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Optimum Insulation Thickness of Roof for Energy Saving in Hot Regions of India

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Abstract – Thermal insulation for roofing is one of the best practices to reduce electrical energy consumption for space cooling and heating. The roof insulation avoids retention heat into the room. The selection of optimum insulation material and optimum insulation thickness plays a vital role. The optimum insulation thickness for five different cities located in South India with varied climatic conditions were determined for four different materials and presented. Data base containing optimum insulation thickness, annual electrical energy consumption, annual energy cost and payback period on selected materials for five cities were also provided.

Keywords – *Degree days, optimum insulation, payback, polystyrene, thermo economics.*

1. INTRODUCTION

The demand for energy in India is steadily increasing as a result of rapid growth in population and economic development. Due to high industrialization for the past two decades, India is facing an increasing deficit in power supply to meet its normal requirements as well as its peak load demand. The total national energy consumption accounts to 3.4% of global energy consumption and is divided among four main sectors such as industrial, building (residential/commercial), transportation and agriculture. Building sector is the third largest consumer of energy and its share is 30% of total national energy consumption. This increases at a rate of 4.3% exceeding the population growth rate of 1.3%. The distribution of energy use pattern in residential and commercial building is shown in Figure 1. The energy required for HVAC is highest share of all utilities and it is ever increasing due to improvement in life standards and growth in IT sector.

On the basis of metrological data containing hourly temperature, various climatic parameters and solar radiation for the period of 30 years collected from 233 base stations located at various parts of India, the country is divided into six climatic zones as shown in Figure 2. This vast climatic diversity along with different income groups developed different energy use patterns which influence energy consumption.

Although the energy consumption in India is much less than the world's average, still due to lack of energy efficient practices, Indian buildings give rise to significant energy wastage. The Vast climatic diversity has resulted in different energy use patterns which influence energy consumption. The air conditioning systems installed both in commercial and residential establishments consume more energy due to lack of awareness on energy conservation needs and poor buying capacity of the people for their homes. Government of India recently has setup Bureau of Energy Efficiency, which has brought out energy conservation building code to promote good practices for energy conservation. BEE has made it mandatory for manufacturers to label their consumer goods which include air conditioners to rises information regarding energy consumption and efficiency of the system. The best way to conserve energy in buildings is to use to energy efficient devices and to avoid heat gain in buildings. Heat gain in buildings can be avoided by insulating walls and roof.

Energy performance index for buildings as per energy conservation building code regulated by Bureau of Indian Standard (BIS) and Bureau of Energy Efficiency (BEE) [1],[2] is high as 200 to 400 kWh/m^2/year. This clearly demands for energy-conscious building design. Thermal insulation to avoid heat gain from the surrounding is one of the simplest methods to conserve energy.

Thermal insulation of buildings can reduce electricity consumption up to 40%. The selection of insulation material is based on its thermal conductivity and price. A tradeoff between insulation thickness and reduction in energy consumption is required as insulation thickness increases the insulation cost. There must be an optimum insulation thickness which reduces the investment cost and energy cost required for space cooling over the life-time of the building.

The heat gain through roof conduction is significant which has to be avoided by incorporating proper roof insulation. The heat transmission mechanism into the room is as shown in Figure 3. Some studies on determination of optimum thickness of insulation for external walls can be found in literatures [3] to [10]. However the literature on roof insulation is limited to the knowledge of authors. Comakli and Yuksel [11] have investigated environmental impacts of heat insulation used for reduction of heat loses in buildings and reported a cut down in CO_2 emission by 50% for optimum insulation thickness and other energy saving methods. Comakli and Yuksel [12] have also reported energy savings up to 12.14$/m^2 for optimum insulation thickness for external walls. Mahlia *et al.* [13] have developed a correlation between thermal conductivity and the thickness of selected insulation materials for

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building wall. Effect of wall orientation on the optimum insulation thickness was also reported [14].

Daouas *et al.* [15] have analysed periodic solution for the study of thermal performance and optimum insulation thickness walls in Tunisia and have reported energy saving up to 58.5% with a payback period of 3.11 years.

2. DETERMINATION OF DEGREE DAYS

The use of proper insulation is the effective way to conserve energy in building applications. Energy requirement for heating-cooling is required to determine suitable insulation material and to optimize its thickness. The annual energy consumption for heating-cooling can be determined by using the degree-days method.

Degree-days method is a simplest and steady-state method to determine their energy requirement for heating-cooling. This method is bound on the assumption that the heating or cooling equipment efficiency is not affected by the variation of outdoor temperature. Energy requirement to space heating-cooling is proportional to the difference between outdoor temperature and indoor base temperature.

The solar radiation absorbed by the outside walls should be taken into account as they are opaque surfaces by considering the sol-air temperature. Therefore the cooling degree days (CDD) and heating degree days (HDD) are expressed as

$$CDD = \sum_{j=1}^{N_c} (T_{so} - T_i)_j \quad \text{for } T_{so} \geq T_i \tag{1}$$

$$HDD = \sum_{j=1}^{N_h} (T_i - T_{so})_j \quad \text{for } T_{so} \leq T_i \tag{2}$$

The data recorded for the period of 30 years provided by the six regional meteorological centers of India meteorological department for cities like Chennai, Trichy, Trivandrum, Hyderabad and Kurnool, is used for calculating degree days. The cities taken for study are located in southern India and its climatic type is tropical. The degree days are calculated for cities considered at various base temperatures are given in Table 1.

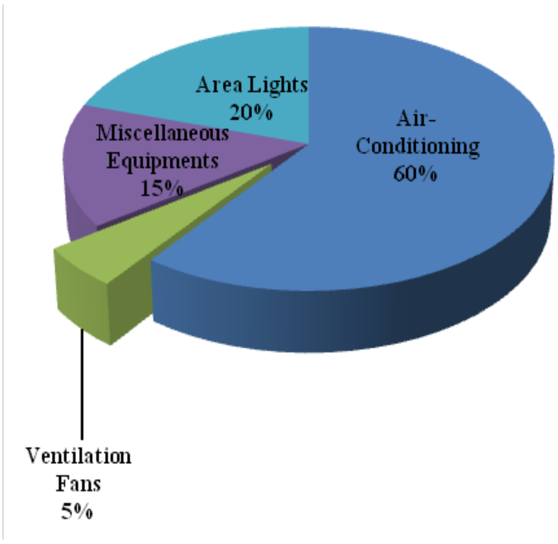

Fig. 1. Typical energy use pattern in building sector.

Table 1. Degree days of the selected cities.

Base Temperature (°C)	Chennai	Trichy	Trivandrum	Hyderabad	Kurnool
18	3756	3936	3576	3048	3840
19	3384	3564	3204	2712	3480
20	3024	3204	2844	2376	3132
21	2664	2844	2484	2052	2784
22	2304	2484	2112	1740	2448
23	1968	2148	1752	1440	2124
24	1644	1812	1392	1164	1812

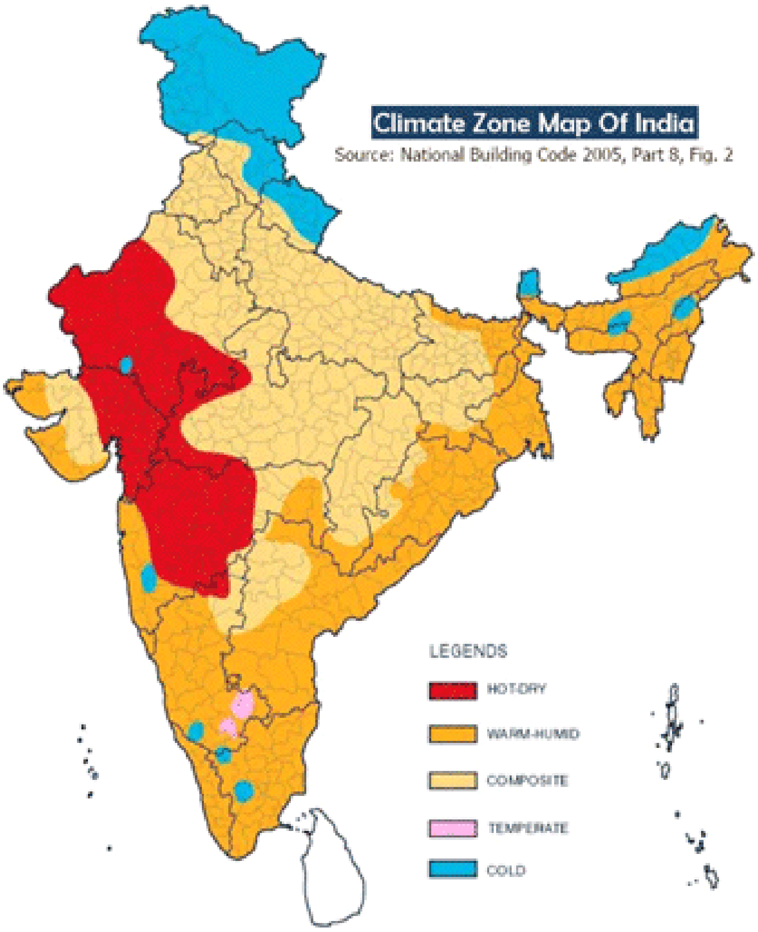

Fig. 2. Climatic zones of India.

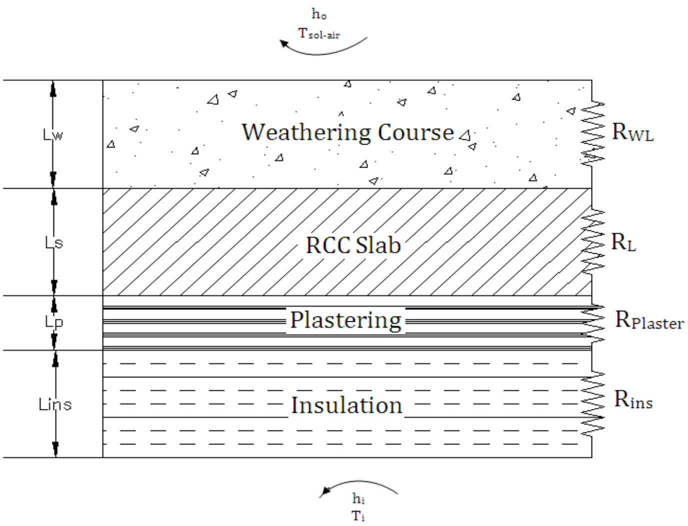

Fig. 3. Resistance network of roof structure.

3. OPTIMUM THICKNESS OF INSULATION

The heat gain in the building envelope occurs due to heat transmission forms ambient to the room through walls, ceiling, windows and basements and by infiltration. Due to absorption of radiant heat, roof retains heat and transmits inside room to increase in temperature. The radiant portion introduces a time lag and also a decrement factor depending upon the dynamic characteristics of the surfaces. Due to this time lag, the effect of radiation will be felt even when the source of radiation is not present due to sunset. Therefore the insulation plays a vital role in minimizing the heat gain in building envelope. Thermal insulation requirement also varies with the climate zone and type of building use. In tropical regions of India, RCC roof is covered with plaster internally and externally with low thermal resistance. We calculate optimum thickness for residential building located in hot regions considering thickness provided in the RCC roof structure. The details of the insulated and un-insulated RCC roof structure are given in Figure 2. The roof is affected by three modes of heat transfer mechanisms: Conduction, convection and radiation. The roof surface exposed to atmosphere absorbs solar radiation and transmits it into the inner surface through conduction. The thermal transmission through the roof for unit area is given as

$$q = U(T_{so} - T_i) \tag{3}$$

The annual energy consumption for cooling per unit area is expressed as

$$E_C = \frac{0.024\ U\ CDD}{EER} \tag{4}$$

The overall heat transfer coefficient for a typical RCC roof structure with insulation and without insulation given in Figure 5 is given as

$$U_{un} = \frac{1}{R_{w1} + R_L + R_{plasetr}} \tag{5}$$

$$U_{un} = \frac{1}{R_{w1} + R_L + R_{plasetr} + R_{ins}} \tag{6}$$

The difference between overall heat transfer coefficient of insulated and un-insulated wall can be written as

$$\Delta U = \frac{1}{R_r} - \frac{1}{\left(R_r + \frac{x}{\lambda_{ins}}\right)} \tag{7}$$

P_1-$P_{2\ method}$ proposed by [16] is adapted to optimize roof insulation thickness. In addition the present worth value of the amount of net energy saving by providing insulation for inner surface is also calculated. P_1 is the life cycle energy related to market discount rate, energy cost inflation rate and economic analysis period. P_2 is the ratio of life cycle expenditures incurred because of additional capital investment to initial investment. The equations for P_1 and P_2 is defined as

$$P_1 = \begin{cases} \frac{N}{1+i} & \text{for } i = d \\ \frac{1}{(d-i)}\left[1 - \left(\frac{1+i}{1+d}\right)^N\right] & \text{for } i \neq d \end{cases} \tag{8}$$

$$P_2 = 1 + P_2 M_s - R_v (1+d)^{-N} \tag{9}$$

The insulation cost per unit area is expressed as

$$C_{ins} = C_i x \tag{10}$$

The life cycle total cost (LCT) of the insulation material and energy consumption can be calculated by the following equation

$$LCT = P_1 C_E E_c + P_2 C_{ins} \tag{11}$$

$$LCT = P_1 C_E \left(\frac{0.024\ U\ CDD}{EER}\right) + P_2 C_i x \tag{12}$$

The life cycle saving (LCS) is the difference between the saved energy cost over the life time and the insulation payout is expressed as

$$LCS = P_1 C_E E_c - P_2 C_{ins} \tag{13}$$

$$LCS = P_1 C_E \left(\frac{0.024\ \Delta U\ CDD}{EER}\right) - P_2 C_i x \tag{14}$$

The optimum thickness of insulation can be determined by differentiating Equation 14 and equating to zero. The optimum thickness in closed from is expressed as:

$$x_{opt} = \left(\frac{0.024\ C_E\ P_1\ \lambda_{ins}\ CDD}{P_2\ C_i\ EER}\right)^{\frac{1}{2}} - R_r \lambda_{ins} \tag{15}$$

By equating Equation 14 to zero and taking $P_2 = 1$ since there is no maintenance cost, the pack back period is obtained as

$$N_p = \begin{cases} \frac{P_2\ C_i\ EER\ (1+i)\ (R_W^2\ \lambda_{ins} + x\ R_W)}{0.024\ CDD\ C_E} & \text{for } i = d \\ \frac{\ln\left[1 - \frac{P_2\ C_i\ EER\ (R_W^2\ \lambda_{ins} + x\ R_W)}{0.024\ CDD\ C_E}(i-d)\right]}{\ln\left(\frac{1+i}{1+d}\right)} & \text{for } i \neq d \end{cases} \tag{16}$$

Five cities Chennai, Trichy, Trivandrum, Hyderabad and Kurnool situated in South India are selected for the study. The degree days of these cities are given in Table 1. The insulation materials considered for study includes expanded polystyrene, polyisocyanurate, glass wool and extruded polystyrene. The properties of insulation materials are shown in Table 2. The properties of residential RCC roof structure and parameters related to economic analysis are given in Table 3.

4. RESULTS AND DISCUSSION

The aim of this study was to determine optimum insulation thickness of roof with respect to cooling loads for various cities located in South India. The suitability of the insulation materials and its thermoeconomic analysis was presented. The base temperature was taken as a varying parameter to construct a data bank on insulation material for various cities. The expression for optimum insulation thickness was presented in closed form, it indicates that optimum insulation thickness is directly proportional to the square root of the degree days and inversely proportional to insulation cost. Figure 4 shows the variation of optimum insulation thickness with respect to base temperature. It was observed from the graph, that the optimum insulation thickness increases with increase in base temperature. Similar patterns were observed for all cities selected for the study. Expanded polystyrene assumes the highest value of optimum thickness for the given base temperature when compared to other insulation materials. The optimum insulation thickness for the base temperature 18°C assumes highest value for all the insulation materials considered for the chosen cities. The city Kurnool assumes highest electrical energy consumption when compared to other cities due to hot climate. The optimum insulation thickness for the city Kurnool is highest since it is hot and for cities Chennai and Trichy, the optimum 18°C, the optimum insulating thickness assumes high value; the LCS for all four materials also assumes high value for all cities. Apart from glass wool LCS for all other materials are closer to each other and their differences is almost insignificant. This similarity is keen for all cities.

Figure 8 shows the payback period when applying optimum insulation thickness for various base temperatures. The base temperature 18°C is taken as reference value since the optimum insulation thickness and LCS assumes high values for all five cities irrespective of the material. The expanded polystyrene assumes high value followed by polyisocyanate, Extruded polystyrene and Glass wool in order.

The insulation cost is independent of energy cost and it increases with insulation thickness. The heat transfer into the room is determined by the parameters like insulation thickness and its thermal conductivity. The heating degree days for all selected cities is zero, therefore the cooling degree days plays an important parameters in optimization. The optimum insulation thickness at low base temperature 18°C is high. Therefore the parameters corresponding to 18°C were taken as reference in determining the suitability of the material. To evaluate the insulation thickness assumes almost similar value. Since the thermal conductivity of polyisocyanerate is lowest when compared to other materials, the optimum insulation thickness assumes lowest value for all the materials considered for the seven cities.

The variation of annual electrical energy consumption per square meter of roof with respect to base temperature for four materials is shown in Figure 5. In all cities the annual electrical energy consumption for expanded polystyrene as insulation material is highest when compared to other materials. The increase in base temperature reduces the annual electrical energy consumption since the degree days gets reduced. The annual electrical energy consumption for the materials extruded polystyrene and Glass wool as insulating material shows similar trend. Figure 6 shows the variation of energy cost with respect to base temperature for all cities. The energy cost of expanded polystyrene is highest when compared to other materials.

The life cycle saving (LCS) equation in closed form shows that LCS is directly proportional to square root of degree-days. Figure 7 shows the variation of LCS with respect to base temperature. For a base temperature suitability of the material a comparison was made with the parameters calculated for a base temperature 18°C. The ranking order for the parameters like optimum insulation thickness, annual Electrical Energy consumption, Annual Energy cost, LCS, Payback period, thermal conductivity value and insulation cost for Chennai city is given in Table 4. Lower thermal conductivity of the walls and ceiling reduces the heat transfer to the room through the wall surface and ceiling. This reduces the electrical energy consumption required for space cooling. The thermal conductivity of expanded polystyrene is high when compared to other materials, therefore the annual electrical energy consumption and annual energy cost is high when compared to the other materials. Due to this the optimum insulation thickness for expanded polystyrene is high when compared to other materials. The cost of expanded polystyrene is very low when compared to the other materials, therefore for this material the annual life savings is high and payback period is low, when compared to other two materials for all the five cities. Therefore the expanded polystyrene seems to be a suitable material for all five cities.

Table 2. Properties of insulation materials.

Insulation	ρ (kg/m^3)	λ (W/m K)	C_p(J/kg.K)	C_i (INR/m^3)
Expanded polystyrene	25	0.05	1380	2226
Extruded polystyrene	35	0.036	1380	3500
Polyisocyanurate	32	0.026	920	7000
Glass wool	16	0.047	670	5000

Table 3. Economical parameters.

Parameters	Value
Roof: 75mm weathering course + 120 mm RCC slab + 15mm plaster	R_{roof}=0.3938 K/W
Cost of electricity	4.715 INR/kWh
EER	3.09
i	5%
d	5%
N	20 years
M_s	0
R_v	0
P_1	19.047
P_2	1

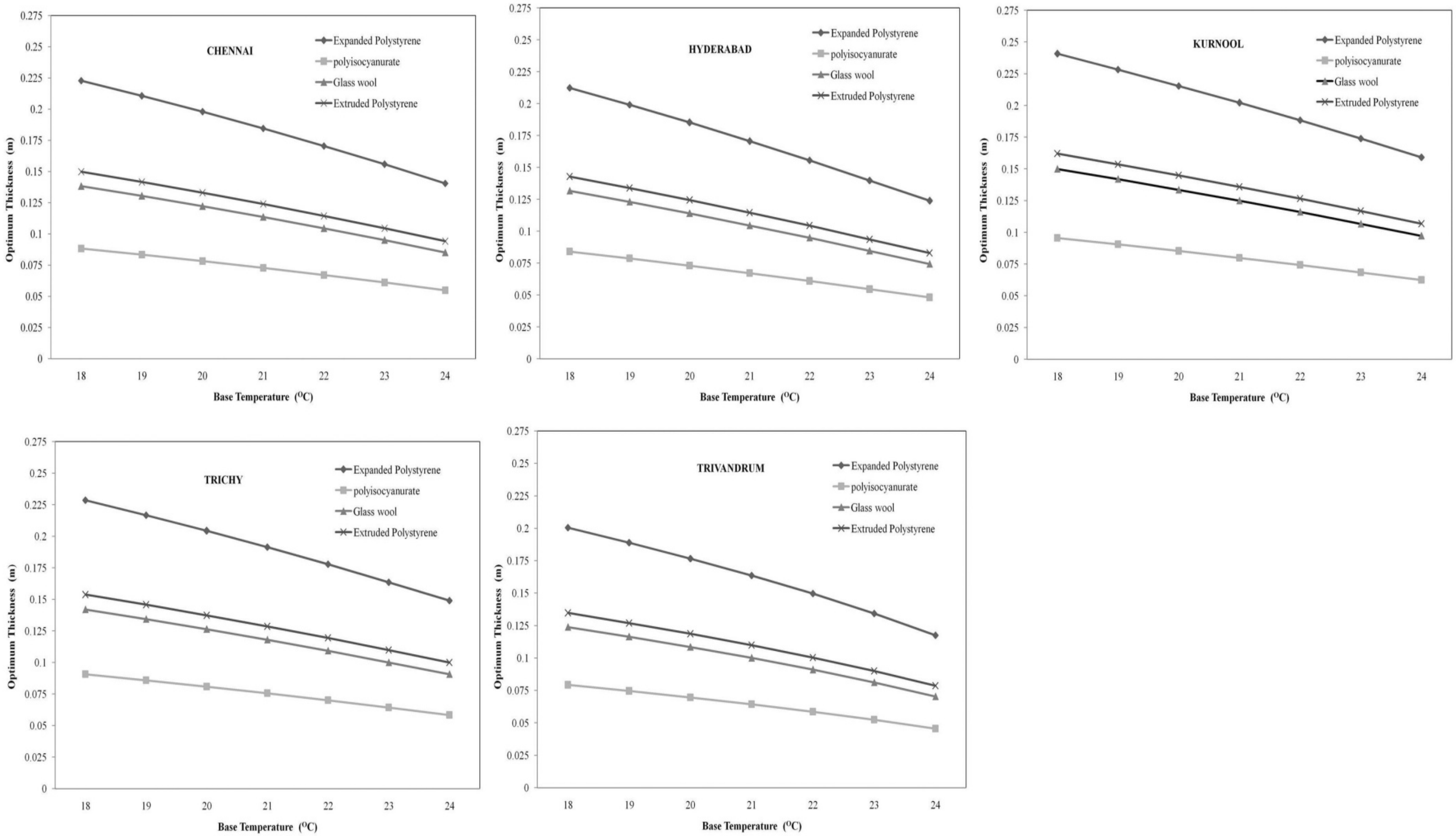

Fig. 4. Optimum thickness versus base temperature for different cities.

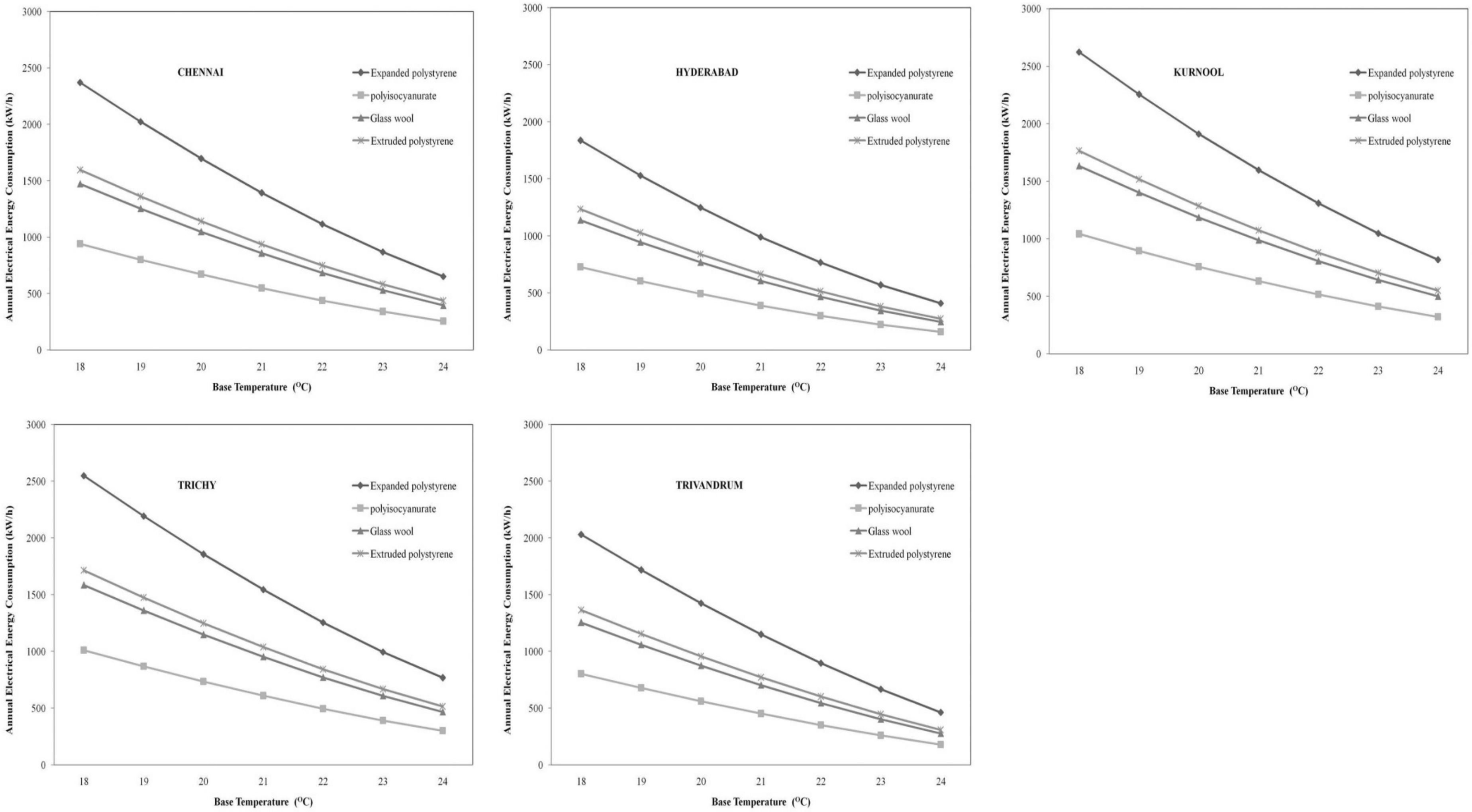

Fig. 5. Annual electrical energy consumption versus base temperature for different cities.

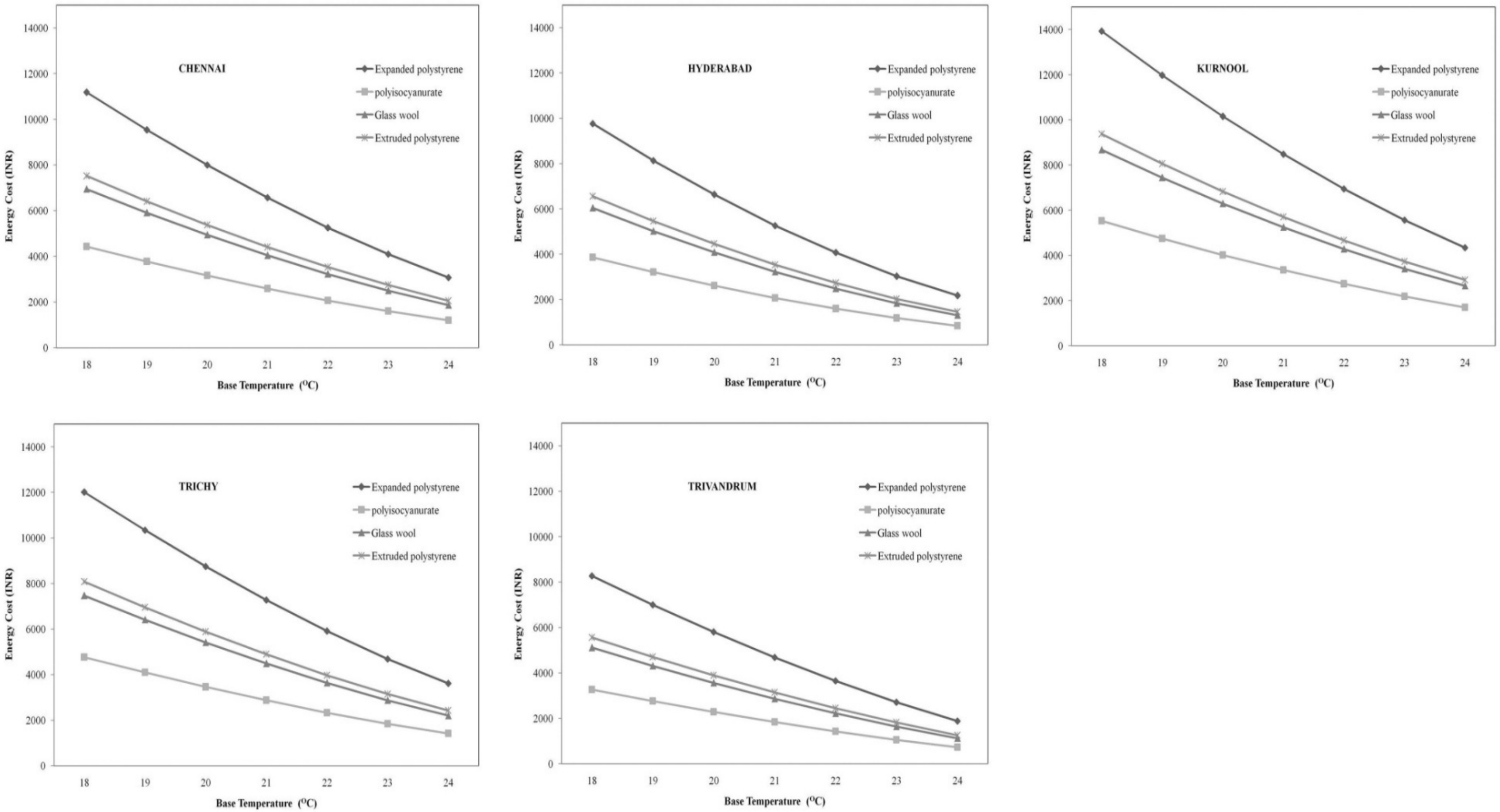

Fig. 6. Annual energy cost versus base temperature for different cities.

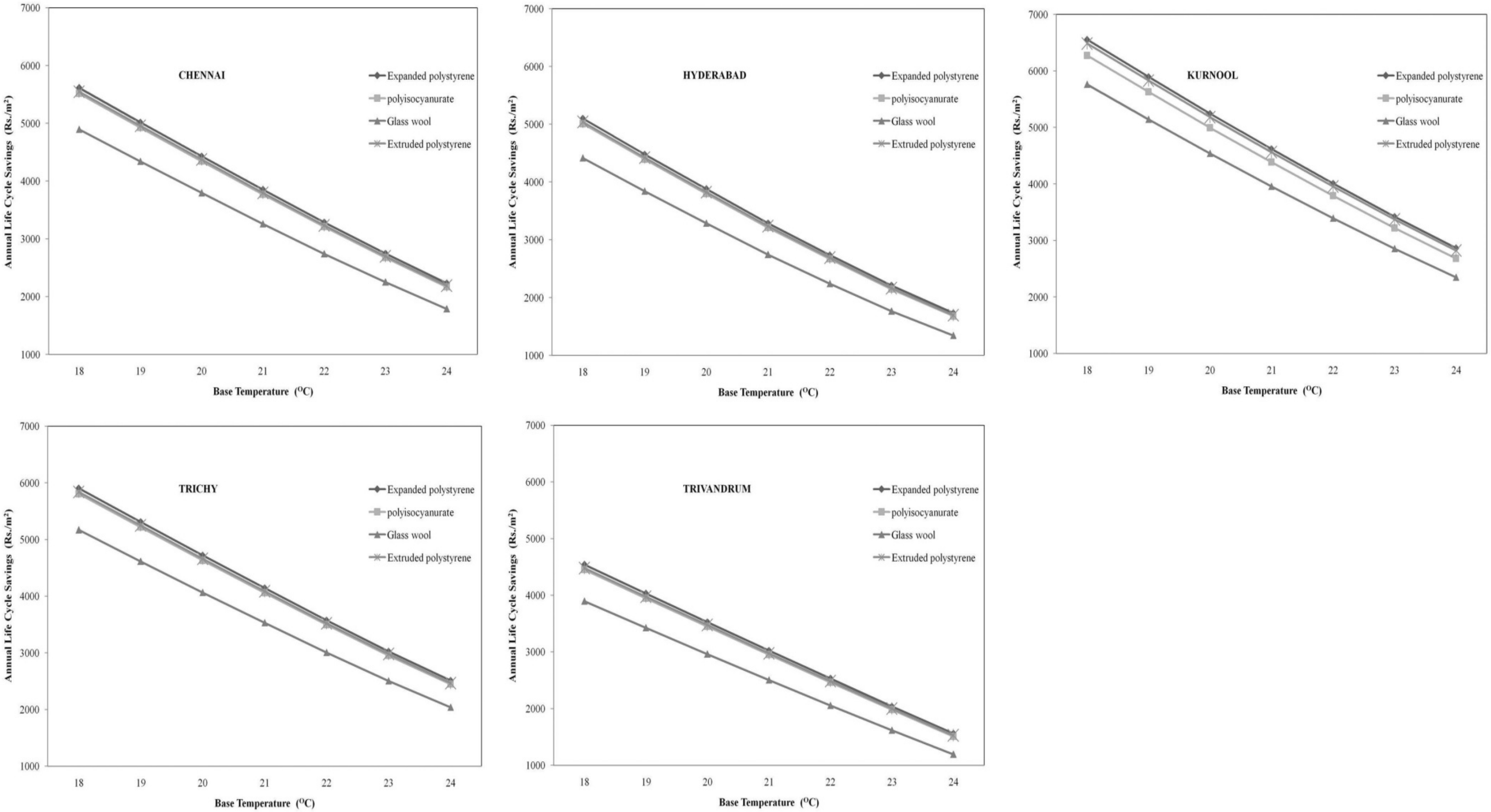

Fig. 7. Annual life savings versus base temperature for different cities.

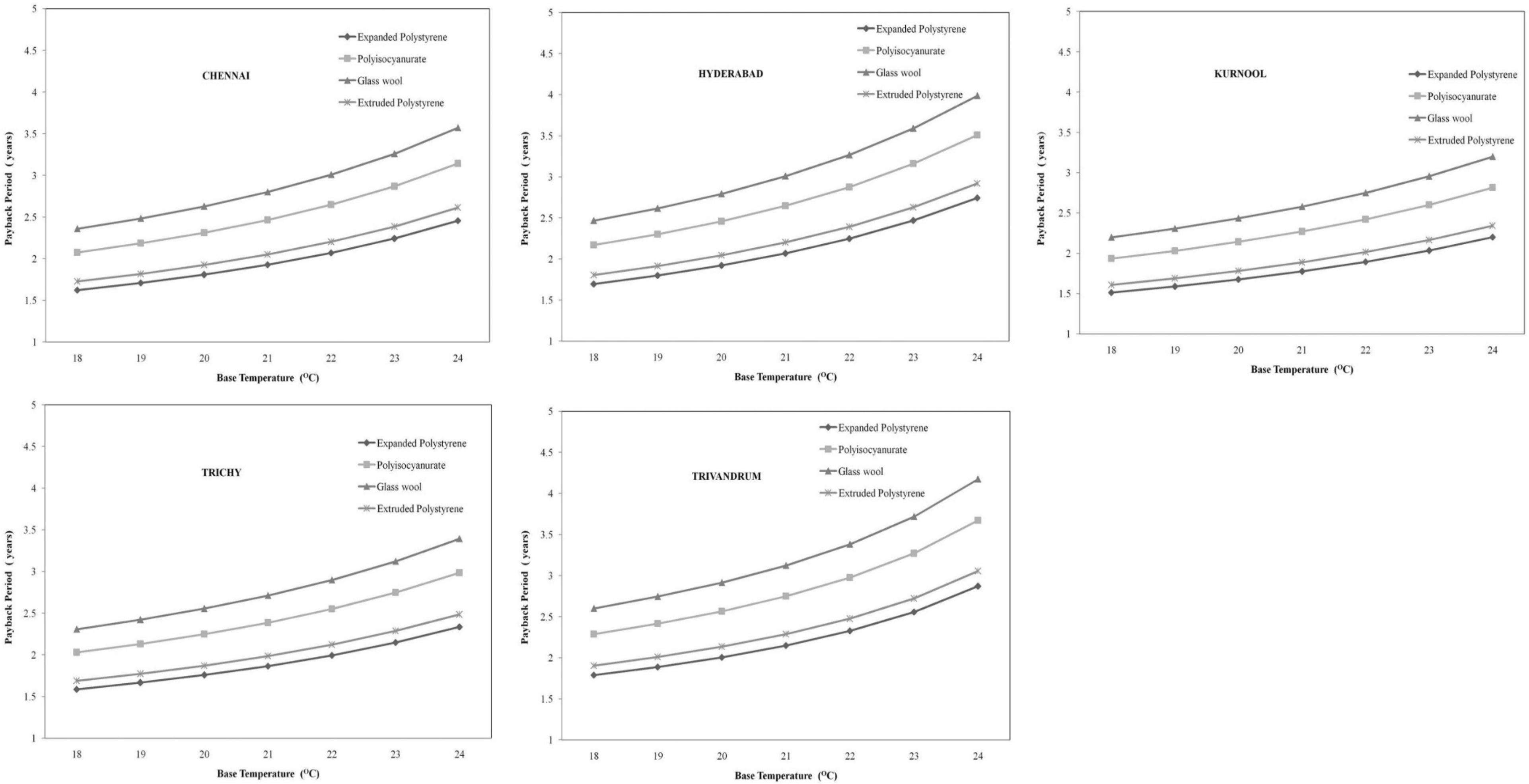

Fig. 8. Payback period versus base temperature for different cities.

Table 4. Parameters range for Chennai city.

Insulation Material	Optimum Insulation thickness	Annual Electrical Energy	Annual Energy cost	LCS	Payback period	Thermal Conductivity value	Insulation cost
Expanded polystyrene	1	1	1	1	3	4	4
Extruded polystyrene	2	2	2	2	4	2	3
Polyisocyanurate	4	4	4	1	2	1	1
Glass Wool	3	3	3	1	1	3	2

5. CONCLUSION

In India, energy efficient air-conditioned residential buildings can be implemented by providing roof insulation. In this study the use of insulation on ceiling is analyzed. The P_1-P_2 method is used to determine the optimum insulation thickness for four different materials in five (5) cities. Data base on insulation materials is provided. Data base will be very useful for the selection of suitable material for a particular city located in South India and design of optimum insulation thickness for ceiling.

NOMENCLATURE

CDD	cooling Degree Days (^{0}C – days)
HDD	heating Degree Days (^{0}C – days)
N_C	total number of cooling days
T_{so}	sol air temperature (^{0}C)
N_h	total number of heating days
T_i	indoor base temperature (^{0}C)
q	heat loss per unit area of wall (W/m^2)
U	heat transfer coefficient of wall (W/m^2 K)
E_c	annual energy consumption for cooling per unit area (kW/ m^2)
EER	energy efficiency ratio of the cooling system
R	thermal resistance (m^2 K/W)
x	insulation thickness (m)
P_1,P_2	defined in Eqs. (8) and (9)
N	life cycle period (years)
i	market discount rate (%)
d	electricity price rate (%)
M_s	ratio of annual maintenance and operation cost into first original cost
R_v	ratio of resale value into first original cost
C_{ins}	insulation cost per unit area (INR)
C_i	price of insulation material (INR/m)
LCT	life cycle total cost
LCS	life cycle saving
C_E	cost of electricity (INR/kWh)
C_p	specific heat capacity (J/kg K)
$_{opt}$	optimum insulation thickness (m)
N_p	payback period (years)
wl	weathering

Abbreviations

C_p	specific heat capacity (J/kg K)
x_{opt}	optimum insulation thickness (m)
N_p	payback period (years)

Greek symbols

λ	thermal conductivity (W/m K)
ρ	density of the material (kg/m^3)

Subscripts

un	un-insulated
ins	insulated
o	outside
i	Inside
r	roof
wl	weathering

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