

Conclusion

Informal settlements reflect urban growth in cities and is a part of its economic workforce. Often only the socio-economic and sanitation aspects are studied when it comes to marginalised housing. Studying thermal comfort is important because it affects the day-to-day activities and productivity of the occupants. The women residents are usually the 24 hours occupants and do strenuous activities which produce heat and increase thermal stress indoor Thus, this research takes a closer look at improving their thermal comfort as a parameter of living conditions by studying the built environment in slums and their community. Through this research, the summer month was found problematic in terms of thermal comfort. However, lack of space indoors makes activities such as cooking, cleaning the main cause of heat stress and discomfort. Though these daily activities can't be curbed, the thermal performance of the house can surely be improved through proper material selection and passive strategies in design. It is clearly seen through these simulation results that efforts to mitigate the impact of thermal stress can be done through efficient and affordable materials. Future research can look to formulate guidelines for improving the building envelope of the existing informal housing through these retrofitting solutions which are in-situ and which act as an optimal solution to provide thermal comfort. The residents also spend a considerable amount of their time outdoors for various activities and due to space limitation, thermal comfort also needs to be looked in these outdoor spaces. Further studies should also seek occupants and users' perception of these spaces and incorporate their feedback to the retrofitting solutions and its adaptability.

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