Journal of Building Engineering 9 (2017) 155–163

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

The determination of the most economical combination between external wall and the optimum insulation material in Cameroonian's buildings

Fohagui Fodoup Cyrille Vincelas*, Tchuen Ghislain

University of Dschang, IUT-FV, LISIE/LETS, PO. Box 134, Bandjoun, Cameroon

ARTICLE INFO

Keywords:
External wall
Degree-days concept
Optimum insulation thickness
Most economical
Energy savings

ABSTRACT

This paper presents a comparative study for the determination of the most economical combination between external wall and optimum insulation thickness for energy saving into buildings. Using the degree-day's concept, the yearly cooling transmission loads of the building was determined. The P_1-P_2 method was used in economic analysis to find out the optimum insulation thickness, energy savings, and payback period for buildings in that locality. Expanded polystyrene was first chosen and used for five typical wall structures (sundry earth block (SEB), hollow concrete block (HCB), compressed earth block (CEB), heavyweight concrete block (HWCB), and stone). Then the investigation was extended to six other insulation materials. As results, It was found that the lowest value of optimum insulation thickness (7.6 cm) and energy savings (48 $\$/m^2$) were obtained for sundry earth block for expanded polystyrene while the payback period (3.23 years) was the highest for the same wall structure. The association of sundry earth block with extruded polystyrene was found to be more economical (23 $\$/m^2$ for minimum cost) with an optimum thickness of 9 cm and 69% of energy savings compared to other wall types.

1. Introduction

Energy consumption of buildings worldwide is increasing due to climate change and the development of new building standard. Substantial shares of energy consumed into buildings go towards heating and cooling loads of buildings. These thermal loads are largely due to heat gain of the building envelope. The reduction of such heat transmission through the building envelope can effectively reduce energy consumption into building. A passive and most effective method of reducing these loads is achieved by applying thermal insulation to the external wall of the building. A thicker insulation results in decreasing the heat transmission load and increases the cost of insulation installation. Thus, the determination of the insulation thickness which minimizes the total cost for insulation and cooling or heating the building over its lifetime is imperative [1].

The determination of such optimum thermal insulation thickness is governed by several design features including the orientation of the wall, the exterior surface, the type of thermal insulating material and the type of external wall type. Several studies were carried out on the evaluation of optimum insulation thickness on the building walls based on the above mentioned design features. Most of the studies calculate the transmission load by using the well-known methods including the degree day concept and dynamic heat transfer models. For instance, Daouas [2], Ozel [3], and Nematchoua [4] investigated the influence of wall orientation on optimum insulation thickness of external walls by using the life cycle cost analysis. In their studies, transmission load was estimated by using the dynamic heat transfer model. As result, a lower optimum insulation thickness of 10.1, 5.5, and 9.25 cm was obtained from Daouas, Ozel, and Nematchoua, respectively. Energy savings of 71.33%, 63.5% and 80.91%, were found by each author, respectively.

Yu et al. [5] examined the impact of the color of exterior surface on optimum insulation thickness, energy saving, and payback period by using P_1-P_2 method. The study was carried out in four typical cities of china and the determination of the transmission load was based on the degree-days concept. The results show that surface color has discrepant impacts on the optimum insulation thickness in different cities. According to their results, the maximum life cycle savings were 54.4 $\$/m^2$ in Shanghai, 54.8 $\$/m^2$ in Changsha and 41.5 $\$/m^2$ in Shaoguan (with a deep-colored northeast wall), and 39.0 $\$/m^2$ in Chengdu (with a light-colored northwest wall). Similarly, Ozel [6] considering both cooling and heating transmission loads and using dynamic heat transfer method concluded that solar absorptivity has insignificant impacts on the optimum insulation thickness in the climatic condition of Elazig, Turkey. Wati et al. [7] emphasized that the shade of building site has a significant effect on optimum insulation thickness, energy savings, and payback period. Their study was carried out in the climatic condition of

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* Corresponding author.
E-mail address: fohacyrille@yahoo.fr (F.F. Cyrille Vincelas).

http://dx.doi.org/10.1016/j.jobe.2016.12.008
Received 22 August 2016; Received in revised form 16 November 2016; Accepted 26 December 2016

Nomenclature

COP	energy efficiency ratio of cooling system (%)
CDD	cooling degree-days (°C days)
CEB	compressed earth block
C_{ins}	insulation cost ($\$/m^3$)
C_t	total cost ($\$/m^2$)
DD	degree-days (°C)
d	inflation rate
E_{cool}	require annual cooling energy
E_{heat}	require annual heating energy
H	lower value of fuel
HCB	hollow concrete block
HVAC	heating ventilating air conditioning
HWCB	heavyweight concrete block
HDD	heating degree-days (°C days)
h_i	inside convective heat transfer coefficient (W/m^2 K)
h_0	outside convection heat transfer coefficient (W/m^2 K)
i	interest rate
I_t	global radiation (W/m^2)
k	thermal conductivity of insulation material (W/m K)
η	energy efficiency of heating system (%)
PWF	present-worth factor
Q	heat flux (W)
R_W	total thermal resistance of wall layers without insulation (m^2 K/W)
SEB	sundry earth block
T	temperature (°C)
T_0	daily mean temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
x	thickness (m)
x_{op}	optimum insulation thickness

Cameroon, the cooling transmission loads were estimated by using the dynamic heat transfer method. The concluded that, an increase of the level of shade leads to a decrease of both the energy savings and the optimum insulation thickness; and the payback period increases significantly.

The effects of the type of insulation material on optimum insulation were studied by many authors. Al-Sanea et al. [8] investigated the influence of the type of insulation material on its optimum thickness for building walls under steady periodic conditions in Saudi Arabia. Their study was based on the present worth analysis in order to minimize the total cost. Their findings reveal that, between the six insulation material examined, the most economical insulator is that made of molded polystyrene with an optimum thickness of 9.3 cm. Likewise, Shanmuga et al. [9] optimized the insulation thickness on wall of buildings by using the degree day's concept. Their study was carried out in five cities located in India by comparing three different insulation materials. According to their results, expanded polystyrene was found to be a suitable material for all five cities. On the other hand, Mahlia et al. [10] compared the savings yield by the used of six insulation materials through a life cycle cost analysis in Malaysia. With regard to the results, the fiberglass-urethane is the most economic insulation material amongst the six others, with a saving of up to 71.773 $\$/m^2$.

Dombayci et al. [11] considering different energy sources and two insulation materials in turkey determined the optimum insulation thicknesses for external walls. Their study was based on heating degree day's concept. They found that, the use of coal and expanded polystyrene as energy source and insulation material, respectively, leads to the optimum case. Using the optimum insulation thickness, the savings and the payback period obtained were 14.09 $\$/m^2$ and 1.43 years, respectively. Al-Sanea et al. [12] used dynamic heat transfer model to study the influence of the electricity cost on the optimum insulation thickness for building walls. They observed that the optimum insulation thickness for different electricity tariffs varies linearly with minimum total cost. Using life cycle cost analysis in a similar study for different fuel types, Bolatturk [13] shows that: (1) the energy savings lies between 22–79%; (2) the optimum thickness lies between 2 and 17 cm and (3) the payback period lies between 1.3 and 4.5 years depending on the fuel type. Ozbalta et al. [14] determined the optimum insulation thickness and savings for some building envelopes by considering four different types of energy sources and expanded polystyrene as insulation material for coldest city of Turkey. The calculation was carried out through the P_1-P_2 method by using the heating degree day's concept. According to their results, optimum thickness and energy savings are more significant when costly fuel is used.

The effect of the wall type on optimum insulation thickness was investigated in few studies [13–15]. Subhash et al. [15] determined the payback period and the optimum insulation thickness for different types of walls with glass wool as insulation material. They found that, the payback periods lay between 1.17 and 1.53 years and the optimum insulation thicknesses in between 15.4 and 17.03 cm with respect to external wall material. In a similar study, Nematchoua et al. [4] compared the optimum insulation of extrude polystyrene with two different wall types (Hollow concrete block (HCB) and compressed stabilized earth block (CSEB)) in Cameroon by using life cycle analysis. Their findings reveal that, the optimum insulation thickness obtained for the case of HCB is greater than that of CSEB, while the payback period is smaller for the case of HCB compared to that of CSEB wall.

As can be seen from the literature survey, most attractive studies aiming to determine the optimum insulation thickness have been carried out. But, however, these studies no actually investigate the most economical combination between external wall and insulation material to achieve energy efficiency of buildings in Cameroon. One of own characters in this work, compare to others similar study was to select the most economical combination between available external wall and insulation material.

The present study aims to find out the optimum insulation thicknesses of external wall, energy savings and payback periods with respect to the wall and insulation types. The study is carried out in the coastal region of Cameroon, under the tropical climate by considering five wall types and seven insulation materials.

2. Methodology

2.1. The structure of external walls

In this study, the common materials used for the construction of external walls of buildings in Cameroon including hollow concrete block (HCB), sundry earth block (SDEB), heavyweight concrete block (HWCB), compressed earth block (CEB), and stone as shown in Fig. 1 are considered [16]. From the exterior to the interior, the insulated composite wall consist of 20 mm-thick layer of cement plaster, 200 mm-thick layer of each building material and 20 mm-thick layer of plaster board with an insulation layer of variable thickness placed on the outside surface as shown in Fig. 2. Seven different insulation materials are selected including expanded polystyrene, extruded polystyrene, foamed polyvinyl chloride, foamed polyurethane, perlite, rock wool, and glass wool.

2.2. Calculation of degree-days

In the tropical climates, heat gains through the envelope of buildings are mostly determined using the degree-days method. In this method, the cooling or heating transmission loads are assumed to be proportional to the difference between the solar-air temperature (T_{sa}) and the fixed indoor base temperature (T_i) since they are opaque surfaces. Hence, the total number of cooling degree-day (CDD) and heating degree-day (HDD) are expressed as:

$$CDD = \sum (T_{sa} - T_i)_{\mathrm{j}} \quad T_{sa} \geq T_i$$
$$HDD = \sum (T_i - T_{sa})_{\mathrm{j}} \quad T_{sa} \leq T_i \tag{1}$$

The solar-air temperature is proportional to the mean daily air temperature (T_O) and the daily global and diffuse solar radiation (I_t) reaching the vertical surfaces and expressed as in reference [7]:

$$T_{sa} = T_O + \frac{\alpha}{h_O} I_t \tag{2}$$

T_0 is determined by adding the maximum and minimum temperature for the day and dividing it by two using 20 years (1985–2005) meteorological data provided by the directorate of national meteorology of Cameroon.

2.3. Cooling and heating load calculation for external wall

Energy loss in buildings generally arises through external walls, named building envelope, windows, floors and ceilings and air infiltration. In this study, the energy consumption due to building envelope is taken into account. The opaque envelope is affected by three heat transfer mechanisms including conduction, convection and radiation. The solar radiation reaching the outer surfaces is transmitted into the building by conduction, while the inner and the outer surfaces of the wall exchange heat with their environment simultaneously by convection. For example, heat transfer process through a unit area of external wall in cooling season can be calculated by the following equation:

$$Q = U.\,(T_{sa} - T_i) \tag{3}$$

where U is the overall heat transfer coefficient ($\mathrm{m^2K/W}$), The annual heat loss in unit area, Q_A can be determined using the degree-days, DD as

$$Q_A = 86400.\,U.\,DD \tag{4}$$

The overall heat transfer coefficient for a typical wall without insulation, U_{un} is explicitly given by:

$$U_{un} = \left(\frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \ldots.. + \frac{x_n}{k_n} + \frac{1}{h_i}\right)^{-1} \tag{5}$$

where h_0 and h_i are combine convection and radiation heat transfer coefficients for inside and outside surface of refrigerated space, respectively. k_1, k_2 etc. are thermal conductivity of layers of wall, and x_1, x_2 etc. are their thicknesses.

The total thermal resistance of un-insulated wall (R_{wall}) can be written as:

$$R_{wall} = \frac{1}{U_{un}} \tag{6}$$

for an insulated wall, the total resistance of the wall can be calculated by the following equation:

$$R_{tot} = R_{wall} + R_{ins} = R_{wall} + \frac{x_{ins}}{k_{ins}} \tag{7}$$

where x_{ins} is insulation thickness (m), k_{ins} is the thermal conductivity of the insulation material ($W/(mk)$) and the overall heat transfer coefficient for a typical wall with insulation, U_{ins} can be determined in an analogous expression as:

$$U_{ins} = \frac{1}{R_{wall} + x_{ins}/k_{ins}} \tag{8}$$

When the energy efficiency ratio of the cooling system is *COP*, the yearly energy requirement for cooling per unit area of external wall (E_{cool}, kW) can be estimated by using the equation [5]:

$$E_{cool} = \frac{86400 \times U \times CDD}{COP} \tag{9}$$

Similarly, when the efficiency of the heating system is η, the yearly energy consumption for heating (E_{heat}, kW) can be estimated in an identical expression as:

$$E_{heat} = \frac{86400 \times U \times HDD}{\eta} \tag{10}$$

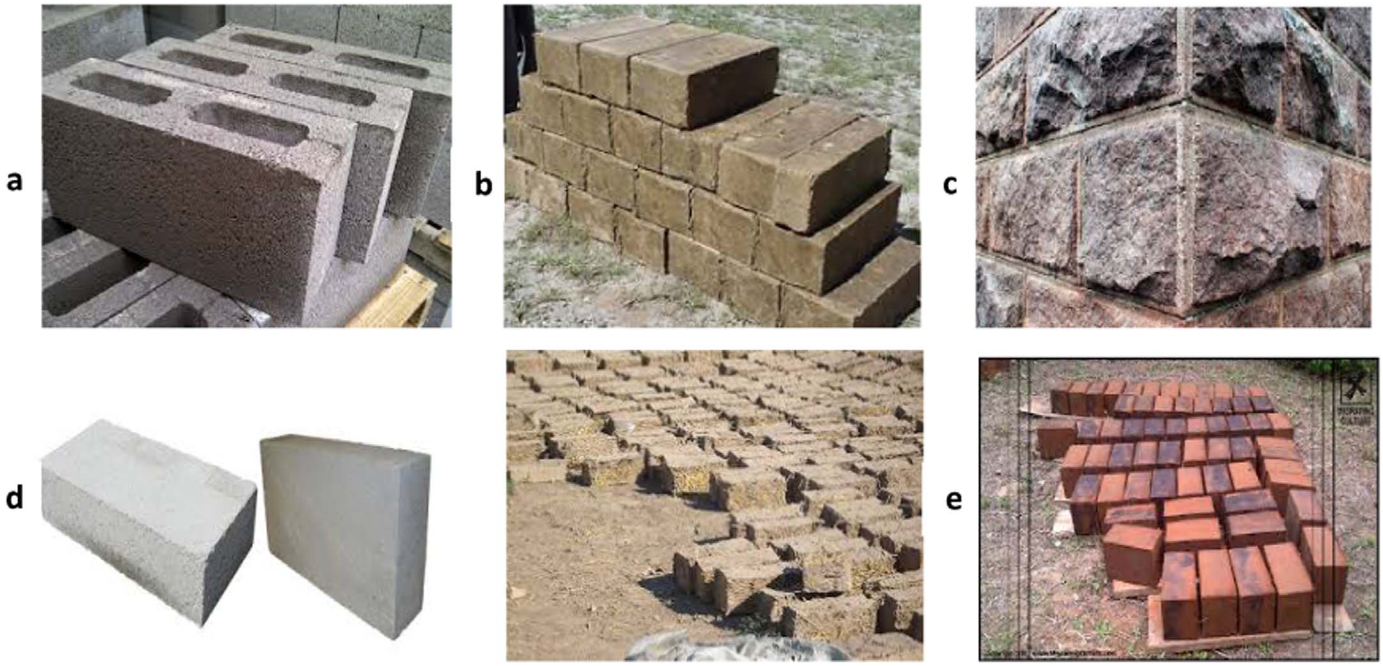

Fig. 1. Building materials found in the tropical region of Cameroon. (a) Hollow concrete block, (b) Sundry block, (c) Stone, (d) Heavyweight concrete block, and (e) compressed earth block.

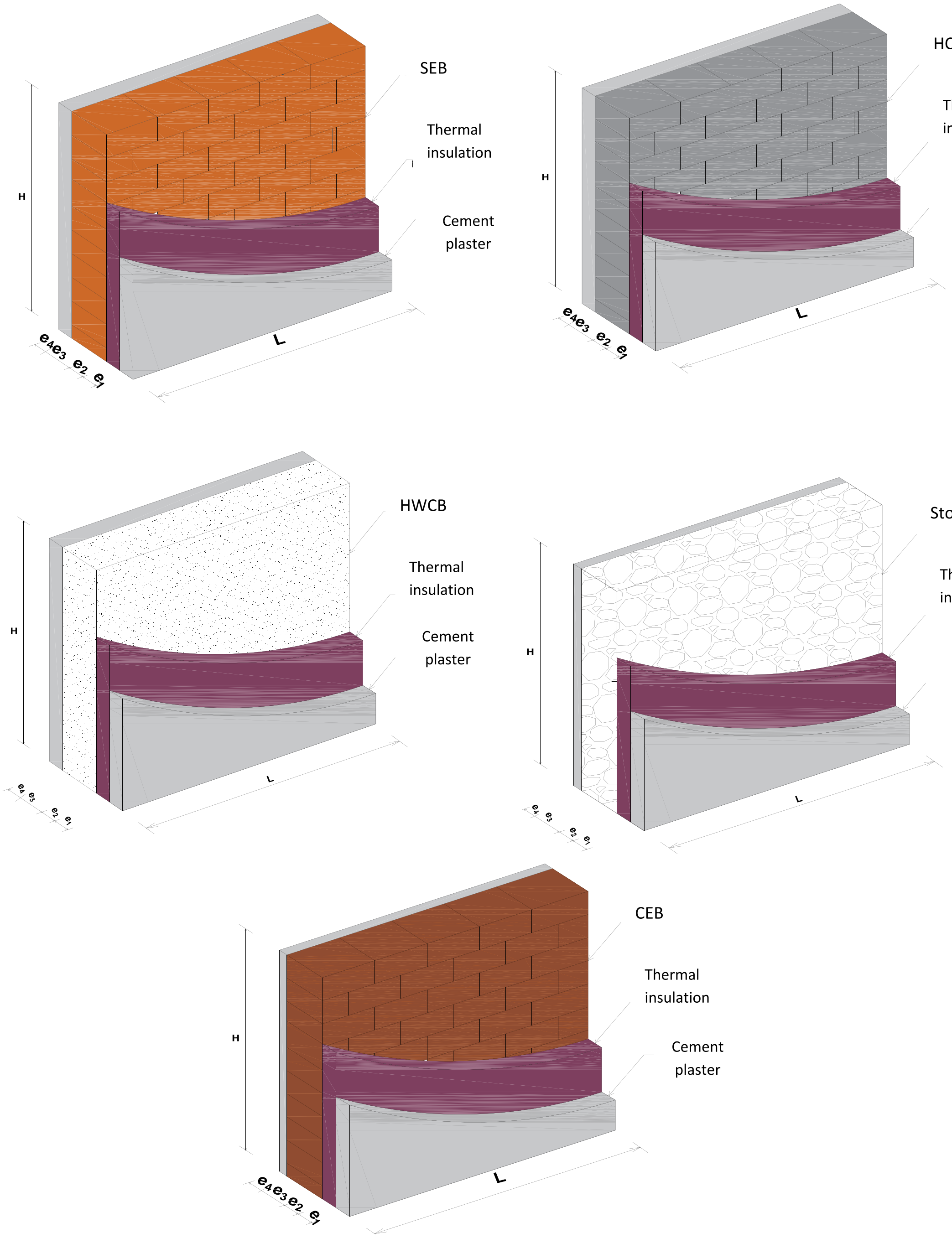

Fig. 2. Composite walls structures.

2.4. Determination of the optimum insulation thickness and energy saving

In order to lower the heat flow through opaque envelope of building having heating ventilation air conditioning system (HVAC), insulation material is usually used. This material has a very low thermal conductivity. A suitable insulation material with its optimum thickness can lead to an economic HVAC system. It is obvious that as the thickness of insulation increases the cost of the insulation material increases while HVAC load drops and consequently energy cost decreases. The optimum insulation thickness is the thickness at which the total cost of energy consumed is minimum [11].

In the present analysis, the P_1-P_2 method was employed for calculating the optimum insulation thickness [17]. P_1 is the life cycle energy related to market discount rate *d*, electricity cost inflation rate *i*, economic analysis period *n*, and the flag *C* indicating incoming or non-incoming producing (1 or 0, respectively). P_1 can be calculated by the following equation:

$$P_1 = (1 - C.\, i)PWF(n\ ,\ i\ ,\ d) \tag{11}$$

PWF is the present worth factor. Since there is non-incoming producing and consequently $C = 0$

$$P_1 = PWF(d,\, i,\, n) = \sum_{j=1}^{n} \frac{(1+i)^{j-1}}{(1+d)^{j}} = \begin{cases} \frac{1}{d-1}\left[1 - \left(\frac{1+i}{1+d}\right)^{n}\right] & i \neq d \\ \frac{n}{1-i} & i = d \end{cases} \tag{12}$$

P_2 is the ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment and can be defined as:

$$P_2 = D + (1 - D)\frac{PWF(0,\, d,\, n_{\min})}{PWF(0,\, m,\, n_L)} + M_s \times PWF(0,\, d,\, n_{\min}) - \frac{R_v}{(1+d)^n} \tag{13}$$

where D is the ratio of down payment to initial investment, M_s is the ratio of the first year miscellaneous costs (insurance maintenance) to initial investment, R_v is the ratio resale value at the end of the analysis period to initial investment, n_L is term of loan and n_{min} is the year over which mortgage payments contribute to the analysis period. The cost of building insulation per unit area can be determined as in reference [2]:

$$C_{i,b} = C_{ins}.\, x_{ins} \tag{14}$$

where C_{ins} is the cost of insulation ($/m^3). Therefore, the total heating and cooling cost for the building as the present worth value for n years can be given by [18]:

$$C_t = P_1.\,(E_{cool} + E_{heat}).\, C_{el} + P_2.\, C_{i,b} \tag{15}$$

where C_{el} is the unit price of electrical energy ($/kWh). Substituting E_{cool} and E_{heat} from Eqs. (9) and (10) into 15 gives the following equation:

$$C_t = PWF.\left(\frac{86400 \times CDD}{(R_{wall} + x_{ins}/k_{ins}).H.COP} + \frac{86400 \times HDD}{(R_{wall} + x_{ins}/k_{ins}).H.\eta}\right).\, C_{el} + P_2.\, C_{ins}.\, x_{ins} \tag{16}$$

where H is the lower cooling or heating value of electricity. The energy saving cost for insulated building is the difference between the energy cost of non-insulated and insulated building, respectively:

$$S_{ins} = \frac{86400 \times PWF}{H}\left(\frac{1}{R_{wall}} - \frac{1}{(R_{wall} + x_{ins}/k_{ins})}\right)\left(\frac{CDD}{COP} + \frac{HDD}{\eta}\right).\, C_{el} \tag{17}$$

The net energy saving (S_{net}) by the use of insulation material is the difference between the energy saving cost for insulated building and the insulation payout [5]:

$$S_{net} = S_{ins} - P_2.\, C_{ins}.\, x_{ins} \tag{18}$$

The optimum insulation thickness is obtained by minimizing the net saving, S_{net}. For this purpose, the derivative of S_{net} with respect to x is taken and set equal to zero, then the optimum insulation thickness x_{opt} is obtained as:

$$x_{opt} = 0.49 \times \sqrt{\frac{k_{ins} \times PWF \times C_{el}}{C_{ins} \times P_2}\left(\frac{CDD}{COP} + \frac{HDD}{\eta}\right)} - k_{ins}R_{wall} \tag{19}$$

The payback period of investment can be calculated by setting the net energy saved cost Eq. (18) to be zero [13]:

$$n = \frac{\ln\left[\dfrac{0.024\,.\,C_{el}(CDD/COP + HDD/\eta) - P_2C_{ins}(d-i)(k_{ins}R^2{}_{wall} + R_{wall}x_{ins})}{0.024\,.\,C_{el}(CDD/COP + HDD/\eta)}\right]}{\ln[1+i] - \ln[1+d]} \qquad i \neq d$$

$$n = \frac{P_2C_{ins}(k_{ins}R^2{}_{wall} + R_{wall}x_{ins})(1+i)}{0.024\,.\,C_{el}(CDD/COP + HDD/\eta)} \qquad i = d \tag{20}$$

3. Results and discussion

The thermal properties of various building materials obtained from [19,20] are summarized in Table 1a. In the coastal region of Cameroon, building do not need energy for heating (HDD=0) since ambient temperatures and solar radiation levels are high enough. For the calculation, the economic parameters are given in Table 1b.

3.1. Impact of building materials of external walls on energy consumption

In this section, the effect of the type of building materials of the envelope is limited to the reduction of the insulation thickness of expanded polystyrene of the wall. Fig. 3(a)-(b) presents the total cooling cost per meter square of wall versus insulation thickness of different walls. The total cooling cost is calculated by using the cost of insulation material plus the present value of the cost of energy spent to remove the heat over the lifetime of the building. The optimum insulation thickness is achieved at the minimum total cost. For the thicknesses above, the total cost increases linearly with the increase in the insulation thickness. The reason is that the increased of the cost of the insulation as the result of the increased insulation leads to the decrease of fuel cost.

The five curves indicate the most economical wall and its optimum insulation thickness. Fig. 3(b) shows the zoom operated on Fig. 3(a) for thicknesses in between 0.05 and 0.15 cm in order to better appreciate the discrepancy of minimum total costs. As can be seen from that figure, the most economical building wall is the sundry earth block wall follow by hollow concrete block, compressed earth block, heavyweight concrete block, and stone walls, respectively. At the optimum thickness, the total cost for the sundry earth block wall is about 7.2% less than that for stone wall. These results are summarized in Table 2. Also Fig. 4 shows the variation of the cooling cost versus insulation thickness with respect to the building material. It is seen that the total cost decreases with the increase of the insulation thickness. The lowest value of cooling cost is observed for sundry earth block wall while the highest value is obtained for stone wall. For uninsulated wall (x_{ins}=0), it is about 78 $/m^2, 100 $/m^2, 108 $/m^2, 157 $/m^2 and 178 $/m^2 for SEB, HCB, CEB, HWCB, and stone wall, respectively. It can be noted from Table 2 that when the thermal resistance of the building wall increases, the insulation requirement decreases. With regard to results, the impact of building materials on energy consumption is more significant for the sundry earth block wall. Applying optimum insulation thickness on external walls provides significant energy savings.

3.2. Impact of building materials of external walls on energy savings

Annual savings per meter square of external wall area were computed as the difference between the cost of cooling insulated and the uninsulated buildings. The variations of energy savings versus insulation thickness with respect to the wall type are shown in Fig. 5(a)-(b). It can be seen that net energy saving decreases when insulation thickness increases from the optimum insulation thickness (Fig. 5(a)). The net energy saving is maximum for optimum insulation thickness for all buildings walls. On the other hand, Fig. 5(b) shows that the energy saving increases with the increase of the insulation thickness for all building walls. The increase is fast at the beginning then becomes more gradual with the increase of the insulation thickness. Obviously, as the thermal conductivity of the building material decreases, the energy savings cost decreases. The saving cost is about 44 $/m^2, 65 $/m^2, 80 $/m^2, 125 $/m^2, and 148 $/m^2 for SEB, HCB, CEB, HWCB, and stone wall, respectively at the optimum insulation thickness. The optimum values for the same building

Table 1a
Thermal characteristic of materials.

Material	k (W m^{-1} K^{-1})	C (J kg^{-1} K^{-1})	ρ (kg m^{-3})
Sundry earth block (SDEB)	0.44	1200	880
Hollow concrete block (HCB)	0.67	1250	880
Compressed earth block (CEB)	1.15	1800	900
Heavyweight concrete block HWCB)	1.7	2400	950
Stone	2.8	3850	920
Cement plaster	0.872	1442	827
Plaster board	0.17	1090	800

Table 1b
Parameters used for calculations [7,22].

Parameters	**Values**
HDD	0 °C days
CDD	3610 °C days
Unit cost of electricity	0.16 $/kWh
Coefficient of performance (COP)	2.5
increase rate, d	2.9%
Discount rate, i	5%
Lifetime, n	30 years
Outer heat transfer coefficient (ho)	$22\ W\ m^{-2}\ K^{-1}$
Inner heat transfer coefficient (hi)	$9\ W\ m^{-2}\ K^{-1}$
Fixe indoor base temperature (Ti)	25 °C
Thickness of the wall	0.2 m
Thickness of the cement plaster	0.04 m
Solar absorptivity	0.6

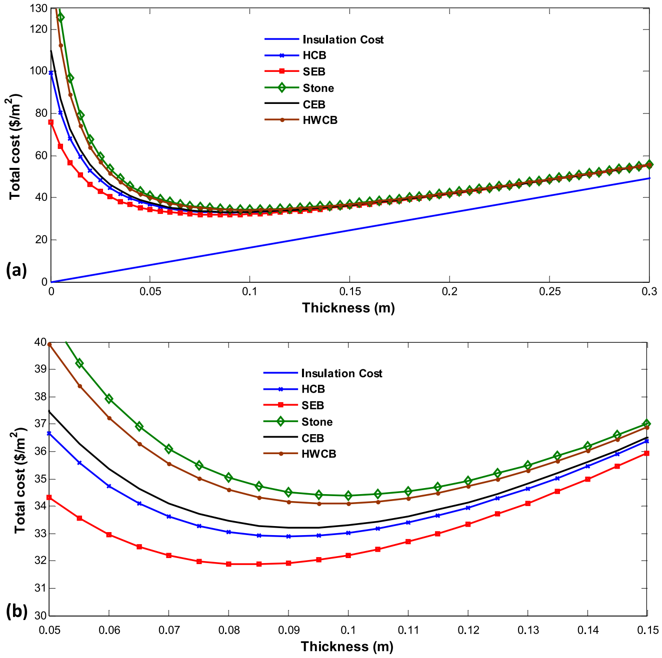

Fig. 3. (a-b): Total costs versus insulation thickness showing effect of building materials of external walls.

materials were found to be 8.2 cm, 9.2 cm, 9.5 cm, 9.6 cm, and 10 cm, respectively. Varying the parameters of the optimum insulation thickness can improve the energy savings cost of the building.

3.3. Impact factors analysis of energy savings and optimum insulation thickness

Energy savings and optimum insulation thickness are proportional to some economic parameters, which depend both on the locality and the year of study, respectively. Since these parameters can vary, in this study, the effect of changing some of them on energy savings and optimum insulation thickness is investigated. For this purpose, each economic factor such as the cost of electricity, price of insulation materials, interest rate, COP, the lifetime and inflation rate is varied appreciably at a time while keeping others constant. Fig. 6(a)–(f) shows, the effect of changing: (a) price of electricity, (b) energy efficiency ratio of the cooling system, (c) building lifetime (n), (d) cost of insulation material, (e) interest rate, i, and (f) inflation rate d, respectively. The changes examined are within a realistic range of the economic factors.

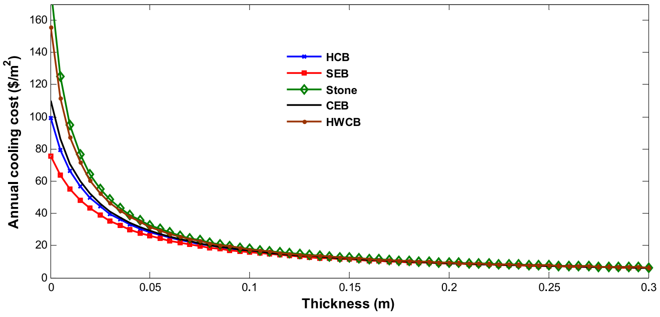

Fig. 4. Annual cooling costs versus insulation thickness showing effect of building materials.

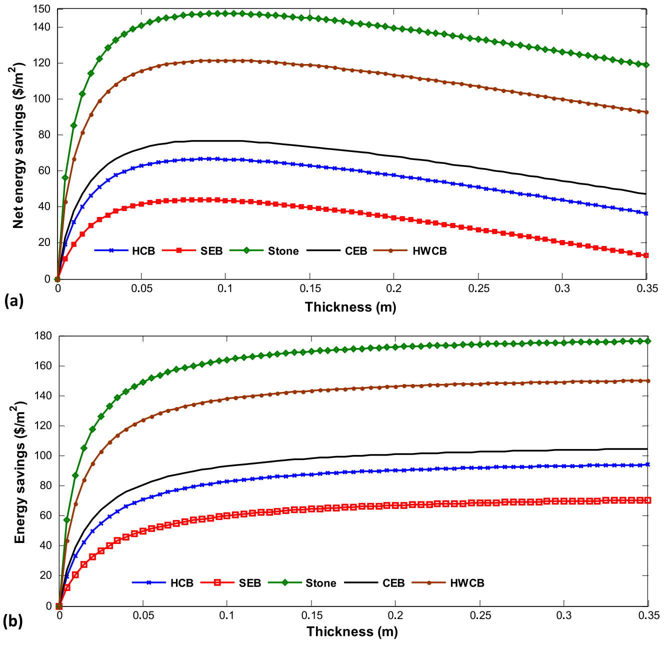

Fig. 5. (a-b): Annual energy costs versus insulation thickness showing effect of building materials; (a) net energy saving cost and (b) energy saving.

Fig. 6(a) shows the variation of net energy savings versus insulation thickness with respect to the cost electricity. It is seen that increasing the electricity prices raises the net energy savings and increases the optimum insulation thickness. Also, the increase of the energy effi-

Table 2
Optimum insulation thickness and total cost with respect of the type of building wall.

Type of building wall	**Thermal resistance W/m²K**	**Optimum thickness (cm)**	**Energy saving ($/m²)**	**Minimum total cost ($/m²)**	**Decrease rate (% of reduction per m²)**
Sundry earth block	0.6570	8.2	44	32	7.2
Hollow concrete block	0.5009	9.2	65	33.2	3.8
Compressed earth block	0.4524	9.4	80	33.4	3.2
Heavyweight concrete block	0.3201	9.6	125	34.2	1
Stone	0.2739	10	148	34.5	–

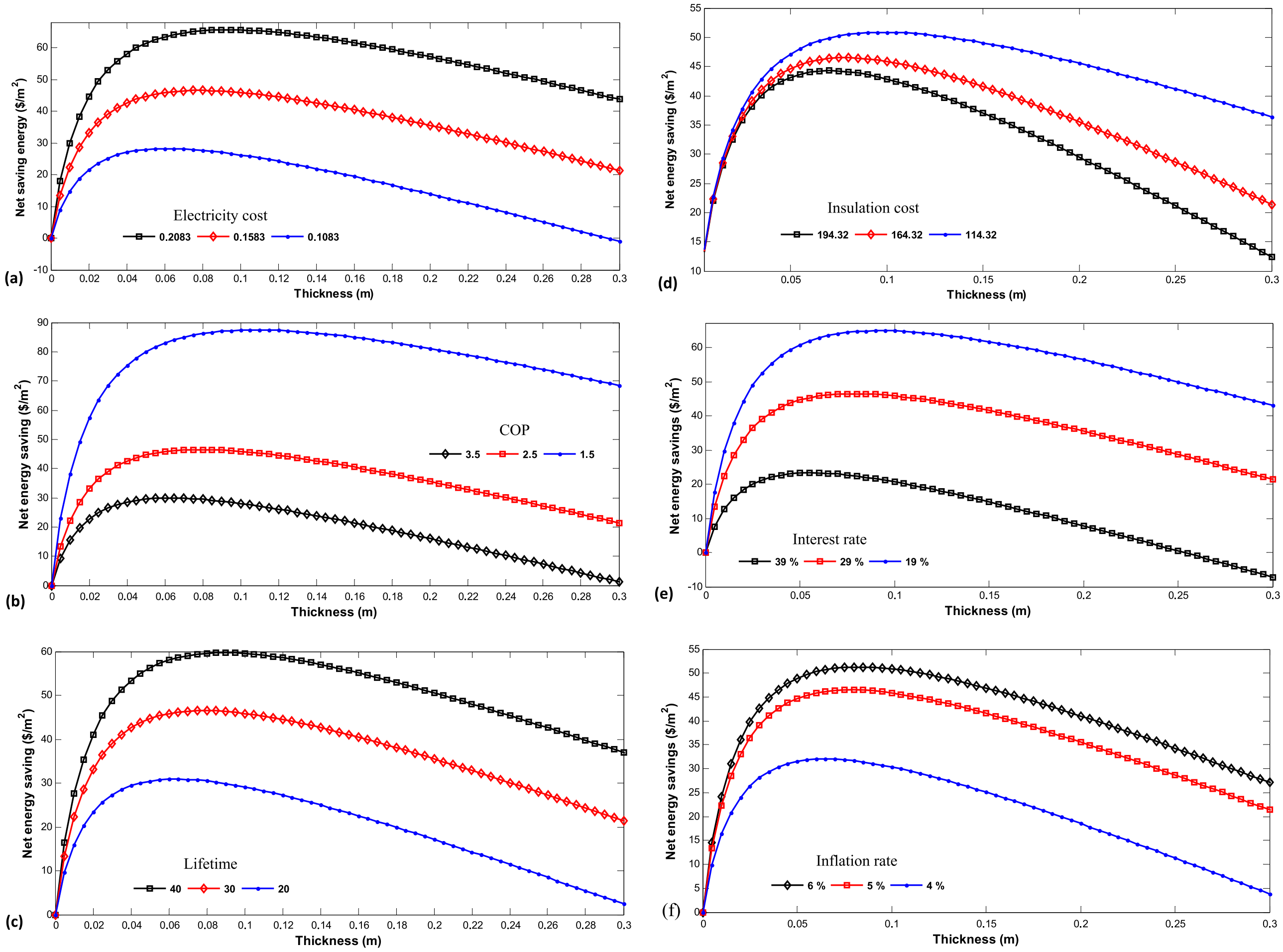

Fig. 6. (a–f): Net energy savings costs versus insulation thickness showing effect of economic parameters: (a) electricity cost, (b) COP, (c) lifetime, (d) insulation cost, (e) interest rate, and (f) inflation rate.

ciency ratio, Fig. 6(b), drops the net energy savings and decreases the optimum insulation thickness. Obviously, increasing the lifetime of the building, Fig. 5(c), or reducing insulation price, Fig. 6(d), raises the net energy savings cost and increases the optimum thickness. Increasing interest rate, Fig. 6(e), drops the net energy savings and leads to lower optimum insulation thickness. Also increasing inflation rate, Fig. 6(f), raises net energy savings and increases the optimum insulation thickness. The last results are similar to those obtained by the reference [11].

3.4. Impact of the type of insulation materials on the optimum thickness and most economical combination

The optimum thicknesses of other insulation materials are determined in order to investigate the most economical combination. In this session, the nominal values of economic parameters in Table 1b and insulation cost in Table 3 is used. The annual cooling transmission loads versus insulation thickness for different types of wall with respect to each insulation material are used in the economic model. The total cost, energy savings, and payback periods of different wall types were calculated and shown in Fig. 7(a)–(g) for each type of insulation material. It was found out that the optimum thickness depends largely on the type of insulation material used. For investigated insulation materials, optimum thicknesses vary between 9.2–11.5 cm, 8.5–10.5 cm, 10–12.5 cm, 9.4–12, and 9.6–12.5 cm for HCB, SEB, stone, CEB, and HWCB walls, respectively. It was observed that whatever the insulation material used, the lowest optimum thickness is obtained with the sundry earth block wall. In this study, the optimum insulation thicknesses for HCB are in good agreement with those obtained by Nematchoua [4]. As can be seen from Fig. 7(a)–(g) the total cost is not only affected by the wall type but is also influenced by the type of insulation material. For example, the minimum total costs for SEB wall are 23.5 and 33 $/m^2 with extruded polystyrene and perlite, respectively. While the minimum costs are 24.8 and 36 $/m^2 for stone wall with the same insulation material.

The optimum insulation thicknesses, minimum total costs, percentage of energy savings and payback periods of each combination of materials are summarized in Table 4. It can easily be seen from the table that the type of insulation material has very profound effect on the energy savings. The percentages of energy saving become more significant with the decrease of the thermal conductivity of the insulation material. For example, the percentage of energy saved for HWCB with extruded polystyrene insulation are 84.2% higher than in the same situation with foamed polyvinyl chloride. On the other hand,

Table 3
Thermal properties and cost of insulation materials.

Insulation material	Thermal conductivity (W/ m^2)	Cost ($/m^3)
Expanded polystyrene	0.04	164.32
Extruded polystyrene	0.028	118.11 $/m^3
Foamed PVC	0.048	156.10
Foamed polyurethane	0.033	138.67 $/m^3 [8]
Perlite	0.14	51.50 $/m^3
Rock wool	0.042	95.00 $/m^3 [21]
Glass wool	0.038	110.00 $/m^3

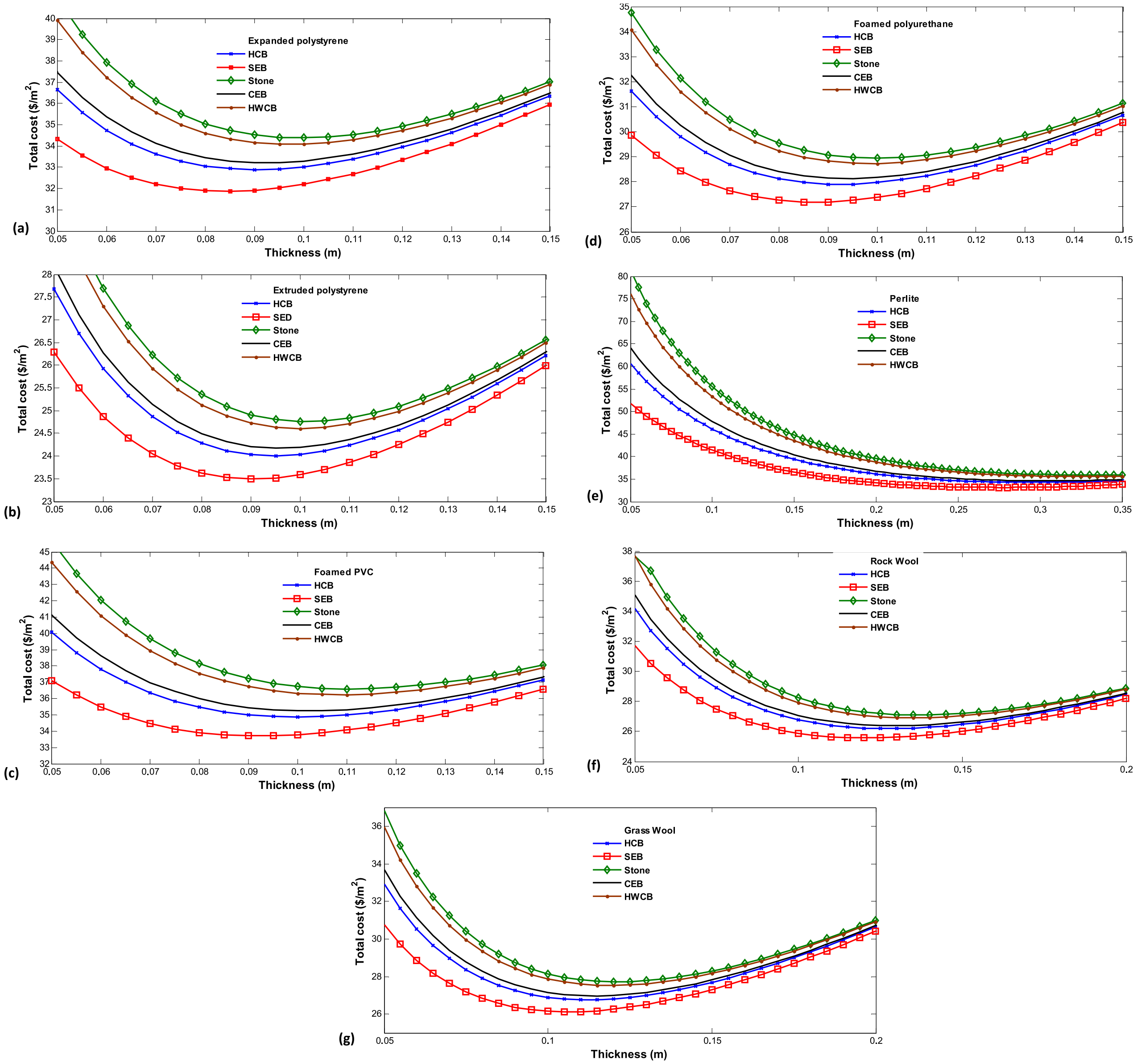

Fig. 7. (a–g): Total costs versus insulation thickness showing effect of the type of insulation materials; (a) extruded polystyrene, (b) extruded polystyrene, (c) foamed PVC, (d) foamed polyurethane, (e) perlite, (f) rock wool, and (g) glass wool.

Table 4
Optimum thermal insulation thicknesses, Minimum total costs, energy savings, and payback periods for different association of wall types with insulations materials.

Wall type	Optimum thickness (cm)							Minimum total cost ($/m^2)						
	a	b	c	d	e	f	G	a	b	c	d	e	f	G
HCB	9.2	9.5	10.5	9.9	30	13	11.5	33	24	35	28	34.2	26.25	26.75
SEB	8.2	9.0	9.5	8.7	27	12	10.5	32	23.5	33.8	27.2	33	25.5	26.2
Stone	10	10.5	11.5	10.5	32	14	12.5	34.5	24.8	36.5	29	36	27.25	27.75
CEB	9.4	9.9	10.8	9.8	30	13.5	12	33.4	24.2	35.3	28.2	34.8	26.4	27
HWCB	9.6	10.0	11.3	10	32	14	12.5	34	24.7	36.2	28.8	35.5	26.9	27.75

Wall type	Net energy saving (%)							Payback period (years)						
	a	b	c	d	e	f	g	a	b	c	d	e	f	G
HCB	67	75.85	64.88	71.88	65.51	73.65	73.07	1.6	1.17	1.85	1.46	1.73	1.27	1.35
SEB	58	69	55.51	64.13	56.21	66.26	65.55	2.21	1.54	2.39	1.81	2.26	1.69	1.72
Stone	81.08	86.37	79.87	84.07	80.24	85.09	84.74	0.91	0.66	0.99	0.78	0.92	0.71	0.74
CEB	70.72	78.71	68.89	75.21	69.46	76.74	76.22	1.46	1.05	1.61	1.24	1.49	1.16	1.2
HWCB	78.09	84.2	76.7	81.53	77.12	82.69	82.29	1.04	0.75	1.17	0.89	1.1	0.85	0.88

a-Expanded polystyrene, **b**-Extruded polystyrene, **c**-Foamed polyvinyl chloride, **d**-Foamed polyurethane, **e**-Perlite, **f**-Rock Wool, **g**-Grass Wool.

it is essential to mention here that the energy savings are less significant when the thermal resistance of the external wall increases. To illustrate this, while the percentage of energy savings achieved in stone walls with rock wool are 85.09%, they are only 66.26% in sundry earth block. The payback periods for different association of walls with insulation materials are also shown in Table 4. It was observed that the payback periods are also profoundly affected both by the cost and the thermal properties of insulation material. For instance, the values are 1.17 and 1.85 years for HCB with extruded polystyrene and foamed PVC, respectively. It is highest with the foamed PVC simply due to its very high material cost and thermal conductivity compared to the other insulations. It can also be seen from the table that the payback period reduces as energy savings rise. These findings are similar to those obtained by references [8,23].

An analysis of these results shows that optimum insulation thickness is lowest in the association of SEB wall with expanded polystyrene than in the others; however, the minimum total cost is not the lowest. On the other hand, the association of SEB wall with extruded polystyrene seen to be suitable since they present lowest minimum total cost, acceptable energy savings and payback period compared to the others. For this reason, the carry parameters are 9 cm, 23 $/m^2, 69%, and 1.54 years for optimum insulation thickness, minimum total cost, energy saved, and payback period, respectively.

4. Conclusion

The main purpose of this study was to optimize the thicknesses of insulation layers in external walls of building in a tropical climate with respect to the wall and insulation types. The yearly transmission loads with respect to the type of external wall were determined by using the degree day concept. These loads are input in an economical model in order to estimate the optimum insulation thicknesses, the energy savings, and the payback periods using expanded polystyrene for five different wall types. The results showed that a suitable choice of the type of external wall can provide reduction of optimum thickness and energy savings. It was found that the optimum insulation thickness varies between 8.2 cm and 10 cm, energy savings vary between 44 $/m^2 and 150 $/m^2, and payback periods vary between 0.91 and 2.21 years depending on the type of wall.

It was also found that energy savings are sensitive to change in the economic parameters. The energy savings are found to increase with building lifetime, inflation rate, and electricity cost; and decrease with increasing cost of insulation material, efficiency of the cooling system, and the discount rate.

The calculation was extended to six insulation materials. The results showed that a suitable association of a wall type with an insulation material results to a minimum total cost. It was found that the optimum insulation thickness varies between 8.2 cm and 32 cm, energy savings vary between 58% and 86.37%, and payback period vary between 0.66 and 2.39 years depending on the type of wall and insulation material. It was also seen that the impact of the type of materials used on the total cost of cooling is more significant for SEB with extruded polystyrene. The values 9 cm and 23 $/m^2 for optimum insulation thickness and minimum total cost were obtained, respectively, compared to 9.2 cm and 33 $/m^2 proposed by reference [4].

Considering the consistent impact of the wall type on optimum insulation thickness, its consideration by designer of external wall thermal insulation is fundamental for the energy efficiency of the building.

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