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Study of thermal performance of building roofs in the city of Tehran

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ABSTRACT

The design of a building can provide the highest thermal comfort in the interior without any mechanical equipment and save energy to a large extent. The roof of a building is an important part for thermal loss. This research studies the thermal performance of 14 conventional roof structures in Tehran city by using designbuilder 4.5. It is found that the polystyrene block performs best compared to other structures. Despite the time and cost required to implement the beam for building roofs, the use of the polystyrene block is recommended. The results indicate that the use of 5 cm of thermal insulation in the structure of the roof results in 5.85% decrease in heat loss during winter and 5.65% decrease during summer. A reverse roof has a more favorable performance on hot days of the year. Also, the performance of roofing with heat insulation is better than that of the reverse roof in cold days.

Keywords: Thermal Performance, Building Roof, City of Tehran, DesignBuilder, Block Joint.

1. Introduction

To select a building's roofing material, it is necessary to consider several features such as the speed and ease of roof implementation, the weight of the structure, space, and the need for less expert personnel and less materials. The thermal performance is also considered necessary to reduce heat loss. The thermal comfort range affects the thermal calculations of the building, the size of the heating, ventilation and air conditioning (HVAC) devices, the thickness of the insulation and materials, and the amount of energy consumed and dissipated. The five climatic factors of temperature, humidity, vapor pressure, air velocity (wind), and irradiance from internal walls are important in determining the thermal comfort range. For each climatic region, the thermal comfort range should be determined precisely [1].

Heidari [2] estimated the comfort temperature of the people in Tehran by using the ASHRAE standard and introduced the following relation. The use of this comfort temperature resulted in 25% energy saving in the buildings.

$$T_{comf} = 0.555T_{out}+12.8 \quad (1)$$

In recent years, understanding the consumption process and explaining the methods for optimization have been focused toward researchers and energy managers in the residential sector. One of the principles of these investigations is to reconcile the crust of buildings with the climate. Researchers are studying the buildings and their materials, insulation of the outer surfaces, and comfort conditions. In the area of building energy efficiency optimization, Swan & Ugursal [3]

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used various techniques in modeling the energy consumption of the residential parts. Dong et al. [4] used a neural network algorithm to predict the energy consumption of buildings in tropical regions. In order to obtain more specialized information on building energy management, Lee and Kung [5] suggested modifying the traditional method by using climate classification and data envelopment analysis (DEA). Using statistical data, Zhang [6] calculated the annual consumption of electricity, liquid gas, natural gas and coal, as well as energy for district heating in different buildings by using regression equations. Hirestet et al. [7] studied NIECS data on household energy consumption, including the total energy consumption, electricity consumption, and the use of major heating fuels for space. Using survey data on energy consumption in residential areas, Kasa [8] used quantitative regression analysis to explain the effects of different parameters on the total distribution of energy consumption. The results indicated that while housing size was important for space ventilation, the type of housing had a lesser impact. Michaliket et al. [9] used the fuzzy system approach to predict residential energy demand.

Aziz-zadeh Esferjani and Kazemzadeh [10] investigated the effective parameters on energy consumption in a residential area in Iran by using ASEAM software and showed that the highest dissipation rate was related to the external wall, and then the windows and gaps between them. Mohammad [1] simulated the thermal performance of the common materials of external walls in Tehran's climate with IESVE software. Tarzaghan and Bagheri Sabzevar [11] studied the effect of external building materials on energy consumption for the city of Yazd. Their results revealed that the polystyrene block had the least amount of annual energy consumption. Viseh and Mazlumi [12] investigated the thermal insulation of flat roofs with a retrofit roof system. They studied the implementation method, the advantages and disadvantages of the reverse roof system, and economical energy saving.

The main objective of this paper is to investigate the thermal performance of roofing structures by using polystyrene block, cement block, clay block, steel deck, roofix, cobiax, mehanit, uboot, green baffle and hollow core. The thermal performance of the case study in the city of Tehran is evaluated for different conditions.

Nomenclature

A	Area, m^2
C_p	Specific heat capacity, *J/kg.K*
K	Thermal conductivity, *W/m.K*
L	Thickness, m
$\dot{m}$	Mass flow rate, kg/s
q''	Heat flux, W/m^2
$\dot{Q}$	Heat transfer rate, *W*
R	Thermal resistance, *K/W*
t	Time, *s*
T	Temperature, *K*
V	Volume, m^3

Greek Symbols

ρ	Density (kg/m^3)

2. Governing equations

The energy equation is expressed as follows:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{si}} \dot{Q}_i + \sum_{i=1}^{N_{surfaas}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zonecs}} \dot{m}_i C_p (T_{zi} - T_Z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \quad (2)$$

the left-side of the equation is the energy stored in the air. The first term on the right-hand side is the total internal convection loads, the second one is the heat transfer from the surface of the examined area, the third is the heat transfer due to input air mixing, and the fourth term is the heat transfer from the constant variation of the outlet air. Q_{sys} indicates the thermal and cooling load to be supplied by the equipment. dT_z/dt becomes zero under equilibrium condition. The external heat balance, which includes the outer surfaces of the area, is calculated in Eq.(3) [13] based on Fig. 1:

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} + q''_{ko} = 0 \quad (3)$$

where, $q''_{\alpha sol}$ is the short-wave radiation absorption and emission, q''_{LWR} is the long-wave radiation heat flux, q''_{conv} is the convective heat transfer, and q''_{ko} is the heat conduction flux (Q/A).

Figure 2 shows the thermal equilibrium of the internal surfaces. Equation 4 is the relationship between the elements involved in the heat balance of the internal surfaces [13].

$$q''_{LWX}+q''_{SW}+q''_{LWS}+q''_{ki}+q''_{sol}+q''_{conv}=0 \quad (4)$$

where, q''_{lwx} is the long-wave radiation between the surface of the region, q''_{sw} is the short-wave radiation, q''_{lws} is the radiation flux of the equipment, q''_{ki} is the conduction heat transfer through the wall, q''_{sol} is the solar heat transfer that is absorbed by the surface, q''_{conv} is the convective heat flux with outside air.

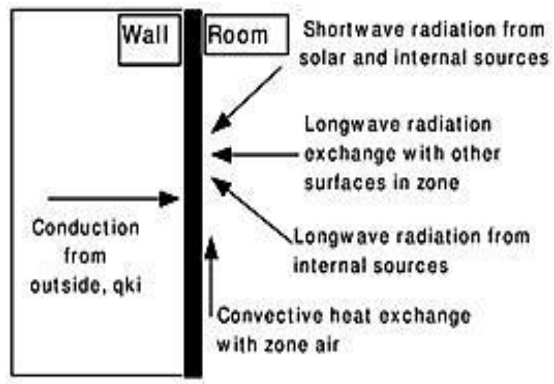

Fig. 1. Internal thermal equilibrium [13]

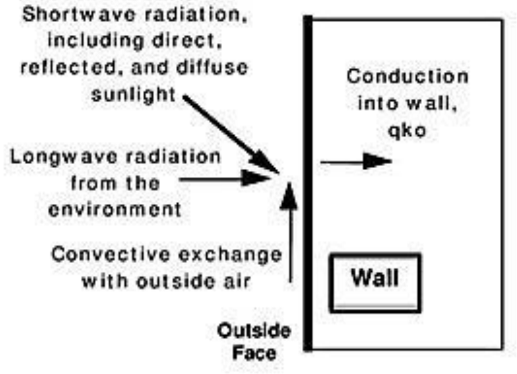

Fig. 2. External thermal equilibrium [13]

3. Results

The building considered in this study is shown in Fig. 3. The details of the structure of the internal walls, the exterior walls, the windows and the floor are listed in Table 1. Also, the thermodynamic properties of the materials used in the building are given in Table 2. Simulations are usually performed during an hour to determine the conditions inside the building include climatic information (radiation and temperature). In addition to the climatic data, it is necessary to specify the geometry and the angle of solar radiation for hours in a year. These climatic data should not be average values in a year or just for a part of the year, but they should be specified daily for all 8760 hours in a year [14].

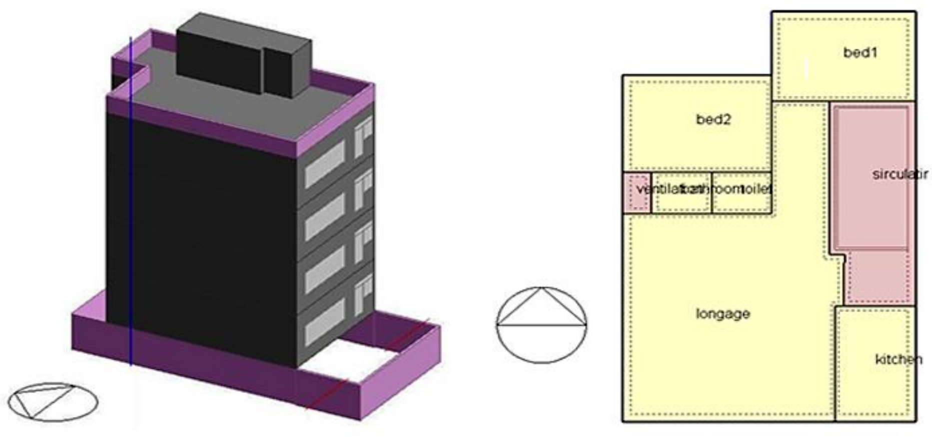

Fig. 3. Considered building for the present simulation

Table 1. Structure of building's envelops

External Walls	1-Plaster (thickness: 2.5 cm) 2-Thermal insulation of stone wool (thickness: 5 cm) 3-Brick (thickness: 10 cm) 4-Cement mortar (thickness: 2.5 cm) 5-Travertine stone (thickness: 2 cm)
Internal Walls	1-plaster (thickness: 2 cm) 2-gypsum (thickness: 3 cm) 3-bricks (thickness: 10 cm)
Floor	1-ceramic (thickness: 1 cm) 2-cement mortar (thickness: 2 cm) 3-Thermal insulation of stone wool (thickness: 5 cm) 4-concrete (thickness: 5 cm) 5-ceiling of the polystyrene block (thickness: 25 cm) 6-gypsum (thickness: 2 cm) 7-plaster (thickness: 2 cm)
Window	1-glass (thickness: 4 mm) 2-layer air (thickness: 12 mm)

Table 2. Thermodynamic properties of materials used in simulation

Materials	**Density** ρ **(kg/m^3)**	**Thermal Capacity** c_p**(*J/kg.K*)**	**Thermal conductivity (*W/m.k*)**
Concrete	2100	1000	1.65
Concrete (with fittings)	2400	1000	2
Pottery	1900	840	0.74
Polystyrene	25	1400	0.04
Steel	7780	450	52
Air	1.2	1000	0.3
Bitumen	2000	1000	0.7
Stone wool	30	840	0.04
Glass wool	12	840	0.04
Gypsum	1500	1000	1.1
Plaster	1000	1000	0.4
Travertine	2600	1000	2.3
Cement mortar	1680	840	0.82
Bricks	1920	840	0.72
Mosaic	2000	1000	1.5
Ceramic	2500	840	1.4

In this study, all the parameters are assumed to be constant due to the fact that all the parameters affect energy consumption. Also, to investigate the influence of the roof structure on the degree of thermal comfort, the simulations are done by ignoring the coolingand heating equipment. The inhomogeneous parts of the roof, such as the sections with beams, blocks, and concrete, are assumed to be homogeneous. For this purpose, the following equations are used:

$$\rho_{tot}=\frac{\Sigma m}{\Sigma V} \quad (5)$$

$$\rho_{tot} C_{p_{tot}} = \frac{\Sigma m C_p}{\Sigma V} \rightarrow C_{p_{tot}} = \frac{\Sigma m C_p}{\Sigma V} \Big/ \rho_{tot} \quad (6)$$

$$K_{tot}=\frac{L_{tot}}{A_{tot}R_{tot}} \quad (7)$$

Also, for the walls containing two materials, the parallel resistance is defined to calculate the heat conduction coefficient:

$$K_{tot}=\frac{\Sigma KA}{A_{tot}} \quad (8)$$

where, ρ is the density, C_p is the heat capacity, m is the mass of materials, V is the volume of materials, L is the total thickness, R is the thermal resistance, K is the thermal conductivity, and A is the area perpendicular to the direction of thermal conductivity.

The inhomogeneous part of the roof contains blocks, beams, and concrete. Roofix, cobiax, mehanit, uboot, green baffle, and hollowcore are the parallel resistance of the air and Ferro concrete. The thermodynamic properties of the heterogeneous portions of roofing types are given in Table 3.

The ANSI/ASHRAE 140-20041 standard specifies tests that can be used to examine the applications and capabilities of a wide range of software designed to calculate the thermal performance of a building and the environmental control systems. A test of 600 in ASHRAE standard is considered for validation as shown in Fig. 4.

In this simulation, the room has a length of 8 m, a width of 6 m and a height of 2.7 m with two windows with an area of 6 square meters to the south. The thermal input and the structure of the window and the structure of the roof and wall floor are provided by the standard. The other information are as follows: Cool and dry climate file with TMY format, penetration rate of 0.5 ac/h, heat generation for electricity and utilization and equipment 200 W with 60% radiation fraction, HVAC model with 100% convective, operating temperature of 20°C, the temperature of the mechanical system for cooling at a temperature of 27°C, and ground temperature of 10°C [14]. The results are presented in Table 4.

Table 3. Thermodynamic properties of the heterogeneous part of the roof

Heterogeneous section of the roof	Density P (kg/m^3)	Thermal Capacity c_p(*J/kg.K*)	Thermal conductivity (*W/m.k*)
Cement Block (20cm)	1207.4	988.612	1.333
Cement Block (25cm)	1125.67	990.277	1
Clay Block (20cm)	693.68	921.453	0.77
Clay Block (25cm)	661.92	928.637	0.714
EPS Block (20cm)	458.28	206.502	0.294
EPS Block (25cm)	454.624	207.8227	0.316
Uboot	750.84	1000	0.93
Cobiax	1440.786	1000	1.942
Hollowcore (20cm)	767.466	1000	1.85
Hollowcore (20cm)	1069.466	1000	1.96
Green Baffle	500.96	1000	0.72
Mehanit	600.912	1000	0.804
Steel Deck	1250.6	1000	1.35
Roofix	Without a heterogeneous part		

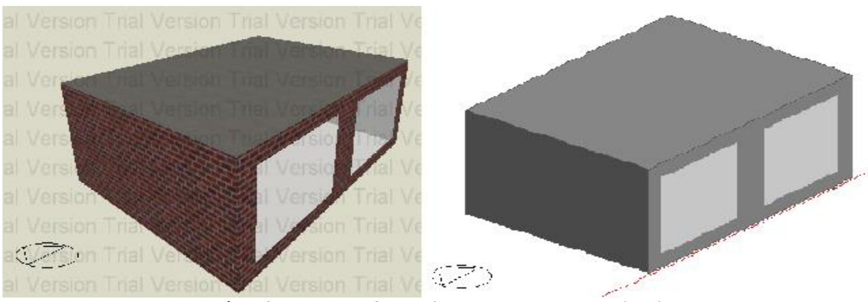

Fig. 4. A test of 600 in ASHRAE standard

Table 4. Annual heating and cooling load

	Cooling load	**Heating load**
Annual heating / Cooling load simulated (Mwh)	7.491	4.708
Maximum annual heating / Cooling load provided in standard (Mwh)	7.964	5.709
Minimum heating / Cooling load provided in standard (Mwh)	6.137	4.298
Annual heating / Cooling load provided in standard for design builder (Mwh)	6.918	4.498
Percentage error	$\frac{(7.491-6.918)*100}{6.918} = 8.28$	$\frac{(4.708-4.498)*100}{4.498} = 4.67$

To estimate the energy consumption of the building, the day of the annual heating and the day of the annual cooling are used. The day of the annual heating is the sum of the difference between the hourly temperature inside the building and the hourly temperature of the reference during one year when the indoor temperature is lower than the reference temperature. The day of the annual cooling is the sum of the difference in hourly temperature inside the building and the reference temperature over a year when the indoor temperature is higher than the reference temperature.

If the reference temperature is the comfort temperature for the people of Tehran, as presented in Eq. 1, then these values are a measure of thermal comfort. To measure the thermal performance of the structure, the amount of heat through the crust when we need to cool the building to get comfort or the heat loss through the crust when we need to heat the building to get thermal comfort is considered. The lower values of this parameter indicate a better thermal performance by the structure.

As shown in Figs. 5 and 6, the minimum day of cooling and the minimum day of heating belong to the roof structure of the polystyrene block with a thickness of 25 cm. Polystyrene itself is a heat insulating material, which improves thermal performance.

Mehanit, green baffle, and uboot roofs are very close to the roofs of the cement block and the clay block. Steel deck roofs have the highest day of cooling. Hollowcore and cobiax have the highest heating day and are inadequate to provide thermal comfort. Also, the worst heat performance is for roofix, which is not widely used.

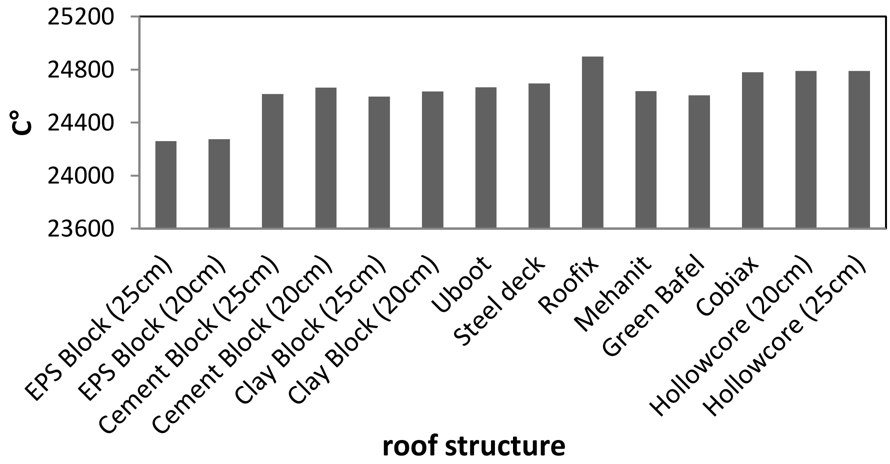

Fig. 5. Day degree of heating for different roof structures

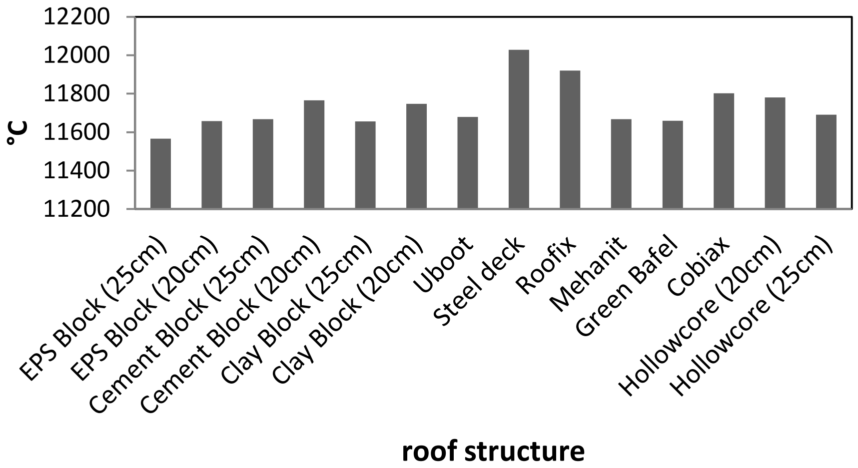

Fig. 6. Day degree of cooling for different roof structures

As seen in Figs. 7 and 8, the polystyrene block roof has a more favorable thermal performance than the other structures. The least difference with this heat loss as compared to the other roofs belongs to the green baffle structure, which has 1.84 $\frac{KW}{m^2}$ higher thermal loss compared to the polystyrene roof per year. The minimum amount of heat consumed throughout the year is for the polystyrene block. The least difference with this heat reception compared to the other roofs is the green baffle and the clay block, which receive 0.83 $\frac{KW}{m^2}$ more heat in comparison to polystyrene per year.

A cobiax roof has more steel rails to strengthen and enhance the performance of the instruments in its structure, and the use of airbags to remove the weight of additional concrete and to lighten this structure is one of the specific and positive features of this roof that distinguishes it from the others. However, the existence of steel with a low heat transfer coefficient and the removal of the effect of the high density of concrete undermine the thermal performance of this roof.

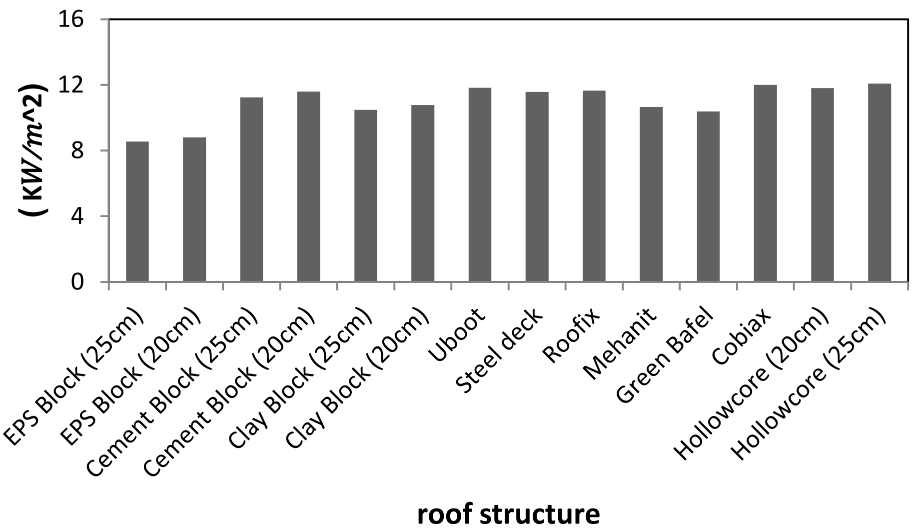

Fig. 7. Heat loss for different roof structures in cold days per year

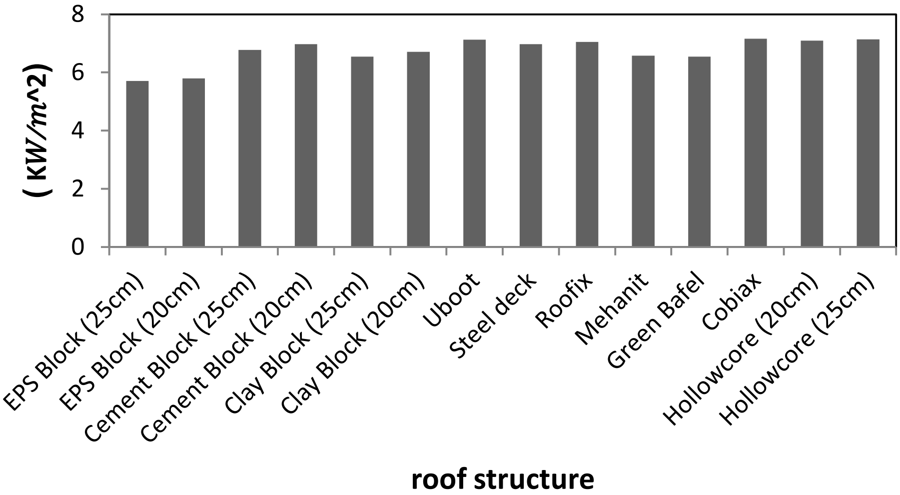

Fig. 8. Heat absorption for different roof structures in hot days per year

Roofing with steel deck structure is widely used due to the ease and speed of execution, very low thickness and space in the building. The thermal performance of these roofs is not desirable, but considering the speed and ease of implementation, roof strength, building spatial and thermal performance, the use of this technology is preferable to cobiax and hollowcore.

Figures 9 and 10 show the day degree of heating and cooling of the roof with no insulation, the roof with insulation of wool stone and insulation with wool stone reverse roof. The roof with no insulation has approximately 1405°C day degree of heating and 820°C day degree of cooling more than those for the insulated roofs. The performance of the wool stone reverse roof is less than the wool stone roof during hot days and vice versa.

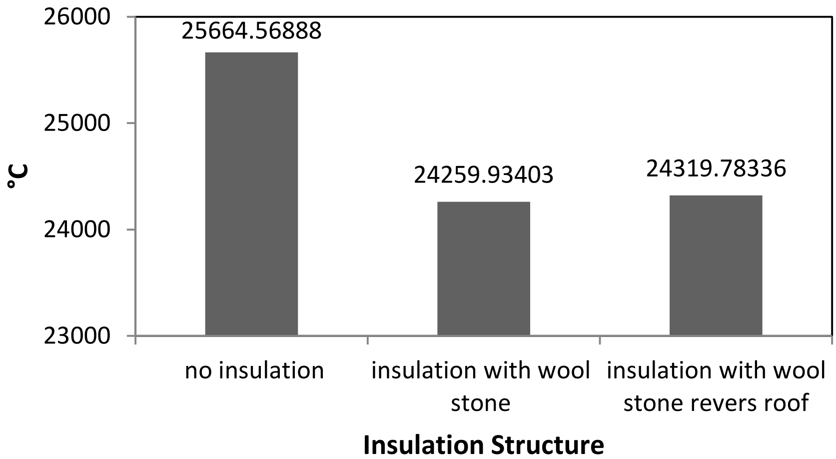

Fig.9. Day degree of heating for different roof insulations for a year

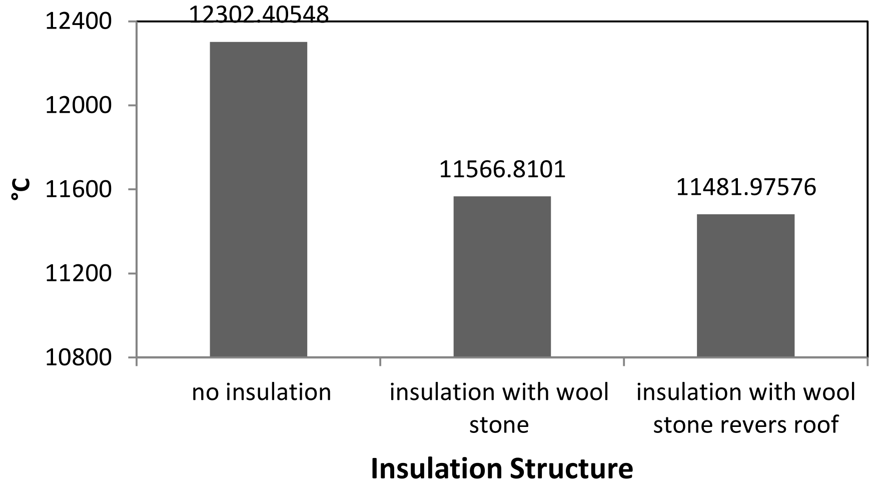

Fig. 10. Day degree of cooling for different roof insulations for a year

The heat loss from the roof over a year for all the hours required to heat the building is shown in Fig. 11. The heat loss for the roof with no insulation is 5.85 kW/ m² more than that for the roof with insulation. The heat loss for the wool stone reverse roof is 0.17 kW/ m² more than that for the wool stone roof. Therefore, the wool stone reverse roof has a more favorable performance in terms of heat loss and the times when it requires heating.

Receiving heat from the roof over a year for all the hours that we need to heat the building is shown in Fig. 12. Heat absorption for the roof with no insulation is 5.65 kW/m² more than that for the roof with insulation. Heat absorption for the reverse roof is up to 0.37 KW/m² lower than that for the wool stone roof.

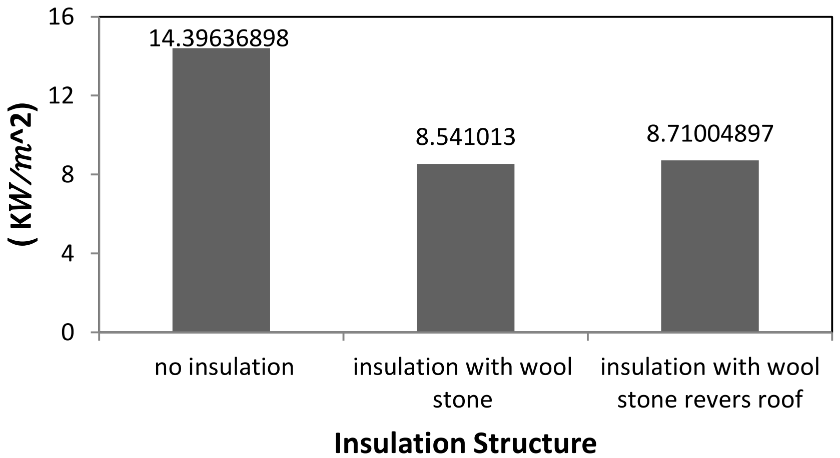

Fig. 11. Heat loss for different roof insulations for a year

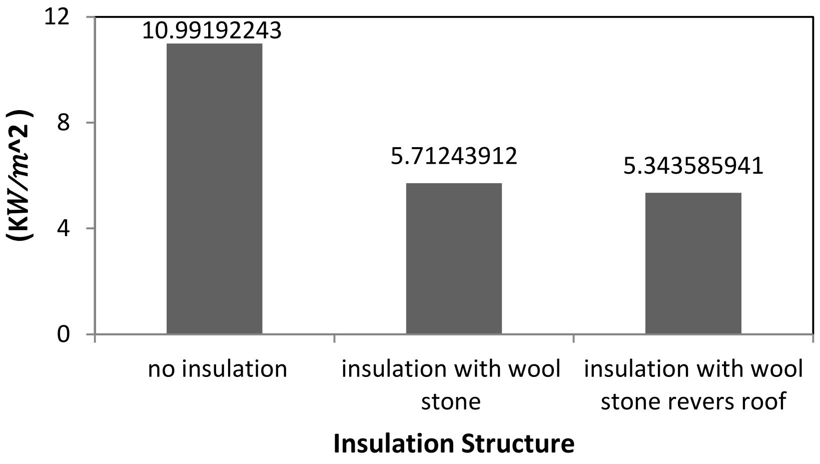

Fig. 12. Heat absorption for different roof insulations for a year

4.Conclusion

In this study, the thermal performance of various types of roof structures in the city of Tehran and its effect on thermal comfort and energy consumption were studied using Designbuilder 4.5. It was found that the minimum day of cooling and the minimum day of heating belonged to the roof structure of the polystyrene block with a thickness of 25 cm. Mehanit, green baffle and uboot roofs were very close to the cement block and clay block roofs. The steel deck roofs had the highest day of cooling. Hollowcore and cobiax had the highest heating day and were inadequate to provide thermal comfort. The results showed that the polystyrene block roof had a more favorable thermal performance than the other structures. Also, it was shown that the wool stone reverse roof had a more favorable performance in terms of heat loss and the times when it required heating.

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