EFFECT OF OPAQUE BUILDING ENVELOPE MATERIAL THERMAL PROPERTIES ON INDOOR THERMAL COMFORT

N. C. Balaji[1], Monto Mani[2], and B. V. Venkatarama Reddy[3]

[1] Research Scholar, Centre for Sustainable Technologies, Indian Institute of Science, Bangalore
[2] Associate Professor, Centre for Sustainable Technologies, Indian Institute of Science, Bangalore
[3] Professor, Department of Civil Engineering, Indian Institute of Science, Bangalore

ABSTRACT

The current study investigates the influence of building envelope materials on indoor thermal comfort in three Indian climatic zones. The study involves actual field measurements and validated simulation model. Two envelope materials were considered for this study are conventional material (Autoclaved Aerated Concrete blocks and Table moulded bricks), and low carbon (low embodied energy) material (Flyash blocks and Cement stabilized soil blocks).

Thermal comfort studies have been based on ASHRAE standard 55 to discern the effect of building envelope materials on indoor comfort. The study results reveal the impact of materials thermal properties in regulating indoor thermal comfort and their suitability for different climatic conditions.

INTRODUCTION

Energy consumption in buildings is the largest single share among all sectors. Most energy consumption is towards cooling and heating of building for indoor thermal comfort. In tropical regions like India, cooling load requirement will be higher. To reduce building energy consumption and to improve building energy efficiency an understanding of the building envelope and its components is necessary. The building envelope is primarily responsible for regulating indoor thermal comfort in response to external climatic conditions. The building heat gain/loss is regulated by the building envelope and can be evaluate based on the indoor thermal comfortable hours. The material selection for envelope component is a challenging task, which should be durable and cost effective, and contribute to energy efficient performance of the building. The energy efficiency of a building depends on the material used in the envelope configuration. The main objective here is to study the impact of building-envelope material on indoor comfort, and thereby evaluate the envelope material suitability for a particular climatic condition

METHODOLOGY

DESCRIPTION OF SITE AND BUILDING

The study has been conducted on three naturally ventilated buildings, one from each climatic zone of India. Centenary visitor's house in moderate climate from Bangalore, residential building from composite climate from Jaipur, and twin residential quarter building from warm-humid climate from Challakere, Chitradurga district (see Figure 1). All three buildings have been modeled in DesignBuilder (3.4.0.064 version) software and validated based on measure data, for building climatic response and thermal comfort studies.

Figure 1 Three buildings from three difference climatic conditions (A) Centenary visitors house, Bangalore. (B) Residential building, Jaipur and (C) Twin residential quarter buildings, Challakere

CLIMATIC CONDITIONS

Following three representative cities/towns have been taken for this study. Bangalore is capital city of Karnataka; its location lies in 12°58' north latitude and

77°34’ east longitude, and is at an altitude of 921m above mean sea level. According to ECBC 2007, it falls in moderate climatic zone of India. The monthly mean outdoor temperature varies between 20.5 °C to 27.6 °C.
Jaipur city is capital of Rajasthan; its location lies in 26°49’ north latitude and 75°48’ east longitude, and is at an altitude of 390m above mean sea level. According to ECBC 2007, Jaipur is in composite climatic zone of India, but as per SP-41 (SP 41, 1987); It is in hot and arid zone. However, in this study Jaipur has been considered as composite climate as per ECBC 2007. The monthly mean outdoor temperature varies between 15.6 °C to 33.4 °C.
Challakere town in Chitradurga district of Karnataka; its location lies in 14.44◦ north latitude and 76.58◦ east longitude, and is at an altitude of 525m above mean sea level. According to ECBC 2007, Challakere falls in warm-humid climatic zone of India. The monthly mean outdoor temperature varies between 22.8 °C to 29.5 °C.
Figure 2 shows the mean monthly outside dry bulb temperature (DBT) for a one year (8760 hours) of Jaipur, Bangalore and Challakere.

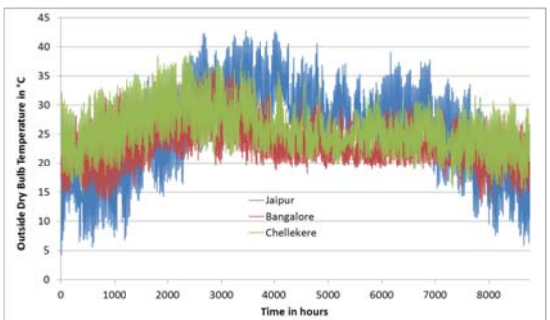

Figure 2 Variation of outside dry bulb temperature of Jaipur, Bangalore, and Challakere

DESCRIPTION OF BUILDINGS

JAIPUR BUILDING

The residential building considered in the composite climate of Jaipur is a two-storey building with a built up area of 225.03 m^3. Comprising 2 bed rooms, 2 children rooms, 1 stair case room (open to sky), 2 guest rooms and a television room at ground floor, and 2 storage rooms at first floor, one over children room and another over television room. The building faces east with a 16° tilt towards south. The building was occupied during the study period. Air temperatures were logged at children room at ground floor and storeroom at first floor measured and data logged at an interval of 30 min for a year.
The construction details of the building include, 260mm thick masonry walls in cement mortar, having cement plaster and lime wash on both sides. Roof comprises 150mm reinforced cement concrete, cement concrete flooring. Fenestration includes wooden doors, windows and lintels. The entire dwelling has been modeled in DesignBuilder.

BANGALORE BUILDING

The building considered in moderate climate of Bangalore is a Centenary Visitor’s House (CVH) at Indian Institute of science. It is 4 storey building (ground + 3 floor structures) has 108 studio apartments and few common rooms for reading, recreation room, kitchen, dining, and reception. For the study purpose, a reading room on the second floor was chosen. Temperature and relative humidity measured were monitored at five different locations within the room at an interval of 30min for a period of 1 year. The building is oriented towards the north face tilted towards east at an angle of 18°. The room was empty with no occupants during the study period.
The building comprises a framed structure with 230mm thick cement concrete block infill masonry walls in cement mortar, having cement plaster and washable paint on both sides. Floor comprise of 150mm reinforced cement concrete (RCC) and with 40mm weathering course, 25mm thick mosaic tile flooring. Fenestration includes wooden doors and iron frame windows with hatched glass shutters. The study portion of the building and adjacent rooms have been modeled in DesignBuilder.

CHALLAKERE BUILDING

A twin residential quarter buildings has been considered in warm-humid climate of Challakere oriented in opposite directions with a common back wall. One of the two detached houses has been considered for this study. The buildings are located in Indian Institute of Science, Kudapura campus, Challakere, Chitradurga district of Karnataka. The building includes a hall, bedroom, verandah, kitchen, bathroom, with the toilet outside the building. In Challakere, two buildings B2 and B11 were monitored. Both these two buildings are oriented in different direction. The building B2 oriented to north face tilted towards east at an angle of 74° direction and B11 orientated to south face tilted towards west at an angle of 106° direction. Air temperature and relative humidity measured at hall and bedroom for both B2 and B11 buildings and data logged at an interval of 30 min for one year.
The construction details include, 260mm thick masonry walls in cement mortar, having 10mm cement plaster and lime wash on both sides. Roof is made up of 150mm reinforced cement concrete, cement concrete flooring. The fenestration includes wooden doors and windows with stone lintels. The roof comprises of 125mm thick having internal ceiling plaster and external weathering screed. The buildings was intermittently occupied, and these occupancy details have been considered in simulation model. Complete building simulation model was done in DesignBuilder software for this study.

MEASUREMENTS

Temperature and relative humidity was measurements were carried out within the building. Supco LTH (having temperature accuracy of ±1°C, 0.05°C resolution and relative humidity accuracy of ±2% full scale, 0.1% RH resolution) and LT2 (having accuracy of ±0.5°C, 0.05°C resolution) data logging instruments were used.

VALIDATION OF SIMULATION MODELS

In this study, all three building models have been validated and used for further studies to understand the thermal comfort response attributed to building components. The reliability of a simulation model is based on the how well model it is validated. Validation includes fine-tuning/calibrating the model to yield near real-time (observed) behavior and is normally carried out with reference (statistical) to measured data. The simulation model has been validated adopting statistical indices (MBE, RMSE, and C_vRMSE). Comparing the output from simulation to measured values, a number of parameters were fine-tuned (such as varying the absorptivity, thickness, thermal properties, etc…) to the simulation model for reducing the error to acceptable ranges/limits. Shivraj (2013) also adopted a similar methodology to reduce the MBE and C_vRMSE error. Sedki et.al. (2012) discusses the error percentage between measured and simulated indoor dry bulb temperatures by using the Root Mean Square Error (RMSE) method. Validation reduces the error between measured and simulated data of simulation model. The acceptable limits for the validation of simulation model suggested by the IPMVP and ASHRAE 14 were considered. Mean Bias Error (MBE) and C_vRMSE statistical indices as shown in equation 1 and 4 were used for calculations. The acceptable tolerance limits of statistical indices from different standards shown in Table 1.

STATISTICAL INDICES

Calculation of MBE and C_vRMSE are as follows

Mean Bias Error (MBE) is calculated using equation 1

$$MBE(\%) = \frac{\Sigma_{Period}\,(S-M)_{Interval}}{\Sigma_{Period}\,M_{Interval}} \times 100 \qquad (1)$$

The C_vRMSE is a normalized measure of variability between two sets of data.

$$RMSE_{Period} = \sqrt{\frac{\Sigma_{Period}\,(S-M)_{Interval}^{\;2}}{N_{Interval}}}$$

(2)

The mean of the measured data for the period is calculated

$$X_{period} = \frac{\Sigma_{Period}\,M_{Interval}}{N_{Interval}} \qquad (3)$$

The Cv(RMSE) is calculated using equation 4

$$C_v(RMSE_{period}) = \frac{\text{RMSE}_{Period}}{X_{Period}} \times 100 \qquad (4)$$

Table 1 Acceptable tolerance limits [FEMP (2008), ASHRAE 14 (2002), & IPMVP (2007)]

Validation type	Index	FEMP (%)	ASHRAE 14 – 2002 (%)	IPMVP (%)
Yearly	MBE $_{yearly}$	± 10	-	-
Monthly	MBE $_{monthly}$	± 15	± 5	± 05
	CvRMSE $_{monthly}$	10	15	20
Hourly	MBE $_{hourly}$	-	± 10	± 10
	CvRMSE $_{hourly}$	-	30	30

THERMAL COMFORT

Thermal comfort been defined by ASHRAE standard 55 – 2004, as *"condition of mind which expresses satisfaction with the thermal environment"*. In thermal comfort studies, a number of factors affect the building indoor thermal environment. There are two personal and four environmental conditions determining thermal comfort. Personal factors include activity level (i.e., metabolic rate) and clothing (insulation) and environmental factors include air temperature, mean radiant temperature, air velocity and relative humidity.

There are two approaches of thermal comfort studies, such as rational approach (steady-state model) and adaptive approach (adaptive model), in the study both thermal comfort approaches are adopted.

THERMAL COMFORT STUDIES (RATIONAL APPROACH)

ASHRAE standard 55 – 2004 defines winter and summer comfort temperature band, for calculating thermal comfort hours. The range of operative temperatures for thermal comfort conditions in winter is 20.00 °C ~ 24.44 °C and in summer is 23.33 °C ~ 27.22 °C. Summer and winter months have been calculated based on T_{mmo}, If T_{mmo} was found lower than the lower limit of summer then it is considered as winter months. In this approach, the range of operative temperatures considered as per ASHRAE standard 55 – 2004 is for 80% (occupant) acceptability. This 80% acceptance based on the 10% dissatisfaction criteria for general (whole body) thermal comfort based on the PMV-PPD index, and an additional 10% dissatisfaction attributed to local thermal discomfort.

ADAPTIVE THERMAL COMFORT STUDIES

Adaptive approach of thermal comfort originated from several field studies. The adaptive thermal comfort model, accommodates for the ability of occupants to achieve comfortable by operating windows, changes in clothing, and shifts in occupant expectations. Many researchers extensively study the acceptance limits of the thermal environment attributed to occupant's behaviour. ASHRAE adaptive thermal comfort model (ASHRAE Standard 55 – 2004) is used globally for. The comfort temperature is calculated based on monthly mean outside dry bulb temperature, as in Equation (5).

$$T_{comf} = 0.31\ T_{mmo} + 17.8 \quad (5)$$

For an 80% acceptable comfortable temperature ranges, a ± 3.5°C temperature tolerance is allowed with respect to calculated neutral temperature, as specified in ASHRAE standard. The monthly comfortable temperature ranges can be calculated using equation (6)

$$T_{comf\ range} = T_{comf} \pm 3.5°C \quad (6)$$

This acceptability range is assumed to account for all local and other thermal discomfort influences in the building (Richard & Brager, 2001).

THERMAL COMFORT MEASURES

After validating the as 'built case' simulation model, the model used for further studies. The total comfortable hours were calculated from building simulation results for various configurations of building materials. The operative temperatures obtained from simulation results used to calculate comfortable temperatures for rational and adaptive approach. Comfortable temperatures were derived for all four material cases and compared with as built case.

Table 2 shows the summer and winter comfortable temperature band and mean monthly outside dry bulb temperatures of Jaipur, Bangalore and Challakere. The Table shows the comfortable temperature and 80% acceptable comfortable temperature range calculated based on the ASHRAE standard 55 – 2004, adaptive thermal comfort model based on mean monthly temperature.

IMPLEMENTATION OF DIFFERENT BUILDING ENVELOPE MATERIALS

Total four building envelope materials considered to evaluate the building indoor thermal comfort in three climatic conditions. Two conventional materials (AAC blocks and Table moulded bricks), and two low carbon and low embodied energy materials (Flyash blocks and CSSB blocks) (Venkatarama Reddy, 2009 & Cabeza et.al., 2013) were selected based on availability. Table 3 shows the thermal properties of these materials used in the simulation studies. In this study, Thermal comfort hours evaluated through building simulation model by varying materials thermal properties (by retaining the properties of other elements in envelope such as plaster and surface finishes). Further, thermal comfort hours were evaluated for composite (Jaipur), moderate (Bangalore), and warm-humid (Challakere) climates based on the two thermal comfort approaches. The simulation study based results were compared with the base case performance to evaluate thermal comfort and performance for the various climatic conditions.

Table 2 Thermal comfort and Adaptive thermal comfort hour's range of Jaipur, Bangalore and Challakere as per ASHRAE standard 55 – 2004

	Composite climate (Jaipur)				Moderate climate (Bangalore)				Warm-humid climate (Challakere)			
Month	**Tmmo**	**T_{comf}**	**Range**	**T_{comf} ±3.5**	**Tmmo**	**Range**	**T_{comf}**	**T_{comf} ±3.5**	**Tmmo**	**Range**	**T_{comf}**	**T_{comf} ±3.5**
Jan	15.6	22.64	20.00 - 24.44	19.14 – 26.14	23.82	23.33 - 27.22	25.18	21.68 – 28.68	23.9	23.33 - 27.22	25.21	21.71 – 28.71
Feb	17.8	23.32	20.00 - 24.44	19.82 – 26.82	23.38	23.33 - 27.22	25.05	21.55 – 28.55	26.29	23.33 - 27.22	25.95	22.45 – 29.45
Mar	23.8	25.18	23.33 - 27.22	21.68 – 28.68	26.04	23.33 - 27.22	25.87	22.37 – 29.37	29.29	23.33 - 27.22	26.88	23.38 – 30.38
Apr	30.2	27.16	23.33 - 27.22	23.66 – 30.66	27.58	23.33 - 27.22	26.35	22.85 – 29.85	29.52	23.33 - 27.22	26.95	23.45 – 30.45
May	33.4	28.15	23.33 - 27.22	24.65 – 31.65	26.83	23.33 - 27.22	26.12	22.62 – 29.62	29.13	23.33 - 27.22	26.83	23.33 – 30.33
Jun	33.4	28.15	23.33 - 27.22	24.65 – 31.65	23.76	23.33 - 27.22	25.17	21.67 – 28.67	25.9	23.33 - 27.22	25.83	22.33 – 29.33
Jul	30	27.1	23.33 - 27.22	23.6 – 30.6	23.36	23.33 - 27.22	25.04	21.54 – 28.54	25.17	23.33 - 27.22	25.6	22.1 – 29.1
Aug	28.7	26.7	23.33 - 27.22	23.2 – 30.2	22.68	20.00 - 24.44	24.83	21.33 – 28.33	24.48	23.33 - 27.22	25.39	21.89 – 28.89
Sept	29.2	26.85	23.33 - 27.22	23.35 – 30.35	23.26	20.00 - 24.44	25.01	21.51 – 28.51	24.75	23.33 - 27.22	25.47	21.97 – 28.97
Oct	26.9	26.14	23.33 - 27.22	22.64 – 29.64	22.91	20.00 - 24.44	24.9	21.4 – 28.4	24.87	23.33 - 27.22	25.51	22.01 – 29.01
Nov	21.9	24.59	23.33 - 27.22	21.09 – 28.09	21.77	20.00 - 24.44	24.55	21.05 – 28.05	23.45	23.33 - 27.22	25.07	21.57 – 28.57
Dec	16.1	22.79	20.00 - 24.44	19.29 – 26.29	20.54	20.00 - 24.44	24.17	20.67 – 27.67	22.82	20.00 - 24.44	24.87	21.37 – 28.37

Table 3 Building envelope (wall) materials and their properties used in building simulation model

Case no.	**Materials**	**Thickness in mm**	**Thermal conductivity in W/(m K)**	**Specific heat capacity in J/kg K**	**Density in kg/m^3**
1	As built case	Properties are as per exiting/original building materials			
1.1	As built case – Jaipur	260	0.811	880	1820
1.2	As built case – Bangalore	230	0.811	1000	1820
1.3	As built case – Challakere	230	0.850	840	1500
2	AAC*	As per case study	0.166	1450.5	700
3	Flyash*		0.856	930.9	1650
4	CSSB*		1.184	1036.4	1800
5	TMB*		0.564	1020.5	1775

* Experimentally measured values

RESULTS

MEASUREMENTS

The simulation results were in consonant with actual measurements. The variation in measured average air temperatures was 1.08°C, 0.21°C and 1.72 °C for Jaipur, Bangalore and Challakere buildings respectivity.

VALIDATION OF SIMULATION MODEL

Based on hourly simulation of air temperature, percentage MBE and CvRMSE were computed. Lower the values of MBE and CvRMSE implies consonance with real-time performance. To decrease these statistical errors, several iterations were carried out till the simulated temperature matched measured temperature within a specified range (see Table 1). Kreider and Harberl (1994) showed the best simulation models yield CvRMSE in the 10 to 20% range. Dhaka (2013) work achieved 8 to 14%. The acceptable limits/tolerances of MBE and CvRMSE values as per ASHRAE 14-2002, FEMP, and IPMVP standards shown in Table 1.

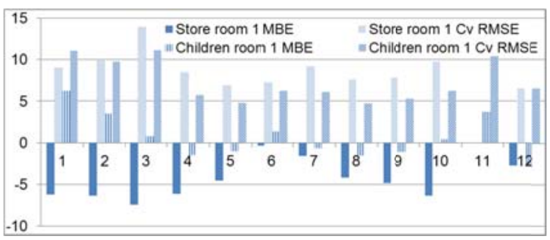

Figure 3 MBE and CvRMSE values for Jaipur residential building simulation model

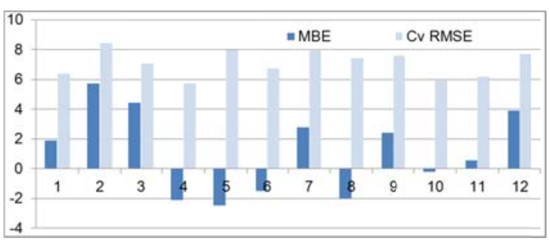

Figure 4 MBE and CvRMSE values for Bangalore building simulation model

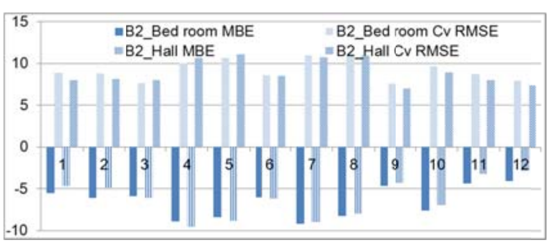

Figure 5 MBE and CvRMSE values for Challakere B2 building simulation model

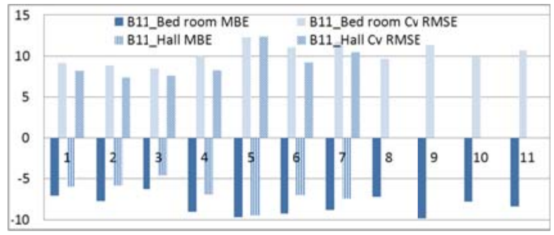

Figure 6 MBE and CvRMSE values for Challakere B11 building simulation model

Figure 3 to 6 shows the MBE and CvRMSE values of validated simulation models for every month, with hourly-simulated data for Jaipur, Bangalore and Challakere buildings.

THERMAL COMFORT STUDIES

In this study, the effects of material thermal properties on indoor thermal comfort were studied based on comfortable hours. Rational and adaptive comfort approaches were adopted. To access comfort in different building envelope materials as listed below, with their properties illustrated in Table 3.

1. As built case
2. Autoclaved aerated concrete blocks (AAC)
3. Fly-ash bricks
4. Cement stabilized soil blocks (CSSB)
5. Table moulded bricks

For rational thermal comfort approach, ASHRAE defines PMV in narrow bandwidth of -0.5 to +0.5PMV as comfortable, whereas in adaptive thermal comfort PMV varies from -1 to +1 for 80% acceptable comfortable range.

COMPOSITE CLIMATE (JAIPUR)

Figure 7 shows the thermal comfort hours obtained through rational approach in a composite climate of Jaipur building. In composite climatic conditions, building envelopes are expected to resist heat gain in summer and prevent heat loss in winter. In building, storeroom 1 and storeroom 2 shows lower number of thermal comfort hours compared to others rooms. These rooms are located on the first floor with greater exposure to solar radiation, making the indoors uncomfortable. The ground floor room's shows some improvement in the comfortable hours when using the AAC blocks as envelope materials compared to others, but overall performance of other material remain comparable. An AAC blocks have low thermal conductivity value and hence has a higher insulating capacity in comparison to other materials. Balaji (2013) earlier showed that cellular concrete having similar AAC block thermal properties, exhibit low decrement factor, which moderates heat gain amplitude into the building. This enables material to perform better in composite climate. AAC blocks improved comfort hours by 4 to 9%.

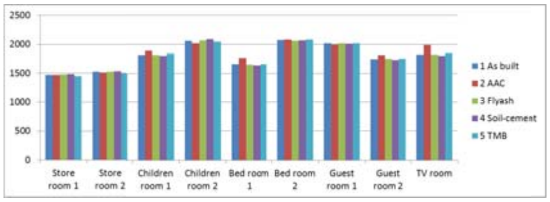

Figure 7 Thermal comfort hours in a composite climate of Jaipur as per ASHRAE 55 (rational approach) for all cases of materials

Figure 8 shows the thermal comfort hours obtained through adaptive comfort approach in a composite climate of Jaipur. The trends were similar to that of rational approach. The increase in the comfortable hours from rational approach to adaptive approach is almost 2.5 times. This can be attributed to the wider range of acceptable thermal comfort from -0.5 to -1.0 PMV and +0.5 to +1.0 PMV. Total thermal comfort hours given in Table A1 of Appendix-1.

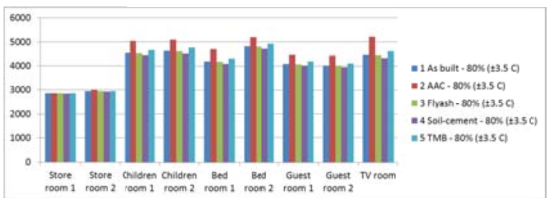

Figure 8 Thermal comfort hours in a composite climate of Jaipur as per ASHRAE 55 (adaptive thermal comfort approach) for all cases of materials

MODERATE CLIMATE (BANGALORE)

Figure 9 shows the thermal comfort hours obtained through rational approach in a moderate climate of Bangalore for reading room in the building. It is observed that by using CSSB blocks as envelope materials, total number of comfortable hours increased more than 50% from 8760hrs (total no. of hours for a year). Similarly, as built case material, flyash bricks and table moulded bricks perform comparably to CSSB blocks. Flyash bricks and CSSB blocks, as building envelope are preferred in this moderate climate.

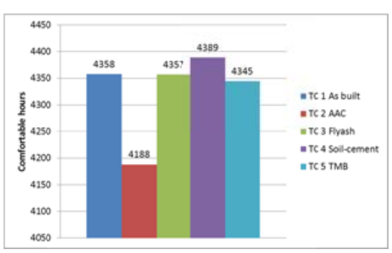

Figure 9 Thermal comfort hours in a moderate climate of Bangalore as per ASHRAE 55 (rational approach) for reading room in the building for all five cases of materials

Figure 10 shows the monthly thermal comfort hours obtained through adaptive comfort approach in a moderate climate of Bangalore for reading room in the building. Similar trends were observed in comparison with rational approach. There is an increase of 45 to 68% of comfortable hours from rational approach. In moderate climate, the performance of AAC block is not satisfactory with respect building comfortable studies. The use of high thermal mass material such as CSSB and flyash blocks as building envelope is advisable.

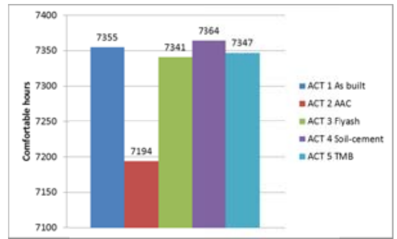

Figure 10 Thermal comfort hours in a moderate climate of Bangalore as per ASHRAE 55 (Adaptive thermal comfort approach) for reading room in the building for all five cases of materials

WARM- HUMID CLIMATE (CHALLAKERE)

Figure 11 shows the thermal comfort hours obtained through rational approach in a warm-humid climate of Challakere for bedroom and hall of B2 and B11 buildings. In this case, there are two buildings B2 and B11 buildings orientated in opposite directions. It is observed that the CSSB and flyash blocks envelope performs well compare to other materials, for both buildings oriented in opposite directions. This reveals that building envelop in certain cases have an overriding influence on (over orientation) in regulating indoor thermal comfort.

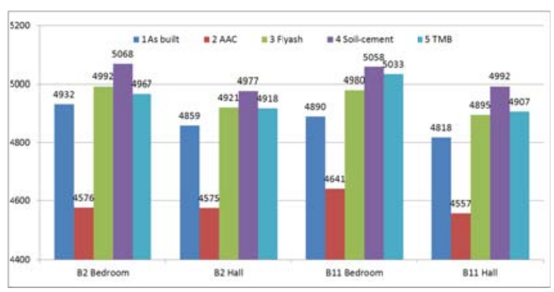

Figure 11 Thermal comfort hours in a warm-humid climate of Challakere as per ASHRAE 55 (rational approach) for bedroom and hall in the B2 and B11 building for all five cases of materials

Figure 12 shows the thermal comfort hours obtained through adaptive approach in a warm-humid climate of Challakere for bedroom and hall of B2 and B11 buildings. Similar trends were obtained for rational thermal comfort approach. AAC blocks having comparatively better insulating property reveal little improvement in indoor comfortable hours. Dhaka (2013) found wall insulation to be not effective in naturally ventilated buildings under warm-humid climatic conditions. The CSSB block shows better performance than all other cases. Another property, which could have a significant role in regulating indoor thermal comfort, is the hygroscopic property of a building material. Jaquin (2009) shows the mechanism by which earth buildings (for example, sun dried mud bricks, rammed earth, soil-cement blocks and cob) regulate relative humidity in his study. This however is not in the scope of the current study. As such, the Challakere climate is warm-humid; CSSB blocks are suitable for this climatic condition, which has high thermal mass.

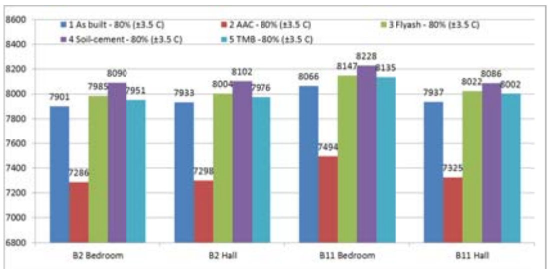

Figure 12 Thermal comfort hours in a warm-humid climate of Challakere as per ASHRAE 55 (adaptive thermal comfort approach) for bedroom and hall in the B2 and B11 building for all five cases of materials

CONCULSIONS

In this study, investigation on the influence of building envelope materials on indoor thermal comfort carried out. Three buildings from each climatic zone of India are considered and study involves field measurements and simulation studies through building simulation models. Thermal comfort analysis (rational and adaptive approaches) carried out as per ASHRAE standard 55 – 2004 to understand the effect of building envelope materials on indoor comfort.

Following are the main conclusion of the study

- The AAC block behaves as insulating material can use in composite climate as envelope material.
- In moderate climatic conditions, flyash and CSSB blocks can use efficiently in regulating indoor thermal comfort. Moreover, table moulded bricks can also use. However, usage of flyash and CSSB blocks are suggested, which can reduce use of high energy materials in building by making building energy efficient.
- In warm-humid climate, the envelope material used should preferably regulate both indoor temperature and humidity. CSSB is likely to be a suitable materials.

This study will be advantageous in understand the basic thermal behaviour of the conventional and low carbon and low embodied energy materials, when integrated in building as envelope material.

To increase the performance of the buildings, studies with thermal mass and other passive cooling strategies can also incorporate in regulating indoor comfort.

NOMENCLATURES

T_{mmo}	= Mean monthly outdoor dry bulb temperature in °C
T_{comf}	= Comfortable temperature in °C
T_{db}	= outside dry bulb temperature in °C
T_o	= Inside operative temperature in °C
T_{comf}	= Comfortable temperature in °C
MBE	= Mean bias error in %
RMSE	= Root mean square error
C_vRMSE	= Coefficient of variation of RMSE in %
N	= Number of hours
M	= Measured temperature during the time interval
S	= Simulated temperature during the same time interval
CSSB	= Cement Stabilized Soil Blocks
AAC	= Autoclaved Aerated Concrete
TMB	= Table Moulded Bricks

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APPENDIX-1

Table A1 Thermal comfortable hours in composite climate of Jaipur as per ASHRAE 55 (Rational & Adaptive thermal comfort approach) for all cases of materials

Case	**As built**		**AAC**		**Flyash**		**CSSB**		**TMB**	
TC Approach	**TC**	**ATC**	**TC**	**ATC**	**TC**	**ATC**	**TC**	**ATC**	**TC**	**ATC**
Store room 1	1466	2855	1470	2865	1476	2854	1481	2841	1446	2863
Store room 2	1522	2944	1509	3005	1526	2942	1533	2935	1493	2943
Children room 1	1818	4535	1886	5035	1815	4524	1804	4436	1839	4667
Children room 2	2059	4622	2016	5087	2067	4604	2084	4503	2043	4754
Bed room 1	1657	4199	1764	4700	1655	4179	1640	4087	1661	4314
Bed room 2	2069	4817	2076	5193	2059	4796	2063	4708	2081	4919
Guest room 1	2015	4096	1990	4459	2013	4082	2004	4031	2014	4200
Guest room 2	1747	4028	1819	4412	1749	4021	1729	3949	1751	4109
TV room	1824	4456	1987	5205	1823	4441	1803	4334	1846	4613