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OPTIMUM THICKNESS OF WALL INSULATIONS AND THEIR THERMAL PERFORMANCE FOR BUILDINGS IN MALAYSIAN CLIMATE

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ABSTRACT

This study clarifies the optimum thickness of insulation materials for buildings by using the life cycle cost analysis. Common external walls including clay brick, sand cement brick and concrete in the Malaysian climate were studied. Various types of buildings including office, residential and hotel were considered. Optimum thicknesses of insulation materials including rockwool, fiberglass and extruded polystyrene were clarified. It was found that the appropriate insulation thickness in Malaysia is in the range of 18–126 mm. Different operating hours and inside-outside temperatures have a significant effect on the life cycle net saving. However, different external wall types have a slight effect on the life cycle net saving. A general index, cost/k for selecting the most cost-effective insulation material was also introduced. The material that has a higher cost/k value but a lower cost compared to other materials has the highest net saving. From all the insulation materials studied, fiberglass urethane was the most cost-effective.

***Keywords*:** Insulation material; energy and building; optimum thickness; life cycle cost.

INTRODUCTION

The world is continuously facing energy depletion and environmental threats and therefore the development of new energy sources and energy-saving techniques is becoming more important. It was reported that 15% of all electricity produced in the world is used for refrigeration and air-conditioning, and energy consumption for air-conditioning has been estimated to be 45% of the whole household and commercial sector (Choudhury et al., 2010). It was also reported that 21% of electricity consumption in the residential sector is used for air-conditioning in Malaysia (Mahlia & Chan, 2011). The increased demand for air-conditioning is due to the increasing population and increasing living standards, especially in developing countries (Zhai & Wang, 2010; Henning, 2007; Pons et al., 1999). Furthermore, the trend in building design to use opaque surfaces for the building walls also contributes to the increased demand for air-conditioning (Zhai & Wang, 2010; Henning, 2007). Air-conditioning demand can be reduced by the installation of proper insulation. Insufficiently thick insulation will be less effective, and excessively thick insulation will be uneconomic. Thus, many studies have been carried out on the optimum thickness of insulation materials in different regions (Mahlia & Iqbal, 2010; Yildiz et al., 2008; Yu et al., 2009; Al-Khawaja, 2004; Ozel, 2012, 2013; Axaopoulos, Axaopoulos, & Gelegenis, 2014). The optimum thickness of insulation material is also affected by the external wall and type of buildings. There are studies on the optimum insulation thickness for a tropical region by

Mahlia et al. (2007) and Chirarattananon, Hien, and Tummu (2012), but only one type of building or one type of wall was considered in these studies. Thus, the objective of this study is to clarify the optimum thickness of insulation materials in various buildings and various external walls. Moreover, the most cost-effective insulation material was also clarified by a general index that consists of two important characteristics of insulation materials, the ratio of cost to the thermal conductivity of the insulation material. The effects of the building type and external wall type on insulation materials and thicknesses were also clarified. Six types of insulation material were studied in four types of buildings including residential, office and hotels, and three types of external walls including clay brick, sand cement brick and concrete. Optimum thickness was studied using life cycle cost analysis, and the payback period and net saving were also clarified.

MATERIALS AND METHODS

Structure of External Walls

Clay brick, sand cement brick and concrete, which are commonly used for external walls in Malaysia, were studied. Details of the walls are shown in Figure 1 and Table 1. In general, clay brick has better thermal resistance because it has lower thermal conductivity, but it costs more. The thickness of the external walls was set on the basis of standard and common practice (Public Works Department, 2005).

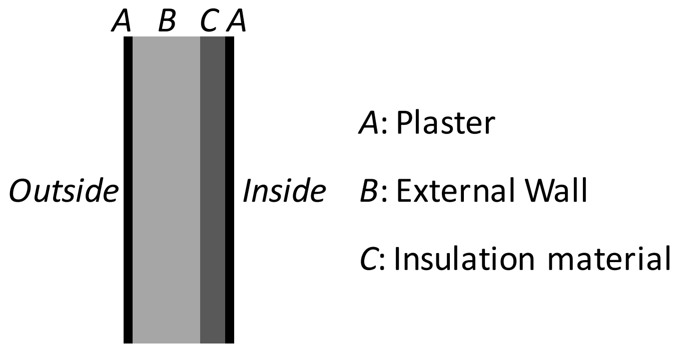

Figure 1. Layers of the wall

Table 1. Thermal conductivity and thickness of every layer

Layer	Thermal conductivity $[10^{-3}$ kW/mK]	Thickness [m]
External Wall		
Clay brick	0.711	0.104
Sand cement brick	1.000	0.114
Concrete	0.546	0.100
Plaster	1.500	0.019

Life Cycle Cost and Optimum Insulation Thickness

Heat Transfer Through the Wall

Heat losses to the environment through the wall per unit area $q_{/A}$ can be calculated by Eq. (1):

$$q_{/A} = U\left(t_{out,ave} - t_{in}\right) \tag{1}$$

where t_{in} is assumed to be 21 [^{o}C], $t_{out,ave}$ depends on the operation time of the building, and the overall thermal coefficient U [kW/m^{2}K] can be calculated by Eq. (2):

$$U = \frac{1}{\left(\frac{1}{h_1} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_{ins}}{k_{ins}} + \frac{x_4}{k_4} + \frac{1}{h_2}\right)} = \frac{1}{\left(R_{total} + \frac{x_{ins}}{k_{ins}}\right)} \tag{2}$$

where both h_1 and h_2 are assumed to be 0.0047 [kW/m^{2}K], x, k and R represent thickness, thermal conductivity and thermal resistance, respectively. Subscripts 1, 2 or 4, *ins* and total represent the plaster layer, external wall layer, insulation and total value, respectively. Details of the average temperature difference, operating time and annual demand hours are shown in Table 2. Six insulation materials that are available in Malaysia are studied and details of their thermal conductivity and cost are shown in Table 3.

Table 2. Details of the average temperature difference, operating time and annual demand hours·

Building type	Average temperature difference [^{o}C]	Daily operating hour (Total operating hours) [h]	Annual demand hours [h]
Office	8.0	8am-5pm (10h)	2086
Residential	4.6	1am-7am, 7pm-12pm(13h)	4745
Shop/ restaurant	7.2	7am-10pm (18h)	5840
Hotel/ convenience store	6.2	1am-12pm (24h)	8760

Table 3. Details of the six insulation materials available in Malaysia

Insulation materials	Thermal conductivity [10^{-3} kW/mK]	Price [\$/m^3]
Rock wool	0.034	175
Fiberglass	0.033	304
Urethane	0.024	262
Fiberglass urethane	0.021	214
Perlite	0.054	98
Extruded polystyrene	0.029	182
(Mahlia & Iqbal, 2010)		

Finally, the annual energy required for space cooling per unit area $E_{/A}$ can be calculated by Eq. (3):

$$E_{/A} = \frac{q_{/A}}{COP} ADH \tag{3}$$

where COP is assumed to be 2.93. Eq. (3) can also be expressed as the following equation:

$$E_{/A} = \frac{\left(t_{out,ave} - t_{in}\right) ADH}{\left(R_{total} + \frac{x_{ins}}{k_{ins}}\right) COP} \tag{4}$$

Cost Analysis and Optimum Thickness

The sum of the cost of the fuel consumed and the initial cost of insulation material can be used as a measurement to calculate the optimum thickness. In general, if the insulation thickness increases, the cost of the insulation material will increase and the cost of electricity will decrease. The cost of the insulation per unit area $C_{ins/A}$ can be calculated by the following equation:

$$C_{ins/A} = C_{ins} \cdot x_{ins} \tag{5}$$

where values of C_{ins} are already shown in Table 3. The cost of electricity per unit area, $C_{ele/A}$ can be calculated by the following equation:

$$C_{ele/A} = PWF \cdot E_{/A} \cdot C_{ele} \tag{6}$$

where C_{ele} is assumed to be 0.078$/kWh and PWF is the factor of the present worth of the fuel consumed for the entire life cycle and can be calculated as Eq. (7):

$$PWF = \frac{(1+i)}{(d-i)} \left[1 - \left(\frac{1+i}{1+d} \right)^{LT} \right] \tag{7}$$

where d is the interest rate [-], i is the inflation rate [-] and LT is the life time [year]. d and i are assumed to be 0.064 and 0.023, respectively, and LT is assumed to be 20 years.

The total cost per unit area, $TC_{/A}$ can be obtained by summing $C_{ins/A}$ and $C_{ele/A}$ as expressed by Eq. (8). It can also be expressed as Eq. (9) by substituting $E_{/A}$ with Eq. (4):

$$TC_{/A} = C_{ele/A} + C_{ins/A} \tag{8}$$

$$TC_{/A} = PWF \cdot \frac{\left(t_{out,ave} - t_{in}\right) \cdot ADH}{\left(R_{total} + \frac{x_{ins}}{k_{ins}}\right) \cdot COP} \cdot C_{ele} + C_{ins} \cdot x_{ins} \tag{9}$$

As shown in Figure 2, if thickness is the only variable, when insulation thickness increases the total cost decreases until it reaches the lowest value, and then the total cost increases again. The optimum thickness is obtained at the lowest value of total cost. By differentiating Eq. (9) with respect to x_{ins}, and by assuming the equation is equal to 0, which indicates the lowest value of the curve, x_{opt} can be obtained by the following equation:

$$x_{opt} = \left(k_{ins} \cdot \frac{\left(t_{out,ave} - t_{in}\right) \cdot ADH}{COP \cdot C_{ins}} \cdot C_{ele} \cdot PWF\right)^{1/2} - R_{total} \cdot k_{ins} \tag{10}$$

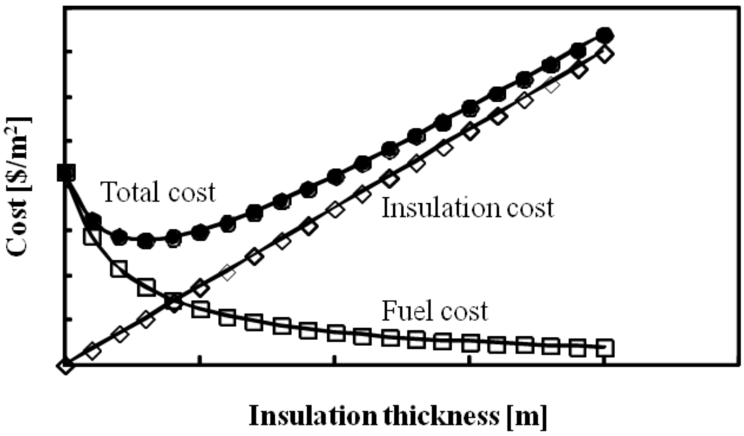

Figure 2. Relationship of total cost, insulation cost and fuel cost.

Net saving per unit area $NS_{/A}$ can be calculated by Eq. (11). The amount of electricity saved can be calculated by the difference between the case with insulation and the case without insulation ($C_{ele/A,unins}$-$C_{ele/A,ins}$). Over time, the saved amount will increase until it can cancel out the insulation cost ($C_{ins/A}$) and the net saving will be equal to 0. This means that the investment is paid back in that particular year. Thus, by assuming the net saving is equal to zero, and by substituting PWF with Eq. (7), the payback period *PBP* can be derived as Eq. (12):

$$\begin{aligned} NS_{/A} &= C_{ins/A} - \left(C_{ele/A,unins} - C_{ele/A,ins}\right) \\ &= C_{ins} \cdot x_{opt} - PWF \cdot \frac{\Delta t \cdot ADH \cdot C_{ele}}{COP}\left(\frac{1}{R_{total}} - \frac{1}{R_{total} + \frac{x_{opt}}{k_{ins}}}\right) \end{aligned} \tag{11}$$

$$PBP = \frac{log_{10}\left(1 - \frac{C_{ins} \cdot COP \cdot R_{total} \cdot k\left(R_{total} + \frac{x_{opt}}{k_{ins}}\right) \cdot (d-i)}{\left(t_{out,ave} - t_{in}\right) \cdot ADH \cdot C_{ele} \cdot (1+i)}\right)}{log_{10}\left(\frac{1+i}{1+d}\right)} \tag{12}$$

RESULTS AND DISCUSSION

Optimum Insulation, Payback Period and Net Saving

Table 4 shows the optimum thickness x_{opt}, payback period (*PBP*) and net saving (*NS*) for a 20 year life cycle for all insulation materials for all types of building when clay brick was used as the external wall. It was found that the office building that had the least operation time had the thinnest x_{opt} for all insulation materials, whereas the hotel and convenience store that had longer operation times had the thickest x_{opt}. It was also found that the thinnest insulation material was fiberglass in the office, 0.019m, whereas the thickest insulation material was perlite in the hotel or convenience store, 0.124m. Different types of building basically result in different annual demand hours (*ADH)* and average outside temperature. The effects of *ADH* and the average temperature difference on *PBP* and *NS* are shown in Figure 3 and Figure 4, respectively. It was found that the average temperature difference and *ADH* significantly affect the performance of the wall. If the temperature difference and operating times are too low, the insulation has a negative value of *NS*. When *ADH* is 8760, which means that a building operates 24 hours a day throughout the year, rock wool can save up to 48\$/m^2. Table 5 shows the optimum thickness x_{opt}, payback period (*PBP*) and net saving (*NS*) for a 20 year life cycle for all types of external wall when the office building was used as the type of building. It was found that there were no big differences of x_{opt}, *PBP* and *NS* when different external walls were used. Concrete had the thinnest x_{opt}, whereas sand cement brick had the thickest x_{opt}. This is because sand cement brick has higher thermal conductivity, which results in lower thermal resistance and therefore a need for thicker insulation.

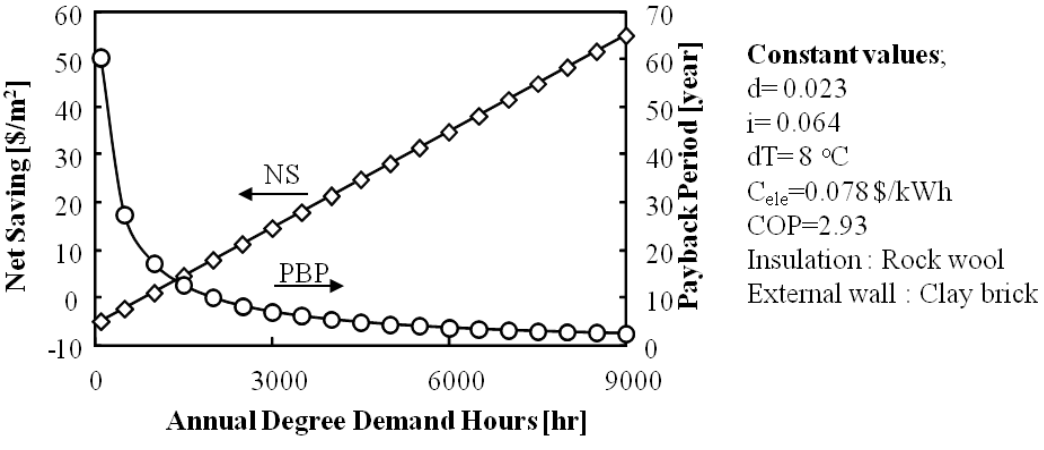

Figure 3. Effect of annual demand hours on the payback period and net saving.

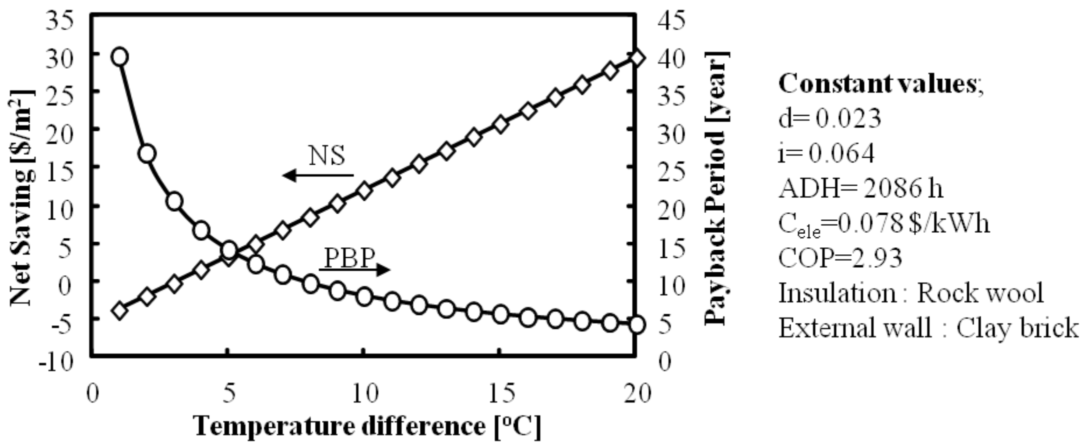

Figure 4. Effect of average temperature difference on the payback period and net saving.

Table 4. Results for optimum thickness, payback period and net saving when clay brick was used as the external wall.

		Material	Optimum thickness, x_{op} [m]	Payback period, PBP [years]	Net saving, NS [$/m^2]
External Wall (Clay Brick)	Office	Rockwool	0.031	9.78	8.5
		Fiberglass	**0.019**	**12.09**	**5.6**
		Urethane	0.021	10.01	8.2
		Fiberglass urethane	0.024	**8.69**	**10.0**
		Perlite	**0.055**	**9.31**	**9.2**
		Extruded polystyrene	0.030	9.30	9.2
	Residential	Rockwool	0.039	8.57	13.0
		Fiberglass	**0.024**	**10.87**	**9.2**
		Urethane	0.026	8.96	12.6
		Fiberglass urethane	0.029	**7.76**	**14.8**
		Perlite	**0.067**	**8.32**	**13.8**
		Extruded polystyrene	0.036	8.31	13.8
	Shop/ Restaurant	Rockwool	0.062	6.57	33.2
		Fiberglass	**0.042**	**8.24**	**27.0**
		Urethane	0.042	6.73	32.6
		Fiberglass urethane	0.046	**5.80**	**36.1**
		Perlite	**0.106**	**6.24**	**34.4**
		Extruded polystyrene	0.057	6.23	34.4
	Hotel/ Convenience Store	Rockwool	0.073	5.90	45.6
		Fiberglass	**0.050**	**7.42**	**38.3**
		Urethane	0.050	6.04	44.9
		Fiberglass urethane	0.054	**5.20**	**49.0**
		Perlite	**0.124**	**5.60**	**47.0**
		Extruded polystyrene	0.067	5.59	47.1

Different types of external wall basically result in different thermal conductivity and wall thickness. Since the wall thickness is usually fixed according to the standard, only thermal conductivity will affect the thermal performance of the wall. The effects of thermal conductivity on the *PBP* and *NS* are shown in Figure 5, where, for a range of thermal conductivity for common walls, only a slight change was found. Rock wool used with an external wall that has lower thermal conductivity, such as clay brick (0.00071kW/mK), resulted in less *NS* than when it was used with an external wall with higher thermal conductivity, such as sand cement brick (0.0010kW/mK).

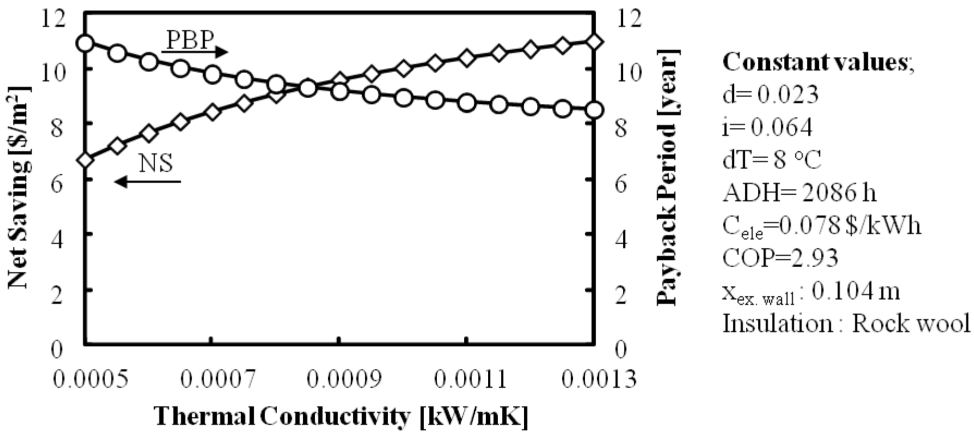

Figure 5. Effect of thermal conductivity on the payback period and net saving.

Table 5. Results for optimum thickness, payback period and net saving when office building was used as the building type.

		Material	Optimum thickness, x_{op} [m]	Payback Period, PBP [years]	Net saving, NS [$/m2]
Building type (Office)	Clay brick	Rockwool	0.031	9.78	8.5
		Fiberglass	**0.019**	**12.09**	**5.6**
		Urethane	0.021	10.01	8.2
		Fiberglass urethane	0.024	**8.69**	**10.0**
		Perlite	**0.055**	**9.31**	**9.2**
		Extruded polystyrene	0.030	9.30	9.2
	Sand cement brick	Rockwool	0.033	9.34	9.7
		Fiberglass	**0.020**	**11.57**	**6.6**
		Urethane	0.022	9.55	9.3
		Fiberglass urethane	0.025	**8.29**	**11.2**
		Perlite	**0.057**	**8.89**	**10.3**
		Extruded polystyrene	0.031	8.88	10.3
	Concrete	Rockwool	0.030	10.28	7.4
		Fiberglass	**0.018**	**12.66**	**4.6**
		Urethane	0.020	10.50	7.1
		Fiberglass urethane	0.023	**9.13**	**8.9**
		Perlite	**0.053**	**9.78**	**8.1**
		Extruded polystyrene	0.029	9.77	8.1

As shown in Table 4 and Table 5, it was also found that fiberglass had the thinnest x_{opt}, whereas perlite had the thickest x_{opt} for any condition. From the result obtained, the range of x_{opt} for all conditions studied was 0.018–0.126 m. The same tendency was found for *NS*, as fiberglass had the lowest *NS*, whereas perlite had higher *NS*. However, *NS* for fiberglass urethane was found to be the highest in any conditions. This phenomenon will be explained in the following section.

Relation Between Cost/K and Net Saving

Two important characteristics of insulation materials that are usually considered for their selection are cost and thermal conductivity. Therefore, it is important to know how they affect the net saving for the entire life cycle. This will help in selecting the most cost-effective insulation material. Figure 6 shows the cost and *Cost/k* value for every insulation material. *Cost/k* will be a beneficial index because it only consists of the two important characteristics of insulation material. As shown in Figure 6, perlite had the lowest cost and fiberglass had the highest cost. Figure 6 also shows that perlite has the lowest *Cost/k* value, and fiberglass, urethane and fiberglass urethane are among materials that have high *Cost/k* value.

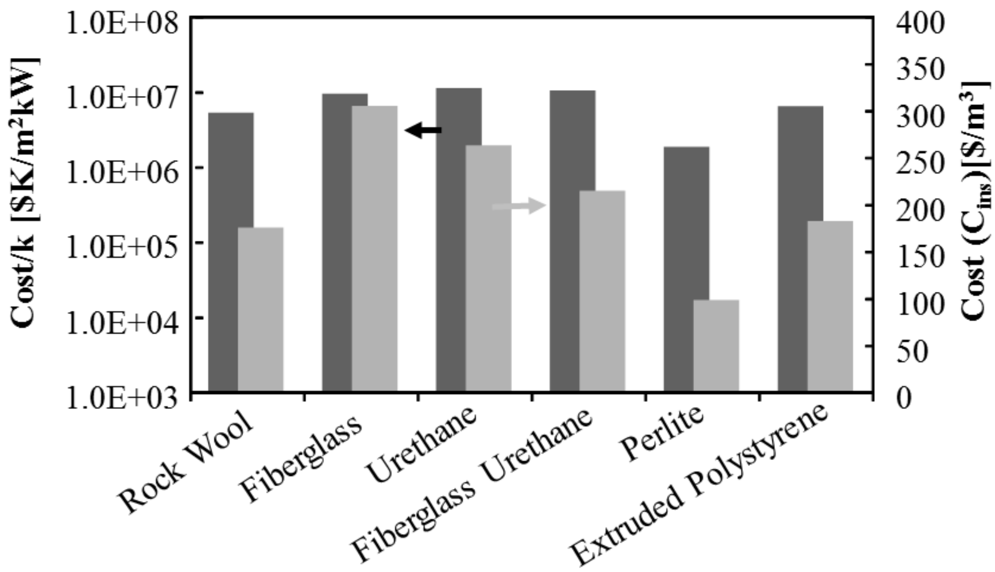

Figure 6. Cost and Cost/k value for all insulation materials.

Figure 7 shows the relation between *Cost/k* and net saving *NS*. It was found that the *NS* increased when the *Cost/k* value increased. However, when the value of *Cost/k* was almost the same as the case of fiberglass, urethane and fiberglass urethane, the value of the cost itself affected the *NS*. For instance, although the *Cost/k* value was the same at approximately 1.5×10^7 as shown in Figure 7, the *NS* for material that had lower cost (175 $\$/m^3$) had 3.8 times higher *NS* than the more expensive material (375 $\$/m^3$). This explains why fiberglass urethane had higher *NS* than fiberglass and urethane, which had slightly higher *Cost/k* values than the fiberglass urethane. It can be concluded that a material that has higher *Cost/k* but lower cost than other materials has the highest *NS* and is the most cost-effective.

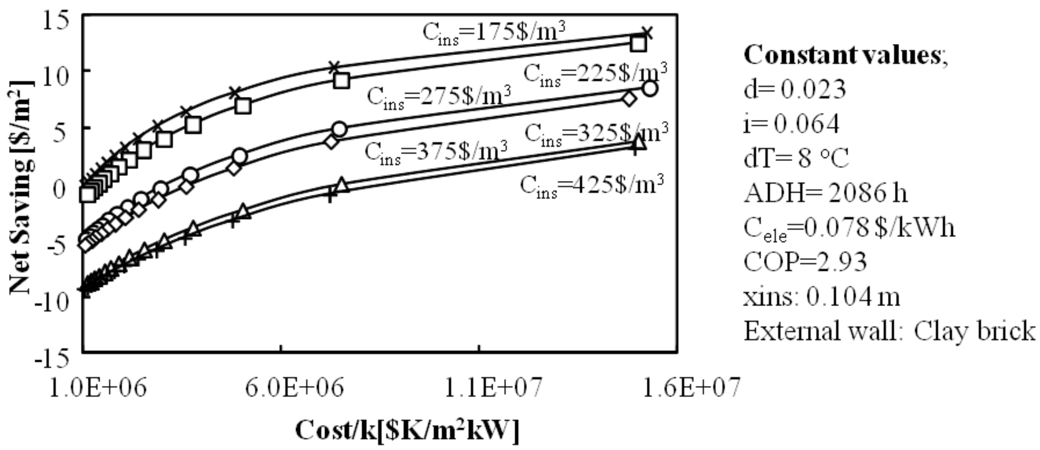

Figure 7. Relation between Cost/k and net saving.

CONCLUSIONS

The optimum thickness of insulation materials and their performance were studied. It is observed that:

i) Fiberglass has the thinnest optimum thickness, whereas perlite has the thickest optimum thickness for any condition. The range of insulation material thicknesses under the Malaysian climate for all conditions studied was 18–126 mm;
ii) The result for net saving has the same tendency as the result for optimum thickness, in which fiberglass has the lowest net saving while perlite has the second highest net saving;
iii) Different types of building significantly affect the performance of insulation. Building types that have a higher average temperature difference and higher annual demand hours result in thicker insulation and higher net saving.
iv) Different types of external wall that can be represented by their thermal conductivity values only slightly affect the net saving of insulation.
v) Material that has a higher Cost/k value but lower cost than other materials has the highest net saving. Of all the insulation materials studied, fiberglass urethane was the most cost-effective.

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