MTECH THESIS REPORT

COMPUTATIONAL INVESTIGATION OF ENERGY CONSUMPTION IN BUILDINGS USING DIFFERENT BIO-INSPIRED MATERIALS AS CONSTITUENT WALL MATERIAL.

by

SABIL HASAN

(2022MEM1003)

Under the supervision of

Dr. Ramjee Repaka & Dr. Navaneeth K.M

Department of Mechanical Engineering

Indian Institute of Technology Ropar

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Certificate

I, hereby submit my M Tech. Project progress report, detailing the work done by me this semester. I certify that this is my original work, and the material referred to from other sources (books, manuals, journals, conference proceedings, etc.) has been duly acknowledged.

Date: 28 June 2024

Sabil Hasan

(2022MEM1003)

The student has worked under my/our supervision for the above-mentioned work. I/We have read this progress report; it meets my/our expectations and accurately reflects the work done by the student.

Date: 28 June 2024

Dr. Ramjee Repaka & Dr. Navaneeth K.M

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Abstract

With the increase in population and advancement in technologies there is a huge increase in the commercial and residential infrastructure resulting in a huge demand for energy for the building to meet the need for heating, cooling, and lighting of the space to maintain a good quality of indoor environment. In India electricity consumption in the commercial and domestic sector accounts for about 34% of electricity consumption for heating, ventilation and air conditioning (HVAC) and lighting [1]. In buildings major portion of heat transfer takes place through the walls resulting in a large increase in the cooling and heating load of the building [2]. In the present study, we are trying to investigate the feasibility of using biomaterial as a constituent for building wall material that can reduce the annual energy consumption of the building. Different types of biomaterial for walls, insulation, and some bioinspired glass for application in windows are considered. Different climatic zones have been selected for simulation for energy consumption analysis.

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Nomenclature

Symbols

P	Perimeter of the surface
A	Surface area
h_f	Forced convection heat transfer coefficient
h_n	Natural convection heat transfer coefficient
R_f	Surface roughness multiplier
W_f	Wind direction modifier
T_o	surface temperature of the outside surface
T_{air}	Outdoor temperature of the air
ΔT	Surface and air temperature difference
V_z	Speed of wind
Φ	Angle between the normal ground and surface

Chapter 1

Introduction

Rapid urbanization all over the world is leading to a huge rise in building construction, which is leading to enormous demand for energy supply. About one-third of the total energy consumption is due to the building sector [1]. The dramatic increase in HVAC energy consumption has led researchers, scientists, and the government to take a step toward a solution for the construction of buildings that are more green and sustainable for the environment. In India, the Indian Green Building Council (IGBC) has launched a system of rating for buildings based on the energy efficiency concept, motivating architects and engineers to build infrastructure to adopt more dependency on renewable sources of energy for buildings energy consumption in a more sustainable way to achieve net zero energy status, which India aims to achieve by 2070. To get a more sustainable solution that is in harmony with nature and the environment, we seek inspiration from nature itself. Biomaterials derived from natural sources can offer a wide range of thermal, hygrothermal, acoustic, and structural properties and characteristics that can be thought of as an alternative to conventional construction materials such as burnt bricks, steel, and concrete. In this study, biomaterials are seen as having the potential to enhance the energy performance and sustainability of buildings. This research is looking into reducing the energy consumption of the building using various biomaterials such as rice straw bales, hempcrete, hemp-lime composite, date palm ash blocks, mycelium-based composite, rammed earth, bamboo bio-concrete, rye straw, rice husk, sugarcane bagasse ash brick, cork as transformative elements in the construction of building walls and insulation material with a focus on reducing energy consumption.

1.1. Motivation

For a fast-developing nation in the infrastructure field like India, there are challenges for sustainable development. One of the major consumers of energy is the building sector, which is of great concern. India has a diverse climate with a huge population, and existing building consumption shares a large part of total annual energy consumption and is responsible for greenhouse gas emissions. To take measures to reduce the above problems, the building sector needs more innovative and nature-friendly solutions for buildings to reduce the existing energy load. Bioinspired materials, when suitably modified and applied as building materials, can significantly improve thermal insulation, thermal inertia, and adaptation to varying climatic conditions, providing energy-efficient buildings. The ultimate motivation of this work is to find, through computational investigation, some biomaterials for application in building as a wall material that take into account India's diverse climate zones and provide solutions that should be locally feasible and in harmony with the natural environment.

Chapter 2

Literature Review

Improvement in the building construction strategy involving the use of bio-inspired materials, improvement in the HVAC system, and modifying the design of the envelope architecturally or from thermally effective and sustainable material can lead to energy-efficient building from an energy consumption point of view. The basic approach followed is generally comprised of controlling energy transfer through the envelope, and windows of the buildings through conduction, convection, and radiation. Materials with low and very low thermal conductivity can be considered for application in the building envelope as a constituent material for brick or insulation. Inspired by the unique hollow microstructure of polar bears hair Zhan et al. [3] developed a carbon nanotube aerogel of thermal conductivity (~ 0.023 W/mK) which can be used as an insulation material in the buildings. Bakatovich et al. [4] characterized various thermal insulating plates manufactured from agricultural waste of vegetables.

Table 2.1 Characteristics of insulating material [4].

Composition			Average physical and mechanical characteristics*			
Number	Fiber	Binder	Density (kg/m^3)	Compression strength (MPa)	Bending strength (MPa)	Thermal conductivity (λ_{25}) W/(m·K)
1	Rye straw	Liquid Glass	215 (5.7)	0.35 (0.023)	0.82 (0.051)	0.059 (0.003)
2	Barley straw	Liquid Glass	205 (6.24)	0.27 (0.021)	0.58 (0.042)	0.063 (0.004)
3	Wheat straw	Liquid Glass	220 (5.91)	0.30 (0.026)	0.65 (0.038)	0.056 (0.004)
4	Oats straw	Liquid Glass	200 (4.74)	0.27 (0.025)	0.60 (0.041)	0.058 (0.004)
5	Rice straw	Liquid Glass	210 (5.7)	0.23 (0.021)	0.50 (0.038)	0.062 (0.005)
6	Flax boon	Liquid Glass	230 (5.05)	0.48 (0.031)	0.62 (0.047)	0.054 (0.004)
7	Rice husk	Liquid Glass	230 (5.43)	0.50 (0.032)	0.34 (0.026)	0.068 (0.004)
8	Rye straw and flax boon	Liquid Glass	225 (4.74)	0.60 (0.03)	0.95 (0.06)	0.049 (0.003)
9	Rye straw and flax boon	Latex	230 (6.12)	0.64 (0.036)	1.03 (0.066)	0.057 (0.005)
10	Rye straw and flax boon	Emulsion PVA	225 (5.7)	0.65 (0.029)	1.00 (0.065)	0.058 (0.004)
11	Rice straw and husk	Liquid Glass	230 (6.56)	0.43 (0.026)	0.68 (0.056)	0.058 (0.003)
12	Rice straw and husk	Latex	225 (6.67)	0.47 (0.03)	0.72 (0.053)	0.067 (0.005)
13	Rice straw and husk	Emulsion PVA	235 (7.14)	0,44 (0.036)	0.70 (0.058)	0.069 (0.004)

* - Numbers between brackets correspond to the standard deviation.

Wheat straw, rice straw, oat straw, barley flax boon, and rice husk were used with binders such as emulsion PVA, latex, and liquid glass to obtain the composite structure. Flax boon and rye straw and husk and rice straw plates showing the lowest thermal conductivity come out to be potential candidates as a biomaterial for cold climates. Marques et al [5] have carried out an experimental test to analyze the intrinsic characteristics like hygroscopic sorption properties, heat capacity, and resistance to biological decay of rice straw fibers in loose form and then experimental characterization for thermal, hygrothermal, and acoustics properties of rice straw bales to investigate the effectiveness as a building wall material with varying densities of 80kg/m^3 and 100 kg/m^3 along with a different combination of coating material lime mortar, gypsum, oriented strand board was considered for possible wall solution. Based on the findings it was found that rice straw bale can be a suitable sustainable wall material for buildings. There has been a review carried out by Alemu et al. [6] exploring the potential use of fungal (Mycelium) based composite material for the construction in the form of bio brick, bioconcrete, board, and biocement.

Table 2.2 Construction materials made of microbes [6].

No.	Species name	Kingdom	Products	Application	R
1	T. versicolor	Fungi	Bioblock	Thermal insulation	
2	*Ganoderma lucidum*	Fungi	Block	Insulation	
3	*Agrocybe aegerita*	Fungi	Block	Design and architecture	
4	*Aspergillus nidulans*	Fungi	Bioconcrete	Construction	
5	*Trametes versicolor*	Fungi	Block	Insulation	
6	*Ganoderma sessile*	Fungi	Block	Architecture	
7	*Pleurotus ostreatus*	Fungi	Block	Packaging	
8	*Trametes multicolor and Pleurotus ostreatus*	Fungi	Block	Construction	
9	*Rhizopus oryzae, Phanerochaete chrysosporium, A. terreus, A. oryzae*, and *Saccharomyces cerevisiae*	Fungi	Bioconcrete	Construction	
10	*T. ochracea* and *P. ostreatus*	Fungi	Board	Board	
11	Not specified (white-rot basidiomycete mycelium)	Fungi	Board	Particle board	
12	*Ganoderma* sp.	Fungi	Sheets	Packaging material	
13	Not specified	Fungi	Sheets	Insulation panel	
14	*Bacillus alkalinitrilicus* and *Bacillus licheniformis*	Bacteria	Biocement	Construction	
15	*Bacillus lentus*	Bacteria	Biocement	Construction	
16	*Bacillus pseudofirmus* and *Bacillus halodurans*	Bacteria	Bioconcrete	Construction	
17	*Bacillus sphaericus*	Bacteria	Bioconcrete	Construction	
18	*Xanthomonas campestris*	Bacteria	Biopolymer	Construction	
19	*Bacillus sphaericus*	Bacteria	Bioconcrete	Construction	
20	*Bacillus megaterium*	Bacteria	Bioconcrete	Construction	
21	*Bacillus subtilis*	Bacteria	Bioconcrete	Construction	
22	*Bacillus massiliensis*	Bacteria	Bioconcrete	Construction	
23	*Escherichia coli*	Bacteria	Bioconcrete	Construction	

Table 2.3 Mycelium-based materials with different strains and substrates [6].

Fungal species	Substrate type	Supplement	Moisture content (%)	Temperature (°C)	Incubation time (days)	Mold type	Drying method	Fabrication method	Target use	Compressive strength (kPa)
Trametes versicolor, Trametes multicolor, and *G. sessile*	Saw dust	Wheat straw	50	23	$6^a + 6^b$	Plastic mold	Oven-dried for 48 h at 60°C	—	—	—
—	Paddy straw, fine paddy powder, and saw dust	—	—	26–27	$(7\text{–}15)^a + 7^b$	Plastic mold	1000 C for 30–45 minutes	—	Construction materials	347
Pleurotus ostreatus	Sawdust, straw, and mixture	Wheat bran	67.5 ± 2.5	24 ± 1	$14^a + 3^b$	Plastic form work	Oven-dried at 90°C for 90 min	—	Construction materials	20 to 188
Ganoderma lucidum and *Pleurotus ostreatus*	Cellulose	PDA	70–80	25–30	20^b	—	60°C for 2 h	—	—	—
P. ostreatus, Pleurotus eryngii, and *Pycnoporus sanguineus*	Coconut powder	Wheat bran	60–70	25	$(15, 30, 45)^b$	—	—	—	—	0.02 ± 0.01 to 0.04 ± 0.01
Ganoderma lucidum	Cotton stalk	Cotton bran	65	25	7^b	Plastic mold	65°C for 10 hr	—	—	—
Pleurotus ostreatus	Sawdust	—	80	25	45^b	Plastic mold	At 130°C for 20 and 40 min	Heat press	Composite board	
Trametes multicolor and Pleurotus ostreatus	Sawdust and straw	—	65–70	25	14^b	Plastic mold	—	Heat press 150°C for 20 min	—	—
Pleurotus ostreatus	Bagasse, sawdust, and wheat bran	—	60	25	$14^a + 14^b$	Wooden mold	90°C for 12 hrs	10 kg load pressing	Packaging material, insulation, and furniture	6500
Pleurotus ostreatus, Volvariella, and Polyporus squamosus	Wood chips and hemp fiber	—	—	25	35^b	—	Oven-dried at 70°C for 18 hrs	Compressing with spoon	Design and architecture	452
Ganoderma sp.	Cotton carpel	Cotton seed hull and starch	—	21	6^b	Plastic mold	Oven-dried at 60°C for 8 hr	Hand press	Packaging	—
P. ostreatus, P. citrinopileatus, Pleurotus eryngii, and G. lucidum	Husk psyllium, flour, feathers, and textile	—	—	25	7^b	Glass beaker	Oven-dried at 90°C for 2 hrs	Hand press	Footwear products	124.80 to 340.08
—	Saw dust and rice bran	—	—	—	33^b	Steel mold	110–115°C for 24 hrs	—	Construction materials	4409 to 7990
Trichoderma asperellum, G. lucidum, Agaricus bisporus, P. ostreatus	Oat husk and rapeseed cake	—	—	21	$14^a + 7^b$	Plate	40°C for 48 hrs	Oil press	Plastic	16.8 to 299.6
G. lucidum	Rapeseed straw	Cellulose fiber	58	30	21^b	EPS mold	65°C for 24 hrs	Hand press	Wall insulation	845 ± 90.0
Coriolus versicolor and Pleurotus ostreatus	Wood chips, hemp hurd and fiber, and hemp mat	—	—	—	30^b	Plastic mold	125°C for 2 hrs	—	Plastic	24–93
Pleurotus ostreatus	Soil, xanthan gum, and guar gum	Hay, glycerol, and molasses	60–70	27	$20^a + 30^b$	Glass tank	—	—	Architectural activity	—
Trametes versicolor	Hardwood chips and hemp shives	—	70 ± 5	22 ± 2	—	Mold	93°C	—	Building materials	360 ± 50.0 to 520 ± 80.0
Trametes versicolor	Yellow birch wood veneers	—	80	28	18^b	—	—	Hot pressing	Wood bonding	1740
—	Sawdust and millet grain	Wheat bran	—	—	14	Tubular mold	60°C for 24 h	—	Biofoam	570

[a]Incubation period before mold. [b]Incubation period after mold.

These composites have features such as low emission, recycling, recyclable, and low cost. A suitable choice of substrate from agriculture waste like sawdust, straws, bagasse, etc. can be combined to get a better composite material with the desired thermal properties and mechanical stability for application as a building material. With a focus on eco-friendly materials having a low carbon footprint, Pochwala et al. [7] carried out an experimental investigation to determine the thermal properties of three hemp lime composites as an eco-friendly construction material for single-family buildings.

Fig.2.1 Sample of hemp lime composite mixture as a block [7].

Results obtained show that it is light and porous with a bulk density (300-400 kg/m^3) and thermal conductivity in the range of (0.038-0.055 W/mK), indicating excellent thermal insulation properties. A heat transfer coefficient of 0.11 W/m^2K and 0.20 W/m^2k was obtained for external and inside walls, respectively. An additional advantage of fire-resistant property was seen when a flame test was carried out. The study and results suggested that hemp-lime composite is a good alternative to conventional construction material without other insulating material for application in buildings when suitable supporting beams are used in combination. Caldas et.al [12] quantified the impact on climate change with bamboo bio concrete as a wall material. The concept of Bamboo Bio-concrete walls (BBC) is introduced, as depicted in Fig.2.2.These walls are crafted through the amalgamation of fly ash, metakaolin, and standard Portland cement with finely powdered bamboo. The mixture is supplemented with a $CaCl_2$ additive and water. The bamboo particles, derived from the by-products of bamboo laminating, serve as discarded materials.

Table 2.4 Properties of BBC panel [12].

Cod.	Material	Thickness	Density	λ	Mass
		mm	kg/m³	W/m.K	kg/m²
1 Bamboo bio-concrete (BBC 10 cm and BBC 20 cm)					
2	Mineral render	10	1900	1.15	19
1	BBC panel[1]	80/180	838	0.38	67.0/150.8
2	Mineral render	10	1900	1.15	19

From existing literature on the dynamic life cycle assessment of BBC, it is considered to be a good alternative to conventional wall material. It proves to improve carbon stock and reduce carbon footprint. Given its recent emergence, the BBC lacks a firmly established technological framework within the industry. Nevertheless, it is designed for construction using commonplace tools and machinery employed in the cast-in-place reinforced concrete process.

Fig.2.2 Sample of Bamboo bio-concrete (BBC) [12].

This BBC wall was tested and compared with conventional brick walls for Brazilian houses as a project. It was found that the BBC wall can be a measure of climate change mitigation and a good alternative to conventional walls where bamboo as a raw material is locally available.
The feasibility of cement-stabilized rammed earth rice husk ash wall was studied by Milan and Labaki [13] as a case study. The prototype building was created on a university campus as shown in Fig.2.3.

Fig.2.3 Prototype of CSRERHA wall house [13].

They investigated the use of rice husk as a sustainable material for the construction of walls. Rice husk ash was incorporated into cement-stabilized rammed earth. From the investigation, it was found that an ash content of 7.5% when stabilized with 10% cement in replacement of sandy soil proved to be a promising alternative high-quality construction material for energy-efficient buildings for environmental sustainability.

Table 2.5 Properties of CSRERHA wall [13].

Mixture ratio/characteristics	(92.5% soil + 7.5% ash) stabilized with 10%	(100% soil + 0% ash) stabilized with 10%
Density (kilograms per cubic meter)	1,600–1,700	1,850–1,950
Optimum moisture (percentage)	15–17	10–12
Water absorption (percentage)	17–18	11–12
Permeability (10^{-6} cm/s)	0.66	1.00
Rupture modulus (megapascals)	3.5–4.5	6.5–7.5
Elastic modulus (megapascals)	5,600–5,900	

Thermal characterization of the CSRERHA wall showed it is less thermally conductive than the soil-cement wall. It is due to the fact that rice husk ash particles have a more porous structure and contain more air which is a bad conductor of heat. Hence reducing heat flow through the wall. Characterization also showed that the CSRERHA wall has good thermal inertia and time lag and is also suitable for different climate zones.

Marques et al. [15] carried out experimental studies to describe the thermal conductivity, specific heat capacity, thermal stability, and water vapor resistance of rice husk and expanded cork granules. They focused on the development and characterization of innovative polymer-based composite materials incorporating rice husk and expanded cork by-products. The initial phase involved separate investigations into the material properties of rice husks and expanded cork granules, including thermal conductivity, water vapor resistance, thermal stability, and specific heat capacity. Subsequently, various composite formulations were created, and resulting boards were assessed for their mechanical, hygrothermal, and acoustic properties. The impact of different mix ratios and composite densities on overall performance was also analyzed.

Experimental results revealed that higher proportions of rice husk contribute to improved acoustic performance, while the inclusion of expanded cork granules reduces thermal conductivity and enhances mechanical behavior. The applicability of these composites in construction systems, such as walls and floors, was evaluated through a multi-criteria analysis, leading to the selection of the most suitable composite formulations. The static and dynamic thermal performance of building solutions incorporating these composites was then assessed. The findings suggest that such construction solutions can be utilized in buildings, thereby contributing to reduced energy consumption during the buildings' service life.

The study underscores the development of sustainable building solutions using polymer-based composite materials containing rice husk and expanded cork granules. Utilizing these by-products helps conserve resources and effectively manages agricultural waste materials with a significant environmental impact. Laboratory tests confirmed the energy storage potential and thermal stability of rice husk and expanded cork granules. Mechanical characterization demonstrated the good mechanical behavior of selected aggregates in composite boards, particularly when incorporating larger amounts of expanded cork granules.

Fig.2.4 Sample of Rice-husk expanded cork composite [15].

In terms of hygrothermal performance, results emphasized the influence of density on dimensional stability, water vapor resistance, and thermal conductivity. Acoustic performance improved with higher rice husk content, and impact sound insulation tests indicated potential improvements with lower density and higher rice husk content. Suitable composite formulations for wall and floor applications were selected through a multi-criteria analysis. The thermal performance of building solutions using these composites demonstrated improvements in thermal transmittance and thermal delay calculations for different thicknesses, emphasizing their potential to enhance the overall thermal performance of buildings. In conclusion, the incorporation of by-products in composite materials presents an environmentally friendly approach, supporting the development of technically feasible construction products with low environmental impact.

Table 2.6 Properties of Rice Husk Expanded Cork Composite [15].

	Material	Density, ρ [kg/m^3]	Thermal conductivity, λ [W/(m K)]	Specific heat, c_p [J/(kg K)]	Refs.
1	Core material (RHC)	199	0.0481	1782*	–
2	Surface material (RHC)	376	0.0634	1695 *	–

Two kinds of composites were taken into consideration for our analysis as possible wall solutions: 25RHC_200, which contains 25% rice husk and a final composite mass density of 200 kg/m3, and 25RHC_400, which contains 25% rice husk and a final composite mass density of 400 kg/m3, for both the core and surface components.

Madurwar et.al. [11] studied the suitability of bricks made up of sugarcane bagasse ash (SBA), which is usually confined to landfills. It has been reused to create a building material that facilitates trash disposal and functions as an energy-efficient substitute for construction. Particle size distribution, scanning electron microscopy (SEM), X-ray fluorescence (XRF), X-ray diffraction (XRD), and thermogravimetric analysis (TGA) were among the characterization techniques used on SBA. XRF, XRD, and physicochemical studies were performed, confirming its potential as a pozzolanic or cementitious material with thermal stability up to 650°C.

Fig.2.5 Sample of sugarcane bagasse ash (SBA) brick [11].

Bricks made of SBA, quarry dust (QD), and lime (L) were created with the goal of maximizing the use of SBA while preserving a consistent 20% weight-based lime content. These bricks underwent extensive testing in accordance with established requirements for physicomechanical, functional, durable, and environmental aspects. Evaluations in comparison between fly ash and traditional clay bricks showed that SBA-QD-L bricks fulfill the requirements, demonstrating their energy efficiency, non-hazardous nature, durability, and lightweight. By carefully evaluating each property, the study seeks to define SBA and identify the optimal SBA-QD-L brick composition.

Table 2.7 Properties of SBA brick [11].

	Material composition (%) ($230 \times 110 \times 80$ mm^3)														
Type of brick	Clay	Fly ash	SBA	Sand	QD	Cement	Lime	Weight (kg)	Density (kg/m^3)	Compressive strength (MPa)	Water absorption (%)	Thermal conductivity (W/mK)	Thermal conductivity (%)	Energy/1,000 bricks (GJ)	Brick energy (%)
Burnt clay	90	—	—	10	—	—	—	3.250	1,600	3.50	20	1.25	100	4.250	100
Fly ash	—	40	—	50	—	10	—	3.640	1,800	6.50	12	1.05	84	2.366	56
SBA-QD-L (Mix 7)	—	—	50	—	30	—	20	2.852	1,409	6.59	19.70	0.480	38	2.282	53
SBA-QD-L (Mix 6)	—	—	55	—	25	—	20	2.567	1,238	5.20	19.61	0.477	38	2.054	48
SBA-QD-L (Mix 5)	—	—	60	—	20	—	20	2.417	1,194	4.32	19.97	0.474	37	1.934	45
SBA-QD-L (Mix 4)	—	—	65	—	15	—	20	2.312	1,142	4.08	20.16	0.47	37	1.850	44
SBA-QD-L (Mix 3)	—	—	70	—	10	—	20	2.273	1,123	3.82	19.74	0.465	37	1.818	43
SBA-QD-L (Mix 2)	—	—	75	—	5	—	20	2.152	1,063	3.69	20.65	0.46	36	1.722	41
SBA-QD-L (Mix 1)	—	—	80	—	0	—	20	2.125	1,050	3.29	20.32	0.455	36	1.700	40

According to Indian standards, SBA's physicochemical characteristics support its appropriateness as a pozzolanic or cementitious material, placing it in class 3.5 for ordinary burnt clay bricks. Compared to conventional bricks, SBA-QD-L bricks, which are made of SBA, quarry dust, and lime, have up to 40% less weight and a higher compressive strength. When compared to traditional bricks, the production technique helps to significantly (up to 60%) reduce energy consumption, solving environmental issues related to the disposal of solid waste. This creative solution offers a feasible supply of energy-efficient building materials in addition to resolving the issue of how to dispose of sugarcane bagasse ash. The SBA-QD-L bricks that are manufactured have the potential to be used in local buildings, particularly in areas with typically high-temperature climates for non-load-bearing walls in inexpensive housing projects.

Ashraf et.al. [14] evaluated how mortar blocks, incorporating local agricultural waste, specifically date palm ash (DPA), perform in terms of thermal and energy efficiency. Their research involved casting mortar blocks with varying DPA percentages (10–30%) to replace ordinary Portland cement (OPC).

Table 2.8 Properties date palm ash brick [14].

Sample type	Description	Equivalent thermal conductivity (W/mK)	Specific heat capacity (J/Kg K)	Density (kg/m^3)	Thermal resistance (m^2K/W)
Type 1 (Base Case)	OPC_{100}-DPA_{0} (Normal mortar block)	0.81	2250	840	0.456
Type 2	OPC_{90}-DPA_{10}	0.693	2184	810	0.5
Type 3	OPC_{80}-DPA_{20}	0.537	2088	796	0.584
Type 4	OPC_{70}-DPA_{30}	0.434	2032	780	0.672

The resulting blocks met the standards for lightweight blocks outlined in ASTM C55-11, based on density data. The analysis indicates that including DPA improves thermal resistance by up to 47%, thereby enhancing the indoor environment and decreasing annual energy consumption by up to 7.6%. This results in an approximate 11% reduction in the production cost of masonry blocks, all while maintaining physical, chemical, and mechanical properties. The DPA-based blocks are considered more economical compared to conventional ones. They concluded that these innovative DPA-based blocks are sustainable products that contribute to the valorization of DPA waste. They also offer the potential for cost savings in both construction and operational expenses. The cost analysis identifies the 30% DPA replacement (Type 3) as the most effective option.

Brose et.al [16] partnered with the Hunnarshala Foundation in Bhuj, India to develop fiber cement composite for application in an envelope of the building. Coconut coir, pine wood fiber, and rattan as a composite ingredients in Portland cement, hydrated lime, and fly ash to fabricate the panel. Experimental investigation showed improved thermal properties of (0.16-0.19 W/mK) as compared to (1.60-1.88 W/mK) of conventional walls. The fabricated panel also showed improvement in flexural strength of up to 70% as an added advantage for the reduction of seismic failure compared to standard specimens.

Table 2.9 Composition of Coir Fiber Panel [16].

Sample	Coir fiber (g)	Sand (g)	OPC (g)	Hydrated lime (g)	Fly ash (g)	Water (g)	Density (g/cm^3)
Control Panel	0	1718	736	49	196	476	1.79
Coir Fiber Panel	103	957	736	49	196	476	1.52

Table 2.10 Properties Coconut Coir Fiber Panel [16].

Wall materials	Conductivity (W/m·K)	Density (g/cm^3)	Thickness (cm)
Sandstone Block	1.88	1.92	45.0
Coconut Coir Fiber Panel	0.168	1.52	2.0
Air Gap	0.111	0.001225	2.0

Sample	Conductivity (W/m·K)	Compressive strength (N/mm^2)	Modulus of rupture (N/mm^2)
Control Panel	0.174	21.98	2.62
Coir Fiber Panel	0.168	33.07	4.55

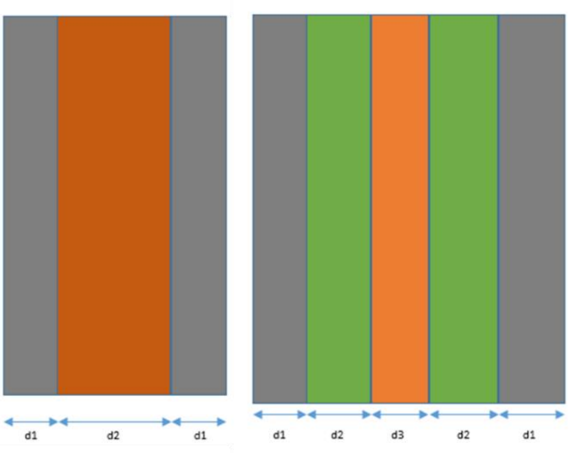
Annual energy simulation using EnergyPlus was performed by the group for hot climate (Bhuj, India) and cooler climate (Kathmandu, Nepal). The incorporation of a composite wall made of fiber cement panel in the model showed annual energy reduction both for heating and cooling.

Chapter 3

Designing of Walls

3.1 Design of wall based on reference papers to investigate the behavior of wall and its effects on annual energy consumption.

Below Fig.3.1 shows the schematic for different biomaterial walls considered for initial simulation results to see how the wall responds to various climatic conditions. Thickness for different biomaterials has been taken according to the respective reference papers. These walls will be compared with the test case and also among themselves. Winter and summer design day results will be used to compare the walls for different parameters to further design the walls according to the criteria discussed in section 3.2.



	Wall type 1	Wall type 2	Wall type 3	Wall type 4	Wall type 5	Wall type 6
d1	Mortar 2cm	Mortar 2cm	Mortar 2cm	Mortar 2cm	Mortar 2cm	Mortar 2cm
d2	HLC 40 cm	BAB 23cm	BBC 18cm	25RHC_200	CSRERHA 8cm	RSB-100 35cm
d3	-----------	-----------	------------	25RHC_400		

Fig.3.1 Schematic of wall.

HLC: Hemp-Lime Composite
RHC: Rice Husk Cork
BAB: Bagasse Ash Bricks
CSRERHA: Cement Stabilized Rammed earth Rice Husk Ash
BBC: Bamboo Bio-concrete
RSB: Rice Straw Bale

3.2 Criteria adopted for designing different types of walls.

1: Compressive Strength Criteria equivalent to standard brick wall [21]

$$C = C_1 + C_2 + C_{3+} \ldots. \tag{3.1}$$

$$C = f_1A_1 + f_2A_2 + f_3A_3 \ldots \tag{3.2}$$

Where

C_i – Compressive bearing capacity of the respective layer.

f_i – Respective axial compressive stress of the material

A_i – Area of the respective layer

2: Criteria for the optimum thickness of the homogeneous biomaterial [22]

$$T_{opt} = \gamma\sqrt{\frac{\alpha P}{\pi}} \tag{3.3}$$

Where γ – Modified thickness coefficient (Average of optimum thickness coefficient)

α – Thermal diffusivity of the biomaterial

P – The time period in seconds for a day

π – 3.14

Here in our case γ is taken as the average values from the table based on the properties of the biomaterial.

Table 3.1 Optimum thickness coefficient.

Optimum thickness coefficient of building envelope based on their thermal properties.

Optimum thickness coefficients	Thermal conductivity in W/(m K)	Density in kg/m^3	Specific thermal capacity in J/kg K	Thermal mass in kJ/K m^2	Thermal diffusivity in m^2/s
Low	< 0.5 **2.12**	< 1100 **2.12**	< 1000 **1.938**	$< 1.5 \times 10^6$ **2.079**	$< 4 \times 10^{-7}$ **2.062**
Medium/moderate	0.5–1.5 **1.939**	1100–2100 **1.939**	1000–1200 **1.951**		4×10^{-7} to 7×10^{-7} **1.933**
High	> 1.5 **1.885**	> 2100 **1.885**	> 1200 **2.088**	$> 1.5 \times 10^6$ **1.926**	$> 7 \times 10^{-7}$ **1.922**

Based on the above criteria different types of walls can be designed whose compressive strength will be comparable to the compressive strength of a standard wall and also optimum thickness criteria are used for maximum heat storage for the biomaterial layer.

3.3 Design of the wall based on the strength criteria and optimum thickness of the homogenous layer of biomaterial.

For the practical applicability of the biomaterial as a part of the envelope in buildings, different types of walls will be designed based on the strength criteria and optimum thickness for energy storage in the wall. For this, a standard wall made up of 22.5 cm of red burnt brick and with 2cm of mortar as both inside and outside layers have been considered as a standard case. All the biomaterial walls, pure or composite walls (11.25 cm of red burnt brick + biomaterial wall of similar strength) will have a strength comparable to that of the standard wall. Compressive strength criteria given by equations (3.1) and equation (3.2) are selected for the analysis to compare the strength of the designed wall. This will give the required thickness of the biomaterial wall when it is replaced with that of the standard wall. Some of the biomaterials like RSB, and RHEC have very little compressive strength with respect to burnt brick. It is suggested that these biomaterials should be used as insulation for the wall. Optimum thickness will be determined based on the given relation in equation (3.3). After determining the thickness, different feasible arrangements of layers of the wall have been taken into account for analysis. This will give different types of walls that can be designed to be analyzed for annual energy consumption.

Following are the design of walls for different types of biomaterial:

(1) Hemp-Lime Composite (HLC):

On comparing the compressive strength of 22.5 cm of the standard wall with that of the HLC wall using equations (3.1) &(3.2), the equivalent thickness comes out to be 75 cm. whereas the optimum thickness for maximum energy storage comes out to be 10.36 from equation (3.3). Based on these thicknesses, the following wall types are considered for energy analysis.

	$T_{o,Mortar}$(cm)	T_{HLC}(cm)	T_{brick}(cm)	T_{HLC}(cm)	$T_{i,Mortar}$(cm)
Case-1	2	0	11.25	37.5	2
Case-2	2	18.75	11.25	18.75	2
Case-3	2	37.5	11.25	0	2
Case-4	2	10	11.25	0	2

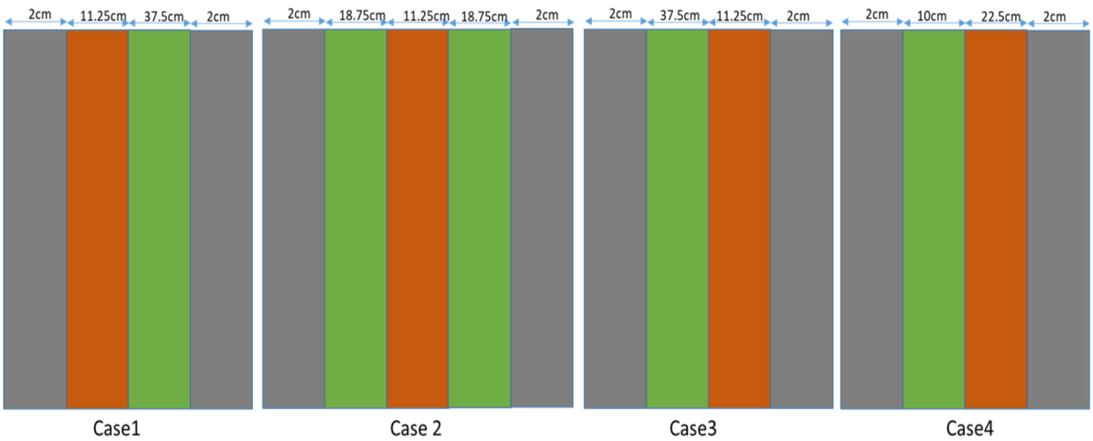


Fig.3.2 Design of wall for HLC

(2) Bagasse Ash Brick (BAB):

On comparing the compressive strength of 22.5 cm of the standard wall with that of the BAB wall using equations (3.1) &(3.2), the equivalent thickness comes out to be 34.14 cm. whereas the optimum thickness for maximum energy storage comes out to be 11.8 cm from equation (3.3). Based on these thicknesses, the following wall types are considered for energy analysis.

	$T_{o,Mortar}$(cm)	T_{BAB}(cm)	T_{brick}(cm)	T_{BAB}(cm)	$T_{i,Mortar}$(cm)
Case-1	2	34	0	0	2
Case-2	2	0	11.25	17	2
Case-3	2	17	11.25	0	2

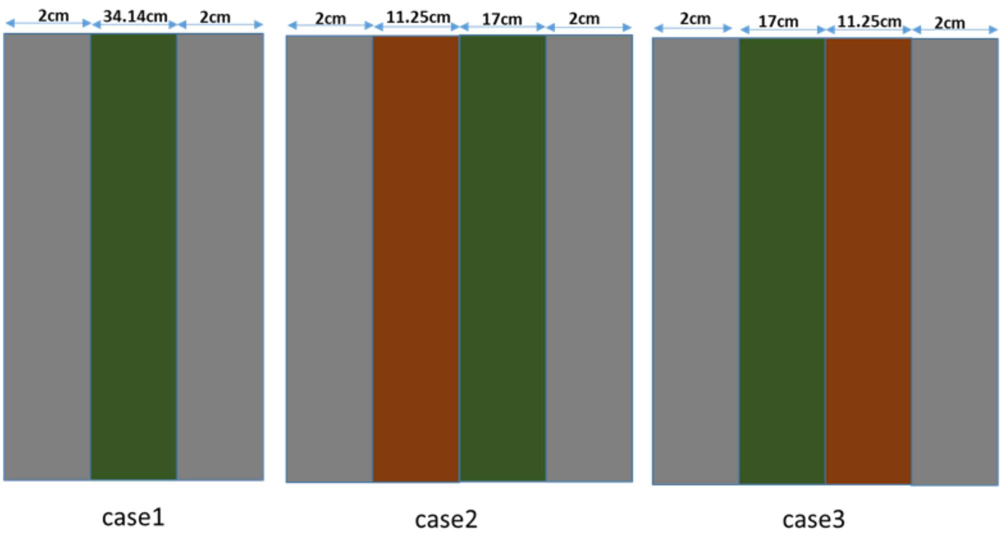


Fig.3.3 Design of wall for BAB

(3) Rice Husk Expanded Cork (RHEC):

RHEC having very less compressive strength than the standard wall can only be used as insulation and not as a load-bearing wall. Hence optimum thickness for maximum energy storage is only considered and is determined only using equation (3.3) for both types of RHEC material. 25RHC_400 and 25RHC_200 have thicknesses of 10.96 cm and 12.85 cm respectively. Based on this thickness following types of walls are considered for energy analysis.

	$T_{o,Mortar}$(cm)	$T_{RHEC-1/2}$(cm)	T_{Brick}(cm)	$T_{RHEC-1/2}$(cm)	T_{brick}(cm)	$T_{i,Mortar}$(cm)
Case-1	2	0	22.5	13	0	2
Case-2	2	0	22.5	11	0	2
Case-3	2	13	22.5	11	0	2
Case-4	2	11+13	22.5	0	0	2
Case-5	2	0	11.25	11+13	11.25	2
Case-6	2	13	22.5	0	0	2
Case-7	2	11	22.5	0	0	2

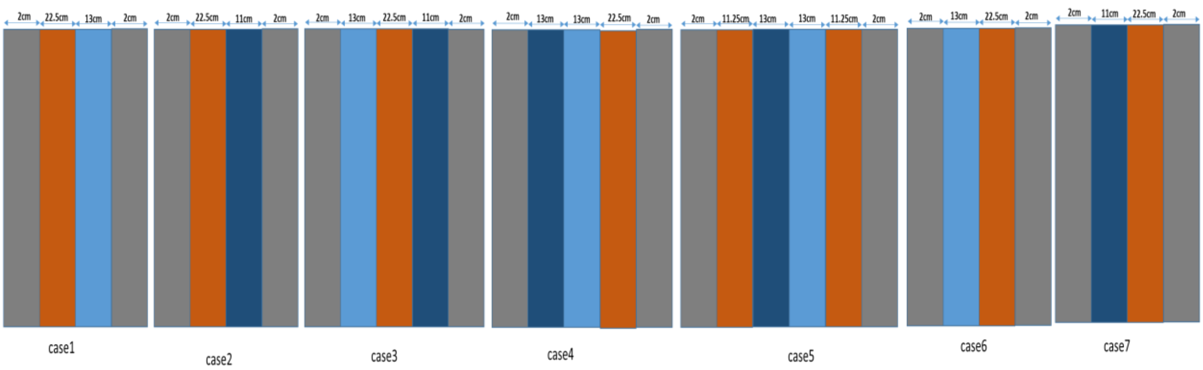


Fig.3.4 Design of wall for RHEC

(4) Bamboo-bio Concrete (BBC):

On comparing the compressive strength of 22.5 cm of the standard wall with that of the BBC wall using equations (3.1) &(3.2), the equivalent thickness comes out to be 21.2 cm. whereas the optimum thickness for maximum energy storage comes out to be 16.5 cm from equation (3.3). Based on these thicknesses, the following wall types are considered for energy analysis.

	$T_{o,Mortar}$(cm)	T_{BBC}(cm)	T_{brick}(cm)	$T_{i,Mortar}$(cm)
Case-1	2	21.2	0	2
Case-2	2	11.25	11.25	2
Case-3	2	16.5	11.25	2
Case-4	2	22.5	0	2

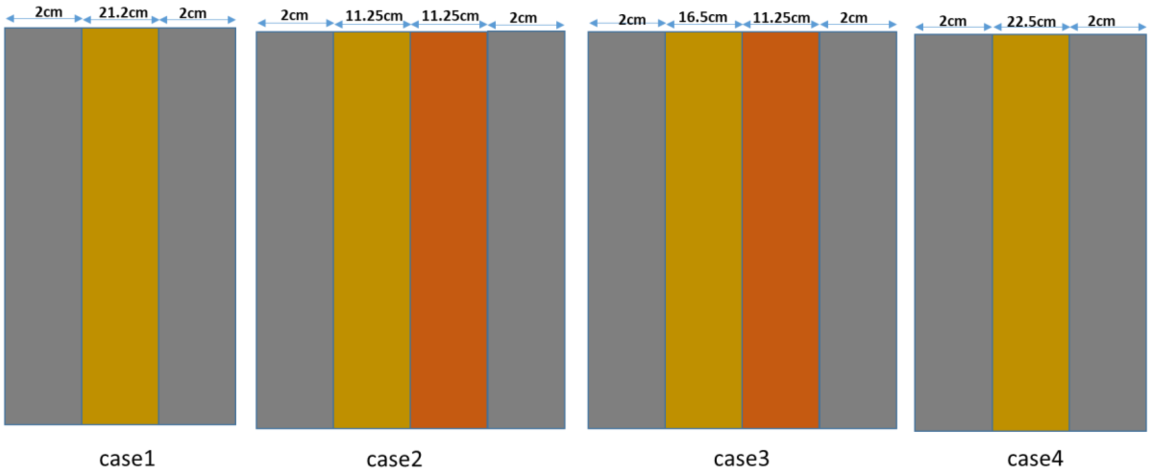


Fig.3.5 Design of wall for BBC

(5) Date Palm Ash (DPA):

On comparing the compressive strength of 22.5 cm of the standard wall with that of the BAB wall using equations (3.1) &(3.2), the equivalent thickness comes out to be 5.54 cm. whereas the optimum thickness for maximum energy storage comes out to be 18.23 cm from equation (3.3). Based on these thicknesses, the following types of walls are considered for energy analysis.

	$T_{o,Mortar}$(cm)	$T_{DPA\ Block}$(cm)	$T_{i,Mortar}$(cm)
Case-1	2	5.54	2
Case-2	2	18.23	2
Case-3	2	22.5	2

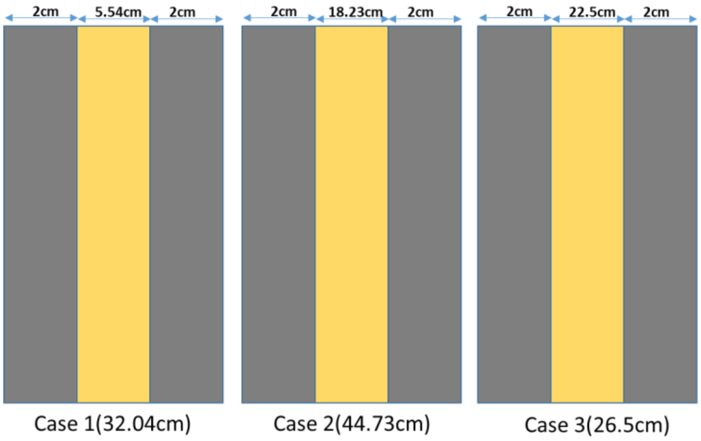


Fig.3.6 Design of wall for DPA

(6) Rice Straw Bale (RSB):

RSB having very less compressive strength than the standard wall can only be used as insulation and not as a load-bearing wall. Hence optimum thickness for maximum energy storage is only considered and is determined only using equation (3.3) which comes out to be 13.2 cm. Based on this thickness following types of walls are considered for energy analysis.

	$T_{o,Mortar}$(cm)	T_{RSB}(cm)	T_{brick}(cm)	T_{RSB}(cm)	T_{brick}(cm)	$T_{i,Mortar}$(cm)
Case-1	2	0	22.5	13.2	0	2
Case-2	2	13.2	22.5	0	0	2
Case-3	2	6.6	22.5	6.6	0	2
Case-4	2	0	11.25	13.2	11.25	2

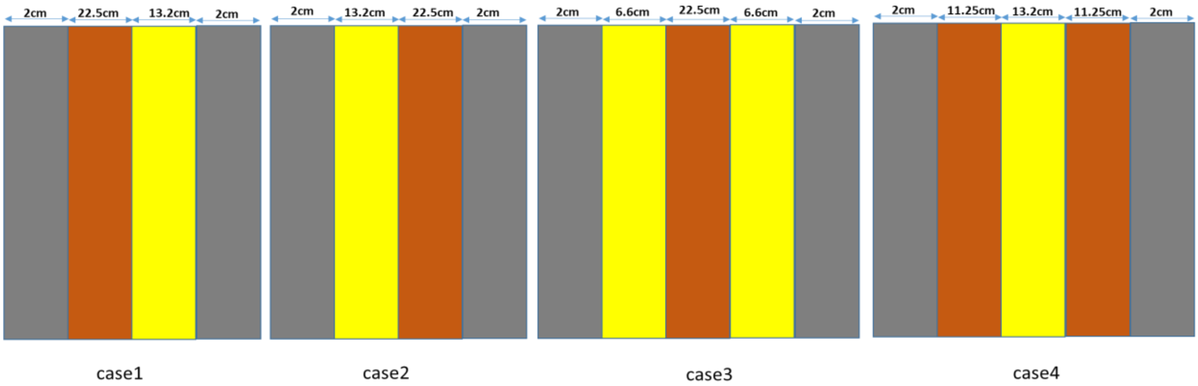


Fig.3.7 Design of wall for RSB

(7) Cement Stabilized Rammed Earth Rice Husk Ash (CSRERHA):

On comparing the compressive strength of 22.5 cm of the standard wall with that of the CSRERHA wall using equations (3.1) &(3.2), the equivalent thickness comes out to be 56.25 cm. whereas the optimum thickness for maximum energy storage comes out to be 20.6 cm from equation (3.3). Based on these thicknesses following types of walls are considered for energy analysis.

	$T_{o,Mortar}$(cm)	$T_{CSRERHA}$(cm)	T_{Brick}(cm)	$T_{CSRERHA}$(cm)	$T_{i,Mortar}$(cm)
Case-1	2	56.25	0	0	2
Case-2	2	0	11.25	28.125	2
Case-3	2	28.125	11.25	0	2

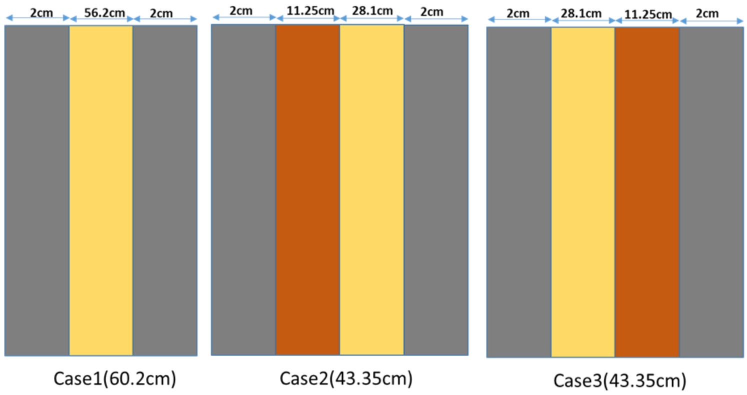


Fig.3.8 Design of wall for CSRERHA

(8) Coconut Coir Fibre Panel (CCFP):

On comparing the compressive strength of 22.5 cm of the standard wall with that of the CCFP wall using equations (3.1) &(3.2), the equivalent thickness comes out to be 6.8 cm. whereas the optimum thickness for maximum energy storage comes out to be 5.5 cm from equation (3.3). Based on these thicknesses following types of walls are considered for energy analysis.

	$T_{o,Mortar}$(cm)	T_{CCFP}(cm)	T_{Brick} (cm)	T_{CCFP}(cm)	$T_{i,Mortar}$(cm)
Case-1	2	11.25	11.25	0	2
Case-2	2	5.625	11.25	5.625	2
Case-3	2	22.5	0	0	2

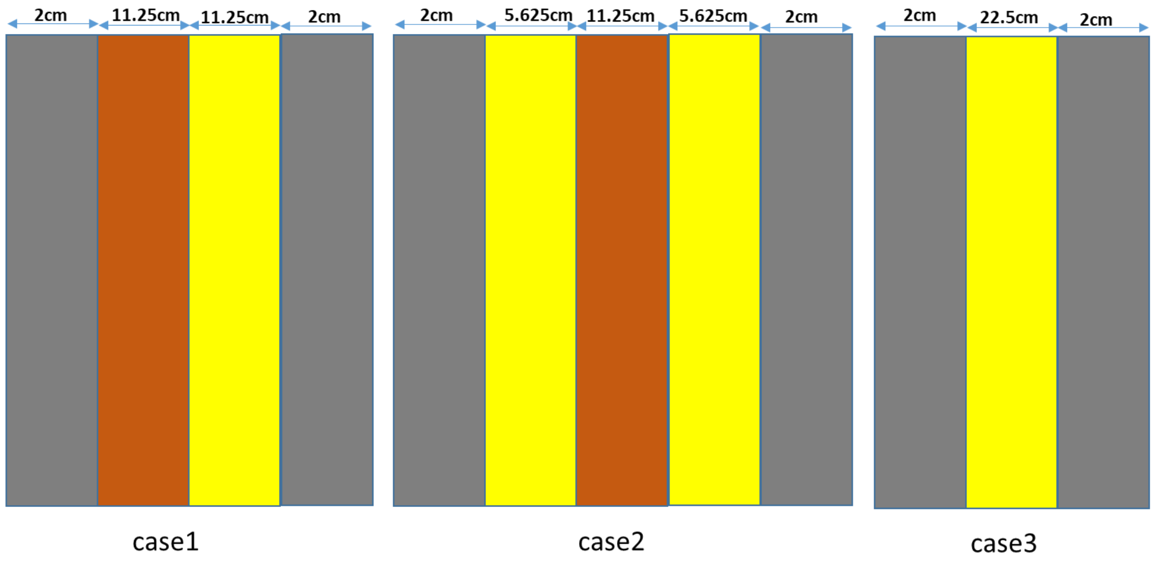


Fig.3.9 Design of wall for CCFP

3.4 Analysis and ranking of the suitable walls for different climates based on the cost of the wall and annual energy consumption.

$$Q_{norm} = \frac{Q_{max} - Q}{Q_{max} - Q_{min}} \tag{3.4}$$

$$C_{norm} = \frac{C_{max} - C}{C_{max} - C_{min}} \tag{3.5}$$

$$\text{Ranking} = Q_{norm} + C_{norm} \tag{3.6}$$

Where

Q- Annual energy consumption

C- Construction cost of the wall.

Q_{max}, Q_{min}, C_{max}, and C_{min} are the maximum and minimum values for the considered case.

To compare different types of walls, a simulation will be done for the total annual energy consumption for the air conditioning system for all five climatic zones. Unit cost of construction of the walls also will be taken into account.

Results obtained for all cases of walls will be analyzed to select the suitable wall cases. Then the results for the selected wall will be normalized using equation (3.4) and equation (3.5) with reference to the maximum (Q_{max}), minimum (Q_{min}) annual energy consumption and minimum (C_{min}) and maximum (C_{max}) unit cost of constructing the wall.

Ranking for the different wall cases will be obtained based on equation (3.6) to get a comparison of performance in saving annual energy consumption and minimum unit cost of construction. A higher ranking of the wall will indicate better cost-benefit.

Chapter 4

Numerical Simulations

4.1 Methodology:

The simulation approach for the analysis focuses on comparing the annual energy consumption of the test case to that of the model in which rice straw bale has been used as a wall material. The building details of the selected test case are described in section 4.1.1. To simulate EnergyPlus for comparative analysis the required input data comprised of the following:

1. Geographical location (Climate): It is required to accurately calculate the load of the building depending on the specific weather conditions at the site location. The data is provided by weather files in epw. format. For the simulation of the considered model, five different cities of different climate zones (as adopted in the National Building Code of India) have been chosen, namely warm and humid (Chennai), moderate(Bangalore), composite (New Delhi), cold (Guwahati), dry and hot(Jaipur).

2. Geometry of the building: It comprises of plan, section, and elevation. It is required to feed the geometrical attributes as per the site requirement and any specific features like surrounding reflection by buildings, trees, shading, etc. This is provided by drawing files modeled in software like SketchUp, AutoCAD, Design Builder, etc. In this no modification has been done and the properties are all the same in both the simulated models.
3. Construction: This is done to model the envelope (walls, roof, window, overhangs) of the building as per the requirement of thermal load and daylighting calculations. This follows the standards given by ISHRAE, ASHRAE, software library, vendors, etc. For the simulation, there has been a modification in constructing the roof and walls of the building to apply rice straw bale as a wall material. As can be seen from Fig. 4.2 the exterior wall is made up of layers of plasterboard, fiberglass quilt, and wood siding, and the roof is made up of plasterboard, fiberglass quilt, and roof deck. This wall and roof were modified with layers of lime mortar and rice straw bale and the required material properties were changed accordingly in the setup for the simulation and comparison.

The modified wall and roof resulted in a decrease in the overall heat transfer coefficient as compared to the base case.

4. Daylighting and lighting: This data is provided as per the requirement of visual comfort. It is generally the feature demanded by the client, lighting consultant, and energy modeler. This section remains the same for both models as per the following ASHRAE standard.
5. Internal Load: It comprises of number of hours (usage) of operation of electrical equipment, number of people, and schedule of operations of equipment. It is defined in the software to accurately model the internal heat gain inside the building. It is the input required by the client, energy modelers. This section remains the same for the models.
6. HVAC system: It is the control specifications, control strategy, and layout of the heating, ventilation, and air conditioning system as recommended by the HVAC consultant, ASHRAE/ISHRAE, etc. The HVAC system components have not been modified for the similarity of comparison under identical conditions.

4.2 Model of building:

In this simulation, ASHRAE test case 600 was chosen as a model (Fig. 4.1).

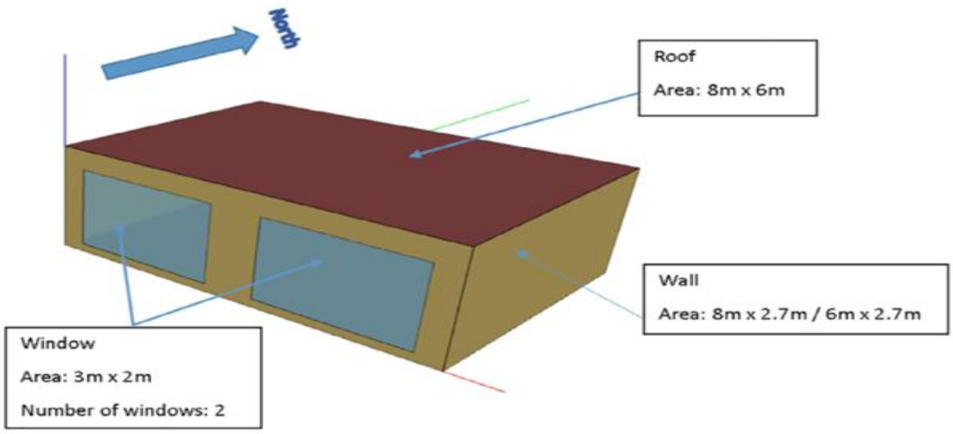


Fig.4.1 ASHRAE Test Case 600.

It is a recommended base case for building envelopes to study the thermal load test of buildings according to ASHRAE Standard 140 [8]. It consists of a rectangular floor with dimensions of dimension of 8m by 6m and a height of 2.7m. It has two double-pane windows of size 3m by 2m on a south-facing wall. Materials and thermal properties are listed in Fig. 4.2

Table 4.1 Material properties of test case 600

Element	Thermal conductivityW/(m.K)	Thickness, m	U-value, W/(m^2.K)	R-value, (m^2.K)/W	Density, kg/m^3	Heat capacity c_pJ/(kg.K)
Lightweight Case: Exterior Wall (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Plasterboard	0.160	0.012	13.333	0.075	950.000	840.000
Fiberglass quilt	0.040	0.066	0.606	1.650	12.000	840.000
Wood sidling	0.140	0.009	15.556	0.064	530.000	900.000
Exterior surface coefficient			29.300	0.034		
Lightweight Case: Floor (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Timber flooring	0.140	0.025	5.600	0.179	650.000	1200.000
Insulation	0.040	1.003	0.040	25.075	0.000	0.000
Lightweight Case: Roof (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Plasterboard	0.160	0.010	16.000	0.063	950.000	840.000
Fiberglass quilt	0.040	0.112	0.357	2.800	12.000	840.000
Roofdeck	0.140	0.019	7.368	0.136	530.000	900.000
Exterior surface coefficient			29.300	0.034		
Summary: Lightweight Case						
Component	**U,W/m^{2}K**	**Area,m^2**	**UA,W/K**			
Wall	0.5144	63.600	32.715			
Floor	0.0394	48.000	1.892			
Roof	0.3177	48.000	15.253			
Window		12.000	36.000			
Infiltration			18.440			
Total UA (with window)			104.300			
Total UA (without window)			68.300			

4.3 Mathematical Model:

In this study heat transfer through the wall is considered to be unsteady, one dimensional. Material properties of the wall are assumed to be constant.

The heat equation for the calculation is given by Eq. (3.1)

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial x} \tag{4.1}$$

And from Fourier's law,

$$q'' = -k\frac{\partial T(x,t)}{\partial x} \tag{4.2}$$

Eq. (1) is a p.d.e and solved numerically using the conduction transfer function method.

Conduction Transfer Function [9]:

The conduction transfer function in the form of the equation is shown below in Eq. (3.3) for heat flux on the outside surface of the wall

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta} \tag{4.3}$$

And Eq. (3.4) for heat flux on the inside surface of the wall.

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta} \tag{4.4}$$

Where $q'' = q/\mathrm{A}$

X_j = outside conduction transfer function coefficient, j=0, 1, 2, ….nz

Y_j = cross conduction transfer function coefficient, j=0, 1, 2,….nz

Z_j=Inside conduction transfer function coefficient, j=0, 1, 2,…..nz

Φ_j= Flux conduction transfer function coefficient, j=1, 2,…….nq

T_i= inside surface temperature

To outside surface temperature

This Eq. considers that heat flux at the inside and outside surfaces of the wall is linearly related to the current temperature, temperature history, and heat flux history of both the inside and outside surfaces of the wall. Theses equation is solved using the state space method which finally expresses Eq. (3.3) and Eq. (3.4) as

$$\frac{d\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}}{dt} = [A]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [B]\begin{bmatrix} T_i \\ T_o \end{bmatrix} \tag{4.5}$$

$$\begin{bmatrix} q''_i \\ q''_o \end{bmatrix} = [\mathrm{C}]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [\mathrm{D}]\begin{bmatrix} T_i \\ T_o \end{bmatrix} \tag{4.6}$$

Where $T_1,\ldots T_n$ are nodal temperatures, n is the number of nodes, T_i, T_o are interior and exterior environment temperatures, [A],[B],[C],[D] are the coefficient matrices.

The algorithm used in convection heat transfer for both inside and outside the zone is the TARP algorithm [9]. This algorithm is used to correlate the temperature differences to the heat transfer coefficient. This model takes total convection as the sum of forced and natural convection as shown by Eq. (3.7)

$$h_c = h_f + h_n \tag{4.7}$$

Where the forced convection component is based on a correlation given by Eq. (3.8)

$$h_f = 2.537 W_f R_f \left(\frac{PV_z}{A}\right)^{1/2} \tag{4.8}$$

Where ,$W_f = 1.0$ for windward surfaces or $W_f = 0.5$ for leeward surfaces and R_f is the surface roughness multiplier.

For vertical surface Eq. (3.9) is used

$$h_n = 1.31|\Delta T|^{\frac{1}{3}} \tag{4.9}$$

For ($\Delta T < 0$ and surface facing upward) OR ($\Delta T > 0$ and surface facing downward) an enhanced convection correlation is used:

$$h_n = \frac{9.482|\Delta T|^{\frac{1}{3}}}{7.283 - |\cos \Sigma|} \tag{4.10}$$

Where Σ is the surface tilt angle.

For ($\Delta T > 0$ and surface facing upward) or ($\Delta T < 0$ and surface facing downward) a reduced convection correlation is used:

$$h_n = \frac{1.810|\Delta T|^{\frac{1}{3}}}{1.382 + |\cos \Sigma|} \tag{4.11}$$

Where Σ is the surface tilt angle.

For a simple two-node layer as shown in Fig. 4.3 the above formulation condenses to

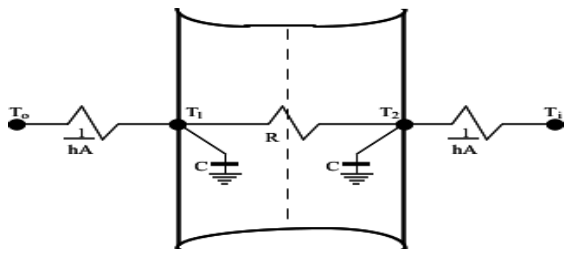


Fig.4.2 Schematic of wall having two nodes

$$C\frac{dT_1}{dt} = hA(T_o - T_1) + \frac{T_2 - T_1}{R} \tag{4.12}$$

$$C\frac{dT_2}{dt} = hA(T_i - T_2) + \frac{T_1 - T_2}{R} \tag{4.13}$$

$$q''_{\ i} = h(T_i - T_2) \tag{4.14}$$

$$q''_{\ o} = h(T_1 - T_o) \tag{4.15}$$

Where $R = \frac{\ell}{kA}, C = \frac{\rho c_p \ell A}{2}$, A is the area of the surface exposed to environmental temperatures

In matrix format:

$$\begin{bmatrix} \frac{dT_1}{dt} \\ \frac{dT_2}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} - \frac{hA}{C} & \frac{1}{RC} \\ \frac{1}{RC} & -\frac{1}{RC} - \frac{hA}{C} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} + \begin{bmatrix} \frac{hA}{C} & 0 \\ 0 & \frac{hA}{C} \end{bmatrix} \begin{bmatrix} T_o \\ T_i \end{bmatrix} \tag{4.16}$$

$$\begin{bmatrix} q''_{\ o} \\ q''_{\ i} \end{bmatrix} = \begin{bmatrix} 0 & -h \\ h & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} + \begin{bmatrix} 0 & h \\ -h & 0 \end{bmatrix} \begin{bmatrix} T_o \\ T_i \end{bmatrix} \tag{4.17}$$

4.4 Model validation:

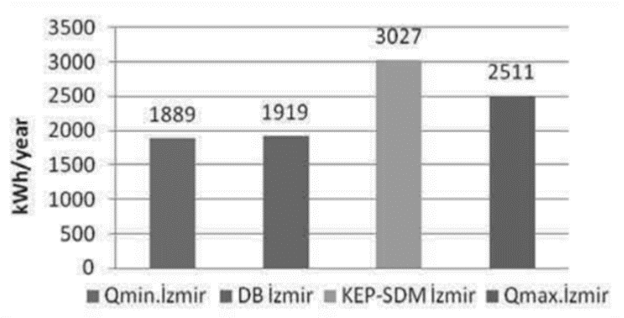


Fig.4.3 Confidence interval for annual heating energy consumption for Test Case 600 [20].

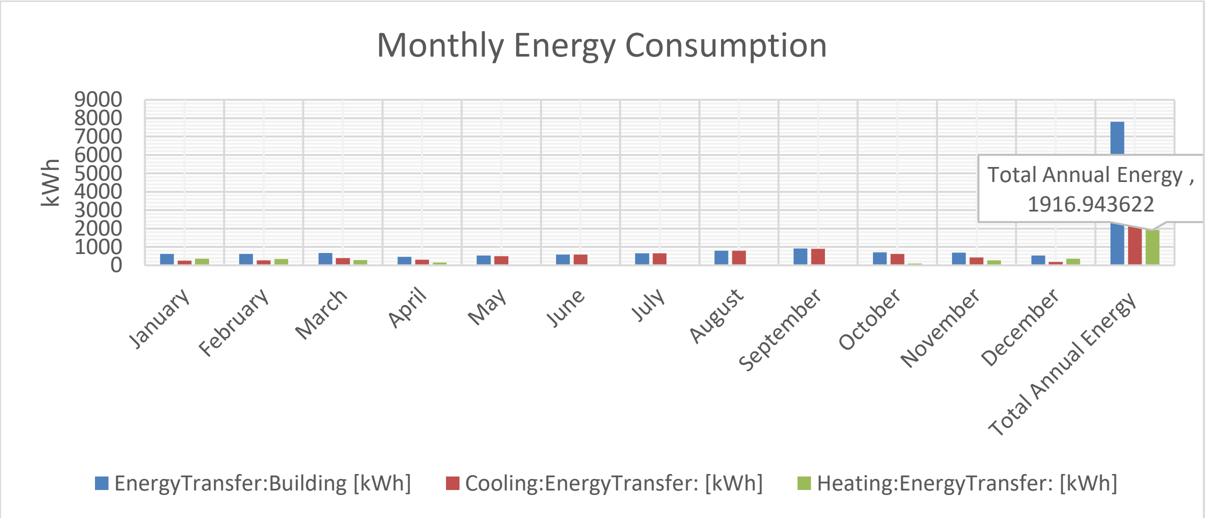


Fig.4.4 Annual heating energy consumption for simulated Test Case 600.

The confidence interval for annual heating load should lie between Q_{min} (1889kWh/yr.) and Q_{max} (2511kWh/yr.) according to the BES (Building Energy Simulation) test for test case BEST case 600 for the given weather in the reference paper [20]. Annual energy simulation for the chosen model comes out to be 1916.94 kWh/yr. as seen from Fig.4.4, which lies in the suggested interval for heating load.

4.5 Simulation results for types of wall discussed in section 3.1

The simulation was done in Energyplus (an open-source energy modeling engine for whole buildings) developed by the US Department of Energy. Based on the above mathematical model, a simulation was performed to obtain the energy consumption data for the year 2020 using the annual weather file for five cities in different climatic zones. Two sets of simulations were performed for each climatic zone one for the standard base case and another for the modified base case with RSB as a biomaterial for the wall.

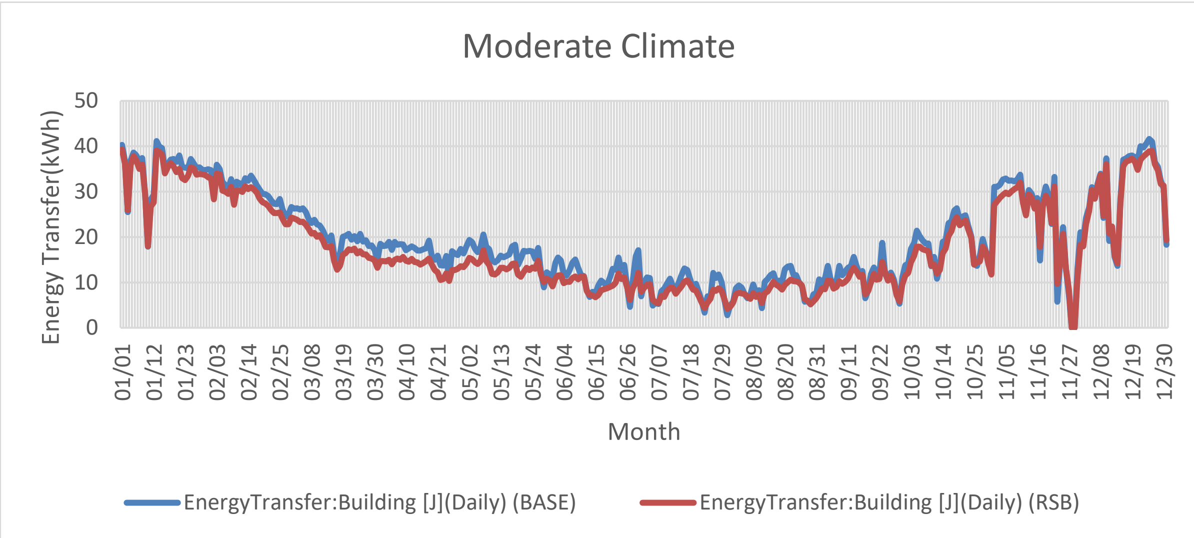


Fig.4.5 Energy transfer over the year in the model for moderate climate

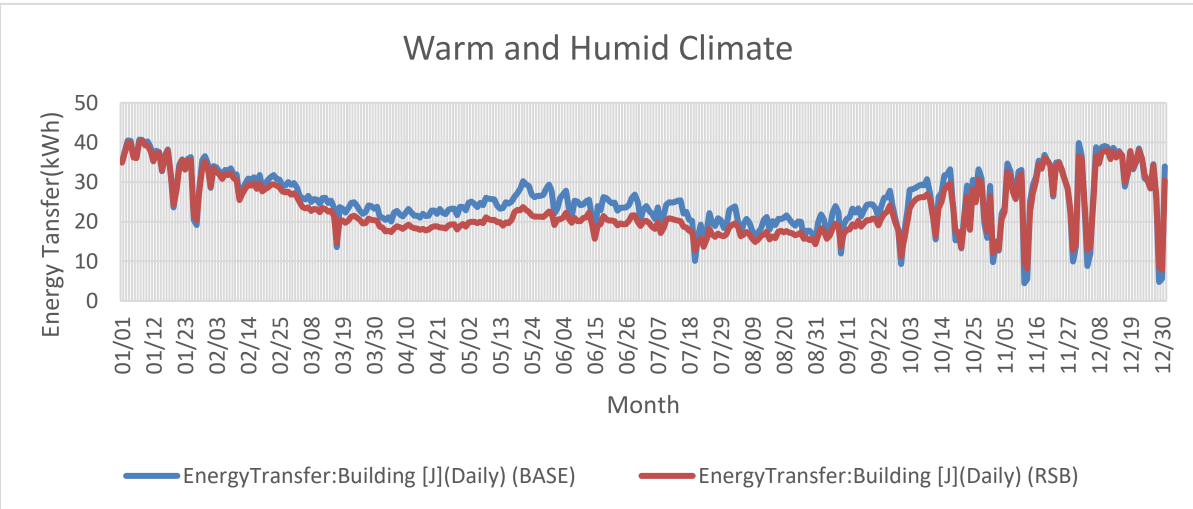


Fig.4.6 Energy transfer over the year in the model for warm and humid climate

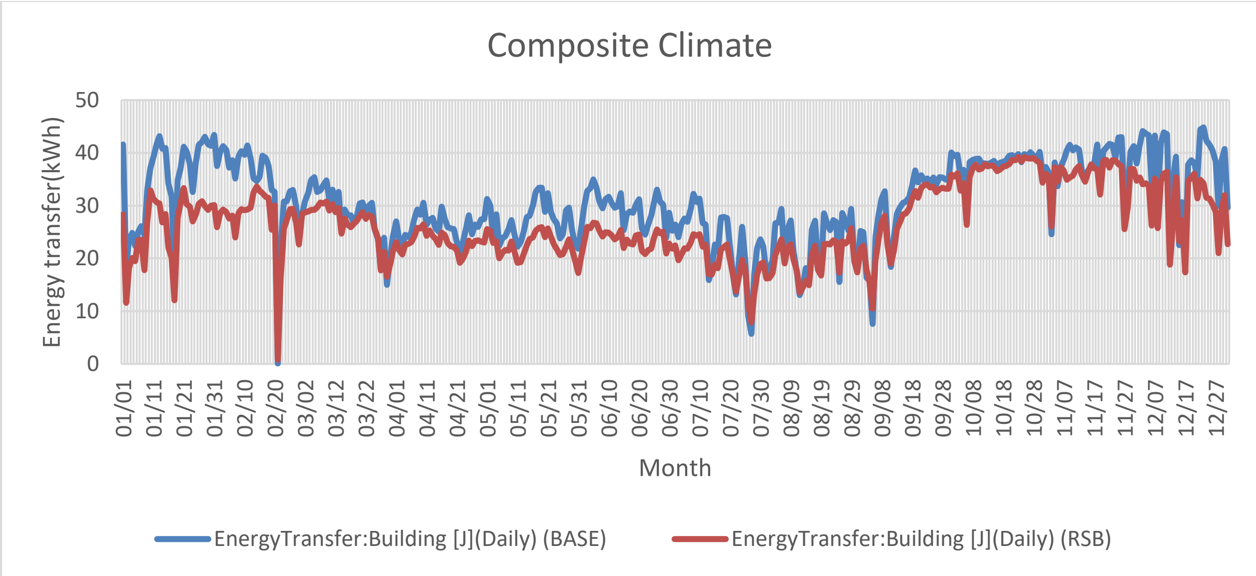


Fig.4.7 Energy transfer over the year in the model for composite climate

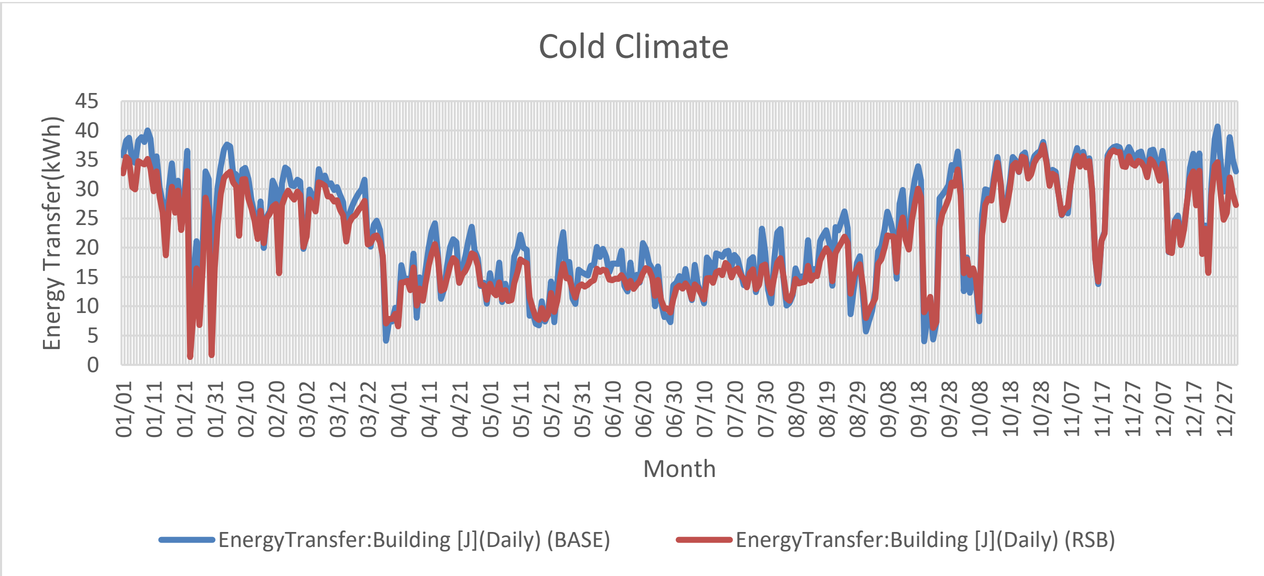


Fig.4.8 Energy transfer over the year in the model for cold climate

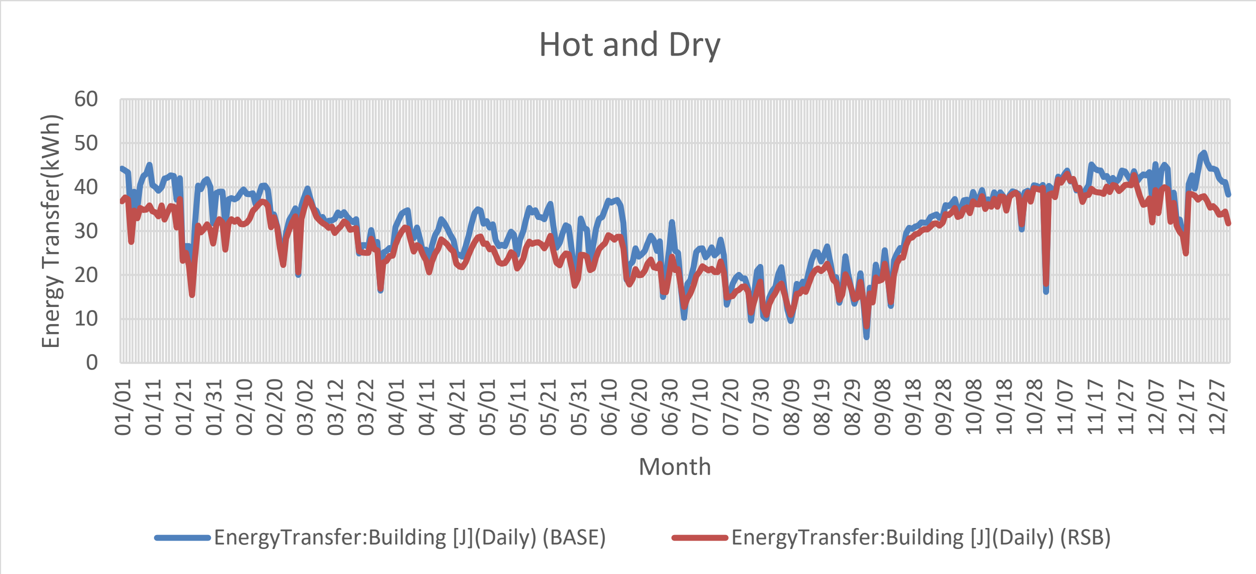


Fig.4.9 Energy transfer over the year in the model for hot and dry climate

From the above simulation results shown in Figure 4.5 to Figure 4.9, it is observed that for each case, the model in which the wall was modified. with RSB as a wall, material showed a reduction in the energy transfer in the building most of the time during the year. This reduction in energy transfer is achieved due to the reduction in the overall heat transfer coefficient (U-factor) of the wall and roof which has been modified in the RSB model.

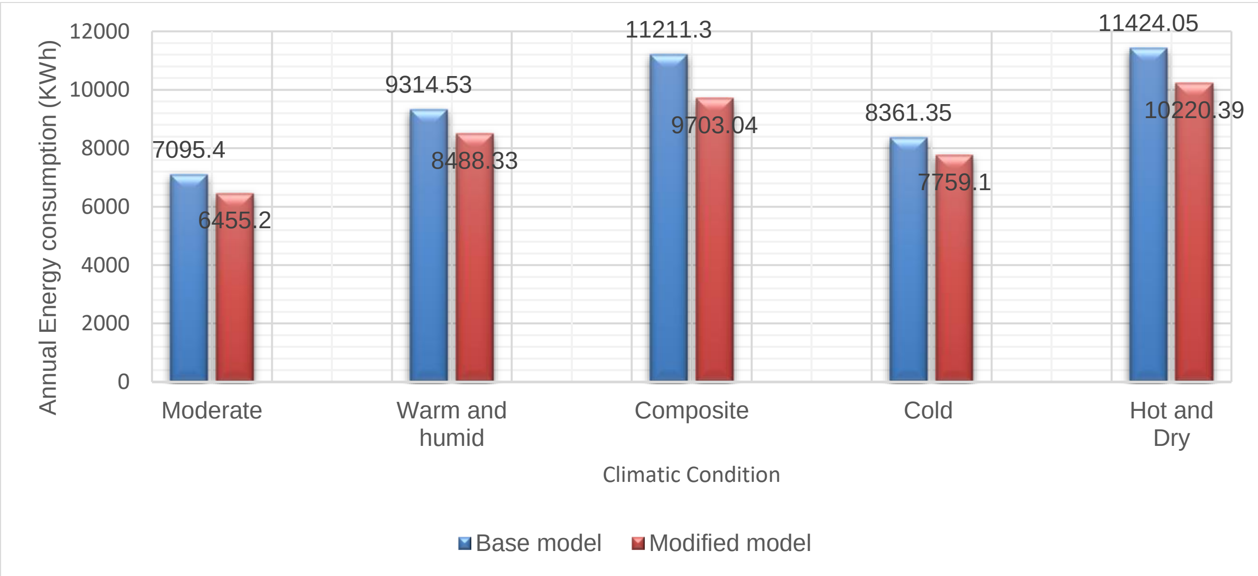


Fig.4.10 Annual energy consumption for two models for five climatic zones.

The simulation was performed for the annual electricity consumption and the results were compared for both cases, and the results obtained were plotted (Fig.4.10) which showed a reduction in the annual cooling load of the building by 8.87% for moderate climate, 8.26% for warm and humid climate, 13.45% for composite climate, 7.2% for cold climate, and 10.45% for hot and dry climate.

Now simulation results are presented for different types of considered biomaterials used in wall construction. Again the annual simulations have been done to get the energy consumption for a whole year for different climatic zones of India. A typical summer and winter design day is also considered to compare the daily energy consumption for the modified model. The behavior of the wall has been analyzed in terms of inside and outside surface temperature variation. Different wall types are compared with each other in terms of annual energy consumption.

Case1: Cold climate (Srinagar)

The winter design day plot of temperature as shown in Fig. 4.11 in a cold climate shows that the outside temperature is much below the heating point, indicating a significant heating demand.

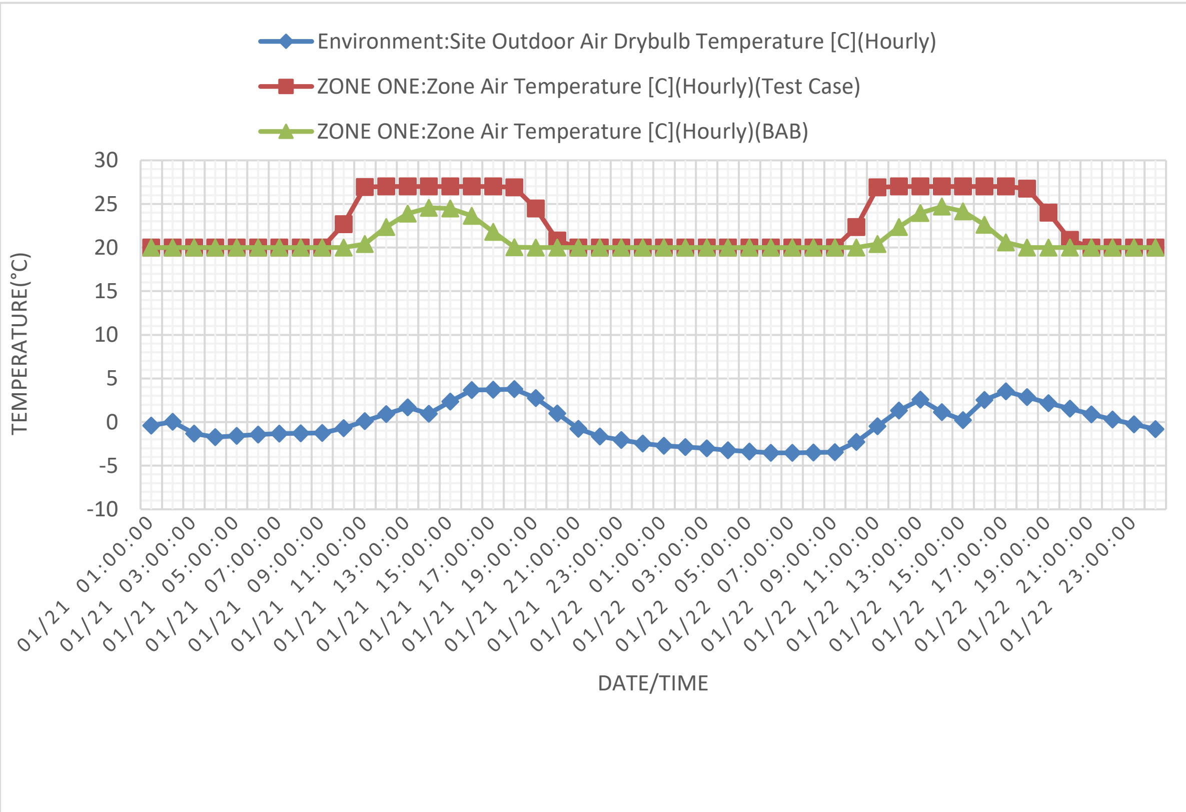


Fig.4.11 Temperature variation of environment, test case, and modified case in winter.

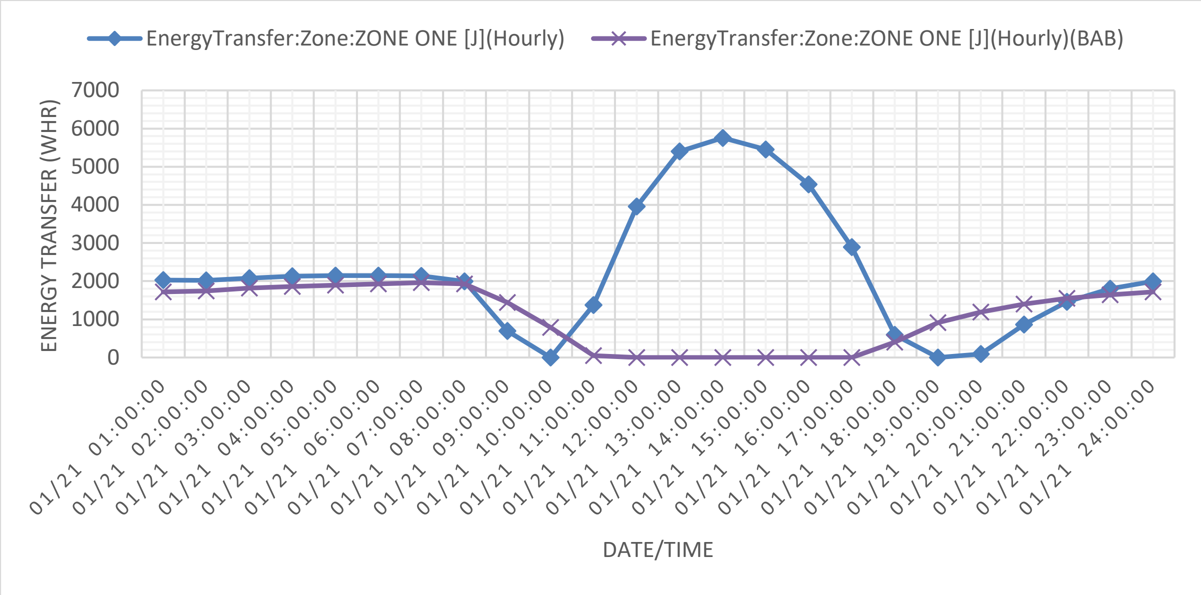


Fig.4.12 Energy consumption for test case and modified case in winter.

The modified wall with BAB as a biomaterial does not require a cooling load because the zone temperature does not rise above 25 °C even during peak radiation hours. In contrast, the test case requires a cooling load for four to five hours when solar radiation is high at noon and the zone temperature rises above 27 °C. The temperature starts to drop after that.

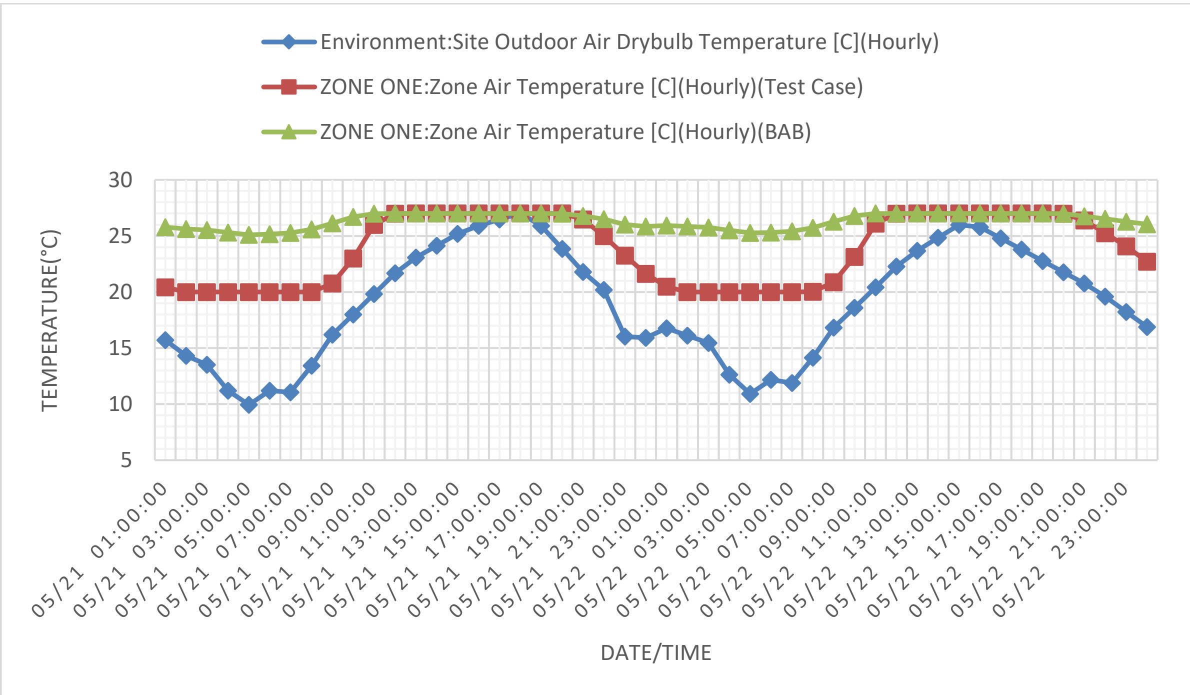


Fig.4.13 Temperature variation of environment, test case, and modified case in summer.

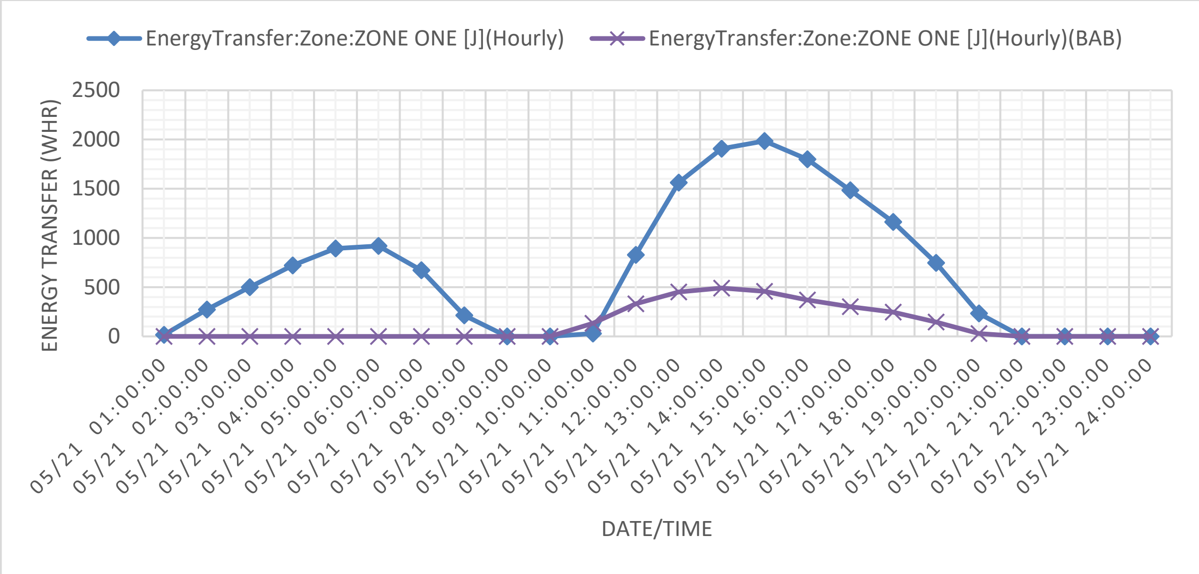


Fig.4.14 Energy consumption for test case and modified case in summer.

The summer design day plot as shown in Fig. 4.13 for this zone shows that there is less cooling demand as shown in Fig. 4.14 during the hours of peak solar radiation because the outside temperature does not reach above 27 °C. In the test instance, heating is necessary when the temperature drops below 20 °C between 1:00 and 7:00 p.m. However, in the case of the BAB wall, there is no heating load present and the temperature is much below the heating point.

The annual energy consumption result as shown in Fig. 4.15 shows that the energy consumption of the walls in BAB, BBC, HLC, RHEC, and RSB is lower than that of the test case; the percentage decrease is 57.14%, 54.16%, 48.48%, 18.55%, and 46.24%, respectively. CSRERHA brick walls use 41.76% more energy than other wall types.

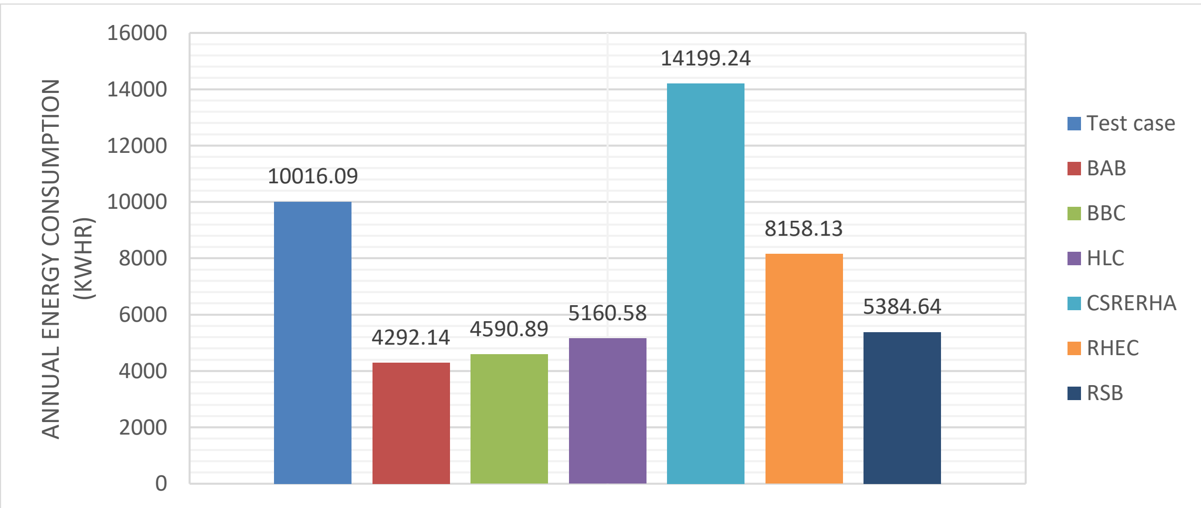


Fig.4.15 Annual energy consumption in cold climate.

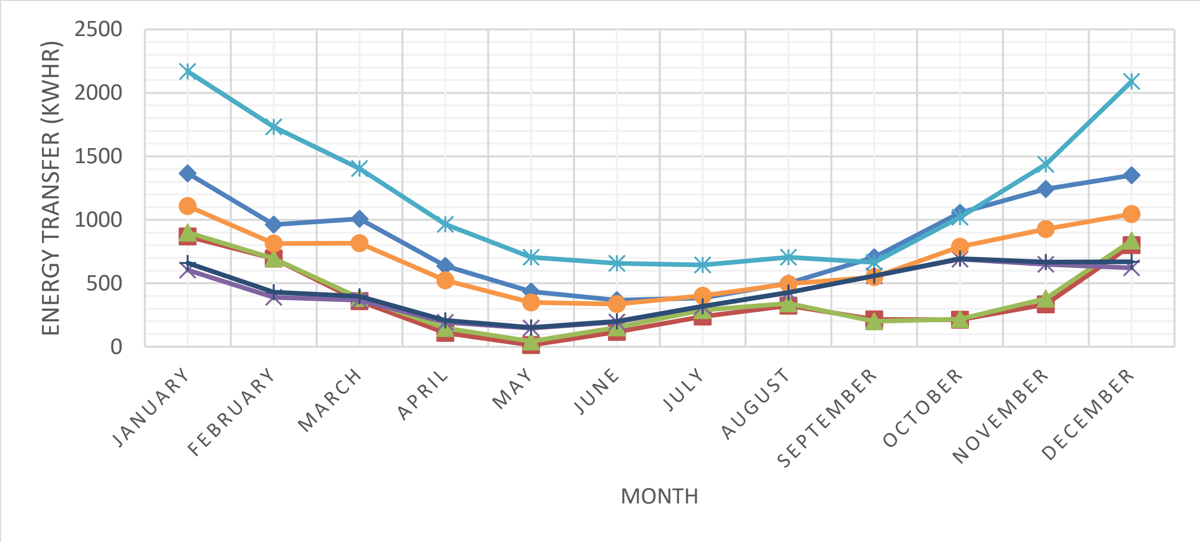


Fig.4.16 Annual energy variation in cold climate.

When it comes to energy reduction, as can be observed from Fig. 4.16 the BBC wall and BAB will perform very similarly, and the energy reduction of HLC and RSB was also comparable.

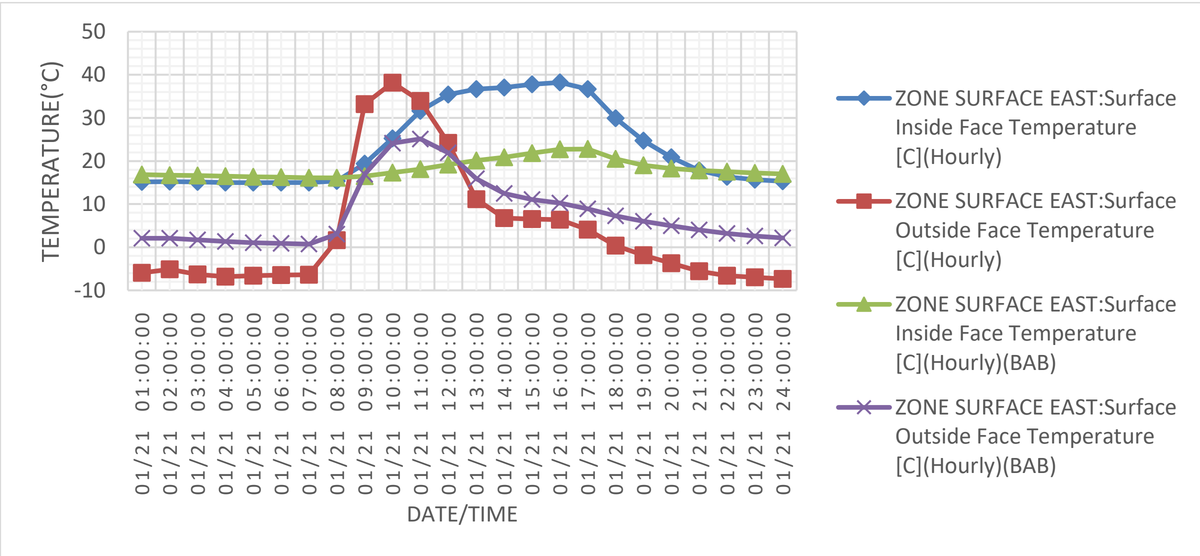


Fig.4.17 Wall surface temperature for winter day.

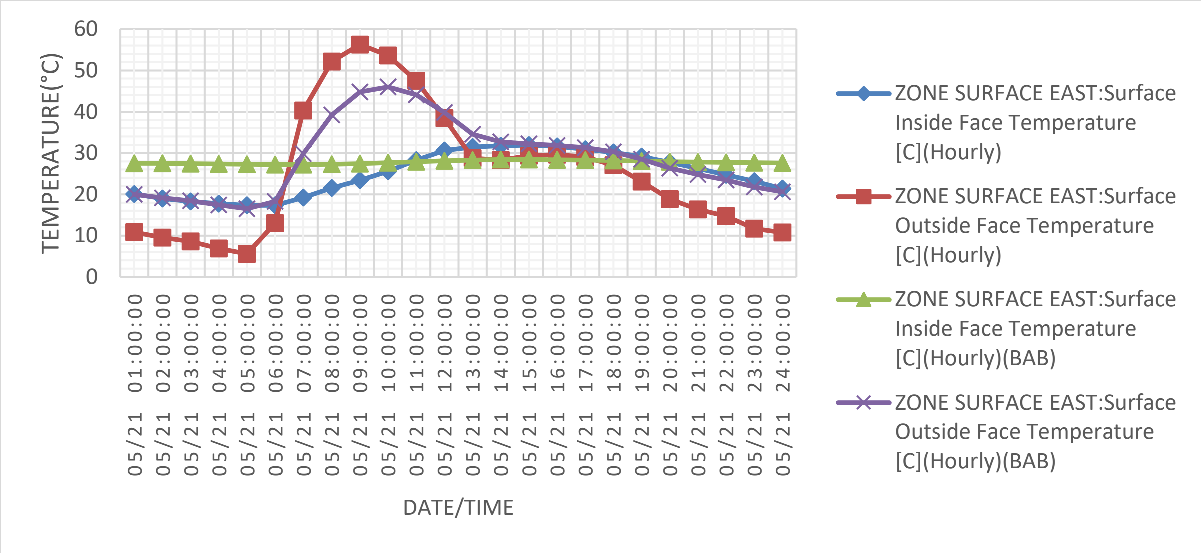


Fig.4.18 Wall surface temperature for summer day.

From the wall temperature profile as shown in Fig. 4.17 and Fig. 4.18 it can be observed that the BAB wall exhibits a notable decrease in amplitude for both the exterior and interior surface temperatures. It is observed that the variation in inside surface temperature has greatly decreased.

Case 2: Hot and dry climate (Jaipur)

In hot and dry climate zones the environment temperature as seen in Fig. 4.19 is much above the cooling set point so summertime cooling is necessary all day.

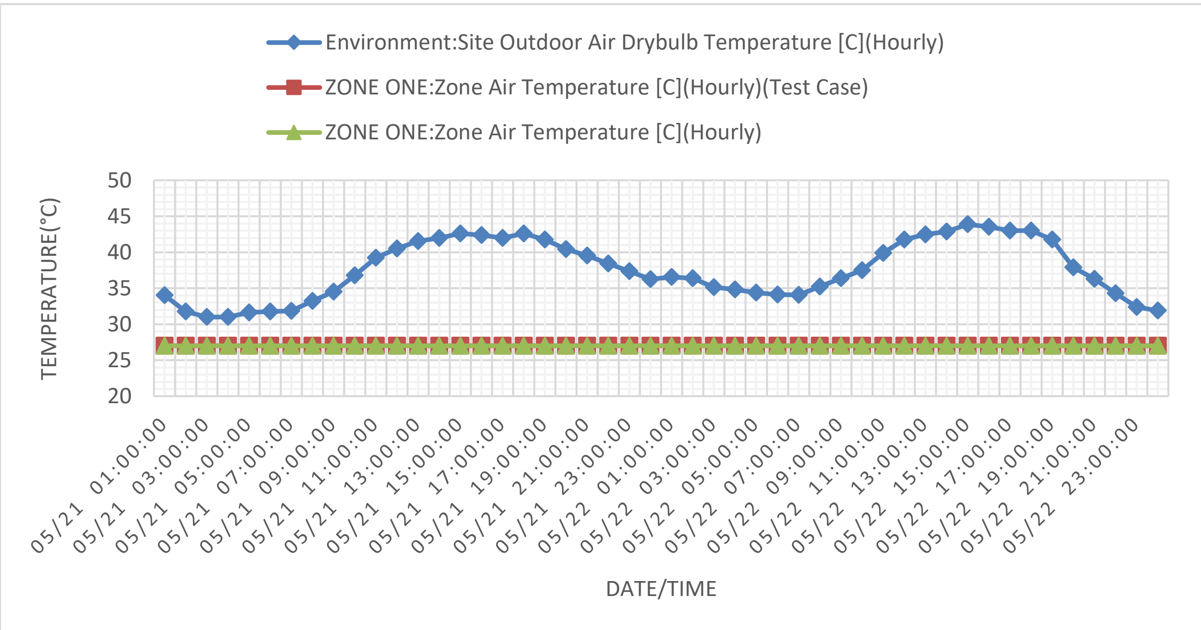


Fig.4.19 Temperature variation of environment, test case, and modified case in summer.

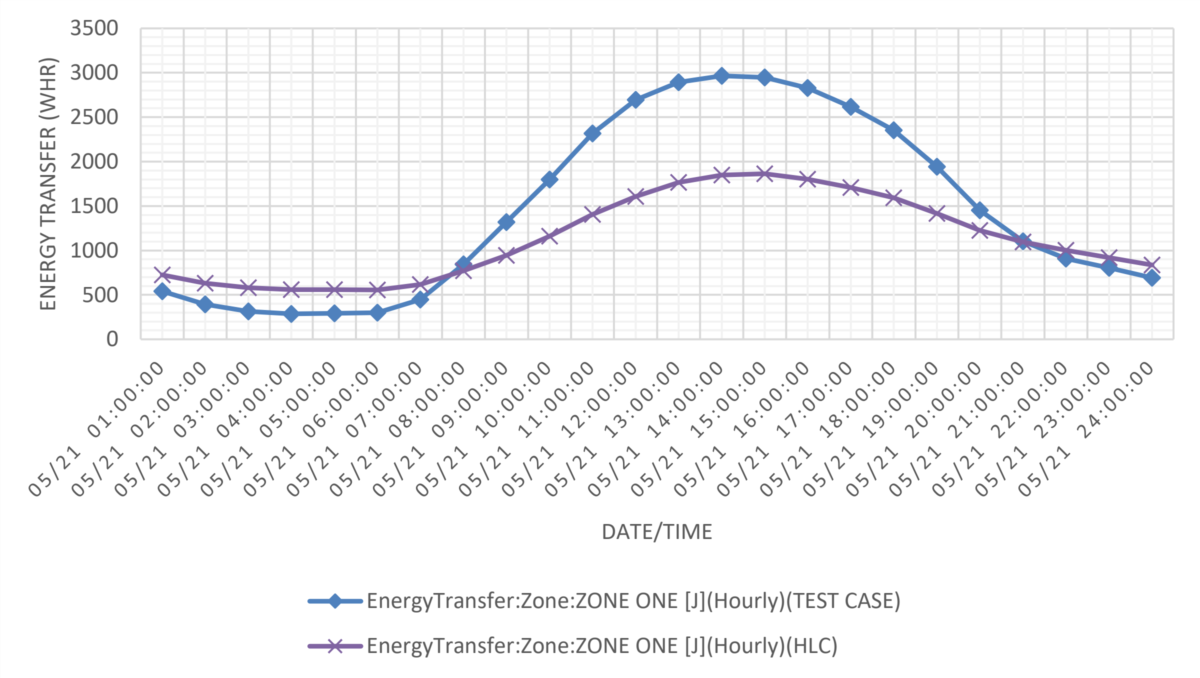


Fig.4.20 Energy consumption for test case and modified case in summer.

For both the test case and the modified example, cooling is needed in the afternoon on cold days.

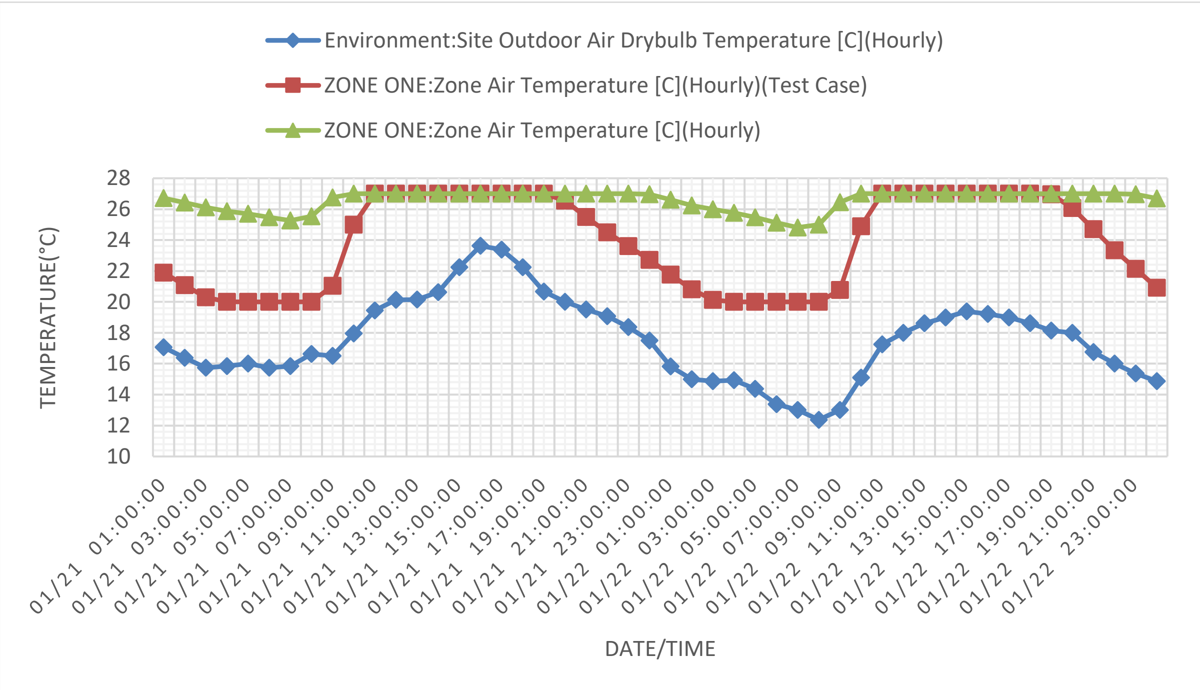


Fig.4.21 Temperature variation of environment, test case, and modified case in winter.

The results show that, on winter days, the modified case reduces cooling load as seen in Fig. 4.22 in the morning from 24:00 to 7:00 hours.

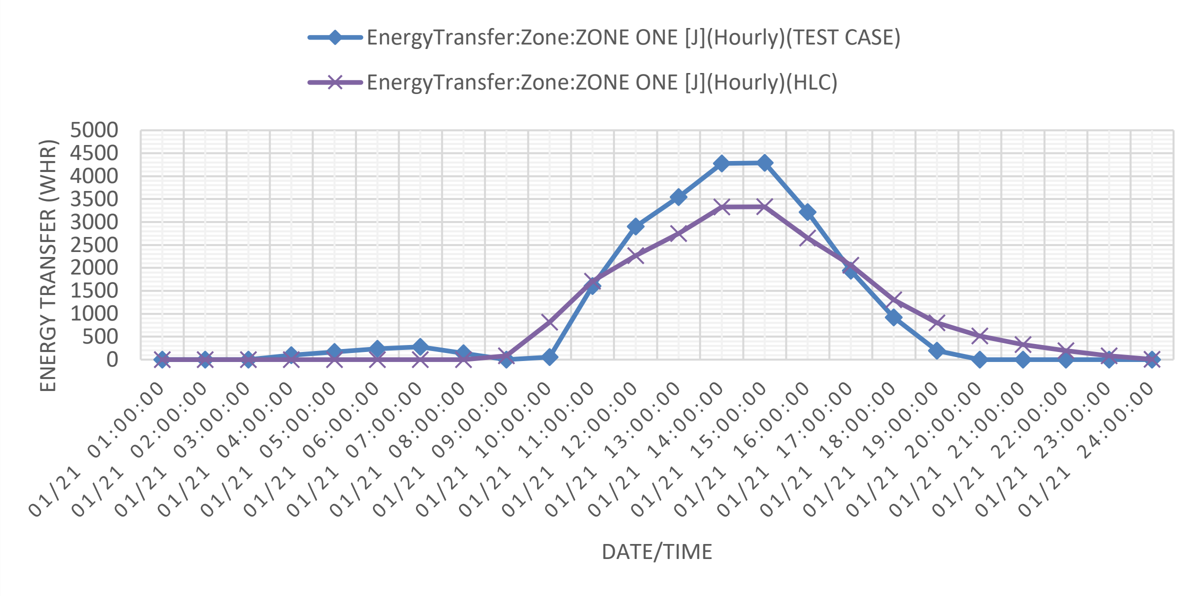


Fig.4.22 Energy consumption for test case and modified case in winter.

In essence, a hot, dry climate will resemble a hot, humid climate zone. Based on the annual energy usage data as shown in Fig. 4.23, HLC was able to save a maximum of 10.83% of energy.

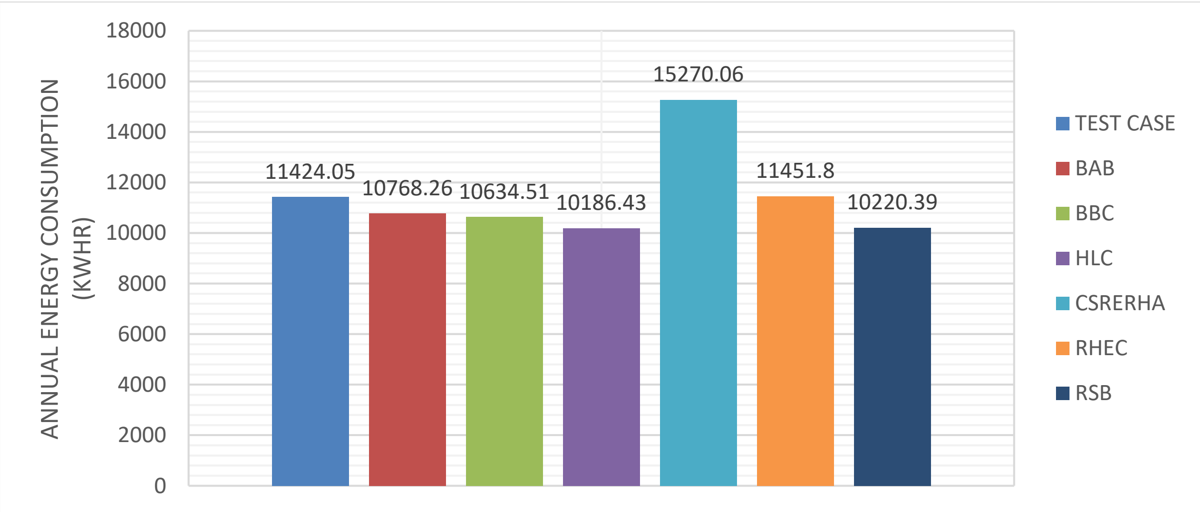


Fig.4.23 Annual energy consumption in hot and dry climates.

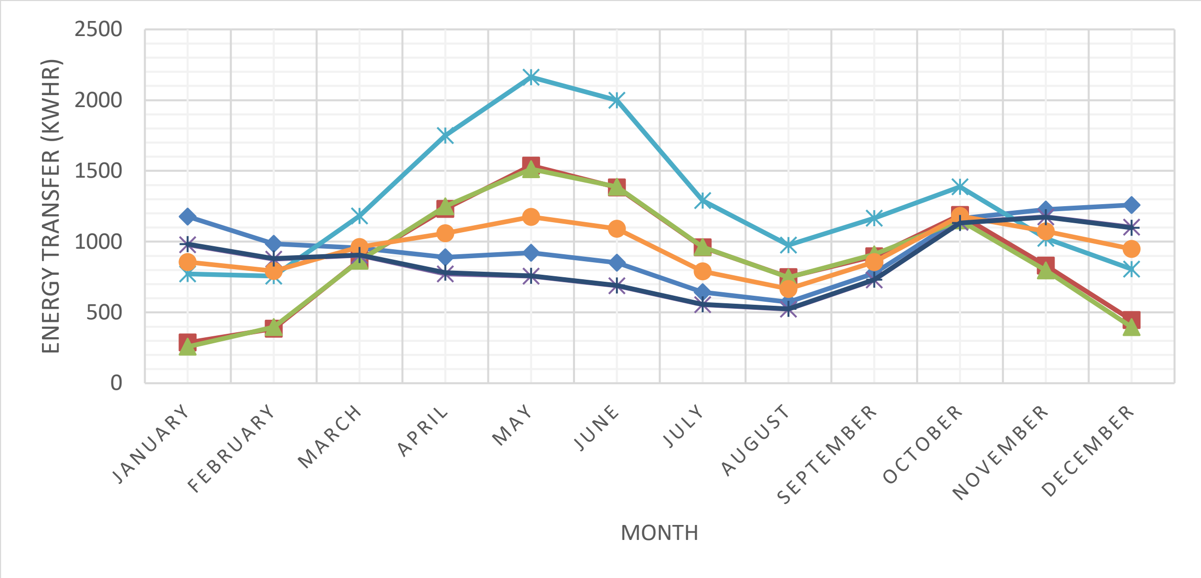


Fig.4.24 Annual energy variation in hot and dry climate.

Despite this, the energy reduction of the BAB, BBC, and RSB walls is similar at 5.74%, 6.91%, and 10.54%, respectively. The energy consumption of the CSRERHA brick wall was 33.66% higher than the test case.

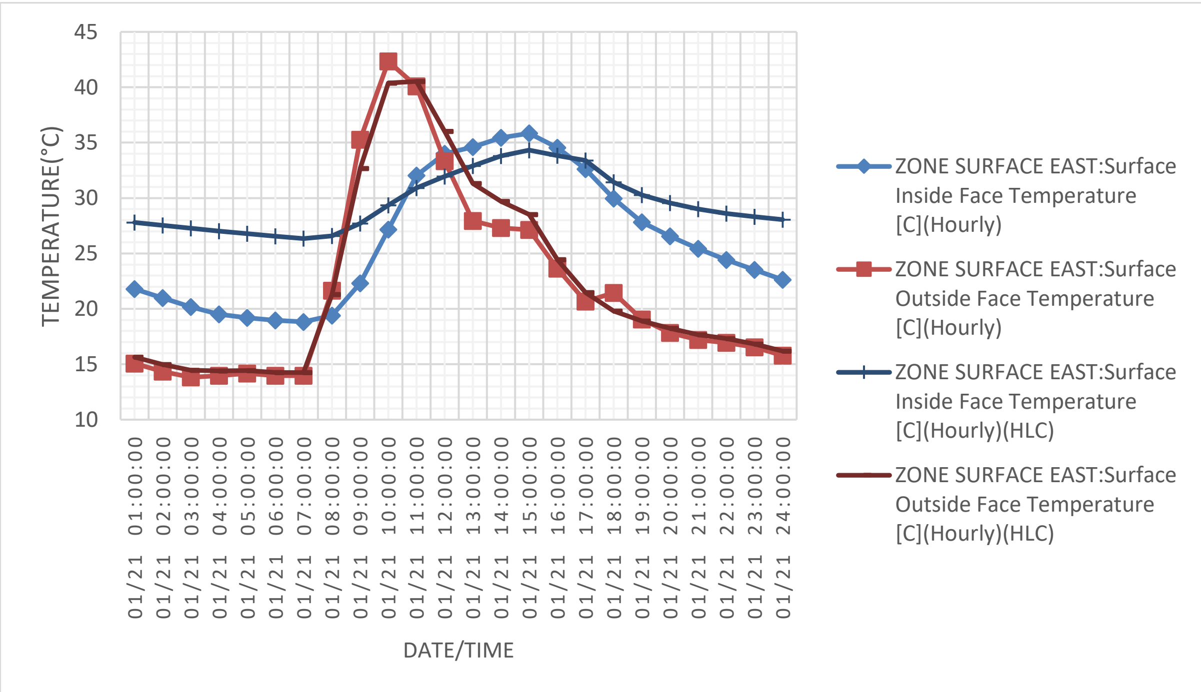


Fig.4.25 Wall surface temperature for winter day.

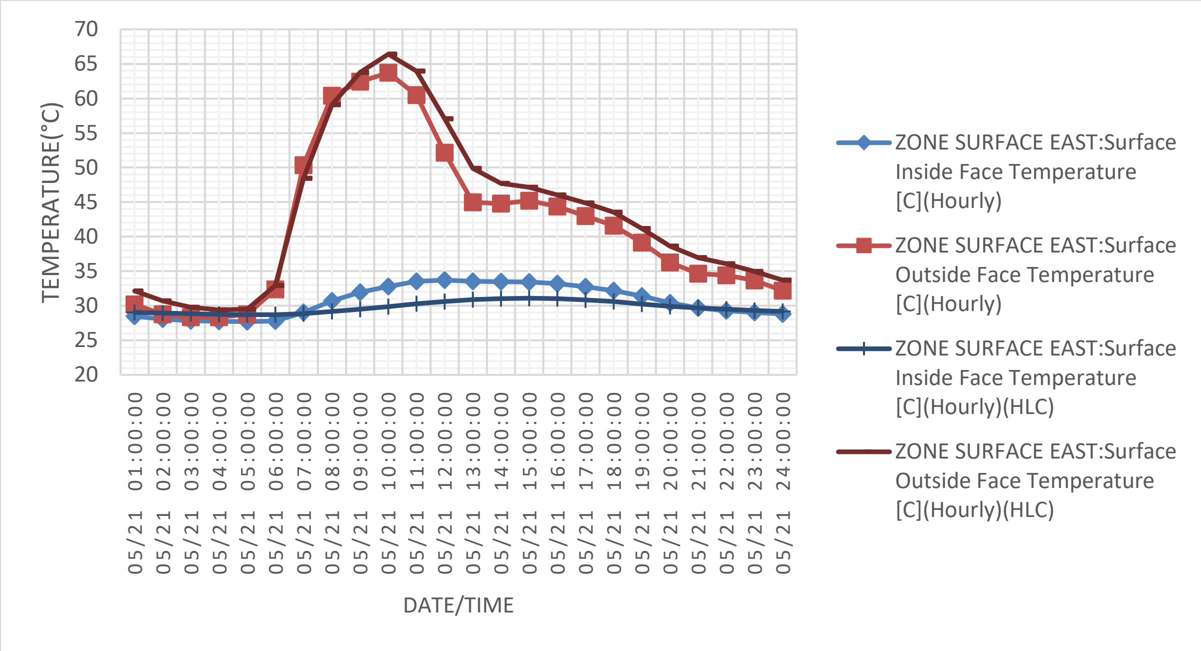


Fig.4.26 Wall surface temperature for summer day.

Case 3: Moderate climate (Bangalore)

It is evident from the moderate climate zone's temperature result as seen in Fig. 4.27 for the winter design day that the environment temperature only increases over 27°C for a short period during the peak solar radiation.

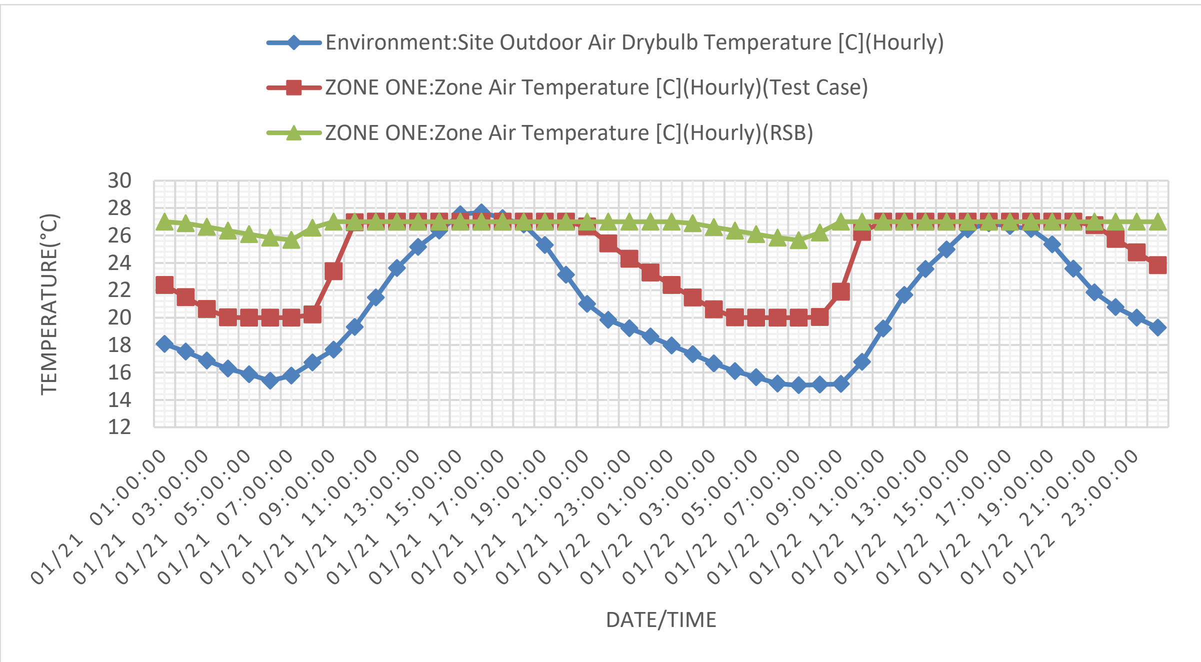


Fig.4.27 Temperature variation of environment, test case, and modified case in winter.

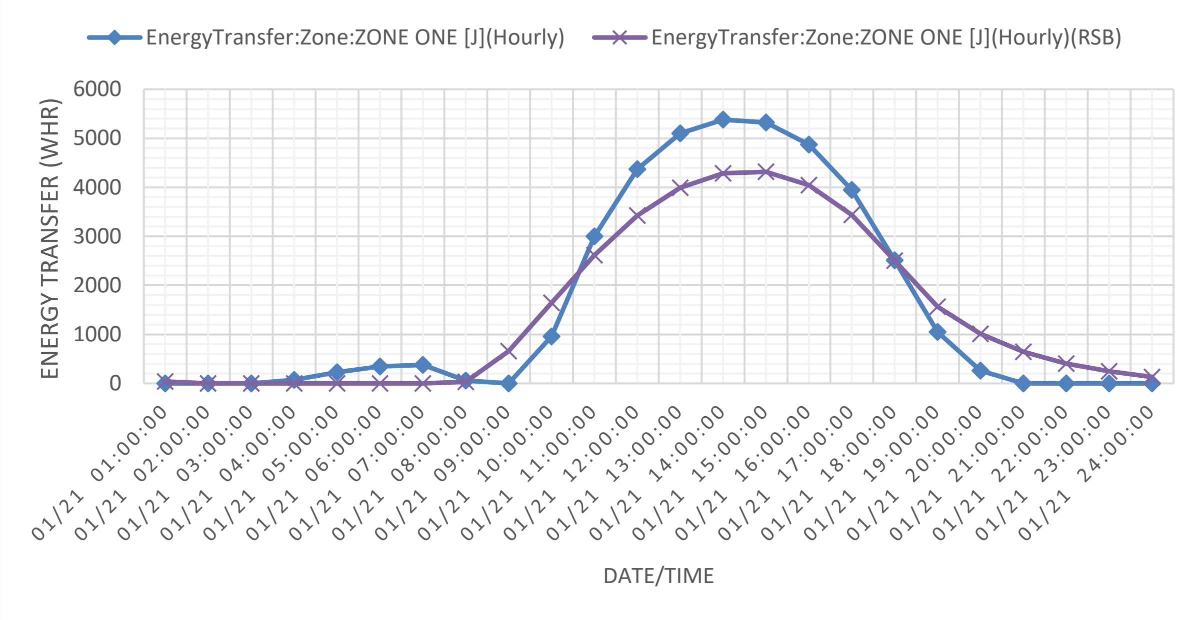


Fig.4.28 Energy consumption for test case and modified case in winter.

In the afternoon, cooling is necessary for both the modified instance and the bot test case. In the morning after 24:00 heating load is also present for the test case but the modified model doesn't need a heating load as can be interpreted from Fig. 4.27 and Fig. 4.28.

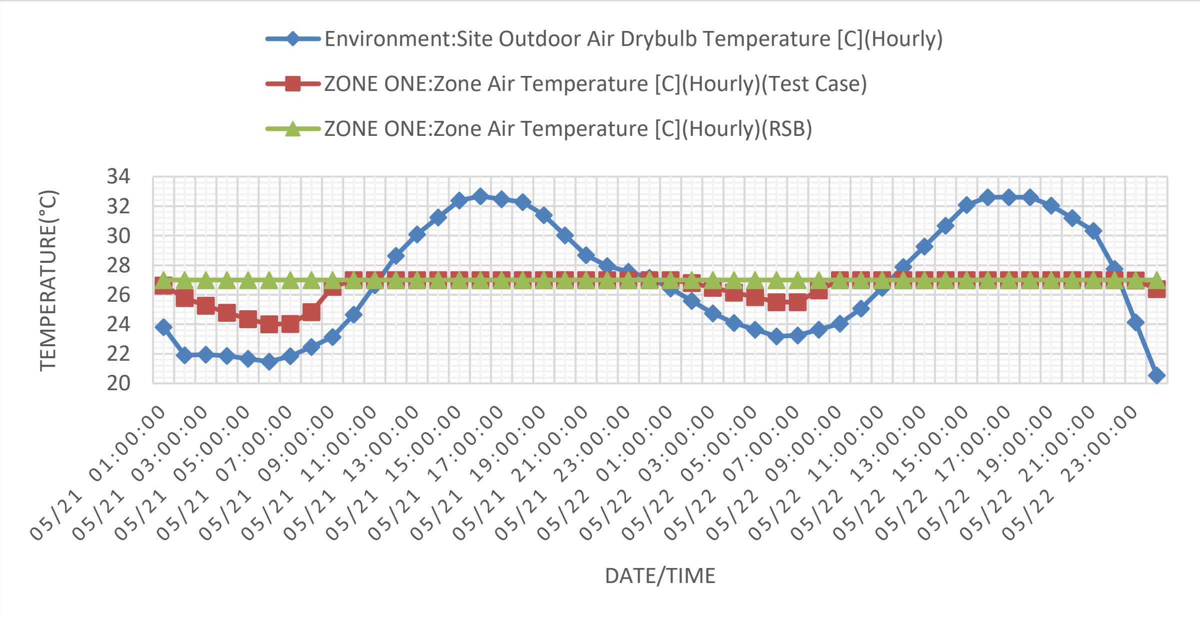


Fig.4.29 Temperature variation of environment, test case, and modified case in summer.

Since the morning temperature on a summer design day as seen in Fig. 4.29 is almost at the heating point, there is very little cooling demand during this time as seen in Fig 4.30.

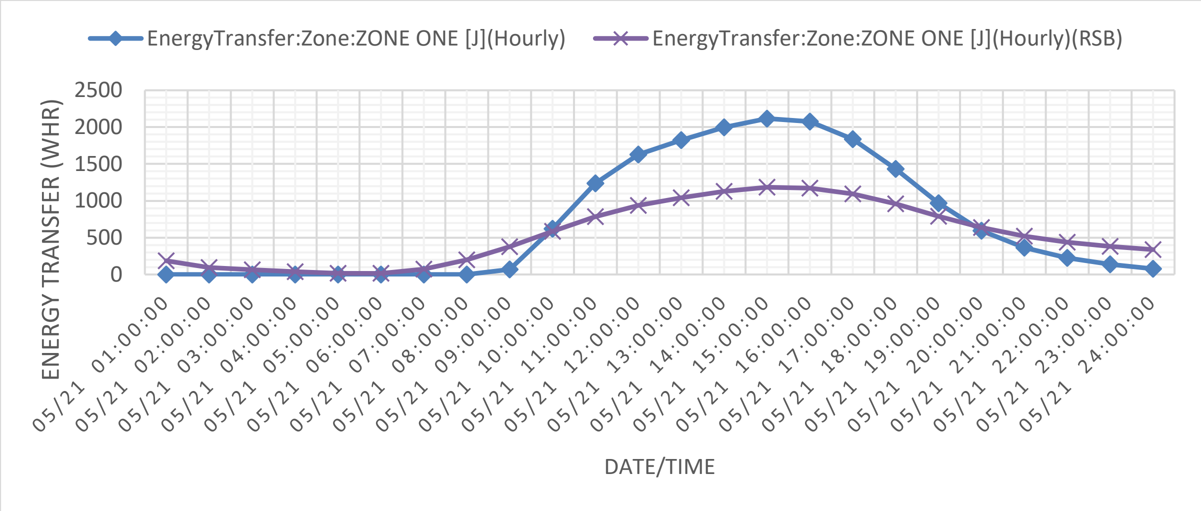


Fig.4.30 Energy consumption for test case and modified case in summer.

It is necessary to have a cooling load throughout the afternoon when the temperature reaches above 27˚C as seen in Fig.4.30.

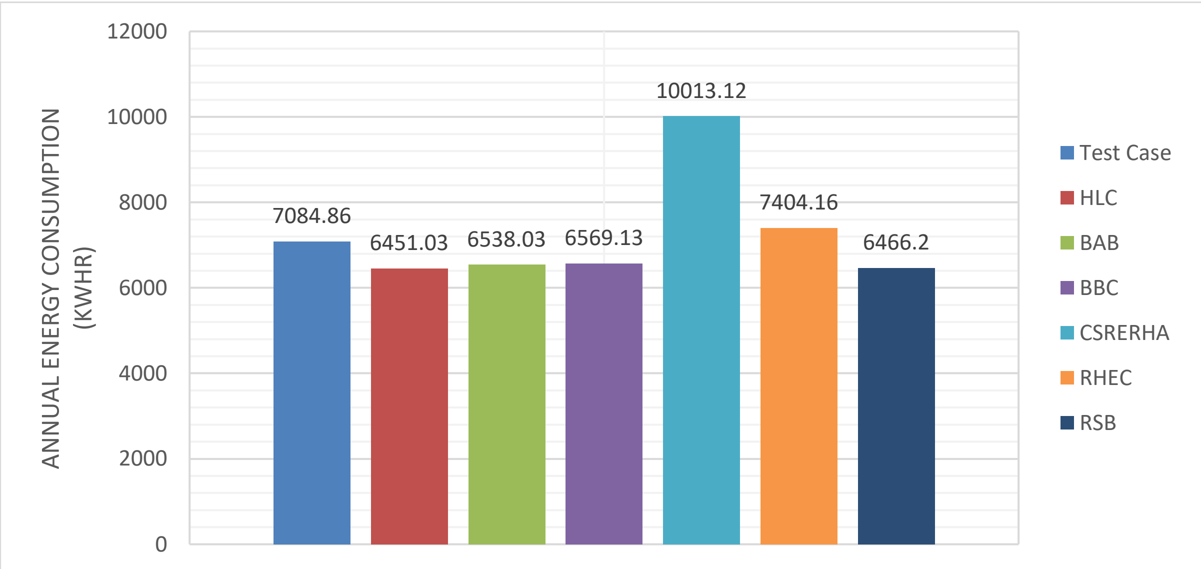


Fig.4.31 Annual energy consumption in moderate climate.

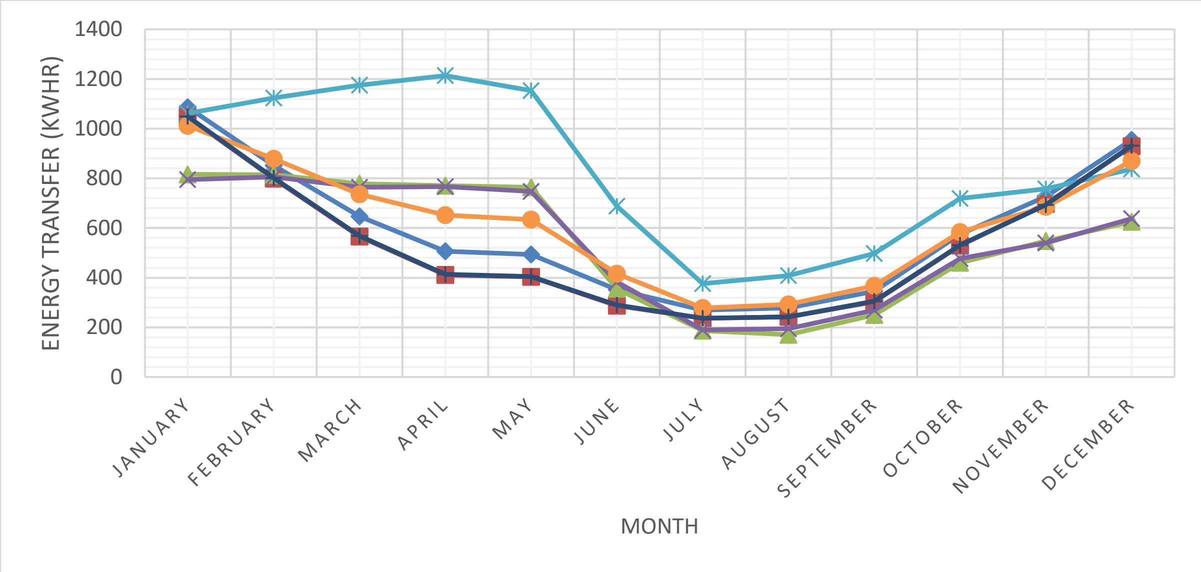


Fig.4.32 Annual energy variation in moderate climate.

Based on the annual energy consumption as seen from Fig.4.31 it can be shown that, in comparison to the test case, HLC, BAB, BC, and RBS exhibit reductions in energy consumption of 8.95%, 7.72%, 7.28%, and 8.73%, whereas CSERHA and RHEC show increases in energy consumption of 41.33% and 4.51%.

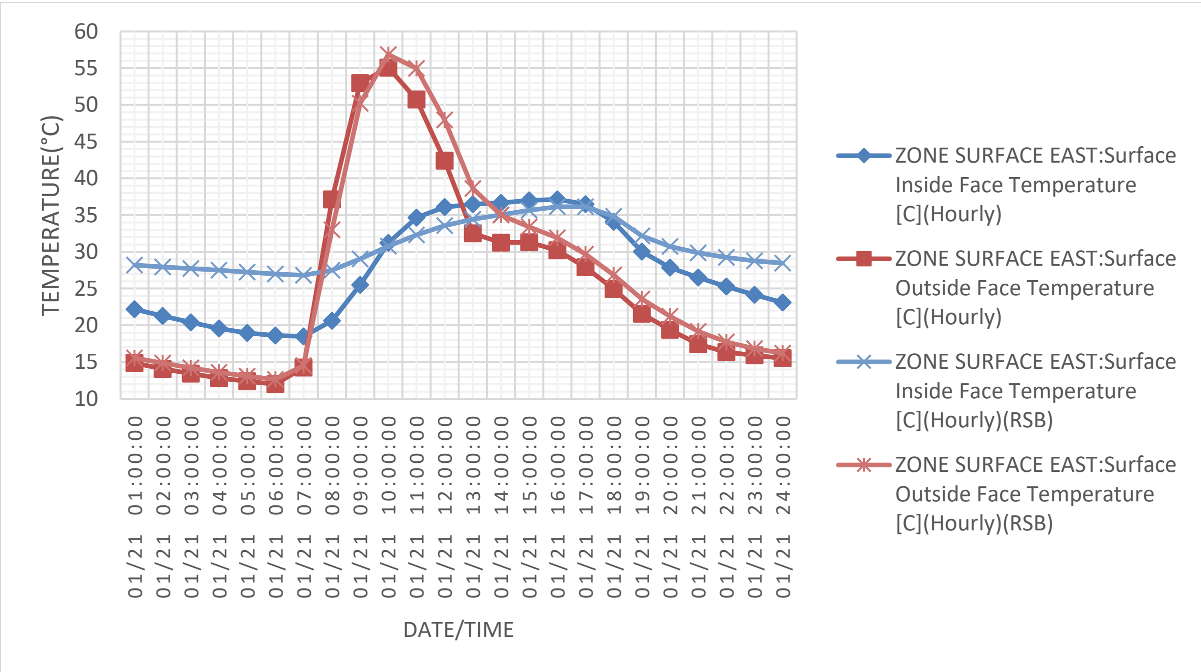


Fig.4.33 Wall surface temperature for winter day.

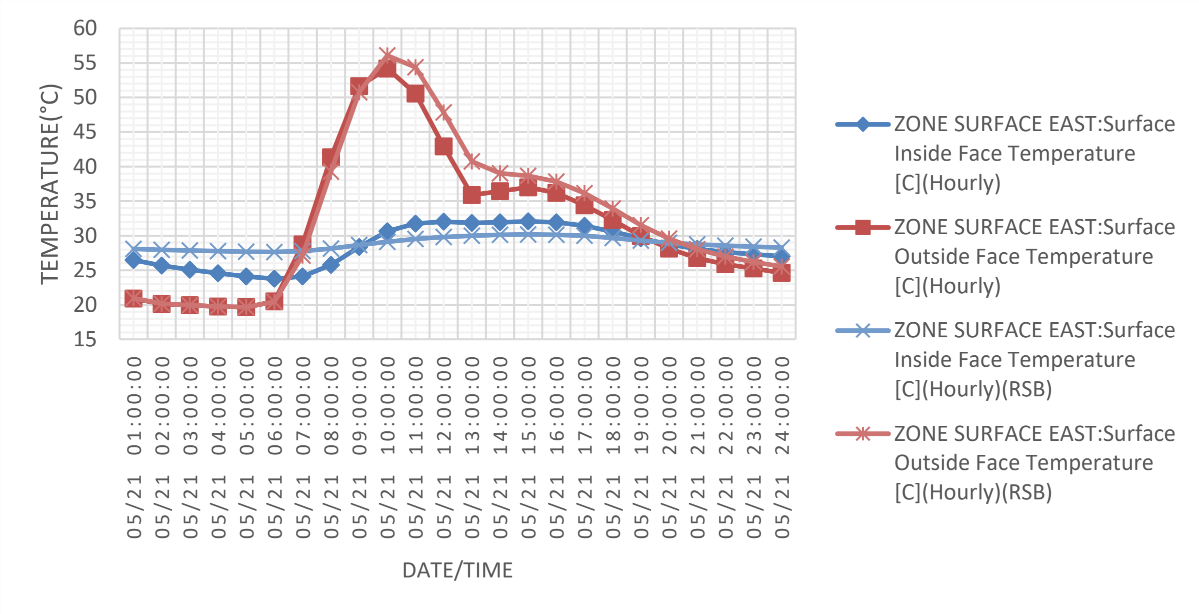


Fig.4.34 Wall surface temperature for summer day.

From the wall temperature profile as seen in Fig.4.33 and Fig. 4.34 it is observed that the RSB wall shows a slight reduction in fluctuation for inside surface temperature.

Case 4: Warm and humid climate (Chennai)

It is evident from the outside environmental temperature from Fig. 4.35 that cooling is needed during the entire summer design day as seen in Fig. 4.36 in the warm and humid climatic zone.

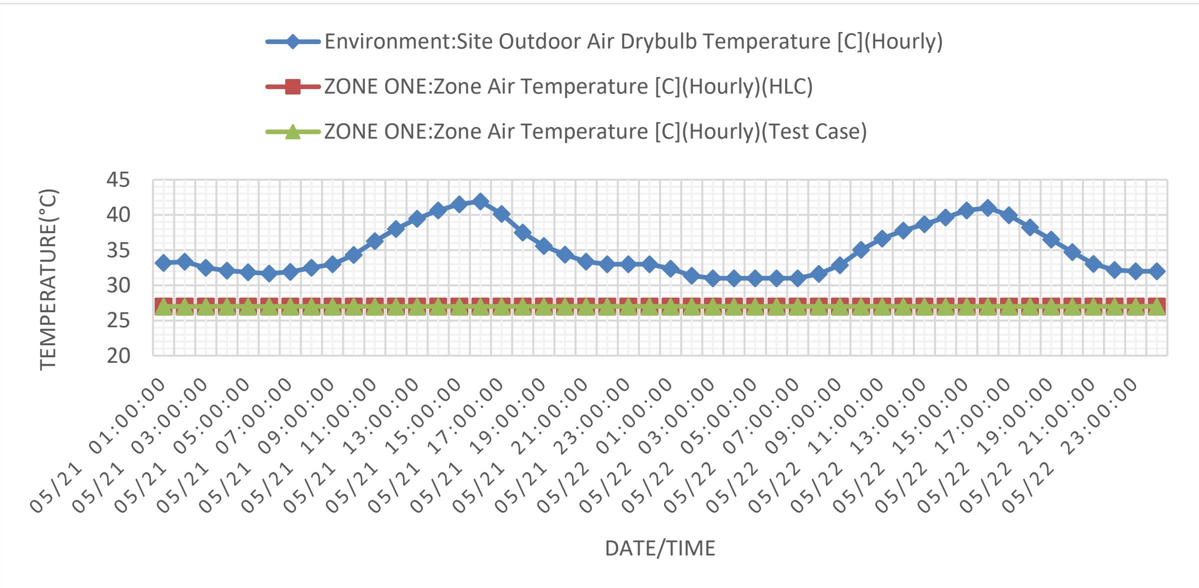


Fig.4.35 Temperature variation of environment, test case, and modified case in summer.

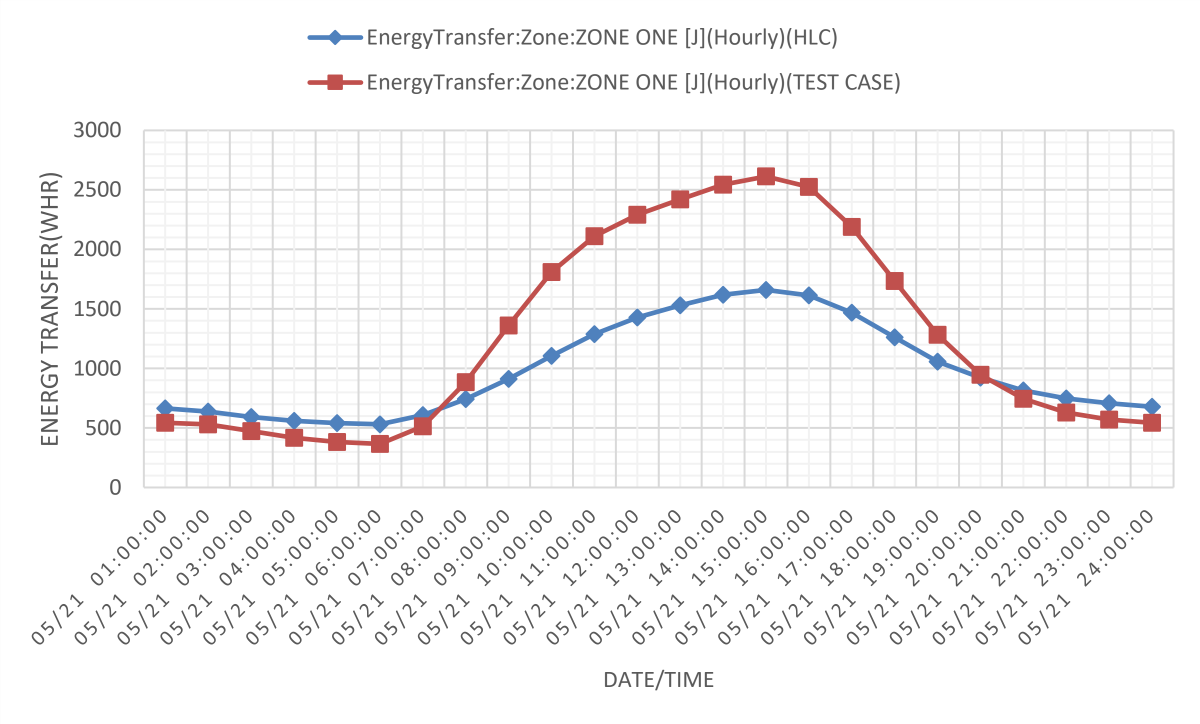


Fig.4.36 Energy consumption for test case and modified case in summer.

During a winter day, high cooling is needed in the afternoon as seen in Fig.4.38 when there is high solar radiation.

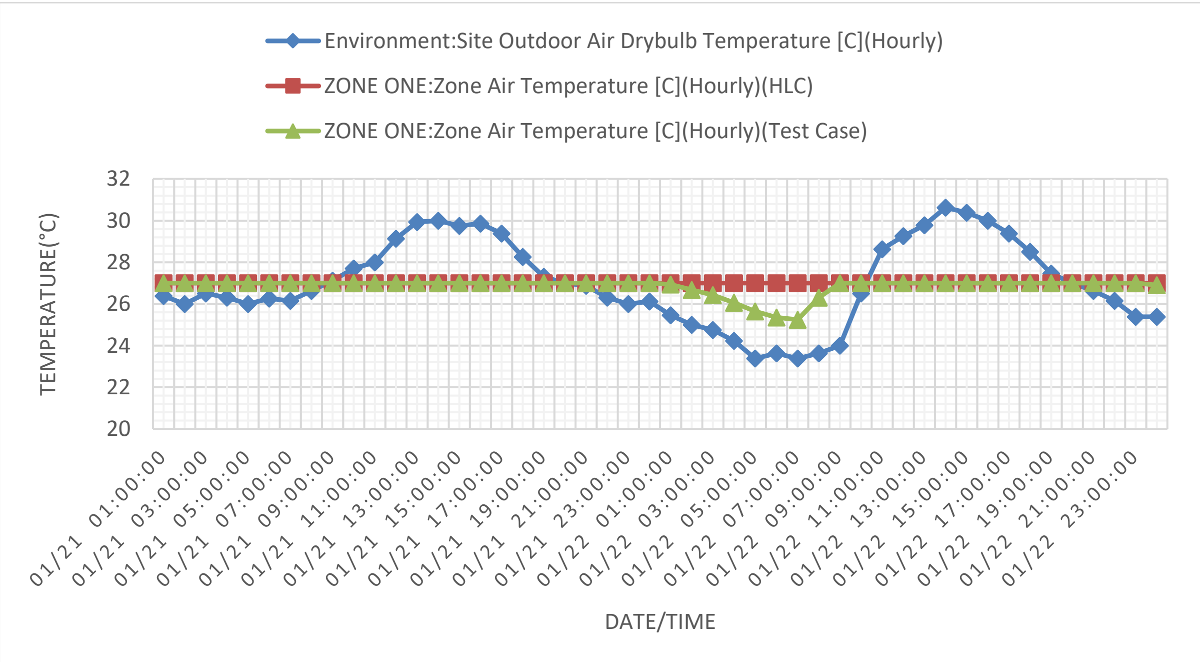


Fig.4.37 Temperature variation of environment, test case, and modified case in winter.

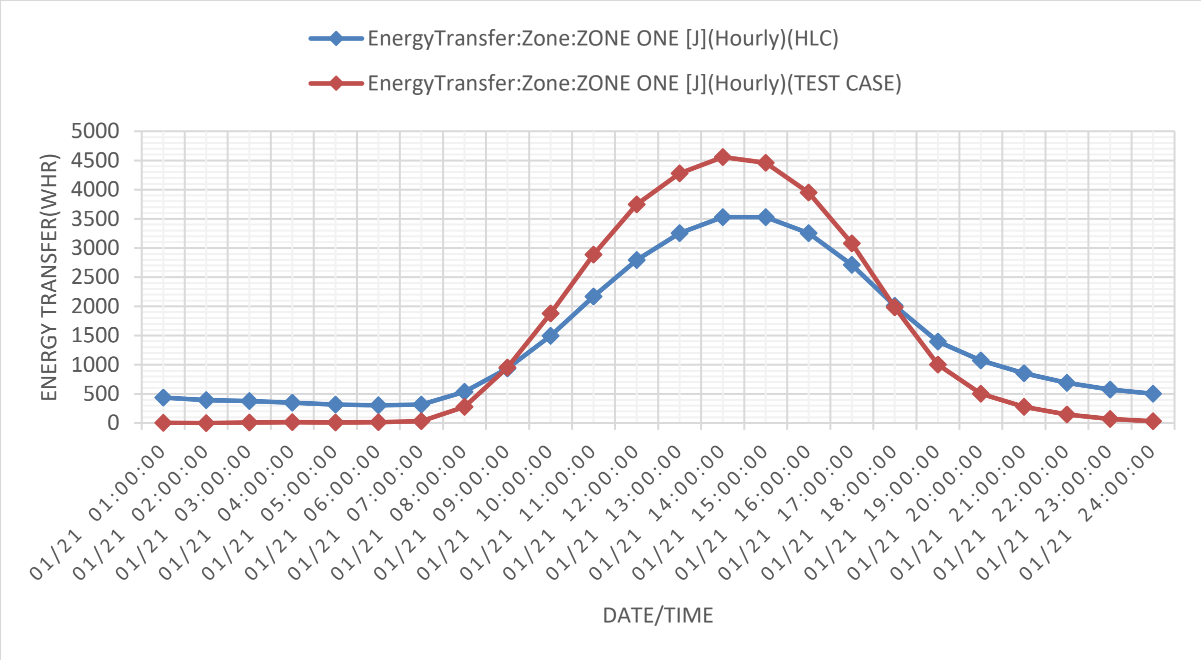


Fig.4.38 Energy consumption for test case and modified case in winter.

From Fig. 4.39 it is observed that the HLC wall was able to provide an energy reduction of 9.13% based on the annual energy consumption results.

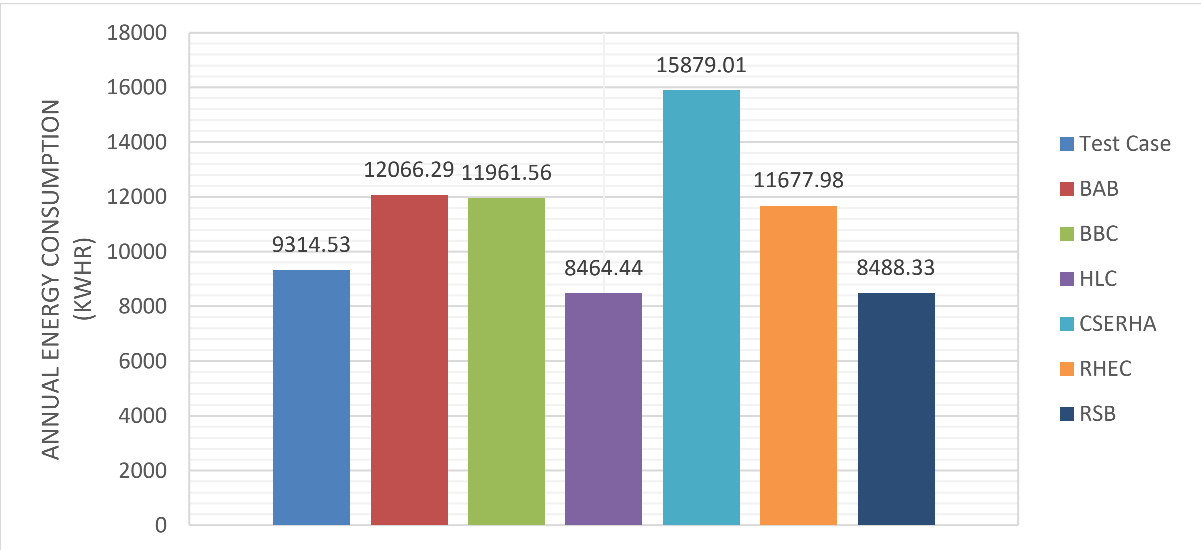


Fig.4.39 Annual energy consumption in warm and humid climates.

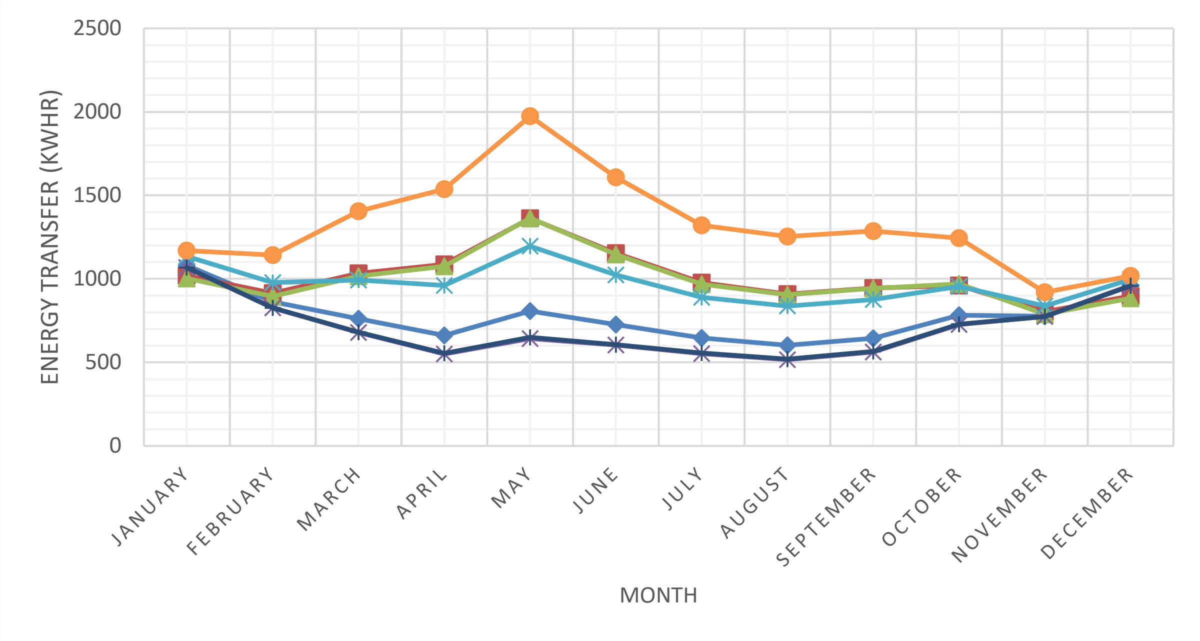


Fig.4.40 Annual energy variation in warm and humid climate.

With respect to the test case, the RSB wall demonstrated good agreement in terms of annual energy savings of 8.87%. Other walls showed an increase in energy consumption than the test case. From Fig.4.40 it is observed that HLC and RSB walls behaved quite similarly for a whole year. Also, BBC and BAB wall behaved the same over the year.

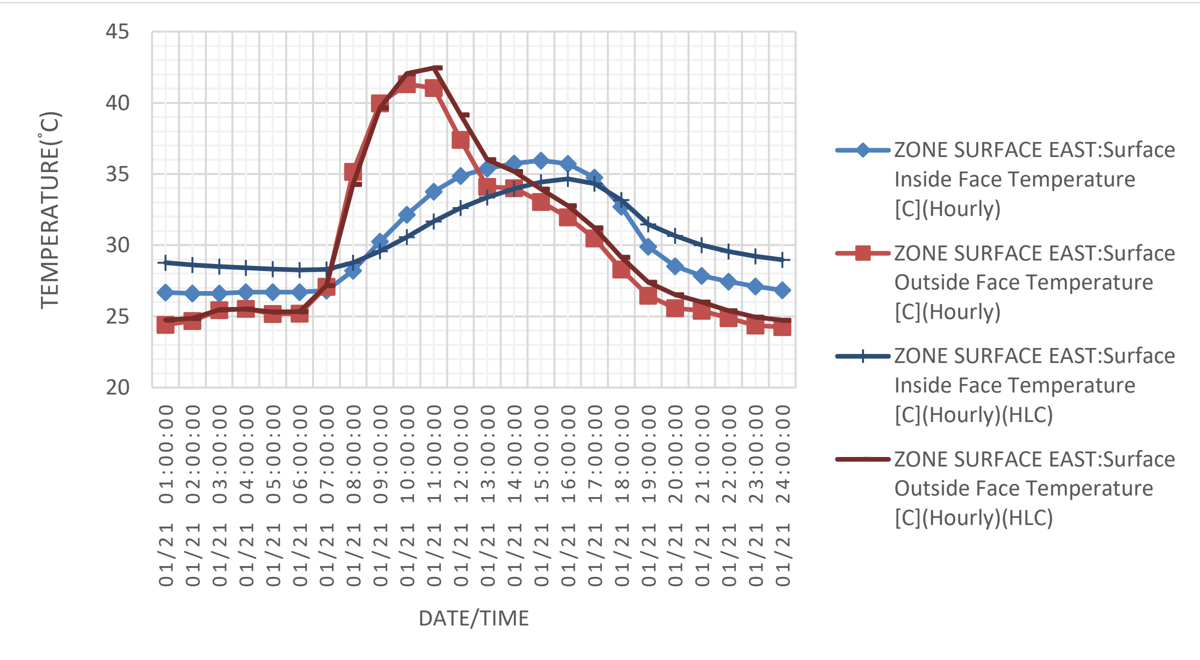


Fig.4.41 Wall surface temperature for winter day.

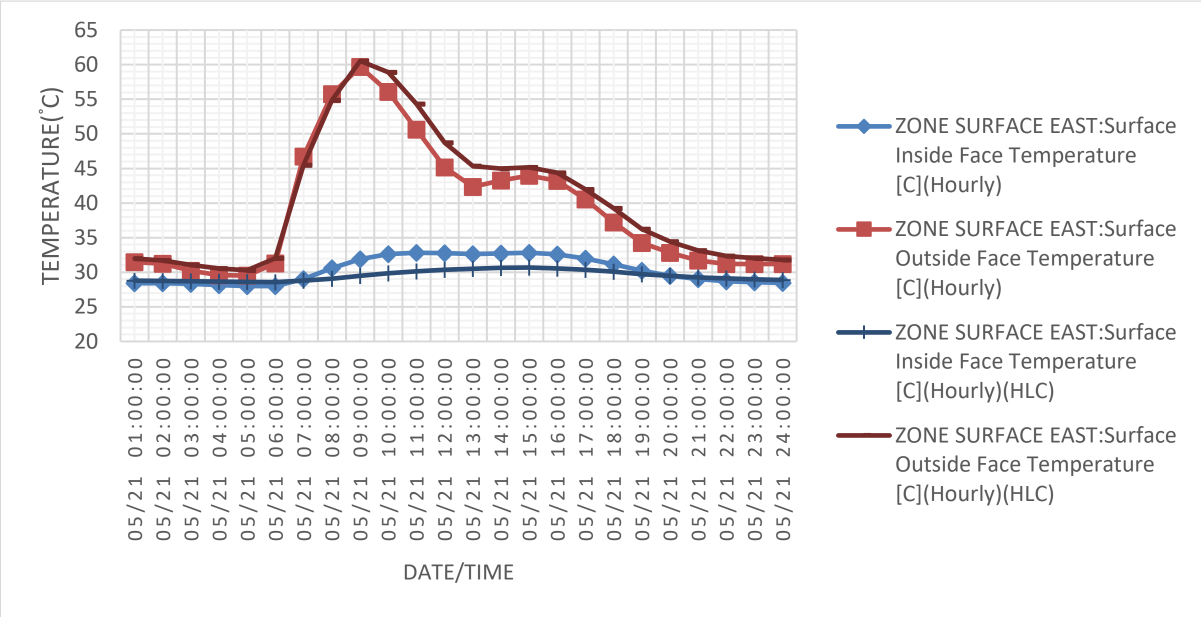


Fig.4.42 Wall surface temperature for summer day.

The wall surface temperature plot as seen in Fig. 4.41 and Fig. 4.42 for both the inside and outside faces shows that, while the outside surface temperature does not significantly change, the inside face temperature does decrease slightly during the peak solar radiation hours on both the summer and winter design days when the outside environment temperature is high.

Case5: Composite Climate (New Delhi)

Due to the extreme climatic conditions experienced in both winter and summer as seen in Fig. 4.43 and Fig. 4.45, there is a significant deviation in outdoor temperature from the comfort range. Consequently, substantial heating and cooling are essential during these seasons as seen in Fig. 4.44 and Fig. 4.46.

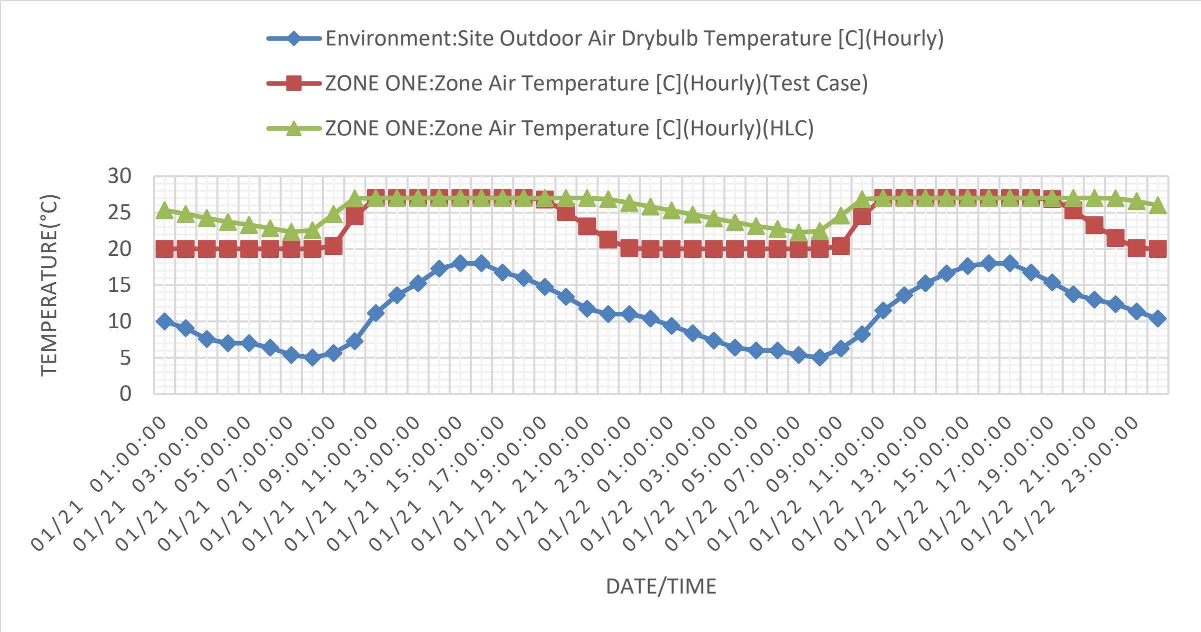


Fig.4.43 Temperature variation of environment, test case, and modified case in winter.

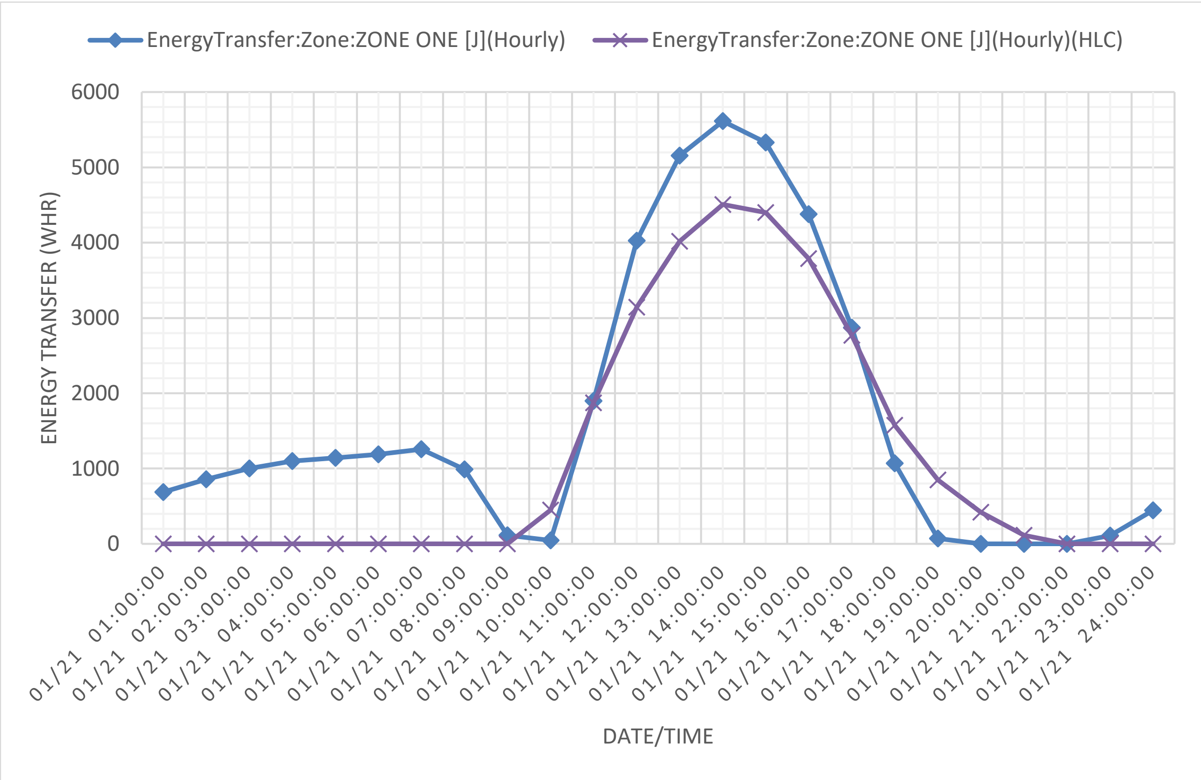


Fig.4.44 Energy consumption for test case and modified case in winter.

On a winter design day, the morning hours exhibit very low temperatures, resulting in the maximum heating load for the test case as seen in Fig. 4.44. However, the HLC wall eliminates the need for cooling during this time, as the temperature remains within the heating and cooling cutoff point as seen in Fig. 4.44 from 22:00 hrs to 9:00 hrs. The zone temperature decreases from 27 °C around 21:00 hrs to 22 °C around 8:00 hrs, followed by an increase due to rising outside environmental temperature and solar radiation. Cooling load becomes necessary as the temperature surpasses 27 °C, occurring until 7:00 hrs for the test case and 21:00 hrs for the HLC case.

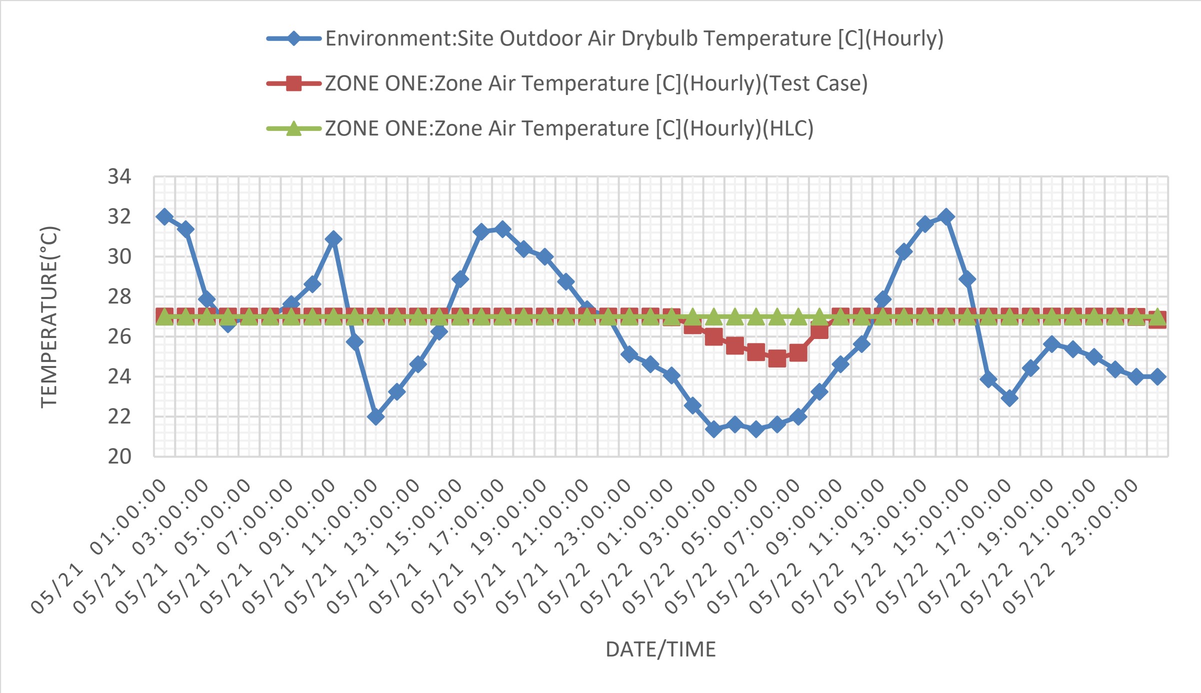


Fig.4.45 Temperature variation of environment, test case, and modified case in summer.

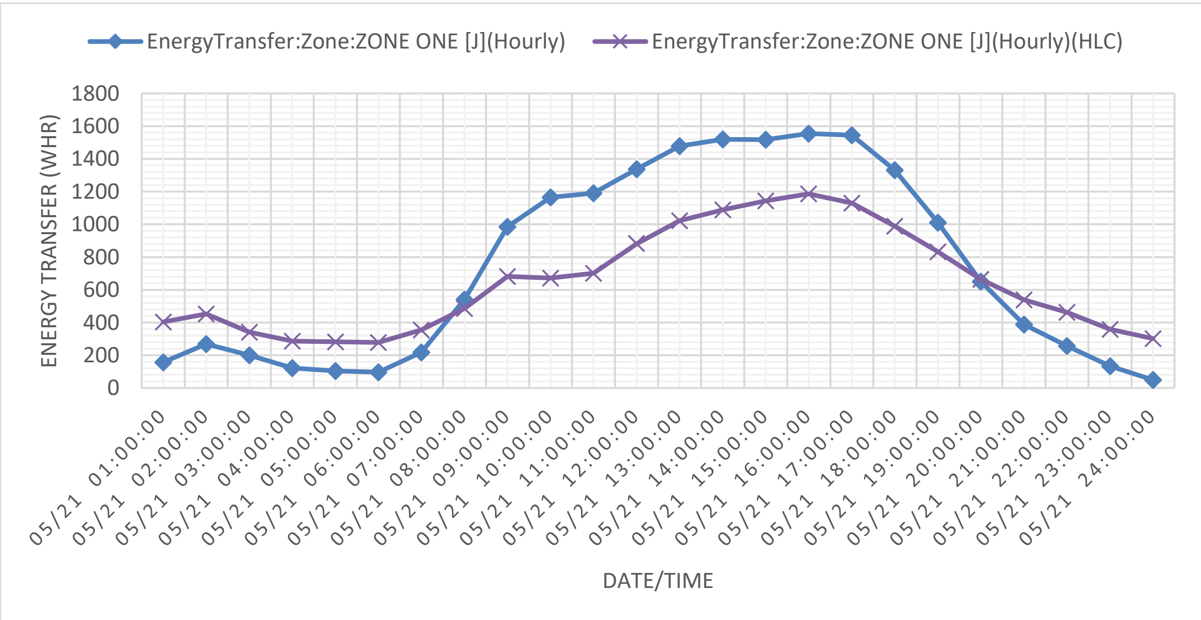


Fig.4.46 Energy consumption for test case and modified case in summer.

During the summer design day, continuous cooling is required since the outside environmental temperature consistently exceeds 20 °C as seen in Fig.4.45.

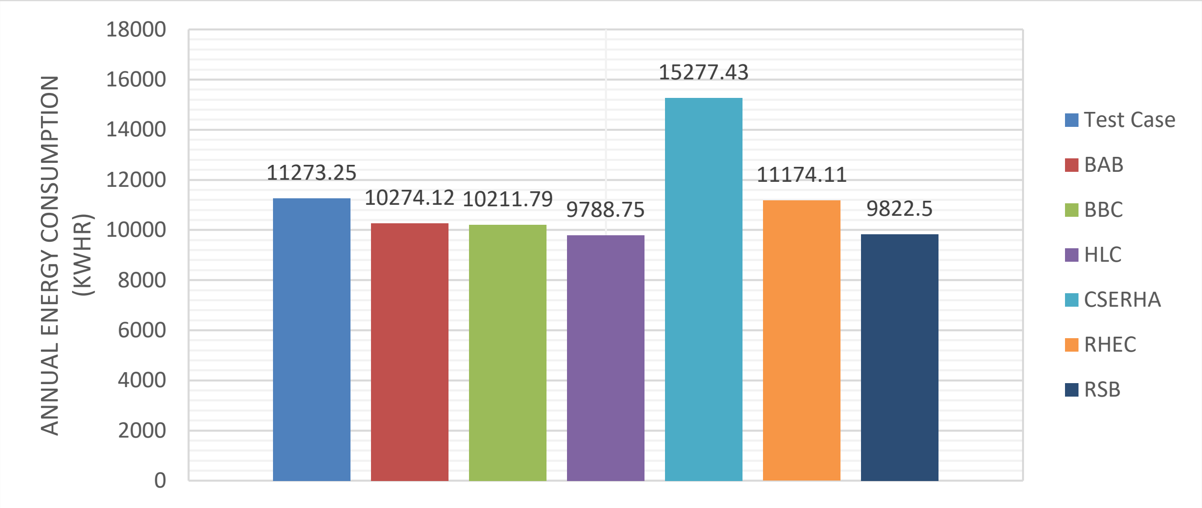


Fig.4.47 Annual energy consumption in composite climate.

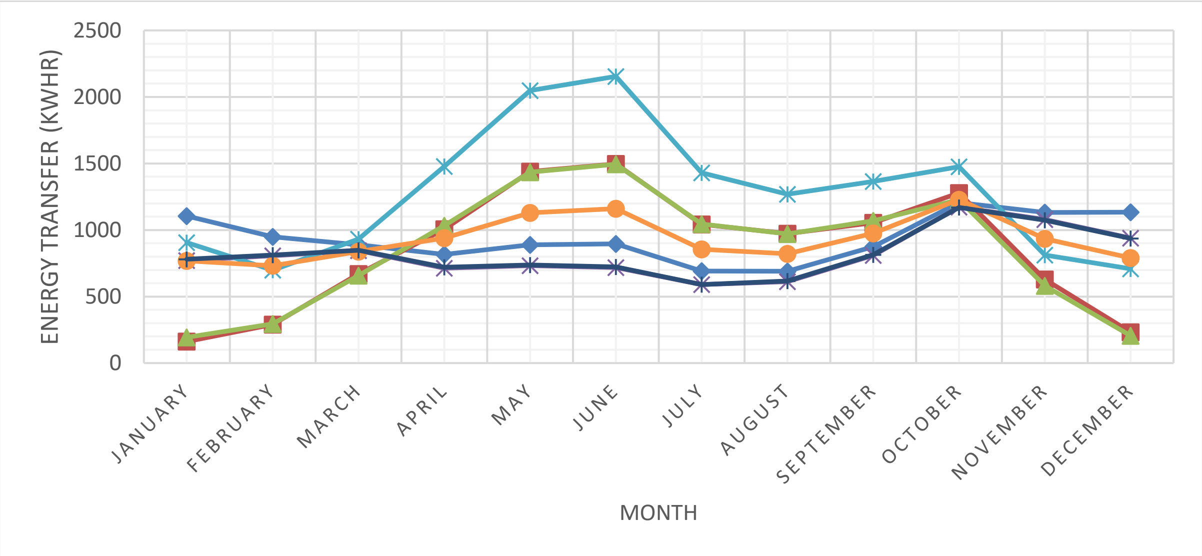


Fig.4.48 Annual energy variation in composite climate.

Analyzing the annual energy consumption results from Fig. 4.47, walls with BAB, BBC, HLC, and RSB as biomaterials demonstrated a decrease in energy consumption of 8.86%, 9.42%, 13.17%, and 12.87%, respectively. In contrast, the RHEC wall exhibited almost identical energy consumption, while the CSRERHA wall showed a 35.52% higher energy consumption compared to the test case.

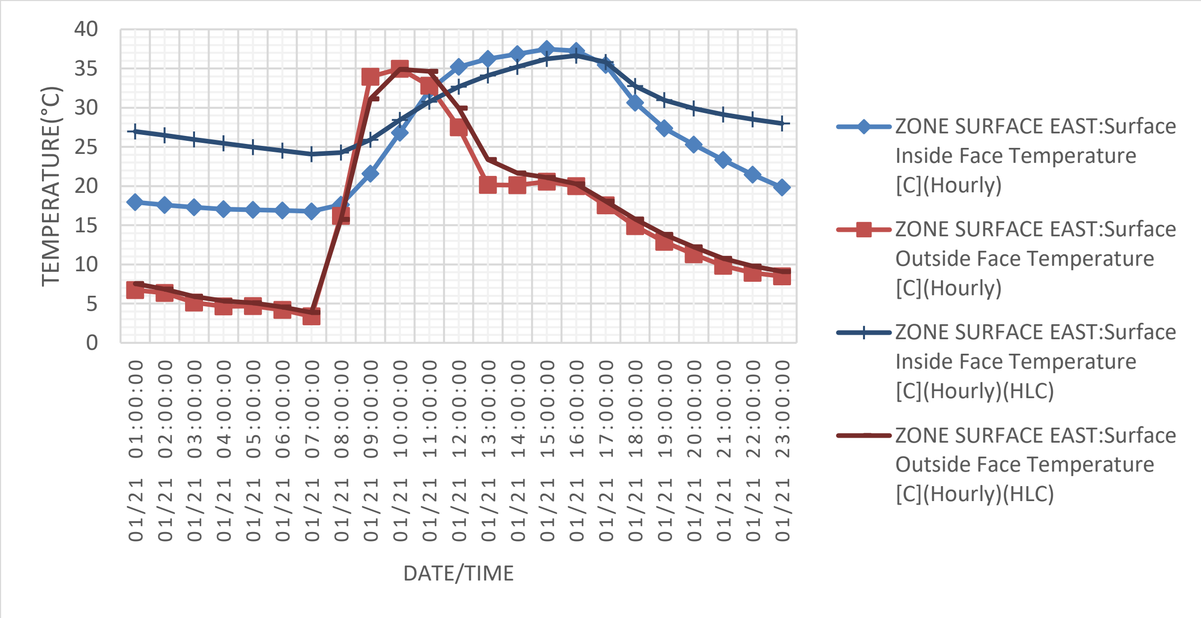


Fig.4.49 Wall surface temperature for winter day.

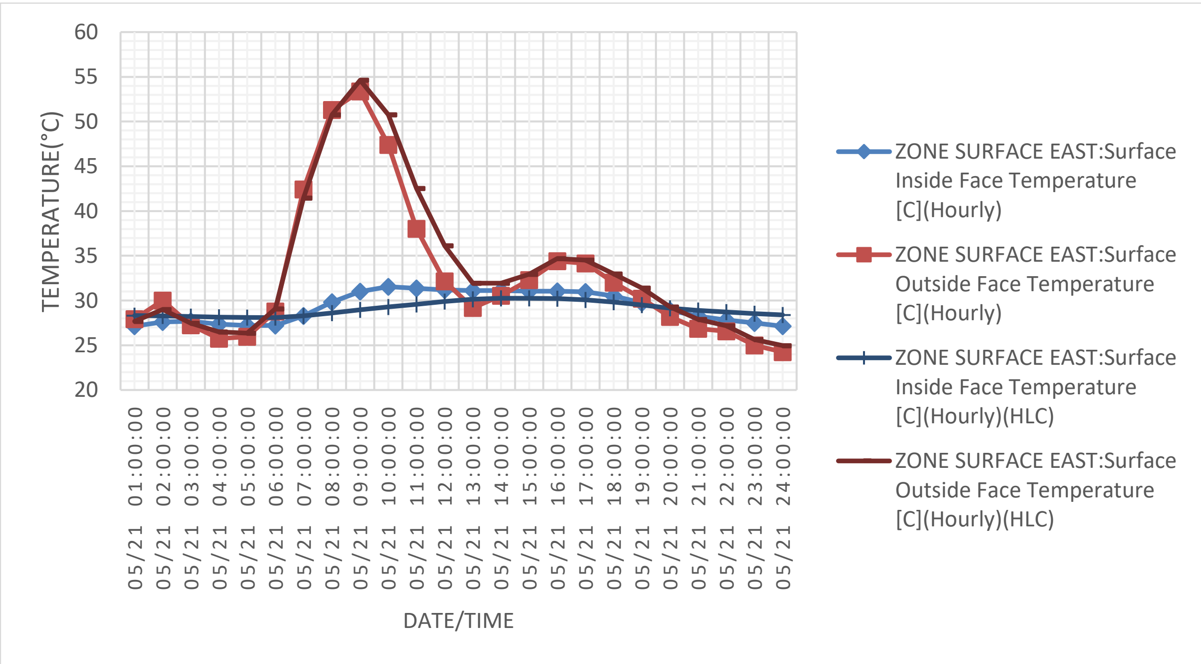


Fig.4.50 Wall surface temperature for a summer day.

From Fig.4.49 and Fig.4.50, it can be inferred that the HLC wall's temperature profile for the outside face exhibits behavior similar to the test case, with a slight reduction in amplitude observed for the inside face in the HLC case.

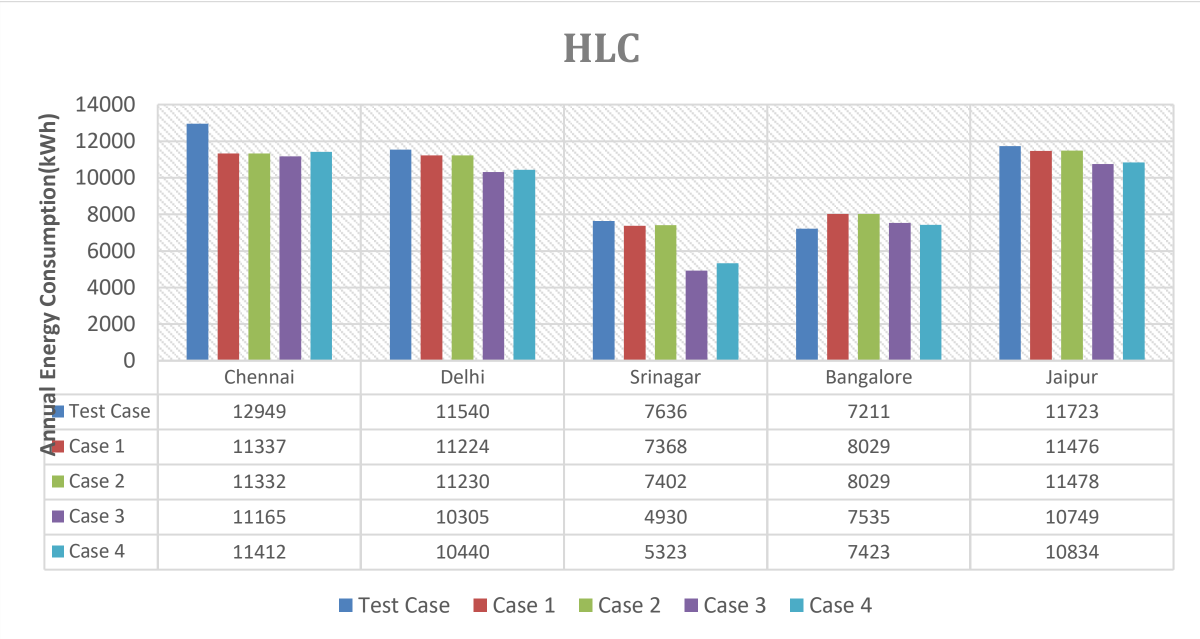
4.6 Simulation Results for wall types discussed in section 3.3

From the above simulation result of section 3.2.1 based on modification in the envelope of test case 600 for the wall, it has been seen that the wall made up of biomaterial performed better in saving energy and also had better thermal behavior in terms of temperature fluctuation and time lag.

Now for the practical applicability of the biomaterial as a part of the envelope in buildings, different types of walls as shown in section 3.3 have been designed based on the strength criteria and optimum thickness of homogeneous layer of biomaterial for maximum energy storage in the wall

In this section simulation results for all five considered climatic zones are shown for each of the designed walls based on strength criteria and the optimum thickness of the homogenous layer of biomaterial wall.

4.6.1 Annual energy consumption for Hemp-Lime Composite (HLC) wall for different climatic zones.

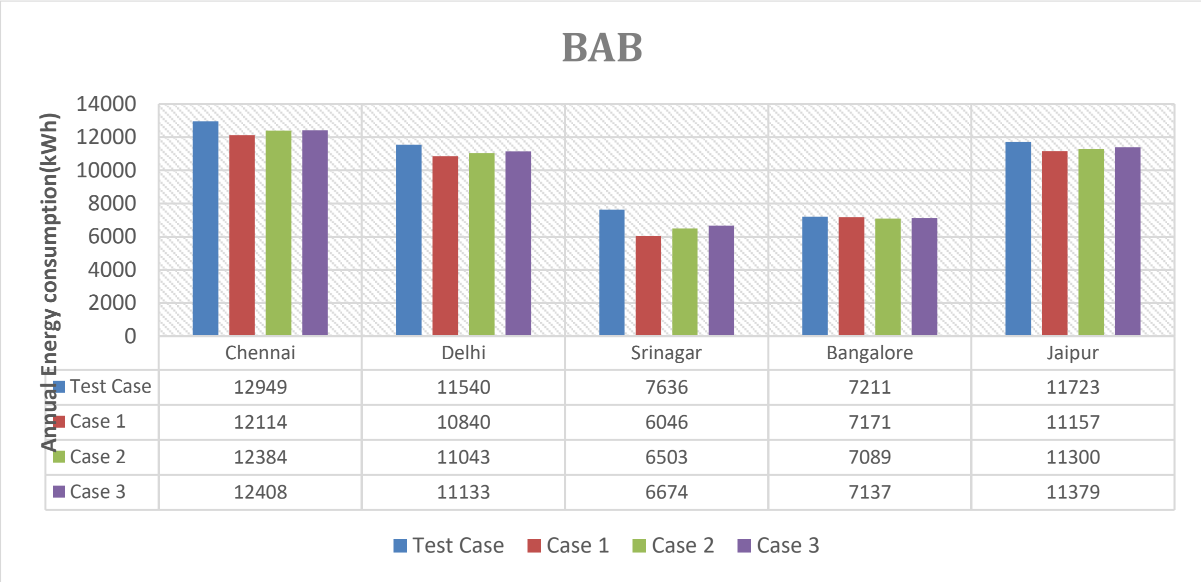


	Chennai	Delhi	Srinagar	Bangalore	Jaipur
Test Case	12949	11540	7636	7211	11723
Case 1	11337	11224	7368	8029	11476
Case 2	11332	11230	7402	8029	11478
Case 3	11165	10305	4930	7535	10749
Case 4	11412	10440	5323	7423	10834

Fig.4.51 Energy consumption for HLC wall.

From the above simulation results for the HLC wall, it can be observed that case 3 is saving maximum energy for all climatic zones, but case 4 will be more suitable as it is 16.25 cm less thick than case 3 with a compromise of only about 2% less saving.

(4.6.2) Annual energy consumption for Bagasse Ash Brick (BAB) wall for different climatic zones.

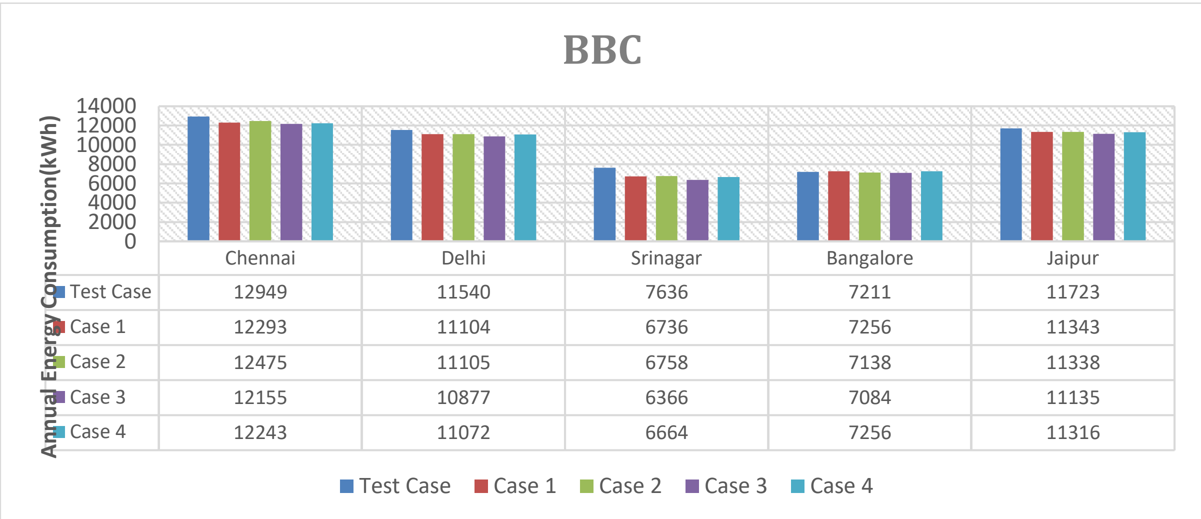


	Chennai	Delhi	Srinagar	Bangalore	Jaipur
Test Case	12949	11540	7636	7211	11723
Case 1	12114	10840	6046	7171	11157
Case 2	12384	11043	6503	7089	11300
Case 3	12408	11133	6674	7137	11379

Fig.4.52 Energy consumption for BAB wall

In this case 1 is saving more annual energy consumption than other cases.

(4.6.3) Annual energy consumption for Bamboo-bio Concrete (BBC) walls for different climatic zones.

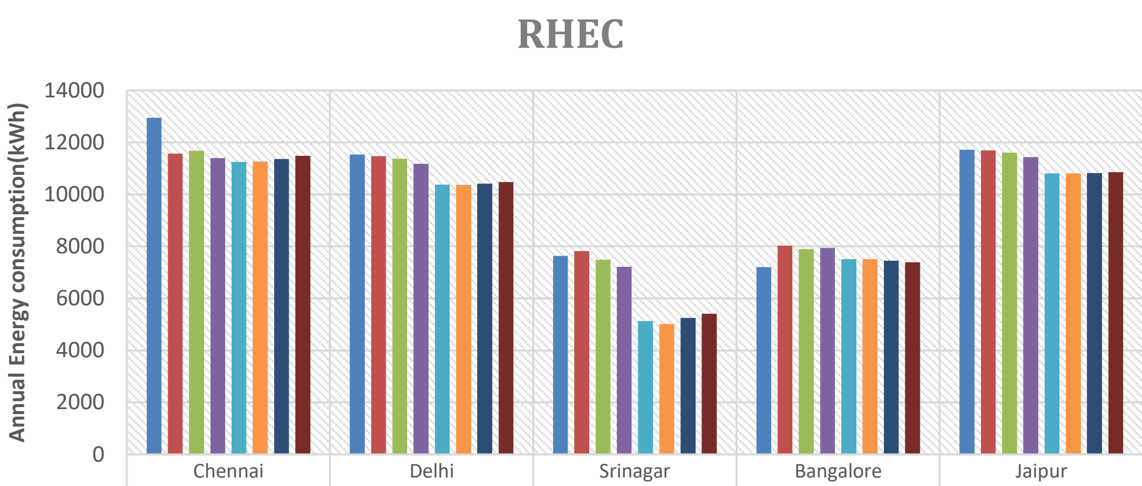


	Chennai	Delhi	Srinagar	Bangalore	Jaipur
Test Case	12949	11540	7636	7211	11723
Case 1	12293	11104	6736	7256	11343
Case 2	12475	11105	6758	7138	11338
Case 3	12155	10877	6366	7084	11135
Case 4	12243	11072	6664	7256	11316

Fig.4.53 Energy consumption for BBC wall

In the case of the BBC wall, both case 3 and case 4 save almost the same annual energy for all climatic zones. Further economic analysis will be required to compare both cases.

(4.6.4) Annual energy consumption for Rice husk and expanded cork (RHEC) wall for different climatic zones.



	Chennai	Delhi	Srinagar	Bangalore	Jaipur
Test Case	12949	11540	7636	7211	11723
Case 1	11576	11472	7820	8034	11695
Case 2	11678	11373	7484	7895	11608
Case 3	11395	11176	7212	7944	11432
Case 4	11250	10379	5122	7515	10805
Case 5	11263	10362	5012	7513	10803
Case 6	11356	10416	5254	7451	10821
Case 7	11482	10476	5415	7394	10858

Fig.4.54 Energy consumption for RHEC wall

From the above results, it can be concluded that in almost all cases energy saving is almost the same for each climatic zone with few percentage variations, so cases that will be less thick will be more suitable. So here case 7 seems to be more suitable among other cases.

Also if we observe the wall design and their annual energy consumption, having similar layers but with different arrangements like case1 with case 6 and case 2 with case 7, it can be said that if we use RHEC (having less thermal diffusivity) as outside layer it will give better result in saving energy when it is used as an inside layer.

(4.6.5) Annual energy consumption for Cement stabilized rammed earth rice husk ash (CSRERHA) wall for different climatic zones.

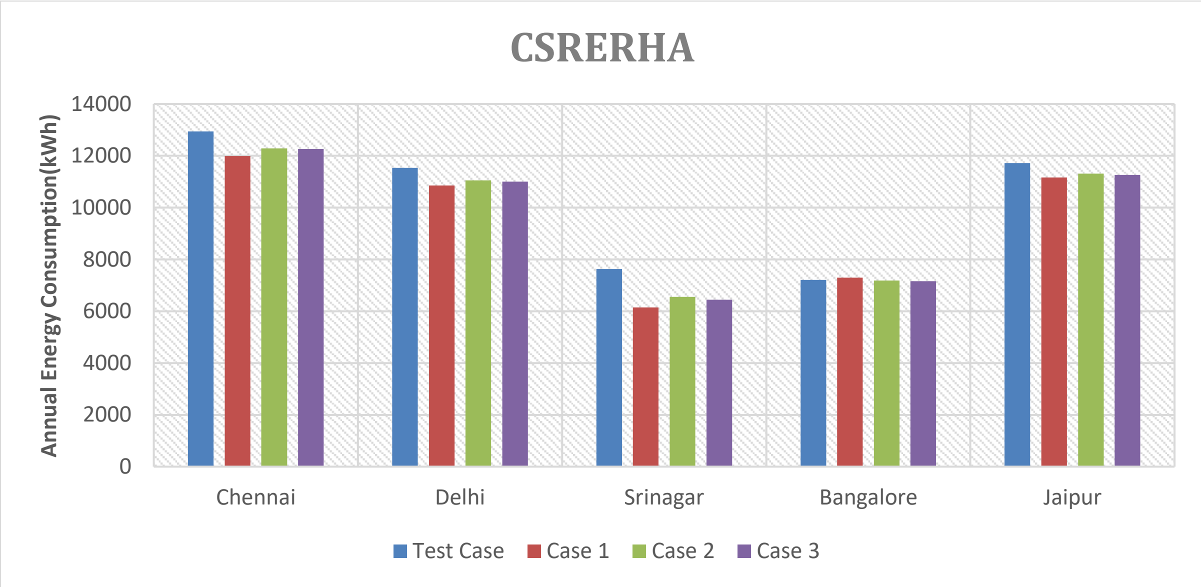
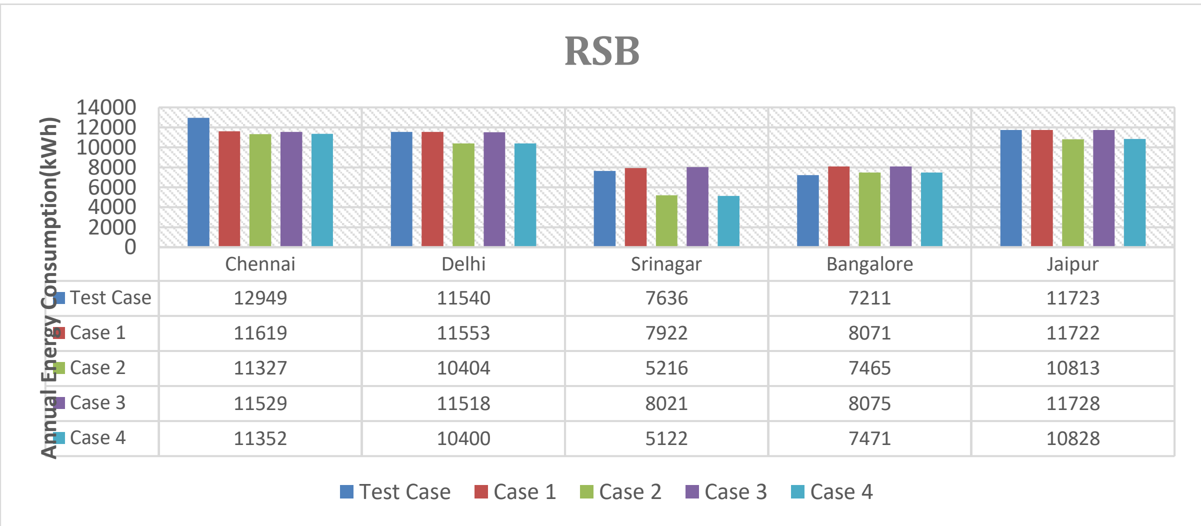


Fig.4.55 Energy consumption for CSRERHA wall

In CSRERHA walls as it is have almost similar thermal properties as compared to red burnt brick (standard wall) it can only save energy if a much greater thickness is considered. So case 1 saves more energy than other cases.

(4.6.6) Annual energy consumption for Rice straw bale (RSB) wall for different climatic zones.



	Chennai	Delhi	Srinagar	Bangalore	Jaipur
Test Case	12949	11540	7636	7211	11723
Case 1	11619	11553	7922	8071	11722
Case 2	11327	10404	5216	7465	10813
Case 3	11529	11518	8021	8075	11728
Case 4	11352	10400	5122	7471	10828

Fig.4.56 Energy consumption for RSB wall

Among the considered cases for RSB, case 2 shows maximum saving in energy consumption. Also, case 4 shows similar energy-saving potential but it will not be considered as of now for further economic analysis because of its unknown structural stability.

(4.6.7) Annual energy consumption for Date palm ash (DPA) wall for different climatic zones.

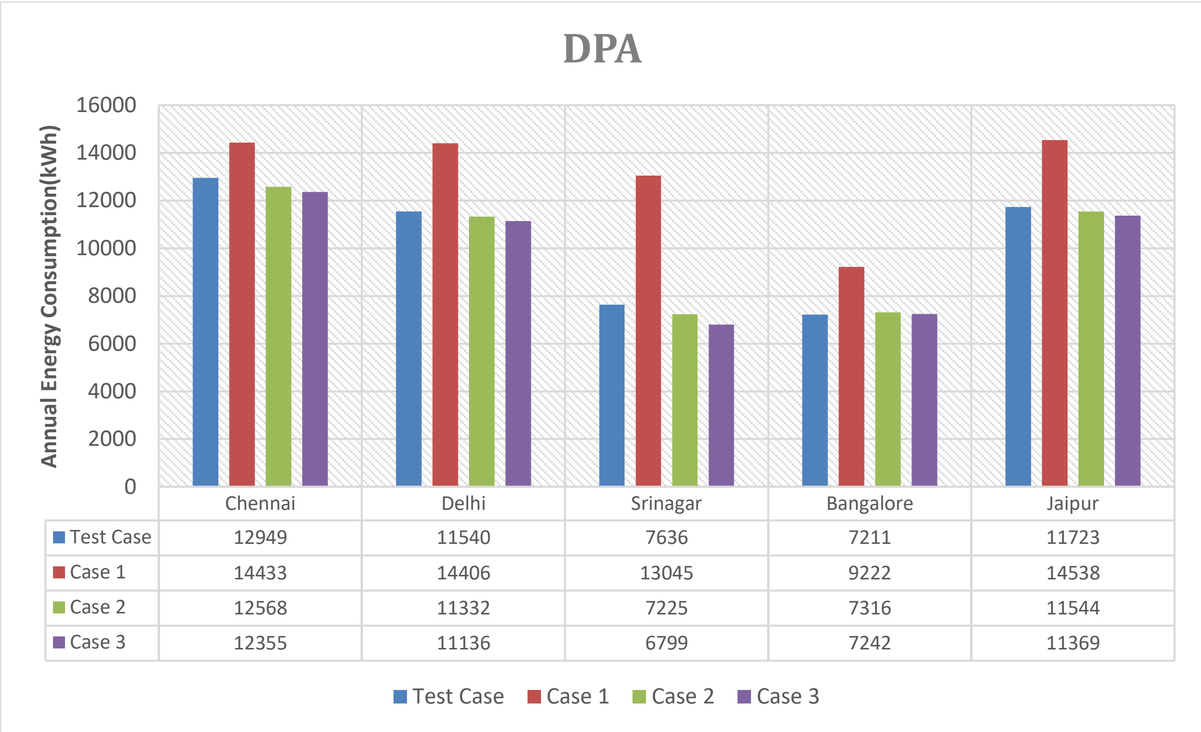
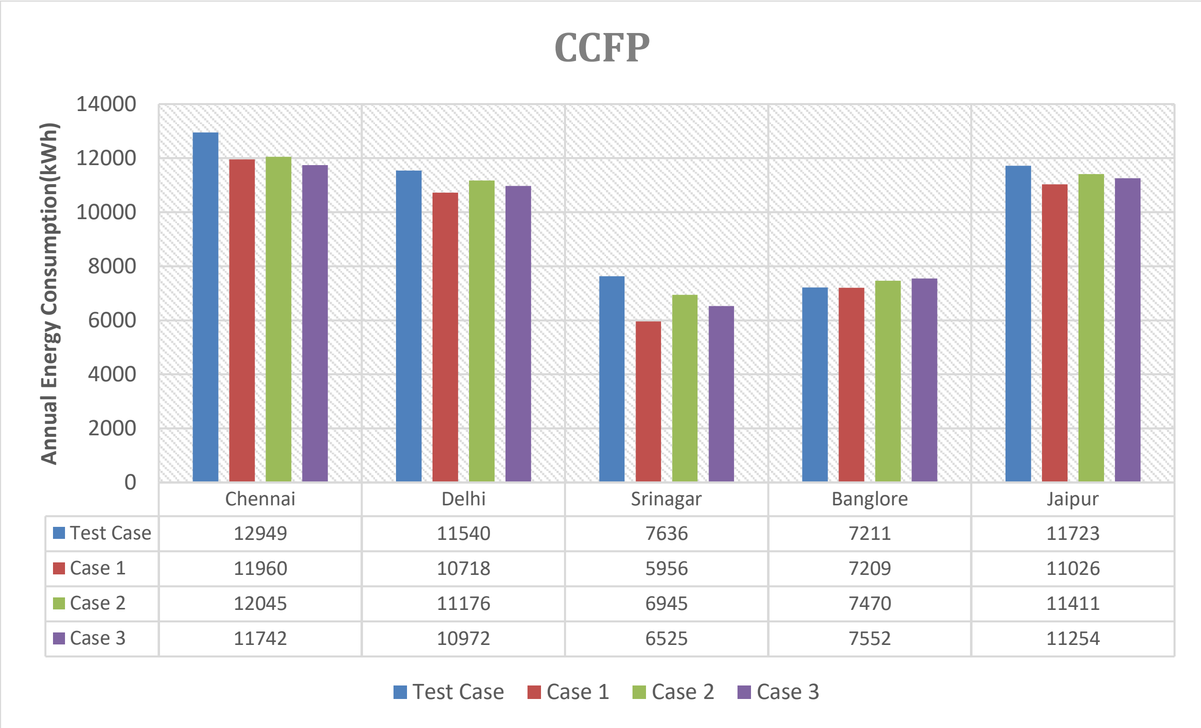


Fig.4.57 Energy consumption for DPA wall

Case 3 of the DPA brick wall is saving more energy and is also structurally feasible hence will be considered for further analysis.

(4.6.8) Annual energy consumption for Coconut coir fiber panel (CCFP) wall for different climatic zones.



	Chennai	Delhi	Srinagar	Banglore	Jaipur
Test Case	12949	11540	7636	7211	11723
Case 1	11960	10718	5956	7209	11026
Case 2	12045	11176	6945	7470	11411
Case 3	11742	10972	6525	7552	11254

Fig.4.58 Energy consumption for CCFP wall

In the case of the CCFP wall case 3 shows maximum energy saving for Chennai and case 1 for Delhi, Srinagar, and Jaipur. Both case 1 and case 3 will be further analyzed for cost-benefit with respect to other wall designs.

After analyzing the simulation results for annual energy consumption for every climate following cases of walls have been suggested based on the strength criteria, optimum thickness, and annual energy saving.

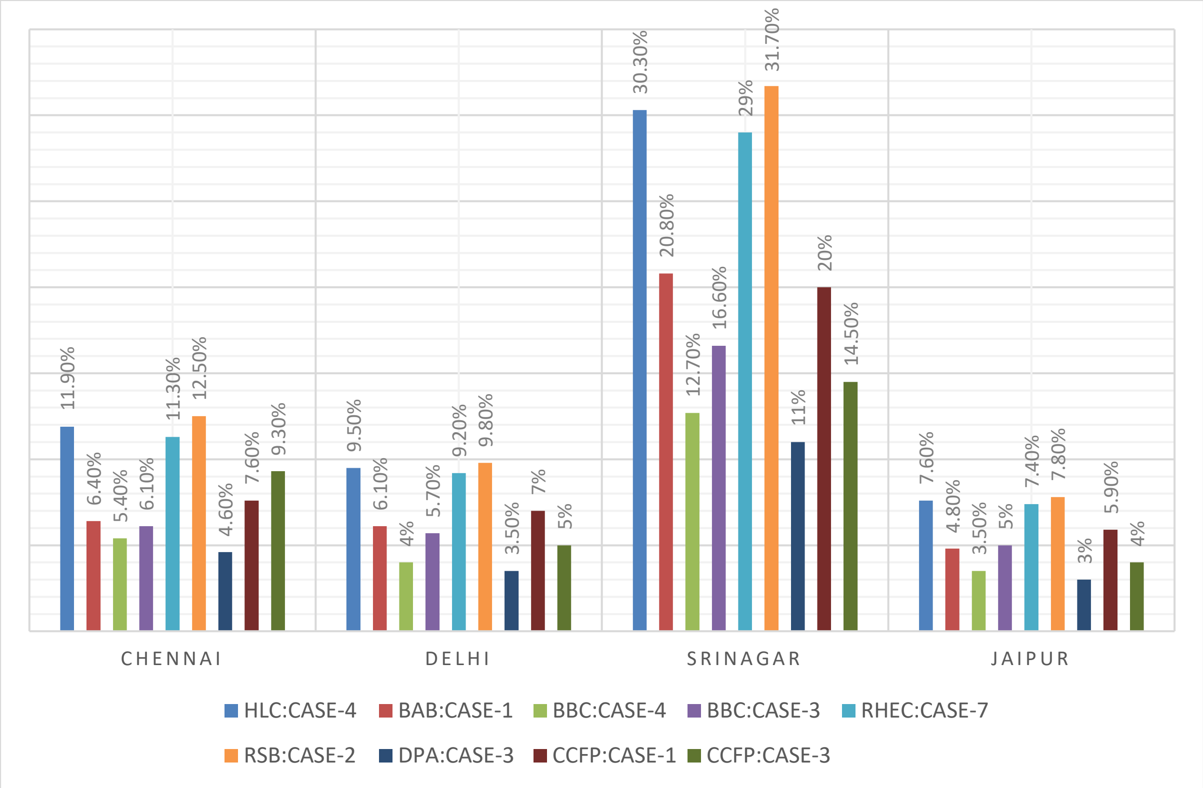


Fig.4.59 Percentage energy saving for different suggested walls.

Now for the suggested walls comparison can be done among the walls for each climatic zone based on cost analysis involving the unit cost of the materials involved in the construction of walls and the unit cost of electrical energy consumption based on the method discussed in section 3.3.

4.7 Cost and Energy Analysis for Different Climatic Zones

4.7.1 Warm and Humid Climate (Chennai)

Table 4.1 Cost and energy analysis of walls for warm and humid climates.

	Std. Wall	HLC:C-4	BAB:C-1	BBC:C-4	RHEC:C-7	RSB:C-2	DPA:C-3	CCFP:C-3
Q(kWh/m^2)	75.5	66.5	70.6	71.3	66.9	66	72	68.4
C(Rs/m^2)	1462	1813.4	1054.8	982.5	4354.4	1730	431.3	2113.8
Q_{norm}	0	0.95	0.52	0.44	0.91	1	0.37	0.75
C_{norm}	0.74	0.65	0.84	0.86	0	0.67	1	0.57
Ranking:	0.74	1.60	1.36	1.30	0.91	1.67	1.37	1.32

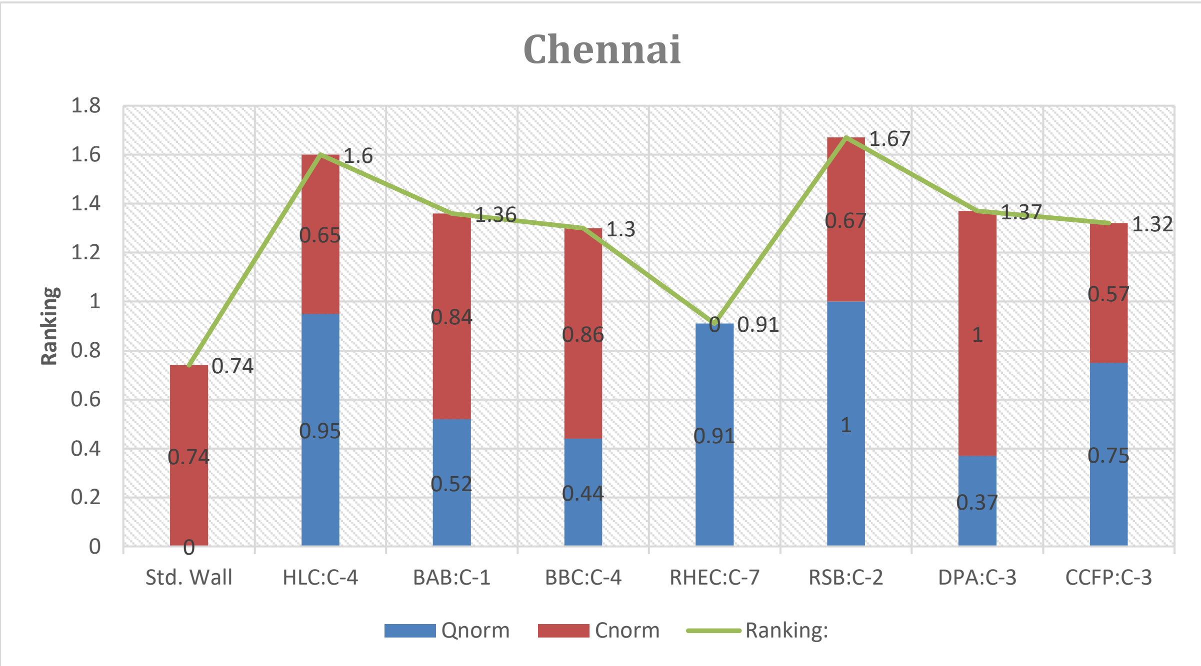


Fig.4.60 Ranking of walls for warm and humid climate.

It can be observed from Fig.4.60 that the standard wall has the lowest ranking because it is the highest energy-consuming wall type leading to a Q_{norm} of zero. Therefore it will act as a reference for comparison with other walls. RSB: C-2 having Q_{norm} equal to one indicates maximum energy saving. Also, RSB has the lowest cost, so combining both Qnorm and Cnorm leads to the highest ranking among all wall types.

Since a warm and humid climate has high temperature and high humidity, the wall having good moisture resistance will be suitable, hence BBC: C-4 having good moisture resistance and HLC: C-4 and BAB: C-1 having moderate moisture resistance will act as good candidates among all wall types.

4.7.2 Composite Climate (New Delhi)

Table 4.2 Cost and energy analysis of walls for composite climate.

	Std. Wall	HLC:C-4	BAB:C-1	BBC:C-4	BBC:C-3	RHEC:C-7	RSB:C-2	DPA:C-3	CCFP:C-1
Q(kWh/m^2) C(Rs/m^2)	67.2 1462	60.8 1813.4	63.2 1054.8	64.5 982.5	63.4 1505	61 4354.4	60.6 1730	65 431.3	62.4 1888.6
Q_{norm} C_{norm}	0 0.74	0.97 0.65	0.61 0.84	0.41 0.86	0.58 0.73	0.94 0	1 0.67	0.33 1	0.73 0.63
Ranking:	0.74	1.62	1.45	1.27	1.31	0.94	1.67	1.33	1.36

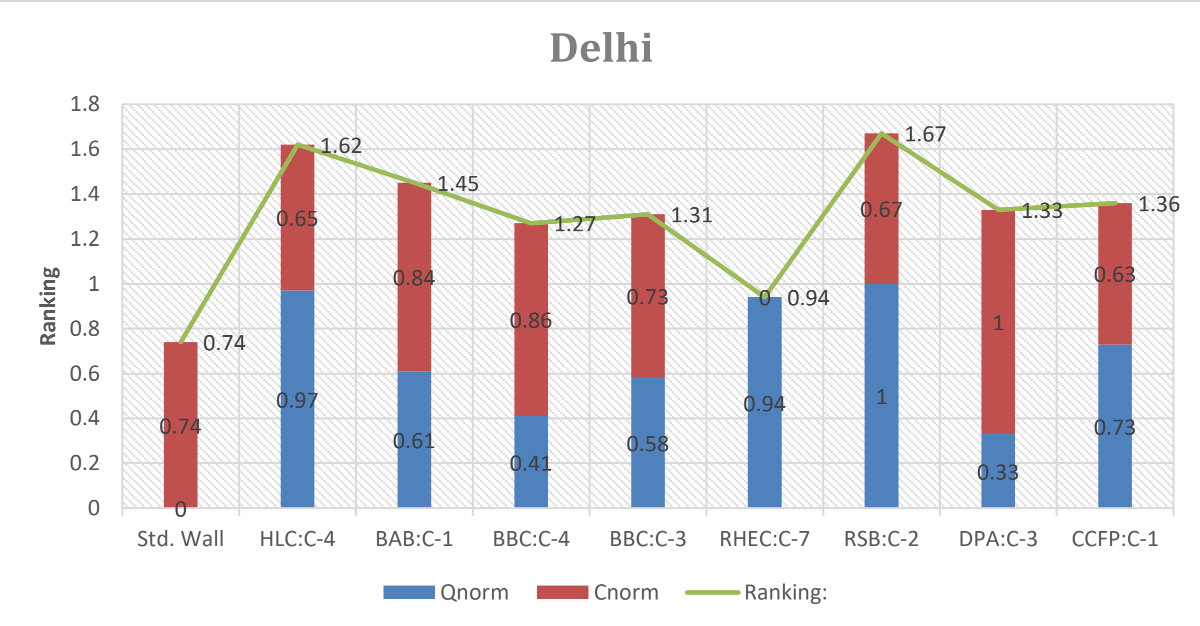


Fig.4.61 Ranking of walls for composite climate.

Composite climates have extreme temperatures during summer as well as winter, so walls need to have both cooling and heating insulation. For this RSB: C-2 and HLC: C-4 wall types are suitable. RHEC: C-7 having a Q_{norm} of 0.94 is also a suitable candidate if cost is not a concern for the construction because of its highest cost.

4.7.3 Cold Climate (Srinagar)

Table 4.3 Cost and energy analysis of walls for cold climate.

	Std. Wall	HLC:C-4	BAB:C-1	BBC:C-4	BBC:C-3	RHEC:C-7	RSB:C-2	DPA:C-3	CCFP:C-1
Q(kWh/m^2)	44.5	31	35.2	38.8	37.1	31.6	30.4	39.6	34.7
C(Rs/m^2)	1462	1813.4	1054.8	982.5	1505	4354.4	1730	431.3	1888.6
Q_{norm}	0	0.96	0.66	0.40	0.52	0.91	1	0.35	0.7
C_{norm}	0.74	0.65	0.84	0.86	0.73	0	0.67	1	0.63
Ranking:	0.74	1.61	1.50	1.26	1.25	0.91	1.67	1.35	1.33

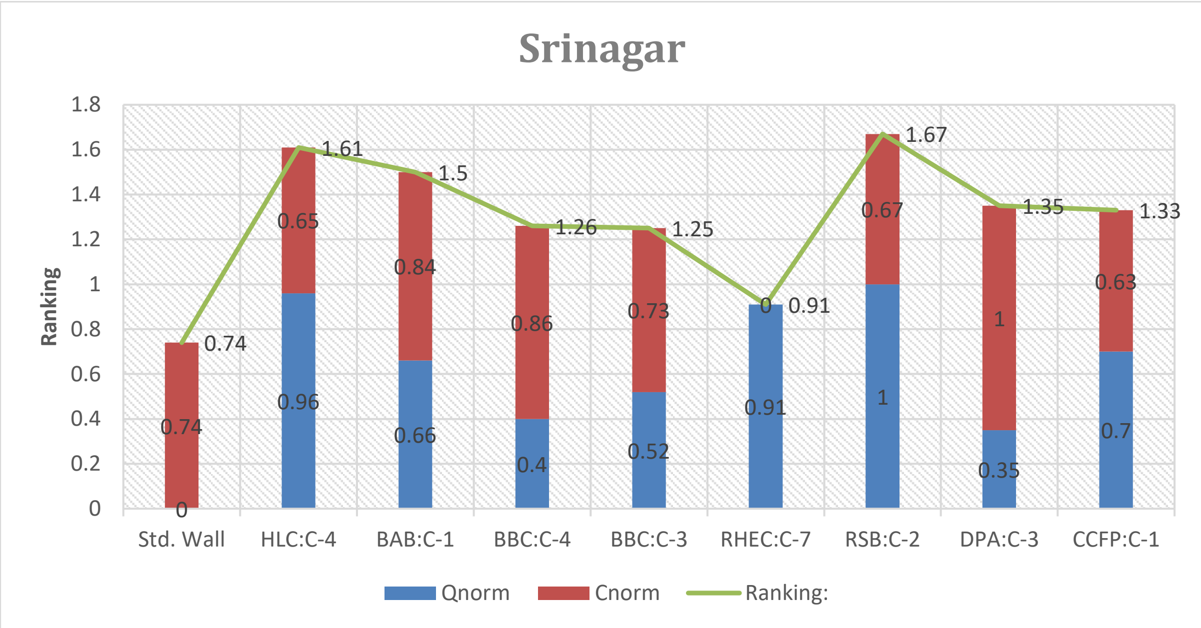


Fig.4.62 Ranking of walls for cold climate.

Since cold climatic zones have very low temperatures therefore walls need to have excellent thermal insulation and low thermal diffusivity properties to retain heat. RSB: C-2, HLC: C-4 and RHEC: C-7 are suitable candidates.

4.7.4 Jaipur (Hot and Dry)

Table 4.4 Cost and energy analysis of walls for hot and dry climates.

	Std. Wall	HLC:C-4	BAB:C-1	BBC:C-4	BBC:C-3	RHEC:C-7	RSB:C-2	DPA:C-3	CCFP:C-1	CCFP:C-3
Q(kWh/m) C(Rs/m^2)	68.3 1462	63.1 1813.4	65 1054.8	65.9 982.5	64.9 1505	63.3 4354.4	63 1730	66.2 431.3	64.2 1888.6	65.6 2113.8
Q_{norm} C_{norm}	0 0.74	0.98 0.65	0.62 0.84	0.45 0.86	0.64 0.73	0.94 0	1 0.67	0.40 1	0.77 0.63	0.51 0.57
Ranking:	0.74	1.63	1.46	1.31	1.37	0.94	1.67	1.40	1.40	1.08

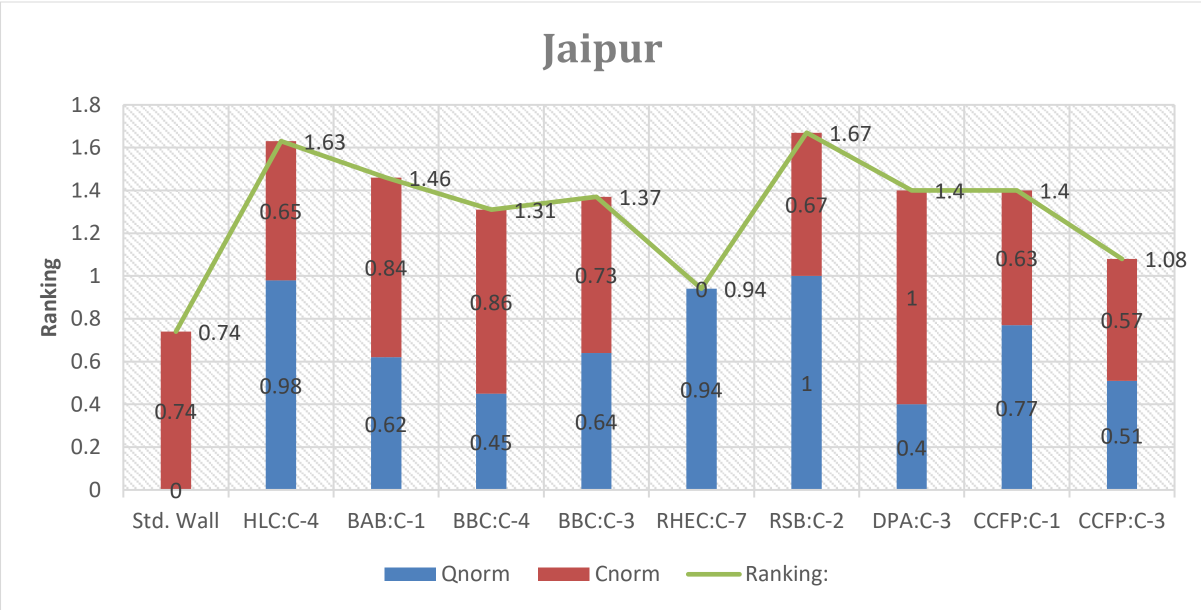


Fig.4.63 Ranking of walls for hot and dry climate.

Hot and dry climates have high temperatures and low humidity suggesting that the wall should have good heat-resistant properties, high thermal capacity, and low thermal conductivity. So among RSB: C-2, HLC: C-4, and BAB: C-1 wall types, the most suitable candidate is BAB: C-1 wall which has high thermal capacity.

4.8 Analysis for Moderate Climate (Bangalore) with RSB as an insulation on the roof:

From simulation results, we can observe that no case gives energy saving when only the wall is modified. So modification in the roof as shown in Fig.4.64 and insulation in the wall as well as in the roof with RSB as an insulation have been considered to see the effect in annual energy consumption.

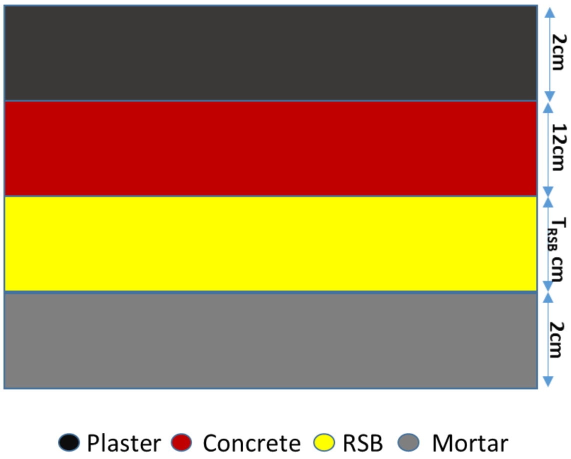


Fig.4.64 Roof design with RSB as an insulation for moderate climate.

Table.4.5 Energy and cost variation with thickness of RSB

T_{RSB}(cm)	Annual Energy (kWh)	Annual Energy (kWh)	Cost of Insulation for (Rs.)
Insulation	Wall + Roof	Roof	Roof
0	7211	7211	0
2	6380(11.5%)	6409(11.1%)	484.8
4	6290(12.8%)	6134(14.9%)	969.6
6	6292(12.7%)	5992(16.9%)	1454.4
8	6309(12.5%)	5902(18.1%)	1939.2
10	6326(12.3%)	5846(18.9%)	2424
12	6345(12%)	5806(19.5%)	2908.8
14	6352(11.9%)	5799(19.6%)	3393.6
16	6370(11.7%)	5765(20%)	3878.4
18	6379(11.5%)	5753(20.2%)	4363.2
20	6386(11.4%)	5744(20.3%)	4848

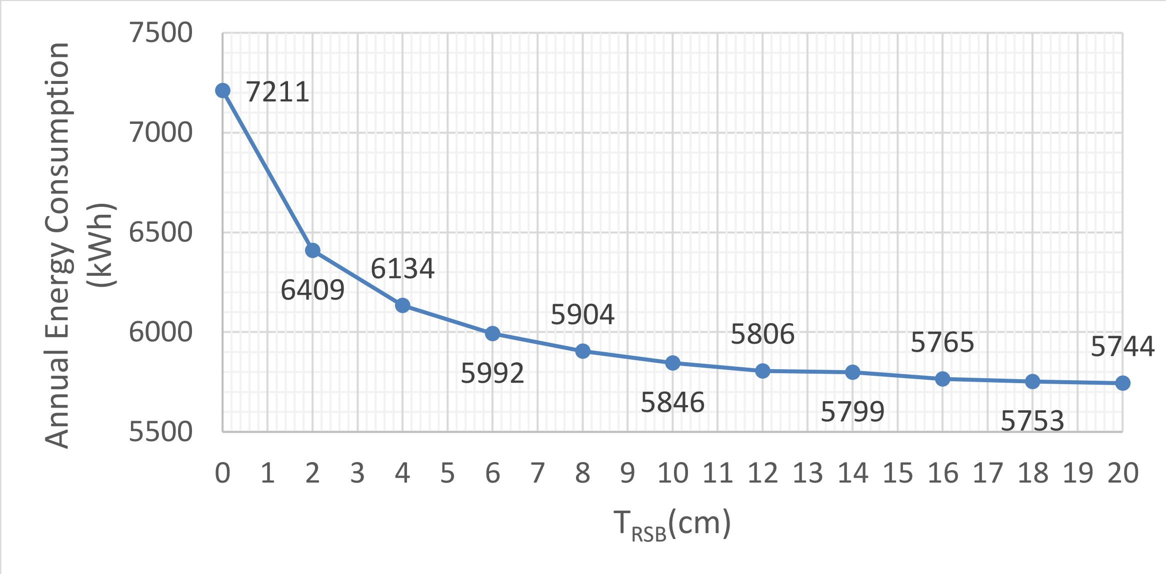


Fig.4.65 Annual energy variation with the thickness of RSB for modified roof.

From the above result for the modified roof and modified wall & roof, it can be observed that using insulation on the roof only results in a reduction of energy consumption better than insulation on both roof and wall.

From Fig.4.65 it can be seen that as the thickness of RSB increases annual energy consumption decreases but the rate of decrement slows down and an optimum thickness of around 13cm is observed after which no significant reduction is seen. This also agrees with the theoretical optimum thickness given by equation (3.3)

Hence RSB as an insulation with optimum thickness proves to be a good candidate for annual energy saving.

4.8 Payback Period for extra cost of investment:

A simple Payback Period is the simplest method that is used to estimate the time (years) that will be taken to recover the total amount invested in construction. But here as we have the simplest model so we will be calculating how many years it will take to recover the extra cost of investment (w.r.t standard wall) through saving in annual energy consumption. Some of the biomaterial walls have unit costs which are higher than the unit cost of standard walls. So the construction cost involved will be higher.

$$SPBP(years) = \frac{Extra\ cost\ of\ investment\ (Rs)}{Annual\ Energy\ Saving\ Cost\ (Rs)}$$

Table 4.6 Payback period (years) for different walls.

	HLC:C-4	BAB:C-1	BBC:C-3	BBC:C-4	RHEC:C-7	RSB:C-2	DPA:C-3	CCFP:C-1	CCFP:C-3
Chennai	0.9	-	-	-	17.7	0.4	-	2.2	3.6
Delhi	1.2	-	-	-	23	0.5	-	2.5	7.2
Srinagar	1.2	-	-	-	21.9	0.5	-	2.4	7.3
Jaipur	1.4	-	-	-	24.9	0.6	-	2.6	7.7

	RSB(T=13 cm)
Bangalore	0.3

Here BAB, BBC, and DPA wall types have no payback period because these walls are cheaper in construction than the standard wall.

Chapter 5

Conclusions & Future Scope

Based on the literature survey it is found that there are certain gaps in the characterization of thermal properties especially the radiative properties for energy analysis and strength properties for structural stability analysis of biomaterial as a constituent for walls of the building. The more exhaustive experimental characterization for relevant hygrothermal properties will lead to the implementation of certain advanced versions of the heat transfer model in energy plus for specific climatic zones that can give more accurate results as compared to the other models. It can be concluded that there are enough biomaterials available in nature that can offer better choices as compared to the existing conventional wall materials. By taking some biomaterial as a substitute for conventional red burnt brick for walls, this study has shown how implementing biomaterials in walls can reduce annual energy consumption thereby reducing the load on the air conditioning system to maintain the desired comfort temperature. It can be said from the study that it is an added advantage where dependency on conventional construction material is reduced thereby lowering the stress on the environment by the construction industry in terms of CO_2 production, pollution, and reduction in overall embodied energy in construction material.

In section 4.7 suitability of different wall types has been seen for each climatic zone. Specifically for each climate following walls can be best suited based on the findings from this research.

Table 5.1 Best-suited wall for each climatic zones.

Warm & Humid Climate (Chennai)	BBC:C-4
Composite Climate (New Delhi)	HLC:C-4
Cold Climate (Srinagar)	RSB:C-2
Hot & Dry Climate (Jaipur)	BAB:C-1

But from an overall perspective from energy and cost analysis, it is observed that RSB comes out to be the better candidate than other wall types because of much cheaper than all other biomaterials and also reduces annual energy due to its better thermal properties than conventional/standard wall. However, due to its very low density, it can be implemented as an insulation in urban cities where space limitation is a concern. For this further research for its feasibility and commercialization as an insulation is needed because of its high susceptibility to moisture. Another best candidate based on ranking comes out to be the HLC wall which can be a suitable candidate both for urban regions and rural regions based on space availability.

RHEC being the insulation material performs well in reducing annual energy but due to its relatively high cost, it will be a feasible option for long-term payback where large investment cost is considered. BBC and BAB walls being relatively cheaper and have comparatively less strength than conventional construction materials can be good candidates for buildings involving less initial investment and for mid-rise buildings. CCFPs have relatively high cost and high strength compared to standard walls and can be a suitable candidate for high-rise buildings with load-bearing walls.

This study has applied the methodology taking into account annual energy consumption and cost of material involved in constructing the wall to compare different types of walls for the air-conditioned model, but the methodology can be applied to the non-air-conditioned model to investigate the performance of wall based on different thermal parameters such as thermal transmittance, inside wall temperature, indoor air temperature decrement factor, time lag, etc.

Based on the analysis it can be said that there is further reduction of energy consumption is possible by modifying the roof of the building using biomaterial based concrete and biomaterial insulation, that can reduce the heat flux due to the roof. Also, there is further possible reduction can be achieved using bio-inspired skin for windows which can block incoming radiation.

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Appendix A

Properties of Various Materials

	ρ	C	λ	C_p	α	Rs/m^3
Red Burnt Brick	1820	10	0.811	880	5.06×10^{-7}	6498
Mortar	1690	3	0.8	565	8.4×10^{-7}	5033
HLC	370	3	0.046	1351.35	0.92×10^{-7}	15000
BAB	1409	6.59	0.48	2812.5	1.2×10^{-7}	2500
BBC	838	10.63	0.38	2015.9	2.25×10^{-7}	3472
25RHC_400	376	0.458	0.0634	1695	0.99×10^{-7}	*2691(Rs/$m^{2+)}$
25RHC_200	199	0.147	0.0481	1782	1.36×10^{-7}	*2691(Rs/m^{2+}
CSRERHA	1650	4	0.65	960	4.1×10^{-7}	*618.35(volume/m^2)
RSB	100.9	0.03	0.0431	2970	1.4×10^{-7}	505
DPA	780	40.6	0.434	2032	2.74×10^{-7}	*230(Rs/m^2)
CCFP	1520	33	0.168	996	1.1×10^{-7}	8500

ρ = Density (kg/m^3)

C = Compressive Strength (N/mm^3)

λ = Thermal Conductivity (W/m K)

C_p = Specific heat (J/kg K)

α = Thermal diffusivity (m^2/s)

Rs/m^3= Unit cost of material

Brief Biodata

Name: Sabil Hasan

Email: sabilhasan1729@gmail.com

Research Interest:

Sustainable Energy, CFD, Fluid Mechanics, Heat Transfer.

Educational Details:

M. Tech., Mechanical Engineering (Computational Mechanics), IIT Ropar.

B. Tech., Mechanical Engineering, CUSAT, Kerala.

Conference Presentation

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