Evaluation of Optimum Thickness of Insulation Materials and Their Carbon Mitigation Potential in Indian Climatic Zone

Debasish Mahapatra (dmahapatra94@gmail.com)
National Institute of Technology Karnataka https://orcid.org/0000-0001-7281-5610
Vasudeva Madav
National Institute of Technology Karnataka
Ashok Babu Talanki Puttaranga Setty
National Institute of Technology Karnataka

Research Article

Keywords: Optimum insulation thickness, green building, energy efficiency, building insulation, carbon mitigation, passive cooling

Posted Date: June 7th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1565499/v1

Evaluation of Optimum Thickness of Insulation Materials and Their Carbon Mitigation Potential in Indian Climatic Zone

Debasish Mahapatra[a*], Vasudeva Madav[b]., Ashok Babu Talanki Puttaranga Setty[c].

[a,b,c] Department of Mechanical Engineering, National Institute of Technology Karnataka, India-575025

(*Corresponding Author-dmahapatra94@gmail.com)

Abstract

Buildings consume an enormous amount of energy and are responsible for emitting massive carbon dioxide. About 33% of total energy is consumed for achieving thermal comfort in buildings. Although building insulation is a sustainable and economical option for passive cooling and guarantees long-term return, its use is still minimal in India. Only 4% of building out of all green-rated buildings are residential In India. In this study, optimum insulation thickness of cellulose, corn-based insulation, polyurethane, and polystyrene when used with different plastered brick materials having different absorptivity of the external surface is evaluated using the life cycle costing method. Four cities of India, such as Delhi, Jodhpur, Mangalore and Pune, are considered for this study to cover all the climatic zones of India. The cost-saving that can be achieved by using optimum insulation thickness is in the range of 15.6$/m^2-133.3$/m^2, 23.5$/m^2-171.2$/m^2, 15.9$/m^2-147.4$/m^2 and 5.7$/m^2-106.3$/m^2 in Delhi, Jodhpur, Mangalore and Pune, respectively. The carbon mitigation potential of optimum insulations is in the range of 22.9 kg/kWh-136.5 kg/kWh, 32.2 kg/kWh -173.9 kg/kWh, 23.1 kg/kWh -150.4 kg/kWh, 10.2 kg/kWh -109.6 kg/kWh in Delhi, Jodhpur, Mangalore and Pune respectively. This study will help create awareness about the cost-saving potential of insulation, thereby increasing its use, which will help India achieve the vision of creating a 10 billion square feet green built-up area.

Keywords- Optimum insulation thickness, green building, energy efficiency, building insulation, carbon mitigation, passive cooling

1. Introduction

Building construction in India has been increasing at a rapid pace. India has a built-up area of 40.8 million square meters and is growing at a rate of 10% (GRIHA, 2011). It has been forecasted that 700-800 million square feet of built-up area will be added in the upcoming twenty years (Sankhe et al. 2010). Buildings consume an enormous amount of energy and emit a large quantity of carbon dioxide. The share of thermal comfort is the highest in total energy consumption in buildings. India's Energy Conservation Building Code (ECBC) reported that 33% of total energy is consumed to achieve thermal comfort in Indian buildings (ECBC 2009). According to World Green Building Council, buildings hold a share of 39% of all carbon emissions globally, out of which 28% comes during the operational phase. The study of Lin et al. (2017) concluded that buildings in the over-urbanized area produce 54% of carbon emissions, and the emission is 11% more in summer because of the use of air-conditioners. One of Chang et al.'s (2019) studies revealed that in Taichung metropolitan, each square meter of building floor area emits 16.51 tons of carbon dioxide per year.

Considering the carbon emission from buildings and the contribution of buildings toward the total energy consumption, it is high time to adopt some sustainable measures. Methods like adjusting temperature setpoint, modifying lighting system, using suitable insulation material, and reducing heat gain through building envelope can help design energy-efficient buildings, thereby saving energy.

The significant portion of the building which is exposed to the Sun throughout the day is the building's envelope. The maximum heat gain into the building happens through the building envelope, which causes thermal discomfort for the occupants. The heat gain through the envelope can be reduced by making the envelope energy efficient. The building envelope majorly includes the walls, roofs and windows. Using sustainable materials to construct the envelope can make the building energy efficient. The impact of building envelopes on energy consumption and methods adopted by different researchers to construct energy-efficient buildings are discussed further.

The thermal transmittance of buildings varies linearly with the ratio of the surface area of the building envelope to the total volume of the building (Loukaidou et al. 2017). Arumugam and Shaik (2021) studied the dynamic thermal performance and carbon mitigation potential of bricks by adding agricultural waste to the conventional mud-brick and found that the addition of the wastes enhances both the structural and thermal performance of the building. A study by Kirankumar et al. (2020) on energy and cost analysis of various glass materials in Indian climatic zones concluded that it is always desirable to place the window in the Southeast direction because of the highest cost-saving potential. Rathore and Shukla (2020) concluded that about 7% to 9%

reduction in peak temperature could be achieved by integrating macro-encapsulated PCM in the building envelope. A comparative analysis of the performances and properties of different insulation materials was carried out by Kumar et al. (2020), and the analysis concludes that insulation materials save energy, protect the environment, and provide acoustic and thermal comfort. Insulating the internal wall is more effective than insulating the external wall in reducing cooling energy expenses and can save 52%-65% energy (Meng et al. 2018; Fallah and Medghalchi 2020). It was found from the study of Sun et al. (2019) that the thermal inertia of the wall can be improved by 60% by integrating PCM. Integration of insulation materials in building envelopes is an efficient way to reduce energy consumption in building (Aditya et al. 2017). The thermal performance of seven insulation materials integrated with a historic building was evaluated by Walker and Pavía (2015), and it was found that insulation materials lowered the overall heat transfer coefficient of the wall between 34% to 61%. The overall heat transfer coefficient of a 130-year-old house was reduced by 10% by using aerogel containing fiber insulation Ghazi Wakili et al. (2014). Kolaitis et al. (2013) found the effect of internal and external insulation on energy-efficient retrofitting of residential buildings, and their study concludes that both types of insulation have the potential of reducing the Heating Ventilation and Air-Conditioning load by 21%-89%. From the study of Kumar and Suman (2013), it is found that the overall heat transfer coefficient achieved by adding insulation to walls and roofs complies with the ECBC standard. The energy-saving and cost-effectiveness of various insulation materials is evaluated by Mishra et al. (2012) and it is found that insulation materials can save upto 2560 Rs/m^2-5510 Rs/m^2 in Indian climatic zones. The study of Al-Homoud (2005) concludes that in envelope load-dominated buildings, especially residential buildings, insulation of walls and roofs can remarkably improve occupants' thermal comfort.

The works of literature associated with various methods to make the building envelope energy-efficient suggest that insulating the wall and roof is an effective and efficient way of turning down the energy used to achieve thermal comfort. Nevertheless, the initial investment required for making the building energy-efficient sounds expensive. Considering the substantial initial investment, the owner may not agree to insulate the house, which could be why India has only 4% of green residential buildings (GRIHA 2007). So, the economic benefits of energy-saving should be conveyed to convince the owners to use insulation. The use of insulation will be economical if and only its use is optimized. The following section presents a few of the works carried out by different authors to optimise insulation thickness in different places across the globe.

In the study of Sisman et al. (2007) the optimum insulation thickness was found for buildings in different Turkish cities, and it was concluded from the study that by using optimum insulation thickness, the operative cost of the building and fuel consumption for achieving thermal comfort reduces. Yu et al. (2009) evaluated the optimum insulation thickness of five different insulation materials using the P1 P2 economic model for walls facing different orientations in both hot and cold climatic zone of China, and they found expanded polystyrene as the best insulation material because of its highest cost-saving and lowest payback period. The optimized insulation thickness of polystyrene and rock wool for buildings of Palestine was calculated in the study of Hasan (1999) considering the present worth method. The maximum payback period was found to be 2.3 years and the maximum saving was 21$/m^2. Hence insulation of buildings was concluded to be economically feasible. In the study of Jie et al. (2018) optimum insulation thickness for a ten-storey residential building in Weifang city of China was evaluated by using an optimization model. To find the optimal insulation thickness, Primary energy saving ratio, global cost-saving ratio and pollutant emission reduction ratio were considered evaluation criteria. Yuan et al. (2017) evaluated the optimal thermal resistance for six climatic zones of Japan by using cost analysis and the degree days method and concluded that a combination of rock wool as insulation and Liquified Natural Gas (LNG) as a fuel source is the optimal combination in all the climatic zones. Using the P1 P2 method Ucar and Balo (2010) evaluated the energy and cost-saving potential of optimum insulation thickness in Turkey and found that a cost-saving ranging from 4.2$/m^2 to 9.5$/m^2 can be achieved by insulating the walls with optimum thickness. The study of Bodalal et al. (2017) concludes that 70%-80% of energy savings can be achieved in Libya by using optimum insulation thickness in the wall. The findings of Bolattürk (2006) say that optimum insulation thickness in Turkey results in energy-saving ranging from 22%-79% with a payback period between 1.3years to 4.5 years. The effect of optimum insulation thickness on energy saving in Tunisia was studied by Daouas et al. (2010), and it was revealed from the study that optimum insulation could save up to 58% of energy. Optimum insulation thickness and energy-saving potential of polystyrene and polyurethane for Palestinian buildings were calculated by Alsayed and Tayeh (2019), and it was found from the study that the optimum thickness of insulation can save 4$/m^2 to 8$/m^2 per year.

The literature review reveals that the study of optimum insulation thickness for Indian climatic zones is minimal. These studies cover only India's limited climatic zones (Mishra et al. 2012; Shanmuga Sundaram and Bhaskaran 2014; Ali Kallioğlu et al. 2020). So in this study, the optimum insulation thickness of 4 insulation materials such as polystyrene, polyurethane, cellulose and corn-based insulation material is found for all the heating-dominated climates of India. The cities chosen for this study are Delhi from the composite climatic zone, Jodhpur from the hot and dry climatic zone, Mangalore from the warm and humid climatic zones and Pune from the Moderate climatic zone. The optimum insulation thickness was found for four different brick materials and three different absorptivities of the external surface of the wall.

2. Methodology

Cooling Degree Days (CDD) and Heating Degree Days (HDD)

Degree day helps determine the energy required for heating and cooling a building. The heat conduction between the buildings to the environment is directly proportional to the temperature difference between them. So, degree day is defined as the difference between the average temperature of a day and the base temperature. As per the ASHRAE standard for the Indian climatic zone, the base temperature is 23.3^0C for summer and 18^0C for winter. Metrological data by ISHRAE was used to calculate the CDD and HDD (ISHRAE 2017). The mathematical method to calculate degree day is as follows

$$Cooling\ Degree\ Days = \sum_{i=1}^{365}\left(\frac{T_{sol_{max_i}} + T_{sol_{min_i}}}{2} - T_b\right)^+ \ldots.(1)$$

$$Heating\ Degree\ Days = \sum_{i=1}^{365}\left(T_b - \frac{T_{sol_{max_i}} + T_{sol_{min_i}}}{2}\right)^+ \ldots.(2)$$

The positive sign in Equations 1 and 2 indicates that only the positive values will be considered for the evaluation, and if the value comes negative, it is considered zero. As India is a tropical country and the buildings require cooling majority of the year, the optimum insulation thickness is calculated considering the cooling degree day.

In Equations (1) and (2), T_{sol} refers to the sol air temperature, which is the combination of the effect of solar radiation and ambient temperature. It is defined mathematically as

$$T_{sol} = T_o + \frac{\alpha I}{f_o} \ldots.(3)$$

Where, "T_o" is the ambient temperature, "α" is the absorptivity of the external surface. "f_o" is the outside heat transfer coefficient. The value of f_o is considered as 25 W/m^{2}K as per CIBSE standard. "I" is the solar radiation. The computational method for total solar radiation is described in the following section.

Computational Method of solar radiation

The total solar radiation falling on the earth's surface is referred to as extra-terrestrial radiation. The extra-terrestrial radiation is the sum of direct, diffused and ground reflected radiation. Various angles are considered for computing the total solar radiation, such as hour, declination, solar altitude, solar azimuth, surface solar azimuth, and incidence angles. The solar radiation was calculated from 6 AM to 6 PM. (Mani and Rangarajan, 1982). Solar radiation was calculated for a clear sky condition in eight directions such as North (N), North-East (NE), East (E), South-East (SE), South (S), South-West (SW), West (W) and North-West (NW).

The following steps are followed to calculate the direct, diffused and ground reflected solar radiation

Declination angle

$$d = 23.45 sin \frac{360(284 + n_d)}{365} \text{....} (4)$$

Solar altitude angle

$$sin\beta = coslcosdcosh + sinlsind \text{....} (5)$$

Solar azimuth angle

$$cos\phi = \frac{sin\beta sinl - sind}{cos\beta cosl} \text{....} (6)$$

Surface solar Azimuth angle

$$\gamma = \phi - \Psi \text{....} (7)$$

The surface azimuth angles measured from the south for the orientations N, NE, E, SE, S, SW, W, and NW are 1800, -1350, -900, -450, 00, 450, 900, and 1350, respectively.

Angle of incidence

$$cos\theta = cos\beta cos\gamma cosk - sin\beta sink \text{....} (8)$$

At the earth's surface on a clear day, solar irradiance at clear atmosphere is given by

$$I_{DN} = \frac{A}{exp(B/sin\beta)} \text{....} (9)$$

Incident direct solar radiation on glazing is given by Eq. (10)

$$I_{DSR} = I_{DN} \cos\theta \text{....} (10)$$

Incident diffused solar radiation from the sky onto the glazing can be computed by Eq. (11)

$$I_{dSR} = CI_{DN} \frac{1 - \sin k}{2} \text{....} (11)$$

The incident reflected radiation from the ground surface onto the glazing is given by Eq. (12)

$$I_{GRD} = (C + \sin\beta) I_{DN} \rho_g \frac{1 - \sin k}{2} \text{....} (12)$$

Where, A, B, and C are the constants for calculating hourly solar radiation in India (Parishwad et al. 1997, 1998)

Incident total solar radiation onto the wall is presented by Eq. (13)

$$I_T = (I_{DSR} + I_{dSR} + I_{GRD}) \dots . (13)$$

This work evaluates the total solar radiation for 4 Indian cities. The cities are so chosen that they cover all the climatic zones of India (ECBC, 2009). The cities considered and the corresponding climatic zone are given in Table 1.

Table 1 Cities and climatic zone considered

City	Climatic zone	Latitude
New-Delhi	Composite	28.61°N
Jodhpur	Hot and dry	26.23°N
Mangalore	Warm and humid	12.91°N
Pune	Temperate	18.52°N

Evaluation of optimum insulation Thickness

The additional investment in the insulation material should prove economical over its entire lifetime. With an increase in the thickness of insulation material, energy-saving also increases. However, this also increases the initial cost. So, the optimum insulation thickness is the thickness of the insulation material at which the total cost is minimum, i.e., the saving is maximum. To find the optimum insulation thickness by maximizing the saving, the following procedure is followed

The total investment for the insulation is

$$\mathrm{C_{ins}} = \mathrm{C_i} * \mathrm{x} \dots . (14)$$

The total saving is calculated by

$$\mathrm{S} = \mathrm{C_{ewo}} - \mathrm{C_{ew}} - \mathrm{C_{ins}} \dots . (15)$$

Where, $\mathrm{C_{ewo}}$ is the cost of energy without insulation and $\mathrm{C_{ew}}$ is the cost of energy with insulation.

$$\mathrm{C_{ewo}} = \mathrm{E_{wo}} * \mathrm{C_e} * \mathrm{n} \dots . (16)$$

$$\mathrm{C_{ew}} = \mathrm{E_w} * \mathrm{C_e} * \mathrm{n} \dots . (17)$$

Where, $\mathrm{E_{wo}}$ is the energy consumption without insulation and $\mathrm{E_w}$ is the energy consumption with insulation.

$$\mathrm{E_{wo}} = \frac{\mathrm{Q_{wo}}}{\mathrm{COP}} \dots . (18)$$

$$\mathrm{E_w} = \frac{\mathrm{Q_w}}{\mathrm{COP}} \dots . (19)$$

$$\mathrm{Q_{wo}} = 0.024 * \mathrm{U_{wo}} * \mathrm{CDD} \dots . (20)$$

$$\mathrm{Q_w} = 0.024 * \mathrm{U_w} * \mathrm{CDD} \dots . (21)$$

$$\mathrm{U_{wo}} = \frac{1}{R_{tw}} \dots . (22)$$

$$\mathrm{U_w} = \frac{1}{\left(R_{tw} + \frac{x}{k}\right)} \dots . (23)$$

Where,

"R_{tw}" is the resistance of the wall without insulation material. "x" is the thickness of insulation, and k is the thermal conductivity of the insulation material. The value of R_{tw} is calculated as

$$R_{tw} = \frac{1}{f_o} + \frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{L_3}{K_3} + \frac{1}{f_i} \dots .(24)$$

Substituting equations 18 to 22 in equations 16 and 17, we have

$$\mathrm{C_{ewo}} = \frac{0.024 * \mathrm{CDD} * \mathrm{C_e} * \left(\frac{1}{\mathrm{R_{tw}}}\right) * \mathrm{n}}{\mathrm{COP}} \dots .(24)$$

$$\mathrm{C_{ew}} = \frac{0.024 * \mathrm{CDD} * \mathrm{C_e} * \left(\frac{1}{\mathrm{R_{tw}} + \frac{\mathrm{x}}{\mathrm{k}}}\right) * \mathrm{n}}{\mathrm{COP}} \dots .(25)$$

Substituting these in equation 15, we have

$$\mathrm{S} = \frac{0.024 * \mathrm{CDD} * \mathrm{C_e} * \mathrm{U_{wo}} * \mathrm{n}}{\mathrm{COP}} - \frac{0.024 * \mathrm{CDD} * \mathrm{C_e} * \mathrm{U_w} * \mathrm{n}}{\mathrm{COP}} - \mathrm{C_i} * \mathrm{x}$$

$$\mathrm{S} = \left[\frac{0.024 * \mathrm{CDD} * \mathrm{C_e} * \mathrm{n}}{\mathrm{COP}}\right] * (\mathrm{U_{wo}} - \mathrm{U_w}) - \mathrm{C_i} * \mathrm{x} \dots .(26)$$

The optimum insulation thickness is evaluated by maximizing the saving i.e.

$$\frac{\mathrm{dS}}{\mathrm{dx}} = 0$$

$$\frac{\mathrm{dS}}{\mathrm{dx}} = \frac{0.024 * \mathrm{CDD} * \mathrm{C_e} * \mathrm{n} * \mathrm{R_{tw}}^2 * \mathrm{k}}{\mathrm{COP}\left(\mathrm{R_{tw}}^2 * \mathrm{k} + \mathrm{xR_{tw}}\right)^2} - \mathrm{C_i}$$

Now equating the above equation to zero and solving for $\mathrm{x} = \mathrm{x_{opt}}$ we have

$$\mathrm{x_{opt}} = \frac{\left(\frac{0.024 * \mathrm{CDD} * \mathrm{C_e} * \mathrm{n} * \mathrm{R_{tw}}^2 * \mathrm{k}}{\mathrm{C_i} * \mathrm{COP}}\right)^{0.5} - (\mathrm{R_{tw}}^2 * \mathrm{k})}{\mathrm{R_{tw}}} \dots .(27)$$

The detailed construction of the wall is given in Figure 1, and the conductivity of the brick material considered for this study is given in Table 2 (IS-3972). The cost of the insulation material is enquired from the local market. The cost and conductivity of the insulation materials studied are tabulated in Table 3.

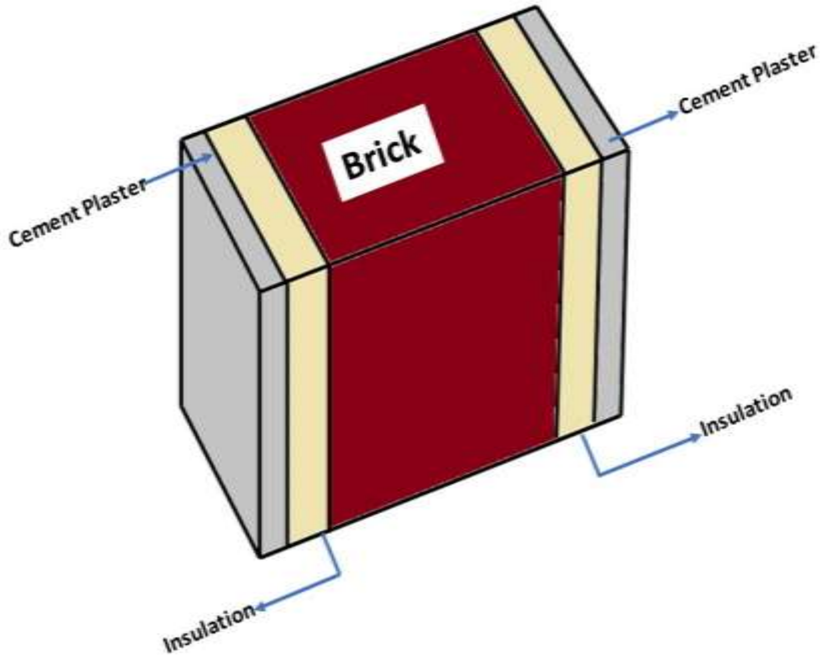


Figure 1 Detailed construction of the wall

Table 2 Thermophysical properties of wall material

Brick Material	Code	k (W/mK)
Brunt brick	BB	0.811
Mudbrick	MB	0.75
Concrete block	CB	1.74
Laterite Stone	CCB	1.369
Fly ash brick	FAB	0.360

Table 3 Cost and conductivity of insulation material

Material	Code	k (W/mK)	Cost ($/m^3)
Polystyrene	PS	0.040	120 (Kumar et al. 2020b)
Polyurethane	PU	0.027	211 (Torres-Rivas et al. 2018)
Corn	CO	0.038	66(Torres-Rivas et al. 2018)
Cellulose	CEL	0.035	58.3(Torres-Rivas et al. 2018)

Payback period is defined as the amount of time required to recover the cost of an investment. Mathematically, it is defined as the ratio of total investment to the savings per year.

The investment made towards insulation material = $C_i * x$

The total cost saving by the use of insulation material is calculated by equation 28

$$CS = \frac{0.024 * CDD * C_e * \Delta U}{COP} \quad \ldots.(28)$$

Where,

$$\Delta U = \frac{1}{R_{tw}} - \frac{1}{\left(R_{tw} + \frac{x}{k}\right)}$$

$$= \frac{x}{{R_{tw}}^2 * k + xR_{tw}}$$

So, the payback period is expressed mathematically as

$$P = \frac{C_i * x}{\frac{0.024 * CDD * C_e * \left(\frac{x}{{R_{tw}}^2 * k + xR_{tw}}\right)}{COP}}$$

$$P = \frac{C_i * COP * \left({R_{tw}}^2 * k + xR_{tw}\right)}{0.024 * CDD * C_e} \ldots.(29)$$

Annual carbon mitigation achieved by cooling energy saving is expressed as

$$ACM = \frac{0.024 * CDD * \Delta U * m_e}{COP} \ldots.(30)$$

Where, m_e is the mass of carbon released in kg per Kwh of electricity production. The value for $m_e$is considered as 0.98*1.6 kg/kWh (Chel and Tiwari 2009). The cost of electricity is considered as 0.082$/kWh, and the COP of the system is considered to be 2.5.

Results and discussion

The optimum insulation thickness for various combinations of wall and insulation material is calculated in the four climatic zones of India. The optimum insulation thickness was calculated for eight directions and three values of absorptivities of the external wall, i.e., 0.3, 0.6 and 0.9. As India is a tropical country and the buildings in the cities considered for this study require cooling most of the time in a year, the optimum insulation thickness was evaluated by considering cooling degree days. The cooling degree days of the cities for different absorptivity values are represented in Figure 2.

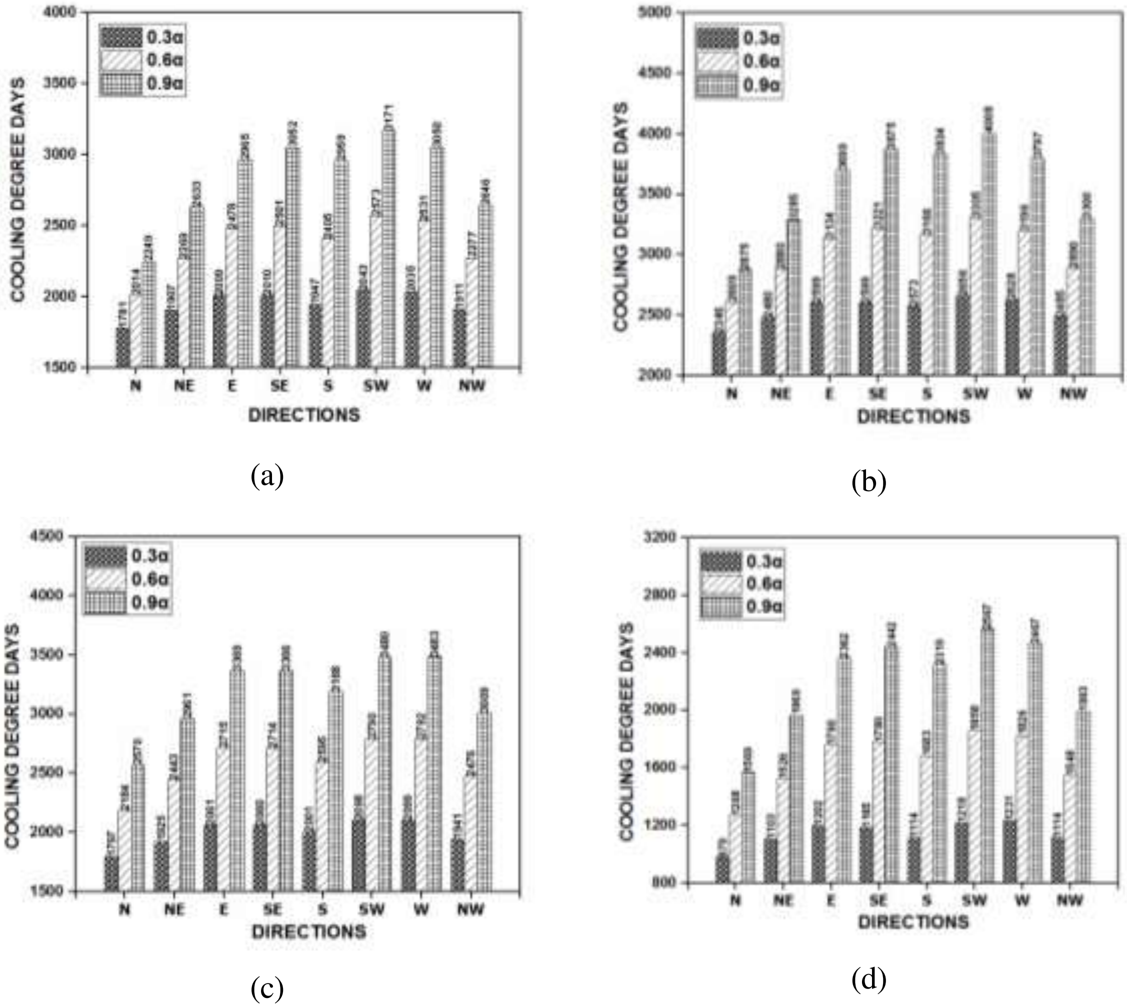


Figure 2 Annual Cooling Degree Days of a) Delhi, b) Jodhpur, c) Mangalore, d) Pune

It is evident from *Figure* 2 that with the increase in the value of absorptivity of the wall, the cooling degree days in each city increases. In Delhi and Jodhpur, the value of cooling degree days is found to be the highest in the South-West direction for all the values of absorptivity considered. Whereas, in Mangalore, for all the values of the absorptivity considered, the value of cooling degree day is the highest in the west direction. In Pune, when the absorptivity of the wall is 0.3, then the west direction has the highest cooling degree days. For higher absorptivity values, i.e., 0.6 and 0.9 South-west direction has the highest cooling degree days. For all the values of absorptivities, the least value of cooling degree days in all the cities is found in the north direction.

Optimum Insulation Thickness

Delhi

Table 4 Optimum insulation thickness for different wall materials in Delhi (0.3 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.114	0.110	0.078	0.048	0.118	0.115	0.084	0.051	0.103	0.098	0.066	0.039	0.117	0.113	0.082	0.050	0.113	0.109	0.078	0.047
NE	0.118	0.114	0.082	0.050	0.123	0.119	0.087	0.053	0.107	0.102	0.069	0.041	0.122	0.118	0.086	0.052	0.118	0.113	0.081	0.049
E	0.122	0.118	0.084	0.051	0.126	0.123	0.090	0.055	0.111	0.106	0.072	0.043	0.125	0.121	0.088	0.054	0.121	0.117	0.084	0.051
SE	0.122	0.118	0.084	0.051	0.126	0.123	0.090	0.055	0.111	0.106	0.072	0.043	0.125	0.121	0.088	0.054	0.121	0.117	0.084	0.051
S	0.120	0.115	0.083	0.050	0.124	0.120	0.088	0.054	0.109	0.104	0.070	0.042	0.123	0.119	0.087	0.053	0.119	0.115	0.082	0.050
SW	0.123	0.119	0.085	0.052	0.128	0.124	0.090	0.055	0.112	0.107	0.073	0.043	0.126	0.122	0.089	0.054	0.122	0.118	0.084	0.051
W	0.123	0.118	0.085	0.052	0.127	0.123	0.090	0.055	0.112	0.107	0.073	0.043	0.126	0.122	0.089	0.054	0.122	0.118	0.084	0.051
NW	0.118	0.114	0.082	0.050	0.123	0.119	0.087	0.053	0.108	0.102	0.069	0.041	0.122	0.118	0.086	0.052	0.118	0.113	0.081	0.049

Table 5 Optimum insulation thickness for different wall materials in Delhi (0.6 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.122	0.118	0.084	0.051	0.127	0.123	0.090	0.055	0.111	0.106	0.072	0.043	0.125	0.122	0.088	0.054	0.121	0.117	0.084	0.051
NE	0.130	0.126	0.091	0.055	0.135	0.131	0.096	0.059	0.120	0.114	0.078	0.047	0.134	0.130	0.095	0.058	0.130	0.125	0.090	0.055
E	0.137	0.132	0.096	0.058	0.142	0.137	0.101	0.062	0.126	0.121	0.083	0.050	0.141	0.136	0.100	0.061	0.136	0.132	0.095	0.058
SE	0.138	0.133	0.096	0.059	0.142	0.138	0.102	0.062	0.127	0.121	0.084	0.050	0.141	0.137	0.100	0.061	0.137	0.132	0.095	0.058
S	0.135	0.130	0.094	0.057	0.139	0.135	0.099	0.061	0.124	0.118	0.082	0.049	0.138	0.134	0.098	0.060	0.134	0.129	0.093	0.057
SW	0.140	0.135	0.098	0.060	0.145	0.140	0.103	0.063	0.129	0.124	0.086	0.051	0.143	0.139	0.102	0.062	0.139	0.135	0.097	0.059
W	0.139	0.134	0.097	0.059	0.143	0.139	0.102	0.063	0.128	0.122	0.085	0.051	0.142	0.138	0.101	0.062	0.138	0.133	0.096	0.058
NW	0.131	0.126	0.091	0.055	0.135	0.131	0.096	0.059	0.120	0.115	0.079	0.047	0.134	0.130	0.095	0.058	0.130	0.125	0.090	0.055

Table 6 Optimum insulation thickness for different wall materials in Delhi (0.9 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.130	0.125	0.090	0.055	0.134	0.130	0.096	0.059	0.119	0.114	0.078	0.047	0.133	0.129	0.094	0.058	0.129	0.125	0.090	0.054
NE	0.142	0.137	0.099	0.060	0.146	0.142	0.104	0.064	0.131	0.125	0.087	0.052	0.145	0.141	0.103	0.063	0.141	0.136	0.098	0.060
E	0.151	0.147	0.106	0.065	0.156	0.152	0.112	0.069	0.141	0.135	0.094	0.057	0.155	0.150	0.110	0.068	0.151	0.146	0.106	0.064
SE	0.154	0.149	0.108	0.066	0.158	0.154	0.113	0.070	0.143	0.137	0.096	0.058	0.157	0.153	0.112	0.069	0.153	0.148	0.107	0.066
S	0.151	0.146	0.106	0.065	0.156	0.151	0.112	0.069	0.140	0.135	0.094	0.056	0.155	0.150	0.110	0.068	0.150	0.146	0.105	0.064
SW	0.157	0.152	0.111	0.068	0.162	0.157	0.116	0.071	0.146	0.140	0.098	0.059	0.161	0.156	0.115	0.070	0.156	0.151	0.110	0.067
W	0.154	0.149	0.108	0.066	0.158	0.154	0.113	0.070	0.143	0.137	0.096	0.058	0.157	0.153	0.112	0.069	0.153	0.148	0.107	0.065
NW	0.142	0.137	0.100	0.061	0.147	0.142	0.105	0.064	0.131	0.126	0.087	0.052	0.146	0.141	0.104	0.063	0.141	0.137	0.099	0.060

Table 4, Table 5 and Table 6 represent the value of optimum thickness of insulation materials when used with different brick materials having different values of absorptivity of the external surface. The optimum insulation thickness is calculated for Delhi. It is depicted in Table 4- Table 6 that the value of optimum insulation thickness increases with increase in the absorptivity of the external surface. Optimum insulation thickness is found to be minimum for fly ash brick walls and maximum for concrete block walls irrespective of the wall facing direction and absorptivity.

For all the combinations of brick and insulation and all the values of absorptivity considered, the optimum insulation thickness is found to be minimum for the wall facing North. For almost all the combinations of brick and insulation, when the absorptivity is 0.3, South-West and West facing wall's optimum insulation thicknesses are found to be equal and the highest except for corn with burnt brick and cellulose with concrete block. For the exceptional cases, the optimum insulation thickness is the highest in the South-West direction.

The highest value of optimum insulation thickness for 0.6 absorptivity is found in the South-West direction for all combinations of bricks and insulation considered. However, for an absorptivity of 0.6, the value of optimum insulation thickness is equal in the South-West and West direction when polyurethane is used with concrete block, fly ash brick and laterite stone. Optimum thickness is maximum in the South-West direction for all combinations when absorptivity of the wall is 0.9.

Jodhpur

Table 7 Optimum insulation thickness for different wall materials in Jodhpur (0.3 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.133	0.128	0.093	0.056	0.137	0.133	0.098	0.060	0.122	0.117	0.080	0.048	0.136	0.132	0.097	0.059	0.132	0.128	0.092	0.056
NE	0.137	0.133	0.096	0.058	0.142	0.138	0.101	0.062	0.126	0.121	0.083	0.050	0.141	0.136	0.100	0.061	0.136	0.132	0.095	0.058
E	0.141	0.136	0.098	0.060	0.145	0.141	0.104	0.064	0.130	0.124	0.086	0.052	0.144	0.140	0.102	0.063	0.140	0.135	0.098	0.059
SE	0.141	0.137	0.099	0.060	0.146	0.142	0.104	0.064	0.130	0.125	0.087	0.052	0.145	0.140	0.103	0.063	0.141	0.136	0.098	0.060
S	0.140	0.135	0.098	0.060	0.145	0.140	0.103	0.063	0.129	0.124	0.086	0.051	0.143	0.139	0.102	0.062	0.139	0.135	0.097	0.059
SW	0.142	0.138	0.100	0.061	0.147	0.143	0.105	0.064	0.132	0.126	0.087	0.052	0.146	0.142	0.104	0.063	0.142	0.137	0.099	0.060
W	0.142	0.137	0.099	0.060	0.146	0.142	0.104	0.064	0.131	0.125	0.087	0.052	0.145	0.141	0.103	0.063	0.141	0.136	0.098	0.060
NW	0.137	0.133	0.096	0.058	0.142	0.138	0.101	0.062	0.126	0.121	0.084	0.050	0.141	0.137	0.100	0.061	0.137	0.132	0.095	0.058

Table 8 Optimum insulation thickness for different walls material in Jodhpur (0.6 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.141	0.136	0.099	0.060	0.146	0.141	0.104	0.064	0.130	0.125	0.086	0.052	0.145	0.140	0.103	0.063	0.140	0.136	0.098	0.060
NE	0.149	0.144	0.105	0.064	0.154	0.149	0.110	0.067	0.138	0.132	0.092	0.055	0.152	0.148	0.109	0.067	0.148	0.143	0.104	0.063
E	0.156	0.151	0.110	0.067	0.161	0.156	0.115	0.071	0.145	0.139	0.098	0.059	0.160	0.155	0.114	0.070	0.155	0.150	0.109	0.067
SE	0.158	0.153	0.112	0.068	0.163	0.158	0.117	0.072	0.148	0.142	0.099	0.060	0.162	0.157	0.116	0.071	0.158	0.153	0.111	0.068
S	0.157	0.152	0.111	0.067	0.162	0.157	0.116	0.071	0.146	0.140	0.098	0.059	0.160	0.156	0.115	0.070	0.156	0.151	0.110	0.067
SW	0.161	0.156	0.113	0.069	0.165	0.161	0.119	0.073	0.150	0.144	0.101	0.061	0.164	0.159	0.117	0.072	0.160	0.155	0.113	0.069
W	0.158	0.153	0.111	0.068	0.162	0.158	0.116	0.072	0.147	0.141	0.099	0.060	0.161	0.157	0.115	0.071	0.157	0.152	0.110	0.067
NW	0.149	0.144	0.105	0.064	0.154	0.149	0.110	0.068	0.138	0.133	0.092	0.056	0.153	0.148	0.109	0.067	0.149	0.144	0.104	0.063

Table 9 Optimum insulation thickness for different wall materials in Jodhpur (0.9 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.149	0.144	0.105	0.064	0.153	0.149	0.110	0.067	0.138	0.132	0.092	0.055	0.152	0.148	0.109	0.066	0.148	0.143	0.104	0.063
NE	0.160	0.155	0.113	0.069	0.165	0.160	0.118	0.073	0.149	0.143	0.101	0.061	0.164	0.159	0.117	0.072	0.159	0.154	0.112	0.068
E	0.171	0.166	0.121	0.074	0.176	0.171	0.126	0.078	0.160	0.154	0.109	0.066	0.174	0.170	0.125	0.077	0.170	0.165	0.120	0.073
SE	0.175	0.170	0.124	0.076	0.180	0.175	0.130	0.080	0.165	0.158	0.112	0.068	0.179	0.174	0.128	0.079	0.175	0.169	0.123	0.075
S	0.174	0.169	0.124	0.076	0.179	0.174	0.129	0.079	0.164	0.157	0.111	0.067	0.178	0.173	0.128	0.078	0.174	0.168	0.123	0.075
SW	0.179	0.173	0.127	0.077	0.183	0.178	0.132	0.081	0.168	0.161	0.114	0.069	0.182	0.177	0.131	0.080	0.178	0.172	0.126	0.077
W	0.173	0.168	0.123	0.075	0.178	0.173	0.128	0.079	0.163	0.156	0.110	0.067	0.177	0.172	0.127	0.078	0.173	0.167	0.122	0.075
NW	0.161	0.156	0.113	0.069	0.165	0.161	0.119	0.073	0.150	0.144	0.101	0.061	0.164	0.159	0.117	0.072	0.160	0.155	0.112	0.069

From Table 7, Table 8 and Table 9, it can be observed that, irrespective of absorptivity of the external surface of the wall, the optimum insulation thickness of all insulation materials is maximum when used with concrete block and minimum when used with fly ash brick in all the direction.

The optimum insulation thickness is minimum for the North facing wall for all the combinations and all the values of absorptivities considered. For 0.3 absorptivity, optimum insulation thickness is equal and maximum in South-West and West directions for some combinations such as cellulose with burnt brick and polyurethane with CB, FAB, LS, MB. For 0.6 and 0.9 absorptivity of the external surface of the wall, the optimum insulation thickness of all combinations of wall and insulation is maximum in the South-West direction.

Mangalore

Table 10 Optimum insulation thickness for different wall materials in Mangalore (0.3 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.114	0.110	0.079	0.048	0.119	0.115	0.084	0.051	0.103	0.098	0.066	0.039	0.118	0.114	0.083	0.051	0.114	0.109	0.078	0.047
NE	0.119	0.115	0.082	0.050	0.123	0.120	0.087	0.053	0.108	0.103	0.070	0.042	0.122	0.118	0.086	0.053	0.118	0.114	0.081	0.049
E	0.124	0.119	0.086	0.052	0.128	0.124	0.091	0.056	0.113	0.108	0.073	0.044	0.127	0.123	0.090	0.055	0.123	0.119	0.085	0.052
SE	0.124	0.119	0.086	0.052	0.128	0.124	0.091	0.056	0.113	0.108	0.073	0.044	0.127	0.123	0.090	0.055	0.123	0.118	0.085	0.052
S	0.121	0.117	0.084	0.051	0.126	0.122	0.089	0.055	0.111	0.106	0.072	0.043	0.125	0.121	0.088	0.054	0.121	0.116	0.083	0.051
SW	0.125	0.120	0.087	0.053	0.129	0.125	0.092	0.056	0.114	0.109	0.074	0.044	0.128	0.124	0.091	0.055	0.124	0.120	0.086	0.052
W	0.125	0.121	0.087	0.053	0.129	0.126	0.092	0.056	0.114	0.109	0.074	0.044	0.128	0.124	0.091	0.055	0.124	0.120	0.086	0.052
NW	0.119	0.115	0.083	0.050	0.124	0.120	0.088	0.054	0.109	0.103	0.070	0.042	0.123	0.119	0.087	0.053	0.119	0.114	0.082	0.050

Table 11 Optimum insulation thickness for different wall materials in Mangalore (0.6 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.128	0.123	0.089	0.054	0.132	0.128	0.094	0.058	0.117	0.112	0.076	0.046	0.131	0.127	0.093	0.057	0.127	0.123	0.088	0.053
NE	0.136	0.131	0.095	0.058	0.141	0.136	0.100	0.061	0.125	0.120	0.083	0.049	0.139	0.135	0.099	0.061	0.135	0.131	0.094	0.057
E	0.144	0.139	0.101	0.062	0.149	0.144	0.106	0.065	0.133	0.128	0.089	0.053	0.148	0.143	0.105	0.064	0.143	0.139	0.100	0.061
SE	0.144	0.139	0.101	0.062	0.149	0.144	0.106	0.065	0.133	0.128	0.089	0.053	0.148	0.143	0.105	0.064	0.143	0.139	0.100	0.061
S	0.141	0.136	0.098	0.060	0.145	0.141	0.104	0.063	0.130	0.124	0.086	0.052	0.144	0.140	0.102	0.063	0.140	0.135	0.098	0.059
SW	0.146	0.142	0.103	0.063	0.151	0.147	0.108	0.066	0.136	0.130	0.090	0.054	0.150	0.145	0.107	0.065	0.146	0.141	0.102	0.062
W	0.146	0.142	0.103	0.063	0.151	0.147	0.108	0.066	0.136	0.130	0.090	0.054	0.150	0.145	0.107	0.065	0.146	0.141	0.102	0.062
NW	0.137	0.132	0.096	0.058	0.142	0.137	0.101	0.062	0.126	0.121	0.083	0.050	0.140	0.136	0.100	0.061	0.136	0.132	0.095	0.058

Table 12 Optimum insulation thickness for different wall materials in Mangalore (0.9 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.140	0.135	0.098	0.060	0.144	0.140	0.103	0.063	0.129	0.123	0.085	0.051	0.143	0.139	0.102	0.062	0.139	0.134	0.097	0.059
NE	0.151	0.146	0.106	0.065	0.156	0.151	0.112	0.068	0.140	0.135	0.094	0.057	0.155	0.150	0.110	0.068	0.151	0.146	0.106	0.064
E	0.162	0.157	0.115	0.070	0.167	0.162	0.120	0.074	0.152	0.146	0.102	0.062	0.166	0.161	0.119	0.073	0.162	0.157	0.114	0.069
SE	0.162	0.157	0.115	0.070	0.167	0.162	0.120	0.074	0.152	0.146	0.102	0.062	0.166	0.161	0.119	0.073	0.162	0.157	0.114	0.069
S	0.158	0.153	0.111	0.068	0.162	0.158	0.116	0.071	0.147	0.141	0.099	0.059	0.161	0.156	0.115	0.070	0.157	0.152	0.110	0.067
SW	0.165	0.160	0.117	0.071	0.170	0.165	0.122	0.075	0.155	0.148	0.104	0.063	0.169	0.164	0.121	0.074	0.165	0.159	0.116	0.071
W	0.165	0.160	0.117	0.071	0.170	0.165	0.122	0.075	0.155	0.149	0.105	0.063	0.169	0.164	0.121	0.074	0.165	0.160	0.116	0.071
NW	0.153	0.148	0.107	0.065	0.157	0.153	0.113	0.069	0.142	0.136	0.095	0.057	0.156	0.152	0.111	0.068	0.152	0.147	0.107	0.065

The optimum insulation thickness of different insulation materials when used with different brick materials in Mangalore, i.e. warm and humid climatic zone, is tabulated in Table 10, Table 11 and Table 12. It is evident from the Tables that the increased absorptivity of the external surface of the wall results in thicker optimum insulation thickness. All values of absorptivity considered and all insulation material, when used with fly ash brick, resulted in the least optimum thickness. The optimum insulation thickness is maximum when insulation material is used with concrete blocks. However, when used with concrete block and laterite stone, the optimum insulation thickness of polyurethane is equal for the south-facing wall when the absorptivity is 0.6.

For all the combinations considered, the value of optimum insulation thickness is minimum for North facing wall. For a wall having 0.3 absorptivity, the optimum insulation thickness in the East, south-east, west and south-west direction is equal when polyurethane is used with concrete block, fly ash brick, laterite stone and mud brick. Irrespective of the absorptivity, an equal value of optimum thickness is found for almost all the combinations in the South-West and West direction. Optimum insulation thickness is maximum and equal in the South-West and west direction for all combinations of wall and insulation.

Pune

Table 13 Optimum insulation thickness for different wall materials in Pune (0.3 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.080	0.077	0.053	0.032	0.085	0.082	0.059	0.036	0.069	0.065	0.041	0.024	0.084	0.081	0.057	0.035	0.079	0.076	0.053	0.031
NE	0.086	0.083	0.058	0.035	0.091	0.088	0.063	0.038	0.075	0.071	0.045	0.026	0.090	0.086	0.062	0.037	0.085	0.082	0.057	0.034
E	0.091	0.087	0.061	0.037	0.095	0.092	0.066	0.040	0.080	0.075	0.049	0.028	0.094	0.091	0.065	0.040	0.090	0.086	0.060	0.036
SE	0.090	0.086	0.061	0.036	0.094	0.091	0.066	0.040	0.079	0.074	0.048	0.028	0.093	0.090	0.065	0.039	0.089	0.085	0.060	0.036
S	0.087	0.083	0.058	0.035	0.091	0.088	0.063	0.039	0.076	0.071	0.046	0.027	0.090	0.087	0.062	0.038	0.086	0.082	0.057	0.034
SW	0.091	0.088	0.062	0.037	0.096	0.093	0.067	0.041	0.081	0.076	0.049	0.029	0.095	0.092	0.066	0.040	0.091	0.087	0.061	0.037
W	0.091	0.088	0.062	0.037	0.096	0.093	0.067	0.041	0.081	0.076	0.049	0.029	0.095	0.092	0.066	0.040	0.091	0.087	0.061	0.037
NW	0.087	0.083	0.058	0.035	0.091	0.088	0.063	0.039	0.076	0.071	0.046	0.027	0.090	0.087	0.062	0.038	0.086	0.082	0.057	0.034

Table 14 Optimum insulation thickness for different wall materials in Pune (0.6 absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.093	0.090	0.063	0.038	0.098	0.095	0.069	0.042	0.083	0.078	0.051	0.030	0.097	0.094	0.067	0.041	0.093	0.089	0.062	0.038
NE	0.104	0.100	0.071	0.043	0.109	0.105	0.076	0.047	0.093	0.088	0.059	0.035	0.108	0.104	0.075	0.046	0.103	0.099	0.070	0.043
E	0.113	0.109	0.078	0.047	0.118	0.114	0.083	0.051	0.102	0.097	0.065	0.039	0.116	0.113	0.082	0.050	0.112	0.108	0.077	0.047
SE	0.114	0.110	0.078	0.048	0.118	0.115	0.084	0.051	0.103	0.098	0.066	0.039	0.117	0.113	0.082	0.050	0.113	0.109	0.078	0.047
S	0.110	0.106	0.076	0.046	0.115	0.111	0.081	0.049	0.099	0.094	0.063	0.038	0.114	0.110	0.080	0.049	0.109	0.105	0.075	0.045
SW	0.116	0.112	0.081	0.049	0.121	0.117	0.086	0.053	0.106	0.101	0.068	0.041	0.120	0.116	0.085	0.052	0.116	0.112	0.080	0.049
W	0.115	0.111	0.080	0.048	0.120	0.116	0.085	0.052	0.105	0.099	0.067	0.040	0.119	0.115	0.084	0.051	0.115	0.110	0.079	0.048
NW	0.105	0.101	0.072	0.043	0.110	0.106	0.077	0.047	0.094	0.089	0.059	0.035	0.108	0.105	0.076	0.046	0.104	0.100	0.071	0.043

Table 15 Optimum insulation thickness for different wall materials in Pune (0.9absorptivity)

Direction	BB				CB				FAB				LS				MB			
	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU	CEL	CO	PS	PU
N	0.106	0.102	0.072	0.044	0.110	0.107	0.078	0.047	0.095	0.090	0.060	0.036	0.109	0.106	0.076	0.047	0.105	0.101	0.072	0.043
NE	0.120	0.116	0.083	0.051	0.125	0.121	0.089	0.054	0.110	0.104	0.071	0.042	0.124	0.120	0.087	0.053	0.120	0.115	0.083	0.050
E	0.133	0.129	0.093	0.057	0.138	0.134	0.098	0.060	0.123	0.117	0.081	0.048	0.137	0.133	0.097	0.059	0.133	0.128	0.092	0.056
SE	0.136	0.131	0.095	0.058	0.140	0.136	0.100	0.061	0.125	0.120	0.083	0.049	0.139	0.135	0.099	0.060	0.135	0.131	0.094	0.057
S	0.132	0.128	0.092	0.056	0.137	0.133	0.097	0.060	0.121	0.116	0.080	0.048	0.136	0.131	0.096	0.059	0.131	0.127	0.091	0.055
SW	0.140	0.135	0.098	0.060	0.144	0.140	0.103	0.063	0.129	0.123	0.085	0.051	0.143	0.139	0.102	0.062	0.139	0.134	0.097	0.059
W	0.137	0.132	0.095	0.058	0.141	0.137	0.101	0.062	0.126	0.120	0.083	0.050	0.140	0.136	0.099	0.061	0.136	0.131	0.095	0.058
NW	0.121	0.117	0.084	0.051	0.126	0.122	0.089	0.055	0.110	0.105	0.072	0.043	0.125	0.121	0.088	0.054	0.121	0.116	0.083	0.050

In Pune, for all the values of absorptivity considered, optimum insulation thickness for all the combinations is found to be minimum for the North facing wall. When the absorptivity is 0.3, the optimum insulation thickness is equal for South-West and West facing walls. For 0.6 and 0.9 absorptivity cases, the optimum insulation thickness is the highest for the South-West direction.

As the absorptivity changes from 0.3 to 0.9, the optimum insulation becomes 1.1 to 4.9cm thicker. When used with fly ash brick, the insulation materials tend to have a lesser optimum thickness. A concrete block wall requires the maximum value of optimum insulation thickness for all the insulation materials considered.

Annual cost saving and payback period

Delhi

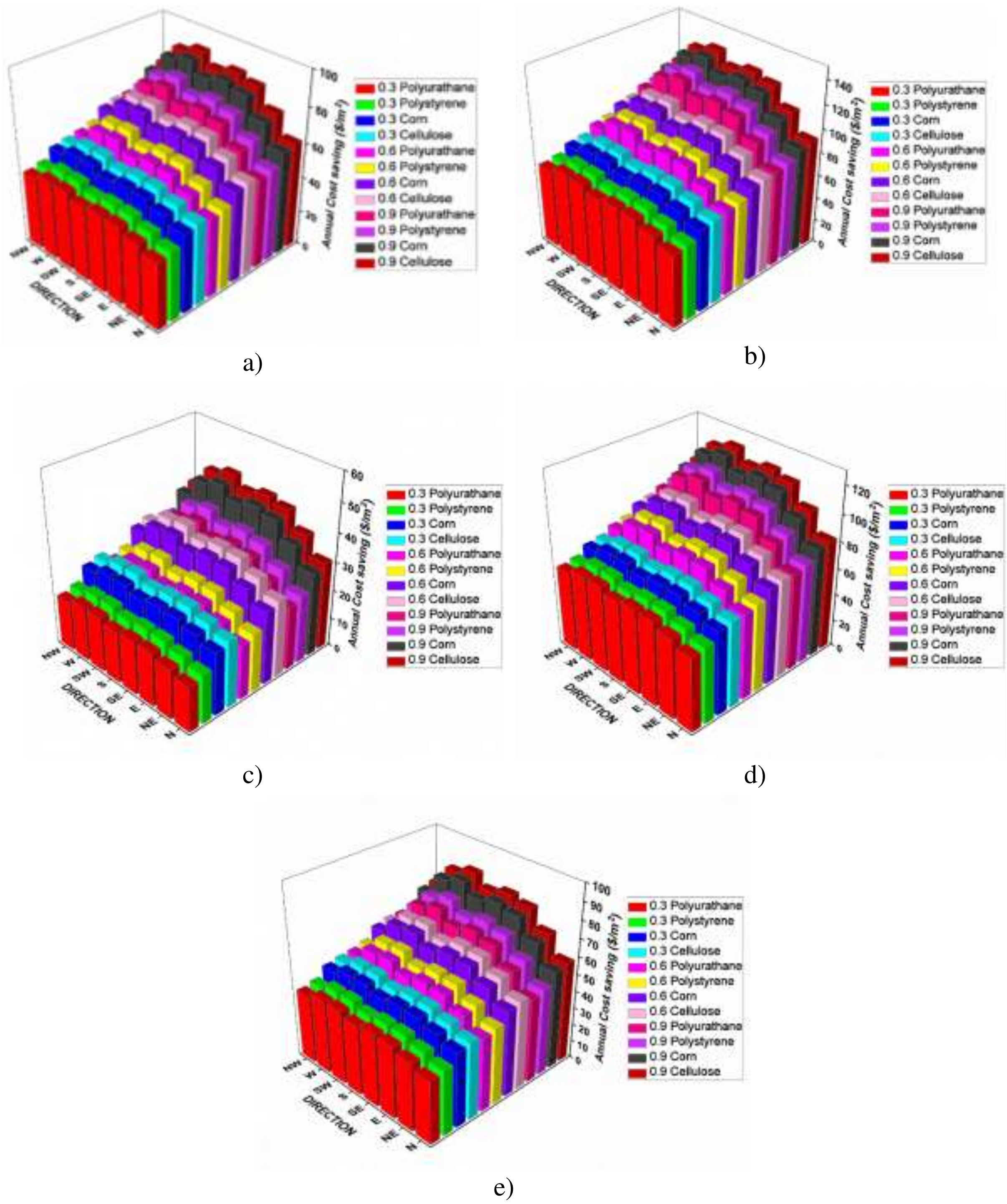


Figure 3 Life cycle cost saving when insulation is used with a) BB, b) CB, c) FAB, d) LS, e) MB at Delhi

Jodhpur

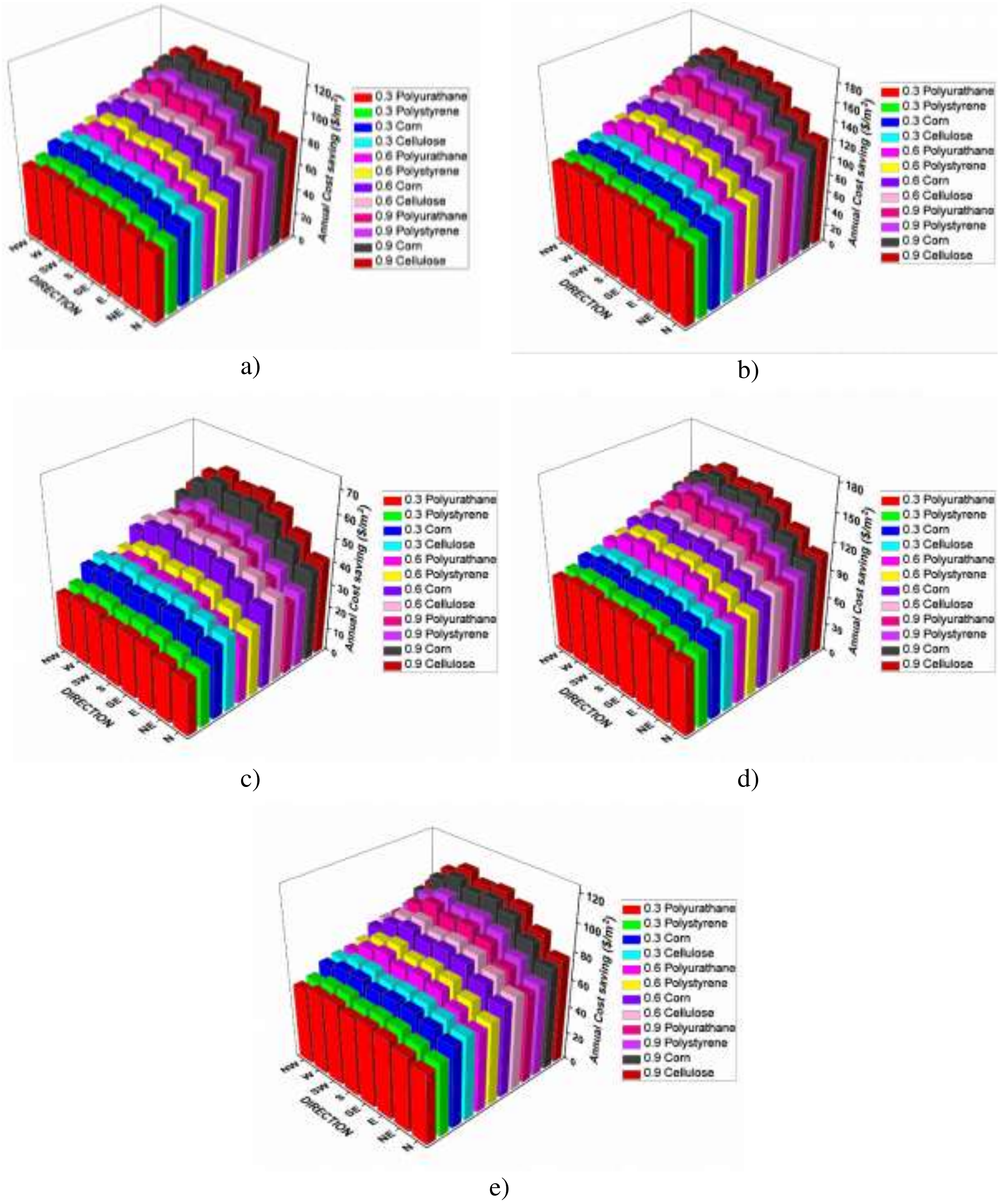


Figure 4 Life cycle cost saving when insulation is used with a) BB, b) CB, c) FAB, d) LS, e) MB at Jodhpur

Mangalore

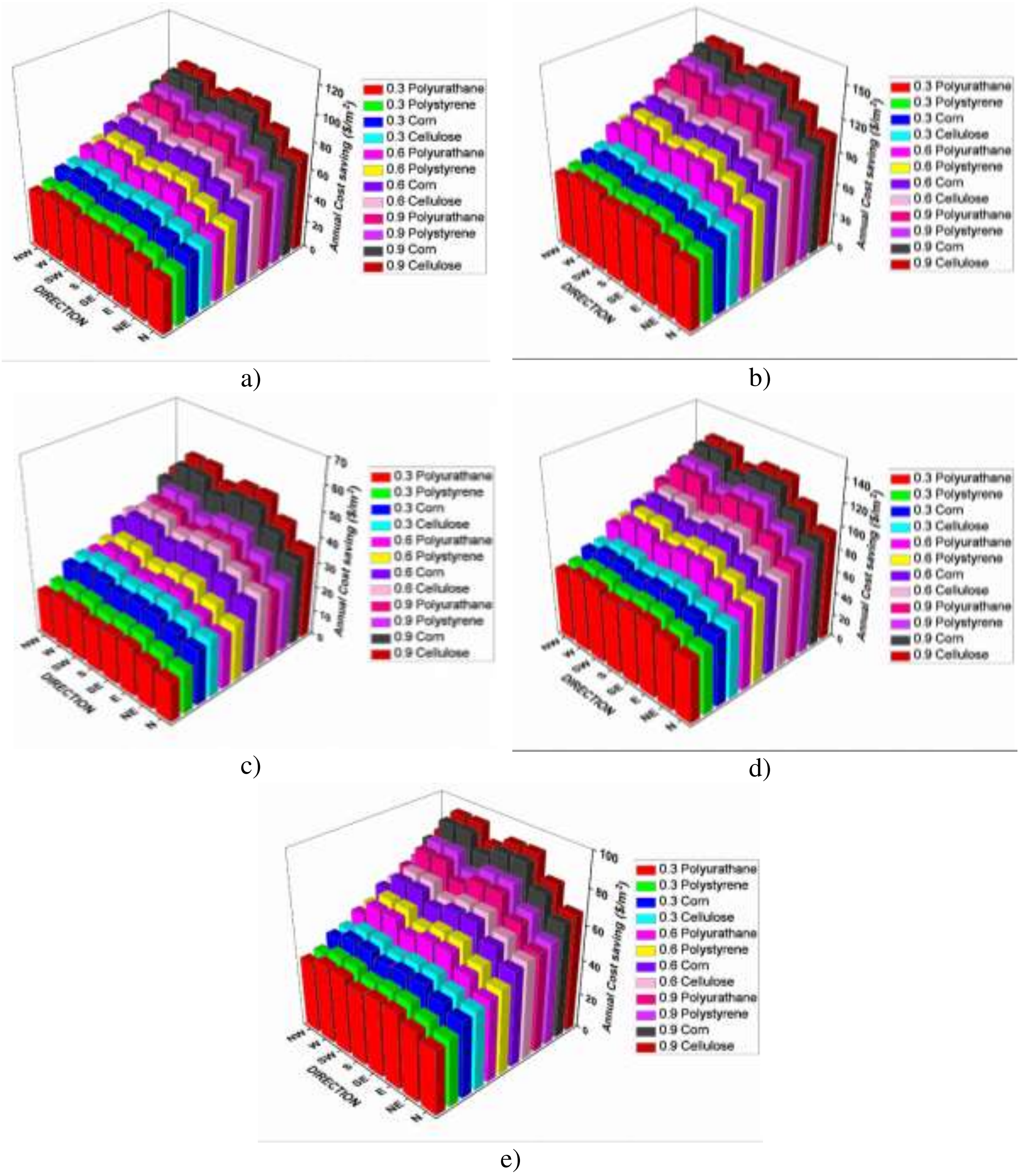
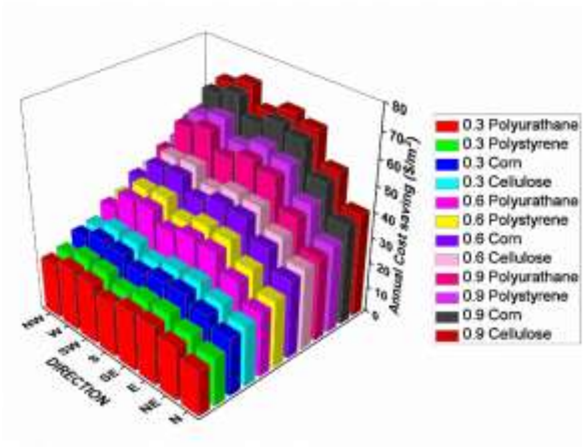
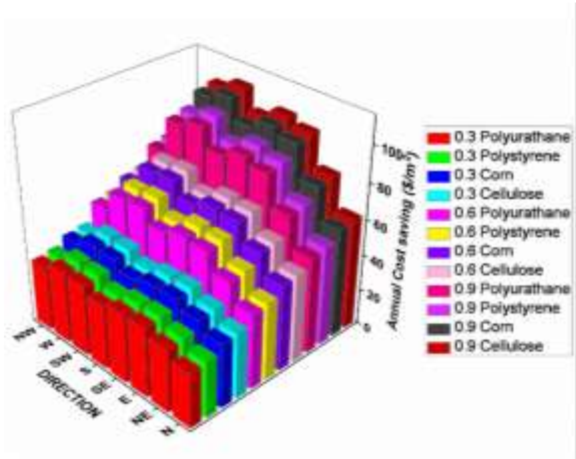


Figure 5 Life cycle cost saving when insulation is used with a) BB, b) CB, c) FAB, d) LS, e) MB at Mangalore

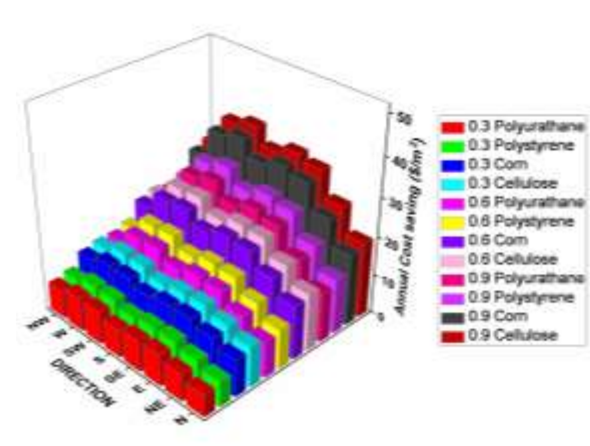
Pune



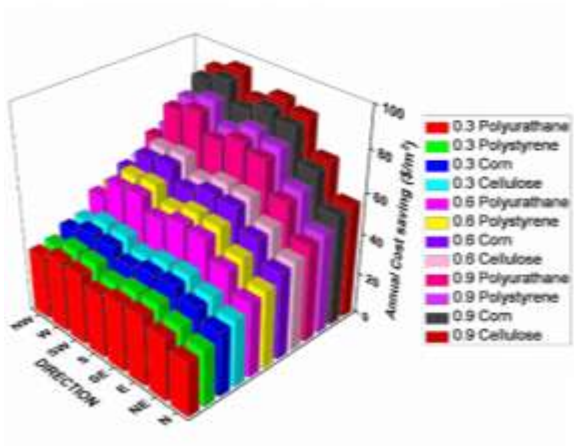
a)



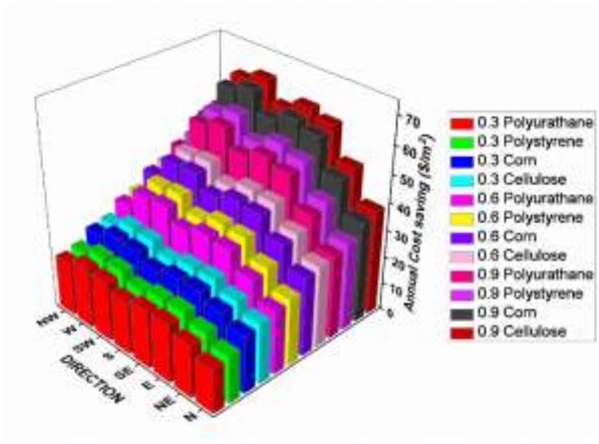
b)



c)



d)



e)

Figure 6 Life cycle cost saving when insulation is used with a) BB, b) CB, c) FAB, d) LS, e) MB at Pune

Figure 3 to Figure 6 shows the cost-saving potential of different insulation materials when used with different bricks. The cost saving is calculated for the entire lifetime of the insulation material, i.e., 20 years. The life cycle cost saving is calculated by using Eq. (28). It is evident from the figure that the cost-saving potential of insulation material is the highest in Hot and dry climatic zone (Jodhpur). The least cost-saving potential of insulation material is found for the moderate climatic zone (Pune). In all the climatic zones, the minimum cost saving is achieved by the North facing wall, whereas the south-west facing wall saves the maximum. All the insulation material, when used with FAB, saves the minimum, and the maximum saving is done when the insulation material is used with concrete block. The ascending order of cost-saving potential of bricks with any of the insulation materials considered is FAB, MB, BB, LS, and CB. It is found from the figures that with an increase in absorptivity, the cost-saving potential of the insulation materials increases because of the increase in the CDD. The maximum cost saving for all the combinations is attained by cellulose, and polyurethane saves the minimum cost.

The payback period is the time required for an investment to reach breakeven. In simpler words, the amount of time taken to recover an investment is known as the payback period. The decision for investment is made by considering the payback period. Shorter the payback period, the more desirable the investment is. Table 16 to Table 19 represent the payback periods of different bricks and insulation materials combinations.

In Delhi, the payback periods for cellulose, corn, polystyrene and polyurethane are 1.3-4.1, 1.5-4.6, 2-6.3 and 2.2-6.9 years, respectively. Similarly, the payback periods of cellulose, corn, polystyrene and polyurethane are 1.5-5.6, 1.6-6.2, 2.3-8.6 and 2.5-9.3, respectively, in Pune. The payback period for cellulose is found to be the least in all the climatic zones considered, and the payback period is maximum for polyurethane. When insulation materials are used with concrete blocks, the payback period is found to be the least, and it is maximum when insulation materials are used with fly ash brick. The ascending order of choice of insulation materials in terms of payback period is polyurethane, polystyrene, corn and cellulose.

Table 16 Payback period for different combinations of bricks and insulation materials in New-Delhi

		0.3				0.6				0.9			
		CEL	CO	PO	PU	CEL	CO	PO	PU	CEL	CO	PO	PU
BB	N	2.5	2.7	3.8	4.1	2.3	2.6	3.6	3.9	2.2	2.4	3.4	3.7
	NE	2.4	2.6	3.7	4	2.2	2.4	3.4	3.7	2	2.3	3.1	3.4
	E	2.3	2.6	3.6	3.9	2.1	2.3	3.2	3.5	1.9	2.1	2.9	3.2
	SE	2.3	2.6	3.6	3.9	2.1	2.3	3.2	3.5	1.9	2.1	2.9	3.2
	S	2.4	2.6	3.6	4	2.1	2.4	3.3	3.6	1.9	2.1	2.9	3.2
	SW	2.3	2.6	3.5	3.9	2.1	2.3	3.2	3.4	1.9	2.1	2.8	3.1
	W	2.3	2.6	3.5	3.9	2.1	2.3	3.2	3.5	1.9	2.1	2.9	3.2
	NW	2.4	2.6	3.7	4	2.2	2.4	3.4	3.7	2	2.2	3.1	3.4
CB	N	1.8	2	2.7	2.9	1.7	1.8	2.5	2.8	1.6	1.7	2.4	2.6
	NE	1.7	1.9	2.6	2.8	1.6	1.7	2.4	2.6	1.4	1.6	2.2	2.4
	E	1.7	1.8	2.5	2.8	1.5	1.7	2.3	2.5	1.4	1.5	2.1	2.3
	SE	1.7	1.8	2.5	2.8	1.5	1.6	2.3	2.5	1.3	1.5	2.1	2.2
	S	1.7	1.9	2.6	2.8	1.5	1.7	2.3	2.5	1.4	1.5	2.1	2.3
	SW	1.6	1.8	2.5	2.7	1.5	1.6	2.2	2.4	1.3	1.5	2	2.2
	W	1.6	1.8	2.5	2.8	1.5	1.6	2.3	2.5	1.3	1.5	2.1	2.2
	NW	1.7	1.9	2.6	2.8	1.6	1.7	2.4	2.6	1.4	1.6	2.2	2.4
FAB	N	4.1	4.6	6.3	6.9	3.9	4.3	6	6.5	3.7	4.1	5.6	6.2
	NE	4	4.4	6.1	6.7	3.7	4.1	5.6	6.1	3.4	3.8	5.2	5.7
	E	3.9	4.3	6	6.5	3.5	3.9	5.4	5.9	3.2	3.6	4.9	5.4
	SE	3.9	4.3	6	6.5	3.5	3.9	5.4	5.8	3.2	3.5	4.8	5.3
	S	4	4.4	6.1	6.6	3.6	3.9	5.5	6	3.2	3.6	4.9	5.4
	SW	3.9	4.3	5.9	6.5	3.4	3.8	5.3	5.8	3.1	3.4	4.8	5.2
	W	3.9	4.3	5.9	6.5	3.5	3.8	5.3	5.8	3.2	3.5	4.9	5.3
	NW	4	4.4	6.1	6.7	3.7	4.1	5.6	6.1	3.4	3.8	5.2	5.7
LS	N	1.9	2.1	3	3.2	1.8	2	2.8	3	1.7	1.9	2.6	2.9
	NE	1.9	2.1	2.9	3.1	1.7	1.9	2.6	2.9	1.6	1.8	2.4	2.7
	E	1.8	2	2.8	3	1.6	1.8	2.5	2.7	1.5	1.7	2.3	2.5
	SE	1.8	2	2.8	3	1.6	1.8	2.5	2.7	1.5	1.6	2.3	2.5
	S	1.8	2	2.8	3.1	1.7	1.8	2.5	2.8	1.5	1.7	2.3	2.5
	SW	1.8	2	2.8	3	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4
	W	1.8	2	2.8	3	1.6	1.8	2.5	2.7	1.5	1.6	2.3	2.5
	NW	1.9	2.1	2.9	3.1	1.7	1.9	2.6	2.9	1.6	1.8	2.4	2.6
MB	N	2.6	2.9	4	4.3	2.4	2.7	3.7	4.1	2.3	2.5	3.5	3.8
	NE	2.5	2.8	3.8	4.2	2.3	2.5	3.5	3.8	2.1	2.4	3.3	3.5
	E	2.4	2.7	3.7	4.1	2.2	2.4	3.4	3.7	2	2.2	3.1	3.3
	SE	2.4	2.7	3.7	4.1	2.2	2.4	3.3	3.6	2	2.2	3	3.3
	S	2.5	2.7	3.8	4.1	2.2	2.5	3.4	3.7	2	2.2	3.1	3.3
	SW	2.4	2.7	3.7	4	2.1	2.4	3.3	3.6	1.9	2.1	3	3.2
	W	2.4	2.7	3.7	4	2.2	2.4	3.3	3.6	2	2.2	3	3.3
	NW	2.5	2.8	3.8	4.2	2.3	2.5	3.5	3.8	2.1	2.3	3.2	3.5

Table 17 Payback period for different combinations of bricks and insulation materials in Jodhpur

		0.3				0.6				0.9			
		CEL	CO	PO	PU	CEL	CO	PO	PU	CEL	CO	PO	PU
BB	N	2.2	2.4	3.3	3.6	2	2.3	3.1	3.4	1.9	2.2	3	3.3
	NE	2.1	2.3	3.2	3.5	1.9	2.2	3	3.2	1.8	2	2.8	3
	E	2	2.3	3.1	3.4	1.9	2.1	2.9	3.1	1.7	1.9	2.6	2.9
	SE	2	2.3	3.1	3.4	1.8	2	2.8	3.1	1.7	1.9	2.6	2.8
	S	2.1	2.3	3.2	3.4	1.9	2.1	2.8	3.1	1.7	1.9	2.6	2.8
	SW	2	2.2	3.1	3.4	1.8	2	2.8	3	1.6	1.8	2.5	2.8
	W	2	2.3	3.1	3.4	1.8	2	2.8	3.1	1.7	1.9	2.6	2.8
	NW	2.1	2.3	3.2	3.5	1.9	2.2	3	3.2	1.8	2	2.8	3
CB	N	1.5	1.7	2.4	2.6	1.5	1.6	2.2	2.4	1.4	1.5	2.1	2.3
	NE	1.5	1.7	2.3	2.5	1.4	1.5	2.1	2.3	1.3	1.4	2	2.2
	E	1.5	1.6	2.2	2.4	1.3	1.5	2	2.2	1.2	1.4	1.9	2
	SE	1.5	1.6	2.2	2.4	1.3	1.5	2	2.2	1.2	1.3	1.8	2
	S	1.5	1.6	2.2	2.4	1.3	1.5	2	2.2	1.2	1.3	1.8	2
	SW	1.4	1.6	2.2	2.4	1.3	1.4	2	2.2	1.2	1.3	1.8	2
	W	1.5	1.6	2.2	2.4	1.3	1.5	2	2.2	1.2	1.3	1.9	2
	NW	1.5	1.9	2.3	2.5	1.4	1.5	2.1	2.3	1.3	1.4	2	2.2
FAB	N	3.6	4	5.5	6	3.4	3.8	5.2	5.7	3.3	3.6	5	5.4
	NE	3.5	3.9	5.4	5.9	3.3	3.6	5	5.4	3	3.4	4.7	5.1
	E	3.4	3.8	5.3	5.7	3.1	3.5	4.8	5.2	2.8	3.2	4.4	4.8
	SE	3.4	3.8	5.3	5.7	3.1	3.4	4.7	5.1	2.9	3.1	4.3	4.7
	S	3.4	3.8	5.3	5.8	3.1	3.4	4.8	5.2	2.8	3.1	4.3	4.7
	SW	3.4	3.8	5.2	5.7	3	3.4	4.7	5.1	2.8	3.1	4.2	4.6
	W	3.4	3.8	5.2	5.7	3.1	3.4	4.7	5.2	2.8	3.1	4.3	4.7
	NW	3.5	3.9	5.4	5.9	3.2	3.6	5	5.4	3	3.4	4.7	5.1
LS	N	1.7	1.9	2.6	2.8	1.6	1.8	2.4	2.7	1.5	1.7	2.3	2.5
	NE	1.6	1.8	2.5	2.7	1.5	1.7	2.3	2.5	1.4	1.6	2.2	2.4
	E	1.6	1.8	2.5	2.7	1.5	1.6	2.2	2.4	1.3	1.5	2.1	2.2
	SE	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4	1.3	1.5	2	2.2
	S	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4	1.3	1.5	2	2.2
	SW	1.6	1.8	2.4	2.6	1.4	1.6	2.2	2.4	1.3	1.4	2	2.1
	W	1.6	1.8	2.4	2.7	1.4	1.6	2.2	2.4	1.3	1.5	2	2.2
	NW	1.6	1.8	2.5	2.7	1.5	1.7	2.3	2.5	1.4	1.6	2.2	2.4
MB	N	2.2	2.5	3.4	3.8	2.1	2.4	3.3	3.6	2	2.3	3.1	3.4
	NE	2.2	2.4	3.4	3.7	2	2.2	3.1	3.4	1.9	2.1	2.9	3.2
	E	2.1	2.4	3.3	3.6	1.9	2.2	3	3.3	1.8	2	2.7	3
	SE	2.1	2.4	3.3	3.6	1.9	2.1	2.9	3.2	1.7	1.9	2.7	2.9
	S	2.1	2.4	3.3	3.6	1.9	2.1	3	3.2	1.8	1.9	2.7	2.9
	SW	2.1	2.3	3.2	3.5	1.9	2.1	2.9	3.2	1.7	1.9	2.6	2.9
	W	2.1	2.4	3.3	3.5	1.9	2.1	3	3.2	1.8	2	2.7	3
	NW	2.2	2.4	3.4	3.7	2	2.2	3.1	3.4	1.9	2.1	2.9	3.2

Table 18 Payback period for different combinations of bricks and insulation materials in Mangalore

		0.3				0.6				0.9			
		CEL	CO	PO	PU	CEL	CO	PO	PU	CEL	CO	PO	PU
BB	N	2.5	2.7	3.8	4.1	2.2	2.5	3.1	3.7	2.1	2.3	3.2	3.4
	NE	2.4	2.6	3.6	4	2.1	2.3	3	3.5	1.9	2.1	2.9	3.2
	E	2.3	2.5	3.5	3.8	2	2.2	2.9	3.3	1.8	2	2.8	3
	SE	2.3	2.5	3.5	3.8	2	2.2	2.8	3.3	1.8	2	2.8	3
	S	2.3	2.6	3.6	3.9	2	2.3	2.8	3.4	1.8	2	2.8	3.1
	SW	2.3	2.5	3.5	3.8	2	2.2	2.8	3.3	1.8	2	2.7	3
	W	2.3	2.5	3.5	3.8	2	2.2	2.8	3.3	1.8	2	2.7	3
	NW	2.4	2.6	3.6	4	2.1	2.3	3	3.5	1.9	2.1	2.9	3.2
CB	N	1.8	1.9	2.7	2.9	1.6	1.8	2.4	2.7	1.5	1.6	2.2	2.5
	NE	1.7	1.9	2.6	2.8	1.5	1.7	2.3	2.5	1.4	1.5	2.1	2.3
	E	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4	1.3	1.4	2	2.1
	SE	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4	1.3	1.4	2	2.1
	S	1.7	1.8	2.5	2.8	1.5	1.6	2.2	2.4	1.3	1.5	2	2.2
	SW	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4	1.3	1.4	1.9	2.1
	W	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4	1.3	1.4	1.9	2.1
	NW	1.7	1.9	2.6	2.8	1.5	1.7	2.3	2.5	1.4	1.5	2.1	2.3
FAB	N	4.1	4.6	6.3	6.9	3.7	4.1	5.7	6.2	3.4	3.8	5.3	5.8
	NE	4	4.4	6.1	6.7	3.5	3.9	5.4	5.9	3.2	3.6	4.9	5.4
	E	3.8	4.3	5.9	6.4	3.4	3.7	5.1	5.6	3	3.3	4.9	5
	SE	3.8	4.3	5.9	6.4	3.4	3.7	5.1	5.6	3	3.3	4.6	5
	S	3.9	4.3	6	6.5	3.4	3.8	5.3	5.7	3.1	3.4	4.7	5.2
	SW	3.8	4.2	5.8	6.4	3.3	3.7	5.1	5.5	3	3.3	4.5	4.9
	W	3.8	4.2	5.8	6.4	3.3	3.7	5.1	5.5	3	3.3	4.5	4.9
	NW	4	4.4	6.1	6.6	3.5	3.9	5.4	5.9	3.2	3.5	4.9	5.3
LS	N	1.9	2.1	2.9	3.2	1.7	1.9	2.7	2.9	1.6	1.8	2.5	2.7
	NE	1.9	2.1	2.8	3.1	1.6	1.8	2.5	2.8	1.5	1.7	2.3	2.5
	E	1.8	2	2.8	3	1.6	1.7	2.4	2.6	1.4	1.6	2.2	2.3
	SE	1.8	2	2.8	3	1.6	1.7	2.4	2.6	1.4	1.6	2.2	2.3
	S	1.8	2	2.8	3	1.6	1.8	2.5	2.7	1.4	1.6	2.2	2.4
	SW	1.8	2	2.7	3	1.5	1.7	2.4	2.6	1.4	1.5	2.1	2.3
	W	1.8	2	2.7	3	1.5	1.7	2.4	2.6	1.4	1.5	2.1	2.3
	NW	1.8	2	2.8	3.1	1.6	1.8	2.5	2.7	1.5	1.6	2.3	2.5
MB	N	2.6	2.8	3.9	4.3	2.3	2.6	3.6	3.9	2.1	2.4	3.3	3.6
	NE	2.5	2.8	3.8	4.1	2.2	2.4	3.4	3.7	2	2.2	3.1	3.3
	E	2.4	2.7	3.7	4	2.1	2.3	3.2	3.5	1.9	2.1	2.9	3.1
	SE	2.4	2.7	3.7	4	2.1	2.3	3.2	3.5	1.9	2.1	2.9	3.1
	S	2.4	2.7	3.7	4.1	2.1	2.4	3.3	3.6	1.9	2.1	3	3.2
	SW	2.4	2.6	3.6	4	2.1	2.3	3.2	3.4	1.8	2	2.8	3.1
	W	2.4	2.6	3.6	4	2.1	2.3	3.2	3.4	1.8	2	2.8	3.1
	NW	2.5	2.7	3.8	4.1	2.2	2.4	3.4	3.7	2	2.2	3	3.3

Table 19 Payback period for different combinations of bricks and insulation materials in Pune

		0.3				0.6				0.9			
		CEL	CO	PO	PU	CEL	CO	PO	PU	CEL	CO	PO	PU
BB	N	3.3	3.7	5.1	5.6	2.9	3.2	4.5	4.9	2.6	2.9	4	4.4
	NE	3.1	3.5	4.8	5.2	2.7	3	4.1	4.5	2.4	2.6	3.6	3.9
	E	3	3.3	4.6	5	2.5	2.8	3.8	4.2	2.1	2.4	3.3	3.6
	SE	3	3.4	4.6	5.1	2.5	2.7	3.8	4.1	2.1	2.3	3.2	3.5
	S	3.1	3.5	4.8	5.2	2.5	2.8	3.9	4.3	2.2	2.4	3.3	3.6
	SW	3	3.3	4.6	5	2.4	2.7	3.7	4	2.1	2.3	3.2	3.4
	W	3	3.3	4.6	5	2.4	2.7	3.7	4.1	2.1	2.3	3.2	3.5
	NW	3.1	3.5	4.8	5.2	2.7	2.9	4.1	4.4	2.3	2.6	3.6	3.9
CB	N	2.4	2.6	3.6	4	2.1	2.3	3.2	3.5	1.9	2.1	2.9	3.1
	NE	2.2	2.5	3.4	3.7	1.9	2.1	2.9	3.2	1.7	1.9	2.6	2.8
	E	2.1	2.4	3.3	3.6	1.8	2	2.7	3	1.5	1.7	2.3	2.6
	SE	2.2	2.4	3.3	3.6	1.8	2	2.7	2.9	1.5	1.7	2.3	2.5
	S	2.2	2.5	3.4	3.7	1.8	2	2.8	3	1.5	1.7	2.4	2.6
	SW	2.1	2.4	3.3	3.6	1.7	1.9	2.6	2.9	1.5	1.6	2.3	2.5
	W	2.1	2.3	3.3	3.5	1.7	1.9	2.7	2.9	1.5	1.7	2.3	2.5
	NW	2.2	2.5	3.4	3.7	1.9	2.1	2.9	3.2	1.7	1.8	2.6	2.8
FAB	N	5.6	6.2	8.6	9.3	4.9	5.4	7.5	8.2	4.4	4.9	6.8	7.4
	NE	5.3	5.8	8.1	8.8	4.5	5	6.9	7.5	3.9	4.4	6	6.6
	E	5	5.6	7.7	8.4	4.2	4.6	6.4	7	3.6	4	5.5	6
	SE	5.1	5.6	7.8	8.5	4.1	4.6	6.4	6.9	3.5	3.9	5.4	5.9
	S	5.2	5.8	8	8.7	4.3	4.7	6.5	7.1	3.6	4	5.6	6.1
	SW	5	5.5	7.7	8.4	4.1	4.5	6.2	6.8	3.4	3.8	5.3	5.8
	W	5	5.5	7.6	8.3	4.1	4.5	6.3	6.8	3.5	3.9	5.4	5.9
	NW	5.2	5.8	8	8.7	4.4	4.9	6.8	7.4	3.9	4.3	6	6.5
LS	N	2.6	2.9	4	4.4	2.3	2.5	3.5	3.8	2.1	2.3	3.2	3.4
	NE	2.5	2.7	3.8	4.1	2.1	2.3	3.2	3.5	1.8	2	2.8	3.1
	E	2.3	2.6	3.6	3.9	1.9	2.2	3	3.2	1.7	1.9	2.6	2.8
	SE	2.4	2.6	3.6	4	1.9	2.1	3	3.2	1.6	1.8	2.5	2.8
	S	2.4	2.7	3.7	4.1	2	2.2	3	3.3	1.7	1.9	2.6	2.8
	SW	2.3	2.6	3.6	3.9	1.9	2.1	2.9	3.2	1.6	1.8	2.5	2.7
	W	2.3	2.6	3.6	3.9	1.9	2.1	2.9	3.2	1.6	1.8	2.5	2.7
	NW	2.4	2.7	3.7	4.1	2.1	2.3	3.2	3.5	1.8	2	2.8	3
MB	N	3.5	3.9	5.3	5.8	3.1	3.4	4.7	5.1	2.7	3	4.2	4.6
	NE	3.3	3.6	5	5.5	2.8	3.1	4.3	4.7	2.5	2.7	3.8	4.1
	E	3.1	3.5	4.8	5.2	2.6	2.9	4	4.3	2.2	2.5	3.4	3.7
	SE	3.2	3.5	4.9	5.3	2.6	2.9	4	4.3	2.2	2.4	3.4	3.7
	S	3.3	3.6	5	5.5	2.7	2.9	4.1	4.4	2.3	2.5	3.5	3.8
	SW	3.1	3.5	4.8	5.2	2.5	2.8	3.9	4.2	2.1	2.4	3.3	3.6
	W	3.1	3.4	4.8	5.2	2.5	2.8	3.9	4.3	2.2	2.4	3.4	3.7
	NW	3.3	3.6	5	5.5	2.8	3.1	4.2	4.6	2.4	2.7	3.7	4.1

Annual carbon mitigation potential

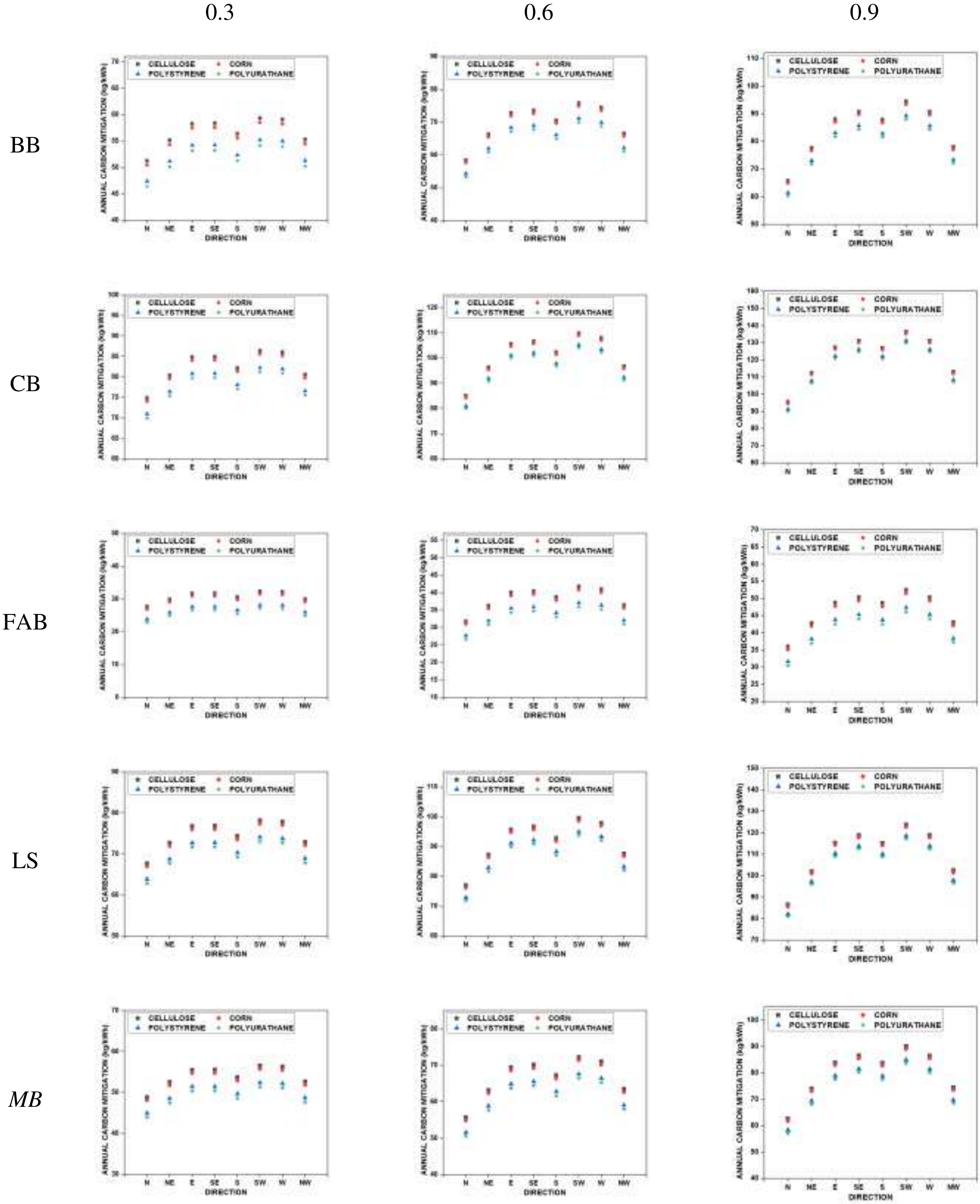


Figure 7 Annual carbon mitigation potential of insulation materials in Delhi

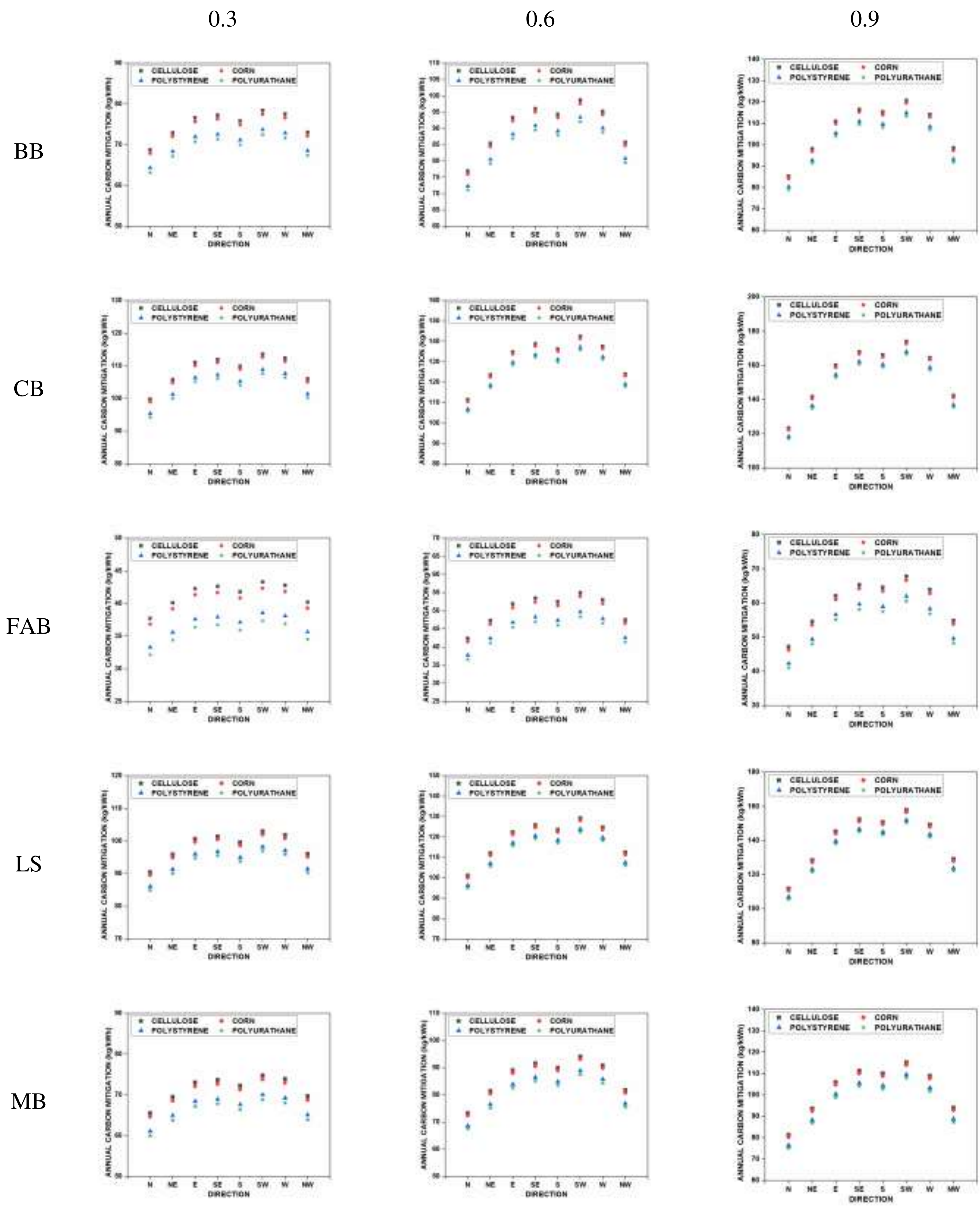


Figure 8 Annual carbon mitigation potential of insulation materials in Jodhpur

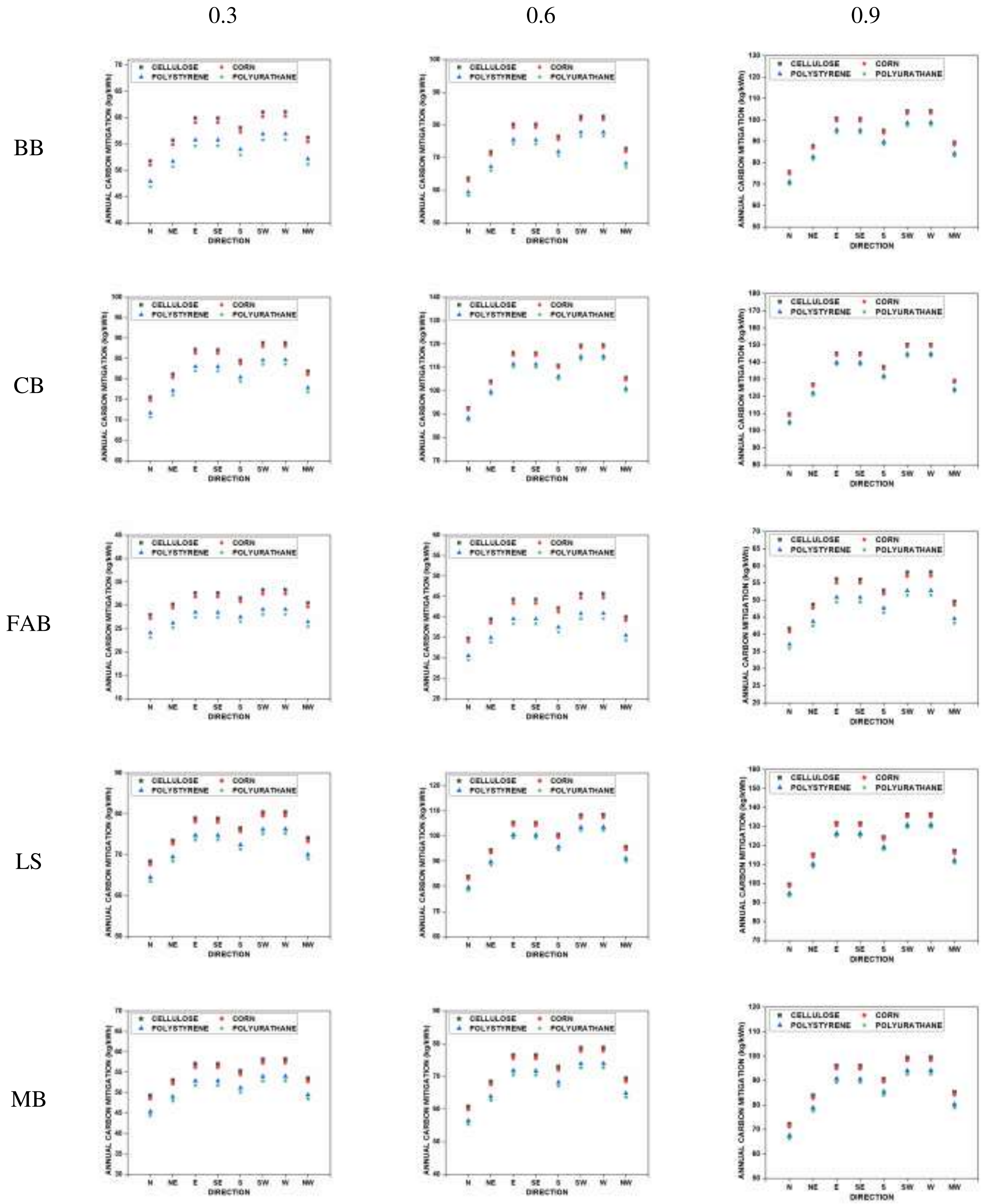


Figure 9 Annual carbon mitigation potential of insulation materials in Mangalore

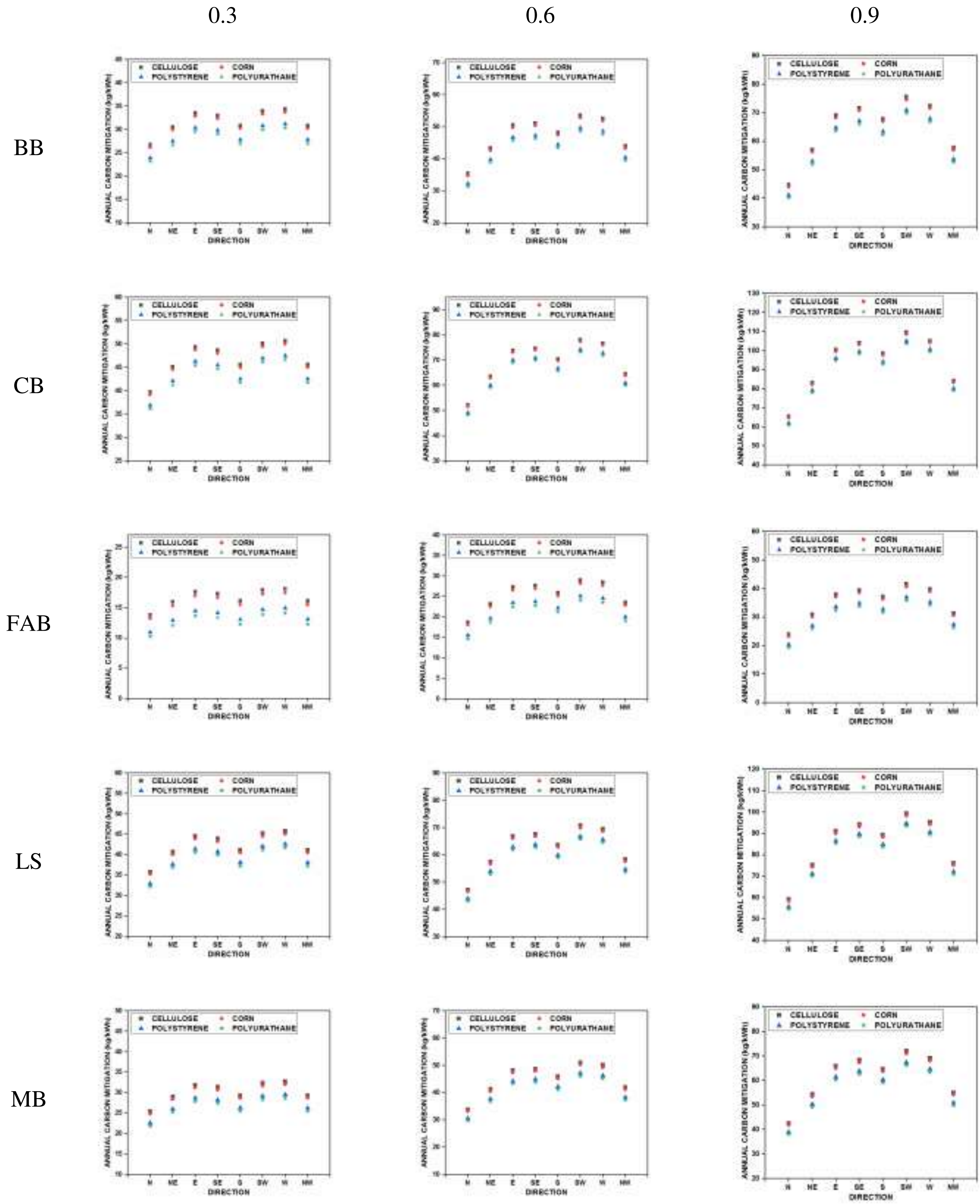


Figure 10Annual carbon mitigation potential of insulation materials in Pune

In this study, the carbon mitigation potential of insulation material is calculated during the operational phase of the building. The carbon mitigation was achieved by reducing the cooling load of the building. Figure 7 to 10 shows the carbon mitigation potential of the optimum thickness of insulation materials when used with different bricks having various absorptivity of the external surface. From the figures, it can be observed that the carbon mitigation potential of the North facing wall is minimum, among others. The South-west facing wall possess the highest carbon mitigation potential. Among all the insulation materials studied, cellulose mitigates the highest carbon emission, and polyurethane is the poorest carbon mitigator. The range of carbon mitigation potentials of cellulose for absorptivity of 0.3 is found to be 46.4-59.4, 70-86.4, 22.9-32.3,62.9-78.2, 44-56.5 kg/kWh when used with BB, CB, FAB, LS and MB, respectively. The carbon mitigation potential of insulation materials is the highest when used with CB and is the least when used with FAB. The carbon mitigation potential of insulation material is more substantial when combined with a wall having a higher absorptivity value.

Conclusions and Recommendation

Economic optimum insulation thickness over a lifetime of 20 years is evaluated for different Indian cities considering different brick materials, different values of absorptivity of the external surface, eight directions, cost of insulation and electricity cost. The total cost saving, payback period for the investment and carbon mitigation potential are also estimated. The following conclusions can be drawn from the study.

- Increased absorptivity of the external surface results in higher degree days and thicker optimum insulation. With an increase in absorptivity, the cost-saving potential of insulation materials also increases. The payback period is lesser for a higher value of absorptivity. The carbon mitigation potential of walls having higher absorptivity is more. Hence, the use of insulation is a must in walls with a higher absorptivity value.
- The optimum insulation thickness is minimum for the North facing wall. The cost-saving potential and carbon mitigation potential of the North facing wall are also found to be minimum. South-West or West facing walls were found to have the highest cost-saving and carbon mitigation potential. The payback period for the South-West and West facing walls is also minimum. Hence, it is recommended to always use insulation in South-west and West facing walls.

- Cellulose is the best insulation material among all the materials considered for this study as cellulose's cost-saving along with the carbon mitigation potential is the highest, and the payback period is the least. The recommended order of insulation material is cellulose >corn >polystyrene > polyurethane
- The cost-saving potential of insulation material is maximum when used with concrete blocks and the payback period is minimum when insulation is used with concrete blocks. The combination of insulation and fly ash brick provided the minimum cost-saving and maximum payback period. From a maximum cost saving and minimum payback period perspective, the choice of brick material to be used with insulation should be CB >LS >BB >MB >FAB.
- It is always recommended to use insulation in places having higher degree days as it is found that the cost-saving potential of insulation is maximum in Jodhpur (CDD=4008) and minimum in Pune (CDD=2567).

It should be worth noting that the results obtained here are specific to the parameters considered. Any difference in electricity price, COP of the system, cost of the insulation, and degree days will produce different results.

Statements & Declarations

Authors Contributions

All the authors contributed to the preparation of this manuscript. Dr. Vasudeva M. and Prof. Ashok Babu T.P have done the conceptualization of the work. Debasish Mahapatra prepared the first version of this manuscript. The final version of this manuscript was prepared by Debasish Mahapatra, considering the comments of the other author in mind. All authors read and approved the final manuscript.

Ethical Approval

The authors declare that this article is an original piece of work and has not been submitted elsewhere for publication.

Consent to Participate and Publish

All the authors have actively participated in preparing the manuscript and approved the version of the manuscript to be published.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and materials

Not applicable

Reference

Aditya L, Mahlia TMI, Rismanchi B, et al (2017) A review on insulation materials for energy conservation in buildings. Renew Sustain Energy Rev 73:1352–1365. https://doi.org/10.1016/j.rser.2017.02.034

Al-Homoud DMS (2005) Performance characteristics and practical applications of common building thermal insulation materials. Build Environ 40:353–366. https://doi.org/10.1016/j.buildenv.2004.05.013

Ali Kallioğlu M, Sharma A, Chinnasamy V, et al (2020) Optimum insulation thickness assessment of different insulation materials for mid-latitude steppe and desert climate (BSH) region of India. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.10.590

Alsayed MF, Tayeh RA (2019) Life cycle cost analysis for determining optimal insulation thickness in Palestinian buildings. J Build Eng 22:101–112. https://doi.org/10.1016/j.jobe.2018.11.018

Arumugam C, Shaik S (2021) Transforming waste disposals into building materials to investigate energy savings and carbon emission mitigation potential. Environ Sci Pollut Res 28:15259–15273. https://doi.org/10.1007/s11356-020-11693-0

Bodalal A, Mashite S, Aladouli O, Ihdash A (2017) Calculation of Annual Heating and Cooling Energy Requirements for Residential Building in Different Climate Zones in Libya. Innov Energy Res 06: https://doi.org/10.4172/2576-1463.1000161

Bolattürk A (2006) Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey. Appl Therm Eng 26:1301–1309. https://doi.org/10.1016/j.applthermaleng.2005.10.019

Chel A, Tiwari GN (2009) Thermal performance and embodied energy analysis of a passive house - Case study of vault roof mud-house in India. Appl Energy 86:1956–1969. https://doi.org/10.1016/j.apenergy.2008.12.033

Daouas N, Hassen Z, Aissia H Ben (2010) Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia. Appl Therm Eng 30:319–326. https://doi.org/10.1016/j.applthermaleng.2009.09.009

Fallah M, Medghalchi Z (2020) Proposal of a new approach for avoiding Anti-Insulation in residential buildings by considering occupant's comfort condition. Therm Sci Eng Prog 20:. https://doi.org/10.1016/j.tsep.2020.100721

Ghazi Wakili K, Binder B, Zimmermann M, Tanner C (2014) Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building. Energy Build 82:237–242. https://doi.org/10.1016/j.enbuild.2014.06.050

Hasan A (1999) Optimizing insulation thickness for buildings using life cycle cost. Appl Energy 63:115–124. https://doi.org/10.1016/S0306-2619(99)00023-9

Jie P, Zhang F, Fang Z, et al (2018) Optimizing the insulation thickness of walls and roofs of existing buildings based on primary energy consumption, global cost and pollutant emissions. Energy 159:1132–1147. https://doi.org/10.1016/j.energy.2018.06.179

Kolaitis DI, Malliotakis E, Kontogeorgos DA, et al (2013) Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings. Energy Build 64:123–131. https://doi.org/10.1016/j.enbuild.2013.04.004

Kumar A, Suman BM (2013) Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate. Build Environ 59:635–643. https://doi.org/10.1016/j.buildenv.2012.09.023

Kumar D, Alam M, Zou PXW, et al (2020a) Comparative analysis of building insulation material properties and performance. Renew Sustain Energy Rev 131:110038. https://doi.org/10.1016/j.rser.2020.110038

Kumar D, Zou PXW, Memon RA, et al (2020b) Life-cycle cost analysis of building wall and insulation materials. J Build Phys 43:428–455. https://doi.org/10.1177/1744259119857749

Lin T-P, Lin F-Y, Wu P-R, et al (2017) Multiscale analysis and reduction measures of urban carbon dioxide budget based on building energy consumption. Energy Build 153:356–367. https://doi.org/10.1016/j.enbuild.2017.07.084

Loukaidou K, Michopoulos A, Zachariadis T (2017) Nearly-zero Energy Buildings: Cost-optimal Analysis of Building Envelope Characteristics. Procedia Environ Sci 38:20–27. https://doi.org/10.1016/j.proenv.2017.03.069

Meng X, Luo T, Gao Y, et al (2018) Comparative analysis on thermal performance of different wall insulation forms under the air-conditioning intermittent operation in summer. Appl Therm Eng 130:429–438. https://doi.org/10.1016/j.applthermaleng.2017.11.042

Mishra S, Usmani JA, Varshney S (2012) Energy Saving Analysis In Building Walls Through Thermal Insulation System. Int J Eng Res Appl 2:128–135

Parishwad G V., Bhardwaj RK, Nema VK (1997) Data bank: Estimation of hourly solar radiation for India. Renew Energy 12:303–313. https://doi.org/10.1016/s0960-1481(97)00039-6

Parishwad G V., Bhardwaj RK, Nema VK (1998) A Theoretical Procedure for Estimation of Solar Heat Gain Factor for India. Archit Sci Rev 41:11–15. https://doi.org/10.1080/00038628.1998.9697402

Rathore PKS, Shukla SK (2020) An experimental evaluation of thermal behavior of the building envelope using macroencapsulated PCM for energy savings. Renew Energy 149:1300–1313. https://doi.org/10.1016/j.renene.2019.10.130

Shanmuga Sundaram A, Bhaskaran A (2014) Optimum insulation thickness of walls for energy-saving in hot regions of India. Int J Sustain Energy 33:213–226. https://doi.org/10.1080/14786451.2012.759573

Sisman N, Kahya E, Aras N, Aras H (2007) Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions. Energy Policy 35:5151–5155. https://doi.org/10.1016/j.enpol.2007.04.037

Sun X, Jovanovic J, Zhang Y, et al (2019) Use of encapsulated phase change materials in lightweight building walls for annual thermal regulation. Energy 180:858–872. https://doi.org/10.1016/j.energy.2019.05.112

Torres-Rivas A, Palumbo M, Haddad A, et al (2018) Multi-objective optimisation of bio-based thermal insulation materials in building envelopes considering condensation risk. Appl

Energy 224:602–614. https://doi.org/10.1016/j.apenergy.2018.04.079

Ucar A, Balo F (2010) Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls. Renew Energy 35:88–94. https://doi.org/10.1016/j.renene.2009.07.009

Walker R, Pavía S (2015) Thermal performance of a selection of insulation materials suitable for historic buildings. Build Environ 94:155–165. https://doi.org/10.1016/j.buildenv.2015.07.033

Yu J, Yang C, Tian L, Liao D (2009) A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China. Appl Energy 86:2520–2529. https://doi.org/10.1016/j.apenergy.2009.03.010

Yuan J, Farnham C, Emura K (2017) Optimal combination of thermal resistance of insulation materials and primary fuel sources for six climate zones of Japan. Energy Build 153:403–411. https://doi.org/10.1016/j.enbuild.2017.08.039