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Investigation of Energy Saving Potential in Buildings Using Novel Developed Lightweight Concrete

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Abstract

In this study, three different composite materials were produced from mixtures of natural and waste materials in different proportions. The produced composites were used to determine the insulation thickness of exterior walls of buildings located in 12 provinces selected from the four different climate zones of Turkey. The selection of provinces was made according to Turkish standard TS 825. The produced materials are thermal insulation elements that can be used instead of construction elements, such as brick, on the exterior walls of the buildings. In this study, only the heating of the buildings was considered and the number of heating degree days of the provinces was taken into account to determine the insulation thickness. The life cycle cost analysis method was used to determine the optimum insulation thickness. It was determined that the optimum insulation thickness values calculated for four different fuel types for the selected provinces varied between 0.170 m and 1.401 m. The annual energy requirement for the unit surface area of the exterior walls of the insulated buildings was determined to be 11,213–965,715 kJ·m^{-2} per year. Moreover, it was determined that the insulation costs ranged between \$ 22,841 m^{-2} and \$ 114,841 m^{-2}, and the payback period ranged from approximately 2.5 to 6.5 years. It was concluded that using these new types of materials in the determined regions were advantageous in terms of thermal insulation, fire resistance, mechanical properties, production costs, extra labor costs, and optimum insulation thickness.

Keywords Degree-day method · Expanded perlite aggregate · Life cycle cost analysis · Optimum insulation thickness · Thermal insulation

Abbreviations

$A_{year,H}$	Difference of annual total heating cost (\$ m^{-2}·-year)
C	Annual energy cost for unit surface without insulation (\$m^{-2}·-year)
$C_{A,H}$	Total heating cost (\$ m^{-2} ·year)
C_{fuel}	Cost of the fuel (\$m^{-3}, \$ kg^{-1})

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$C_{ins.}$	Cost of the insulant ($\$$ m^{-2})
COP	Coefficient of performance
$C_{t,H}$	Total heating cost of the insulated building ($\$$ m^{-2}-year)
Cy	Cost of the insulant ($\$$ m^{-3})
DD	Degree-day value (°C-days)
$E_{year,H}$	Annual energy need for heating (J·m^{-2}·-year)
g	Inflation rate (%)
HDD	Heating degree-day value (°C-days)
Hu	Low heat value of the fuel (J·kg^{-1}, J·m^{-3})
i	Interest rate (%)
k	Thermal conductivity of insulation (W·m^{-1}·K^{-1})
LPG	Liquefied petroleum gas
N	Lifetime (year)
Spp	Payback period (year)
PWF	Present Worth Factor
q	Annual heat loss (Wm^{-2})
r	Actual interest rate
R	Heat transfer resistance (m^2·K W^{-1})
$R_{ins.}$	Thermal resistance of the insulant (m^2·K W^{-1})
R_o	Outside heat transfer resistance (m^2·K W^{-1})
R_w	Thermal resistance of wall layers without insulation (m^2·K W^{-1})
$R_{w,t}$	Thermal resistance of non-insulated wall (m^2·K W^{-1})
T	Temperature (K)
U	Total heat transfer coefficient (W·m^{-2}·K^{-1})
X	Insulation thickness (m)
X_{opt}	Optimum insulation (total) thickness (m)

1 Introduction

The energy consumption in Turkey has been divided into four main industries, namely industrial, housing, transportation, and agriculture, while the housing industry accounts for 33 % of total energy consumption [1]. Factors, such as limited energy resources, environmental problems that occur as a result of the unconscious use of these limited resources, and dependence on foreign sources for energy make it inevitable to use the existing energy resources efficiently. Therefore, considering the investment and operating costs, it is very important to select the right insulation material and insulation thickness for the air-conditioning needs, such as heating and cooling in the housing industry, which has a significant share in Turkey's energy consumption [2]. In this context, several studies have been carried out to provide the most suitable insulation in residential buildings with different structural features and climatic conditions [3, 4]. When these studies are examined, it can be seen that some of them investigate the production of special insulation materials and some of them investigate the application and optimum thickness of the insulation material. Especially the materials used in residential buildings are required to be lightweight construction materials not to put an extra load on the structure as well as providing sound and heat insulation, and most importantly, they should be resistant to dangerous situations such as a fire. In the literature, it is possible to find many studies carried out for this purpose. For example, Soykan and Özel [5] investigated the use of waste marble powders as aggregates with polymer concrete technology. Köksal et al. [6] produced foam concrete with thermal insulation properties. They used cement, expanded vermiculite, and silica fume in the production of foam concrete. The foam concretes were poured into 200 mm × 200 mm × 500 mm prism size molds and Ø150 mm × 300 mm cylinders. They kept the foam concretes at laboratory ambient temperature and exposed them to 300 °C. They discussed the test results taking into account the effects of foam concentration and high temperature. As a result, they found the thermal conductivity of foam concretes containing expanded vermiculite powder suitable. Gündüz et al. [7] solidified the cures they obtained by mixing the blended Portland cement with waste marble powder particles in certain proportions in different periods and compared the thermo-mechanical properties of these samples. Şengül et al. [8], in an experimental study, replaced the expanded perlite with natural aggregate in lightweight concrete mixtures and investigated the effect of the new product on thermal insulation. Köksal et al. [9] produced insulation mortar with expanded vermiculite and waste expanded polystyrene. They used five vermiculite + polystyrene/cement ratios of 3, 4, 5, 6, and 7 by volume to produce mortar. They produced a total of 25 mortars with dimensions of 4 cm × 4 cm × 16 cm to investigate physical, mechanical, and thermal properties. As a result, they found that samples containing vermiculite and polystyrene showed good insulating properties. Demirboğa and Gül [10] investigated the compressive strength and thermal conductivity of the mineral blended expanded perlite aggregate concrete. Ören et al. [11] studied the physical and mechanical properties of foam concretes containing fly ash and blast furnace slag. As a result, the increased water binder ratio (wb^{-1}) due to the decrease in binder content caused an increase in the porosity of foam concretes. They found that increased porosity in foam concretes caused a decrease in bulk density, compressive strength, and thermal conductivity and an increase in water absorption in foam concretes. Shastri and Kim [12] aimed to produce heat-insulated lightweight concrete using light aggregate (pumice, perlite, and EPS) in concrete. They investigated the mechanical and physical properties of the light concretes they produced. Sütçü et al. [13] studied the thermal behavior of hollow clay bricks obtained from paper waste and optimized their thermal performance. They studied both the strength and thermal properties of different paper waste concentrations. They found that the thermal conductivity of microporous brick materials with additives decreased from 0.68 $Wm^{-1}{\cdot}K^{-1}$ to 0.39 $Wm^{-1}{\cdot}K^{-1}$ compared to the non-additive sample. Gencel et al. [14] studied the physical and mechanical properties of composites obtained with the addition of vermiculite and polypropylene fiber to light gypsum. They found that thermal conductivity decreased with the addition of vermiculite. Statistical response surface method with three-level factorial was employed to evaluate the effect of the addition of vermiculite and polypropylene fibers on gypsum composites.

Regarding the studies investigating the application method and thickness of the insulation material, in a study carried out by Al-Sallal, two types of roof insulation found in hot and cold climates were compared and it was stated that the insulation cost payback period in the cold climate was shorter than that in the hot climate [15]. In a study by Bolattürk, the optimum insulation thickness, energy saving, and payback periods of various fuels were compared for a total of 16 cities selected from four different climate regions. As a result of the study, it was stated that energy saving varied between 22 % and 79 % and that optimum insulation thickness varied between 2 cm and 17 cm [16]. Yu et al. [17] investigated the optimum insulation thickness for four typical cities in China's hot summer and cold winter regions. In their research, they used five different insulation materials and found that the optimum insulation thickness ranged from 0.053 m to 0.236 m and that the cost of insulation payback periods ranged from 1.9 to 4.7 years. Han et al. [18] aimed to determine the optimum insulation thickness and minimize the energy cost by combining the structural insulation panel (SIP) and the vacuum insulation panel (VIP) for five cold climate regions of China. They stated that the findings of their study confirmed the economic feasibility of combining SIP with VIP in cold regions and provided viable parameters for the design of low-energy buildings in cold regions of China. Liu et al. [19] calculated the optimum insulation thickness of extruded polystyrene (XPS) and expanded polystyrene (EPS) insulation materials for three selected states (Changsha, Chengdu, and Shaoguan) in China. They determined that the optimum XPS thickness was between 0.053 m and 0.069 m and the optimum thickness of EPS was between 0.081 m and 0.105 m. Ustaoğlu et al. [20], performed an analytical simulation of lightweight concrete with different rates to decide on the thermal properties of vermiculite in real building applications using four different climatic regions and various fuels in Turkey to determine the energy consumption. Axaopolos et al. [21] investigated the optimum insulation thickness on the exterior walls of buildings in Larnaca, Cyprus, considering the wind speed and direction as well as heating and cooling times. They determined that the optimum insulation thickness was between 4.25 cm and 15.5 cm and that the payback period of the insulation was between 5.47 cm and 12.11 years. Liu et al. [22] developed a novel high-performance building material to create the heating and cooling loads of the building envelope due to the increased energy consumption due to the increasing number of commercial buildings in the United States. Therefore, they produced a novel foam concrete reinforced with SiO_2 aerogel (FC-SA). (FC-SA) found the thermal conductivity of foam concrete as 0.049 $Wm^{-1}{\cdot}K^{-1}$. As a result, the energy saving simulation results showed that the use of FC-SA in cold and hot regions can significantly reduce energy consumption. Uçar and Balo [23] investigated the optimal insulation thickness with four different insulation materials in four different climatic regions in Turkey, considering different fuel types and different wall structures. As a result of their research, they stated that energy cost savings varied between \$ 4.2 m^{-2} and \$ 9.5 m^{-2} depending on the city and the insulation material. Fleur ve diğ.[24] used an optimization approach to identify life cycle cost (LCC) optimal energy efficiency measures (EEM) to implement as part of a renovation of a building in Sweden. The optimization tool OPERA-MILP was used. As a result, they showed that under certain framework conditions and assumptions, applying heat recovery ventilation measures to reduce the demand for space heating in the building was not cost-effective.

Low thermal conductivity and low density are the main desired properties of the materials to provide thermal insulation in buildings. For this purpose, it is possible to find many studies investigating the use of heterogeneous and composite lightweight concretes produced using natural light aggregates as insulation materials. Several models have been developed for effective thermal conductivity of heterogeneous and composite materials and these models have been compared with experimental results. For example, Collishaw and Evans [25], developed a model based on the geometric simplification of the microstructure related to the distribution of the pore phases in the solid matrix to calculate the effective thermal conduction coefficient of a porous solid and proved the accuracy of the selected model. In another study, Koçyiğit [26] compared thermal conductivity and mechanical properties of samples produced using pumice aggregates, tragacanth, and cement in different combinations. Koçyiğit [27] has produced a novel building material by using different proportions of waste marble powder, expanded perlite, cement, and natural resin. He determined the best insulation material by performing mechanical and thermal experiments on this insulation material. Furthermore, there are many studies in the literature to examine the hydrothermal properties of lightweight concrete, which is considered as an insulation material in buildings. Záleská et al. [28] examined the physical, mechanical, thermal, and hygrothermal properties of lightweight concretes produced from waste plastics and compared them with reference data. They found that even if the mechanical parameters decreased with the increase in the amount of waste plastic, it could be used in non-bearing structures. Besides, they found that there were seven times lower thermal conductivity than the reference material. They found that the designed concretes were characterized by plastic aggregates with increased hygric properties, increased water and water vapor transport parameters, and decreased water vapor adsorption capacity. Del Coz Díaz et al. [29] conducted an experimental study to determine the hydrothermal properties of different lightweight concrete mixtures (LWC) produced from expanded clay. In their experimental work, they optimized the hydrothermal behavior for different LWC mixtures with material densities ranged from 900 $kg{\cdot}m^{-3}$ to 1400 $kg{\cdot}m^{-3}$. Del Coz Díaz et al. [30] developed a novel hybrid methodology to numerically and empirically examine moisture transport and heat transfer in wall structures that occurred from lightweight concrete hollow bricks (LWHBs). To perform hygrothermal analysis, they exposed one square meter of a wall to eight different humidity stages for a total of 1480 h under laboratory conditions with a special test device. In this regard, they found a very good agreement between numerical and experimental results.

In this study, it was aimed to determine the optimum thickness for housing in 12 province centers in four different climate zones by using three different novel developed composite insulation materials consisting of waste and natural materials for thermal insulation purposes in the housing by Turkey's TS 825 [31]. The study differs from other studies available in the literature due to the use of specially produced composite materials. Calculations were made considering the houses heated by using four different types of fuels: natural gas, coal, fuel oil, and LPG. The required optimum insulation thicknesses, net savings, and repayment period were calculated for each case. In this respect, it was aimed to use novel developed insulation materials as an alternative to traditional insulation materials used in determining optimum insulation thicknesses of houses in different climatic regions.

2 Materials and Method

2.1 Production of Insulation Materials

The raw perlite was expanded at 800 °C in the perlite facility located in İzmir Bergama region and was sized by sifting through sieves of desired dimensions in order to produce insulation materials. The supplied samples were divided into three different grain sizes as 0 mm–3 mm, 3 mm–5 mm, and 5 mm–8 mm (Fig. 1). The marble powder additive was obtained from the powder released in the processing of marbles at the Dimer Marble and Mining plant in Diyarbakır. As cement, CEM I 42.5 N standard number Portland cement was used. Expanded perlite aggregates divided into three groups in grain sizes of 0 mm–3 mm, 3 mm–5 mm, and 5 mm–8 mm and at the rate of 15 %, 30 %, and 45 % by weight and 0.300 mm sieved waste marble powder at the rate of 5 % and 15 % were added to tragacanth and cement mixtures at the rate of 0 %, 0.5 %, and 1 %. The tragacanth resin used in the experiments was powdered with a grinder. 100 g powdered tragacanth resin weighed with precision scale was mixed in a 5-L water-filled container.

In preliminary studies, it was determined that 100 g tragacanth resin can dissolve in approximately 5 L of water. Expanded perlite(EP) was placed in a waste marble powder and cement mix bucket. Molten resin was added to these mixtures at the calculated rate. Furthermore, in this study, thermal conductivity values of the previous study presented with reference number [27] were used. The material properties and production costs of the composite samples used in the experiments are presented in Table 1.

Fig. 1 Perlite samples divided into three different grain sizes

Table 1 Properties of composite samples produced

Samples	Volumetric ratio (%)			Mixing ratio (kg·m^{-3})			Compressive strength (MPa)	Abrasion loss (%)	Porosity (%)	(Water + Resin)/Cement	Cost (\$ m^{-3})
	Expanded perlite	Marble powder	Cement	Expanded perlite	Marble powder	Cement					
TIM (0 mm–3 mm)	15	5	80	300	120	950	33.25	0.68	0.264		19
SIM (3 mm–5 mm)	30	5	65	417	80	700	22.05	1.22	0.424	0.4	16
FIM (5 mm–8 mm)	45	15	40	461	135	400	14.14	2.05	0.608		12

Fig. 2 Sample preparation molds

Fig. 3 Produced samples

2.2 Determination of Thermal Conductivity Coefficients of Composite Samples Produced

The thermal conductivity of the samples was measured with the hot-wire method by using the "Shotherm QTM-D2" device developed according to DIN51046. In the catalog values of the device, the measurement sensitivity was given as $\pm 5\ \% + 1$ digit and the measurement range was given as 0.02 $Wm^{-1}\cdot K^{-1}$–10 $Wm^{-1}\cdot K^{-1}$. With this method, the real thermal conductivity coefficient can be measured without creating a change in the humidity in the samples produced. The difference of this method from the plate type thermal conductivity coefficient measurement method is that the measurement can be made even if the medium where the thermal conductivity coefficient is measured is heterogeneous. In order to determine the thermal conductivity coefficients of the produced samples, 20 mm $\times$ 60 mm $\times$ 150 mm sized molds (Fig. 2) suitable for the thermal conductivity meter probe were produced and the mixture materials were poured into these molds. After 24 h, the samples were removed from the mold (Fig. 3) and let rest for 28 days for the test. The measured thermal conductivity values of the samples at the end of this period were as follows, respectively: The thermal conductivity coefficient of the first insulation material (FIM) was 0.167 $Wm^{-1}\cdot K^{-1}$, the thermal conductivity coefficient of the second insulation material (SIM) was 0.311 $Wm^{-1}\cdot K^{-1}$, and the thermal conductivity coefficient value of the third insulation material (TIM) was 0.468 $Wm^{-1}\cdot K^{-1}$.

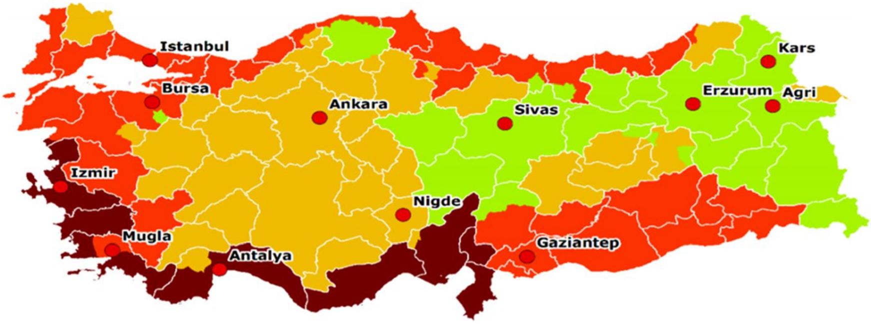

Fig. 4 Provinces whose insulation properties were examined

Table 2 Seasonal average temperature values of the selected cities [32]

Season	Winter			Summer		
Province	Dec	Jan	Feb	Jun	Jul	Aug
İstanbul	8.2	5.9	5.9	21.3	23.8	23.9
Bursa	7.2	5.3	6.2	21.9	24.4	24.3
İzmir	10.4	8.7	9.5	25.3	27.8	27.6
Muğla	6.9	5.3	6.0	22.8	26.3	26.2
Antalya	11.6	10.0	10.6	25.3	28.4	28.3
Ankara	2.4	0.1	1.6	19.9	23.3	23.3
Sivas	− 0.7	− 3.4	− 2.1	16.9	19.9	20.1
Niğde	1.8	− 0.3	1.1	19.1	22.4	22.3
Gaziantep	4.9	3.0	4.4	24.2	27.9	27.7
Kars	− 6.9	− 10.8	− 9.0	13.8	17.5	17.8
Erzurum	− 5.8	− 9.1	− 7.7	14.8	19.1	19.4
Ağrı	− 6.4	− 10.6	− 9.2	16.4	21.0	21.2

2.3 Selected Cities and Features of the Exterior Walls Studied

It is known that heat losses in buildings are generally caused by exterior walls, window openings, roof, and floor. In this study, only heat losses and gains occurring in the exterior walls were taken into account. The optimum insulation thickness calculation was made by taking account 12 of the provinces in four different regions, which were exemplified by the Turkish Standard TS 825 [31] (Fig. 4).

Monthly average temperatures of winter and summer seasons between 1929 and 2019 in these provinces obtained from the Meteorology General Directorate of Turkey (MGM) are given in Table 2 [32]. The location information of the selected provinces and the Heating degree-day (HDD) values of 2019 obtained from MGM [33] are given in Table 3.

In this study, a comparison was made between two types of walls, considering that the composite insulation materials produced can be used as a lightweight

Table 3 Data for selected cities [32, 33]

Province	Longitude	Latitude	Altitude (m)	Population	Number of households	HDD
İstanbul	28.58 E	41.01 N	120	15,519,267	3,886,990	1865
Bursa	29.04 E	40.11 N	155	3,056,120	782,935	1497
İzmir	27.09 E	38.25 N	10	4,367,251	1,263,121	1119
Muğla	38.22 E	37.12 N	625	983,142	283,213	1705
Antalya	30.42 E	36.54 N	39	2,511,700	638,424	788
Ankara	32.52 E	39.56 N	850	5,639,076	1,512,363	2169
Sivas	37.02 E	39.45 N	1285	638,956	167,355	2862
Niğde	34.42 E	37.59 N	1229	362,861	92,929	2467
Gaziantep	37.22 E	37.05 N	843	2,069,364	400,637	1751
Kars	43.10 E	40.61 N	1768	285,410	62,971	4253
Erzurum	41.27 E	39.90 N	1890	762,062	168,074	4339
Ağrı	43.02 E	39.62 N	1640	536,199	87,671	4050

building material instead of brick or similar building elements. The first type of wall consisted of inner plaster, TS EN 771-1 horizontal type perforated brick [34], and outer plaster. The second type of wall consisted of the inner plaster, the composite insulation material produced, and the outer plaster (Fig. 5). The properties of the walls are presented in Table 4.

2.4 Parameters Used in Calculations

2.4.1 Fuels

In this study, research has been made according to four different fuel types and the information related to these fuels are presented in Table 5.

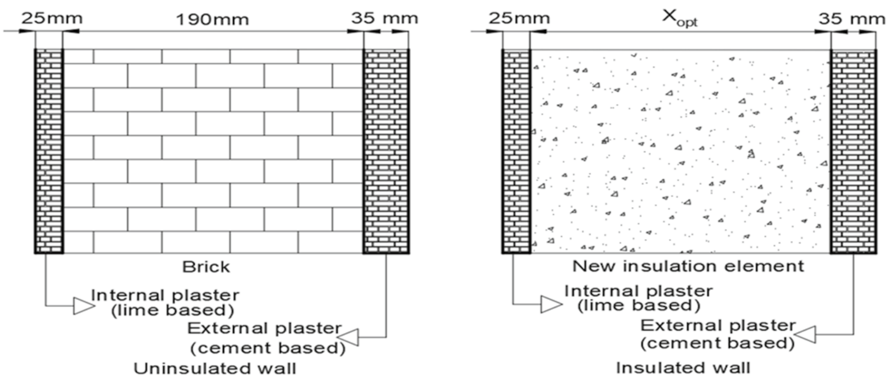

Fig. 5 The reference and the insulated walls

Table 4 Physical properties of exterior wall elements [26, 27, 35]

Wall structure	Pressure resistance (MPa)	Density (kg·m^{-3})	Thickness (m)	k (W·m^{-1} K^{-1})	R (m^{2}KW^{-1})
Internal plaster (lime-based)	–	1200	0.025	0.87	0.029
Brick	≥ 13.2	750	0.190	0.50	0.380
External plaster (cement-based)	–	2100	0.035	1.40	0.025
R_i	–	–	–	–	0.130
R_o	–	–	–	–	0.040
$R_{w,t}$ (uninsulated)	–	–	–	–	0.604
FIM	14.14	0.933	0.01	0.167	0.060
SIM	22.05	1.5221	0.01	0.311	0.032
TIM	33.25	1.983	0.01	0.468	0.021

Table 5 Used fuels and their properties [36–38]

Fuel	Hu	η	Price (C_{fuel})
Natural Gas	34,485,000 J·m^{-3}	0.90	0.234 $ ·m^{-3}
Coal	25,080,000 J·kg^{-1}	0.65	0.176 $·kg^{-1}
Fuel–oil	40,546,000 J·kg^{-1}	0.80	0.525 $·kg^{-1}
LPG	45,980,000 J·kg^{-1}	0.88	0.548 $·kg^{-1}

Table 6 Financial values [39]

Parameters	
Interest rate (i)	12.1 %
Inflation rate (g)	11.2 %
Life cycle (N)	10 years
Present Worth Factor (PWF)	9.569

2.4.2 Financial Values

In this study, the life cycle cost analysis method was used to determine the optimum insulation thickness, and the interest rate, inflation rate, system life, and current value factor are presented in Table 6.

2.5 Determination of Heating Load and Optimum Insulation Thickness

Heat loss from the unit surface of any wall can be calculated from Eq. 1:

$$q = Ux\Delta T. \tag{1}$$

In Eq. 1, the U thermal conductivity coefficient ($Wm^{-2}\cdot K^{-1}$) and ΔT (K) are the difference between indoor and outdoor temperatures. Accordingly, annual heat losses or gains in the unit surface area of the wall can be calculated from Eqs. 2 and 3 by using U and Degree-day values [1, 2, 40]:

$$q_{year,H} = 86400xHDDxU. \tag{2}$$

$$q_{year,C} = 86400xCDDxU. \tag{3}$$

where $q_{year,H}$ represents annual heat loss in heating; $q_{year,C}$ (Wm^{-2}) represents the annual heat loss in cooling. The formulas given in Eqs. 4 and 5 were used to determine the total thermal conductivity coefficient:

$$U = \frac{1}{R_i + R_w + R_o}, \tag{4}$$

$$U = \frac{1}{R_i + R_{ins} + R_o}. \tag{5}$$

Equation 4 gives the total thermal conductivity coefficient for the wall without thermal insulation, while Eq. 5 gives the total thermal conductivity coefficient for the wall with a thermal insulation element (without bricks). In these equations, R_i and R_o indicate the heat resistance coefficients of the internal and external environment, while R_w and R_{ins} indicate the thermal conductivity resistance coefficients of the non-insulated wall and the insulated wall, respectively. R_{ins}, which indicates the thermal resistance of the insulation, can be calculated with the formula given in Eq. 6:

$$R_{ins} = \frac{x}{k}. \tag{6}$$

The term x given in Eq. 6 indicates the insulation thickness (m) and k indicates the thermal conductivity coefficient ($Wm^{-1}\cdot K^{-1}$) of the insulation. Also, for a wall without thermal insulation, the total thermal resistance can be calculated by Eq. 7:

$$R_{w,t} = R_i + R_w + R_o. \tag{7}$$

Total annual heating energy requirement for the heating season $E_{year,H}$ can be calculated with the formula given in Eq. 8 [1]:

$$E_{year,H} = \frac{86400xHDD}{\left(R_{w,t} + R_{ins}\right)x\eta}. \tag{8}$$

With the insulation processes applied on the exterior surfaces of the buildings, it is possible to prevent heat loss or gain from the exterior surfaces per unit area according to the season. However, it is essential to select the insulation element that will provide this saving in optimum thickness. Otherwise, the process may be far from being economical even it performs the insulation task. Therefore, cost analysis is essential to determine the optimum insulation thickness. Annual energy costs from the unit surfaces of the exterior walls are given in Eq. 9 for the heating season:

$$C_{A,H} = \frac{86400xHDDxC_{fuel}}{\left(R_{w,t} + R_{ins}\right)xHux\eta}, \tag{9}$$

where $C_{A,H}$, is the total heating cost ($\$m^{-2}$-year). *Hu* refers to the lower thermal value (heating value) of the fuel according to the type of fuel used. The efficiency of the heating system is expressed with the symbol η. The life cycle cost analysis method was used to determine the optimum insulation thickness. The annual energy cost was calculated based on the life of the insulation elements and the current value factor [1, 2, 41]. The current value factor according to inflation and interest rates was calculated by Eqs. 10, 11, 12, and 13:

If $i > g$,

$$r = \frac{i - g}{1 + g}. \tag{10}$$

If $i < g$,

$$r = \frac{g - i}{1 + i}, \tag{11}$$

$$PWF = \frac{(1 + r)^N - 1}{rx(1 + r)^N}. \tag{12}$$

If $i = g$,

$$PWF = \frac{N}{1 + i}. \tag{13}$$

In addition, the statement giving the cost of insulation is presented in Eq. 14:

$$C_{ins} = C_y \times x. \tag{14}$$

According to the life cycle cost analysis of an insulated building, the total heating cost is given in Eq. 15, respectively [1]:

$$C_{t,H} = C_{A,H} \times PWF + C_y \times x. \tag{15}$$

The expression that gives the optimum insulation thickness that will minimize the total heating cost for the heating season is given in Eq. 16 [1, 2, 41]:

$$X_{opt,_H} = 293.94 \times \left(\frac{HDD \times C_{fuel} \times PWF \times k}{Hu \times C_y \times \eta} \right)^{1/2} - k \times R_{w,_t}. \tag{16}$$

The calculations of the annual net savings to be obtained with the insulation material to be applied to the buildings are presented in the equations below. Accordingly, the net earnings from heating during the heating season are given in Eq. 17, and the expression referring to the payback periods for this term is given in Eq. 18:

$$S_{year,_H} = C_H - C_{t,_H}, \tag{17}$$

$$S_{PP,_H} = \frac{C_{ins}}{S_{year_H}}. \tag{18}$$

2.6 Uncertainty Analyses

In the experimental studies, an uncertainty analysis was performed for the heat conduction coefficient, water absorption and drying amounts, compression, and tensile strength tests of the samples in order to give information about the degrees and amounts of possible uncertainties. The uncertainty values of the measured quantities were determined theoretically by making use of the uncertainty values recommended by the manufacturers of the measuring instruments and the calibration studies and experimental experiences. Fixed errors and random errors were been taken into account for uncertainty analysis. Errors that occur due to manufacturing errors were not been taken into account. In this case, the total error calculation has been obtained with the help of Eq. 19. Also, uncertainty values that may arise for each independent variable are presented in Table 7.

$$W_R = \left[\left(\frac{\partial R}{\partial_{x1}} w_1 \right)^2 + \left(\frac{\partial R}{\partial_{x2}} w_2 \right)^2 + \ldots \left(\frac{\partial R}{\partial_{xn}} w_n \right)^2 \right]^{1/2}, \tag{19}$$

where R is a function of the independent variables $x_1, x_2, \ldots x_n$ and $w_1, w_2, \ldots, w_n$ are the uncertainty of the independent variables.

Error parameters that may occur during the experiments are presented in Table 7 and the magnitudes of possible errors were calculated with the help of Eq. 19. Accordingly, the values obtained are given in Table 8.

When the magnitude of the error values given in Table 8 was compared, it was determined that the greatest possible error value that could occur during experiments could occur during measurements of the heat conduction coefficient. Accordingly, it was calculated that the total error value that may occur in the measurement of the heat conduction coefficient will be between ± 0.059 $Wm^{-1}\cdot K^{-1}$–0.067 $Wm^{-1}\cdot K^{-1}$. From these values, it can be seen that the experimental measurements have acceptable accuracy sensitivity.

3 Results and Discussion

In this study, insulation thickness was calculated to prevent the heat losses that will occur in the heating of the buildings. Three different insulation materials (FIM, SIM, and TIM) which have been developed for determining the insulation

Table 7 Possible error parameters that may occur in experiments

Error parameters	Error	Unit
Uncertainties caused by the measurement of heat conduction coefficient		
Uncertainty caused by the measuring probe	±0.02	$Wm^{-1}\cdot K^{-1}$
Uncertainty due to set resistance (potentiometer)	±0.01	$Wm^{-1}\cdot K^{-1}$
Uncertainty caused by microcomputer	±0.01	$Wm^{-1}\cdot K^{-1}$
Uncertainty due to the structure and transmission ability of the hot wire	±0.02	$Wm^{-1}\cdot K^{-1}$
Uncertainty due to heat conduction coefficient measuring device	±0.05–0.06	$Wm^{-1}\cdot K^{-1}$
Uncertainties caused by time measurement		
Uncertainty due to the vibration of the timer	±0.001	s
Uncertainty due to the residence time of the samples in water	±0.1	s
Uncertainty due to the drying time of samples	±0.1	s
Uncertainties caused by the measurement of weight losses		
Uncertainty caused by a precision scale	±0.001	g
Uncertainty caused by the reader	±0.01	g
Uncertainty caused by the friction of samples to the abrasive disc	±0.03	g
Uncertainty caused by water absorption experiments of samples	±0.02	g
Uncertainty caused by drying experiments of samples	±0.01	g
Uncertainties arising from compressive and tensile strength measurement		
Uncertainty caused by the precision of the compression experiment device	±0.02	$kgf\cdot cm^{-2}$
Uncertainty caused to the load applied to the samples	±0.02	$kgf\cdot cm^{-2}$
Uncertainty caused by the reader during compression–tensile stress measurements	±0.02	$kgf\cdot cm^{-2}$
Uncertainty in the cross-sectional area of the samples		
Uncertainty caused by cross-sectional area measurements of prepared samples	±0.002	cm^2

Table 8 Values of possible errors that may occur in experiments

Error parameters	Error	Unit
Uncertainties caused by the measurement of heat conduction Coefficient	±0.059–0.067	$Wm^{-1}\cdot K^{-1}$
Uncertainties caused by time measurement	±0.014	s
Uncertainties caused by the measurement of weight losses	±0.039	g
Uncertainties arising from compressive and tensile strength Measurement	±0.035	$Kgf\cdot cm^{-2}$
Uncertainty in the cross-sectional area of the samples	±0.002	cm^2

thickness were examined and compared. X_{opt} (optimum insulation thickness) stated in the calculations refers to the thickness of the insulation material to be used, that is, the material that will replace the brick. Hence, it is accepted that the insulation material thicknesses up to 0.40 m can be used for the insulation thickness to be practically feasible. Insulation material thicknesses above 0.40 m are shown in bold. Thus, it can be easily seen in Table 9 that material thicknesses without coloring are practically feasible.

3.1 Examination of Insulation Thickness Change According to HDD Values

It was investigated how three different insulation materials changed according to the type of fuel used based on the number of heating degree days (HDDs) for 12 provinces determined in accordance with Turkish Standard TS 825. The results are presented in Table 7.

When Table 9 is examined, it is seen that the first insulation material (FIM) is suitable for regions whose HDD values are between 1000 and 3000 for natural gas use, it is suitable for regions whose HDD values are between 1000 and 2000 for coal use, and it is suitable for regions whose HDD values are up to 1000 for regions for fuel oil use. Likewise, in buildings heated with LPG, it is suitable for use where HDD values are between 1000 and 2000. It was determined that the insulation thickness of the second type of insulation material (SIM) is not among the accepted values for buildings heated by using fuel–oil. Likewise, it is seen that the third type of material (TIM) is suitable only for regions heated by natural gas and with HDD values up to 1000.

Table 9 X_{opt} change according to fuel type and HDD values

HDD	Natural gas	Coal	Fuel–oil	LPG
FIM ($k=0.167\ Wm^{-1}\cdot K^{-1}$) X_{opt} (m)				
1000	0.196	0.242	0.305	0.276
2000	0.294	0.358	0.447	0.406
3000	0.368	0.447	0.556	0.506
4000	0.431	0.522	0.648	0.590
5000	0.486	0.588	0.729	0.664
6000	0.536	0.648	0.802	0.731
SIM ($k=0.311\ Wm^{-1}\cdot K^{-1}$) X_{opt} (m)				
1000	0.205	0.309	0.439	0.3958
2000	0.319	0.466	0.649	0.588
3000	0.406	0.587	0.811	0.736
4000	0.480	0.688	0.947	0.861
5000	0.544	0.778	1.067	0.971
6000	0.603	0.859	1.162	1.070
TIM ($k=0.468\ Wm^{-1}\cdot K^{-1}$) X_{opt} (m)				
1000	0.389	0.485	0.617	0.556
2000	0.593	0.729	0.917	0.830
3000	0.750	0.917	1.146	1.040
4000	0.883	1.075	1.340	1.217
5000	0.999	1.214	1.511	1.374
6000	1.105	1.340	1.665	1.515

3.2 Examining the Insulation Thicknesses According to the Selected Provinces

When three different materials produced are used in 12 provinces and with four different fuels, the material thickness (X_{opt}) that will minimize the heating cost was obtained with the help of Eq. 16. The results are presented in Table 10. Moreover, the change of insulation thickness by cities is given in Fig. 6.

When Table 10 is examined, it can be seen that the materials produced require insulation thicknesses greater than 0.40 m, which is the insulation thickness accepted for provinces with an HDD value greater than 4050, and therefore, it is difficult or impossible to apply it for these provinces. It was determined that the first insulation material (FIM) with the lowest thermal conductivity coefficient was used more than others in the application, whereas the third insulation material (TIM) was only suitable in Antalya and for natural gas heating systems.

When Fig. 6 and Table 10 are examined together, it is seen that the thickness of the insulation material increases with the increase in the number of heating degree days (HDDs), and the insulation thickness is thinner in the materials with a low thermal conductivity coefficient of the insulation material. When a comparison was made among all three materials, it was determined that the material price decreased as the thermal conductivity coefficient increased; however, it was not applicable in practice. Especially in provinces where HDD values vary between 1000 and 2000, these materials seem to be more functional for use in heating.

3.3 Examining the Heating Energy Requirements of the Buildings in the Selected Provinces

The heating energy requirements of the buildings in the selected provinces were calculated with the help of Eq. 8 according to the reference wall given in Fig. 5, and the values found are given in Table 11. The comparison of the heating energy requirements of the uninsulated building walls according to four different fuel types is presented in Fig. 7.

A comparison of the amount of energy required to heat the unit surface areas of the exterior walls of buildings in 12 provinces during the heating season is given in Fig. 7. When Fig. 7 is examined, it can be seen that the amount of energy to be spent in heating increases as the efficiency of the fuel used in heating decreases. Furthermore, considering the X_{opt} values given in Table 10 and the type of fuel used, the energy values required for heating in 12 provinces are given in Table 12.

3.4 Examining Financial Values

In the heating process carried out using four different fuels in 12 selected provinces, the annual heating energy costs required when the buildings are not insulated are calculated with the help of Eq. 9, and the values found are presented in Table 13 and Fig. 8.

Table 10 X_{opt} values according to the fuel and material type

X_{opt} (m)													
City	HDD	FIM				SIM				TIM			
		NG	Coal	Fuel–oil	LPG	NG	Coal	Fuel–oil	LPG	NG	Coal	Fuel–oil	LPG
İstanbul	1865	0.282	0.345	*0.431*	0.391	0.405	*0.498*	*0.625*	*0.566*	*0.569*	*0.701*	*0.882*	*0.798*
Bursa	1497	0.249	0.305	0.382	0.346	0.355	*0.439*	*0.553*	*0.499*	*0.499*	*0.617*	*0.779*	*0.704*
İzmir	1119	0.210	0.259	0.325	0.294	0.298	0.370	*0.468*	*0.422*	*0.417*	*0.520*	*0.660*	*0.594*
Muğla	1705	0.268	0.328	*0.410*	0.372	0.384	*0.473*	*0.595*	*0.538*	*0.540*	*0.666*	*0.839*	*0.758*
Antalya	788	0.170	0.211	0.267	0.241	0.238	0.299	0.382	0.343	0.333	*0.419*	*0.537*	*0.482*
Ankara	2169	0.307	0.375	*0.468*	*0.424*	*0.442*	*0.542*	*0.679*	*0.615*	*0.622*	*0.764*	*0.960*	*0.869*
Sivas	2862	0.359	*0.436*	*0.543*	*0.493*	*0.518*	*0.633*	*0.791*	*0.717*	*0.730*	*0.894*	*1.118*	*1.014*
Niğde	2467	0.330	*0.402*	*0.501*	*0.455*	*0.476*	*0.583*	*0.729*	*0.661*	*0.670*	*0.822*	*1.030*	*0.933*
Gaziantep	1751	0.272	0.333	*0.416*	0.377	0.390	*0.480*	*0.603*	*0.546*	*0.548*	*0.676*	*0.851*	*0.770*
Kars	4253	*0.445*	*0.540*	*0.670*	*0.609*	*0.647*	*0.787*	*0.979*	*0.890*	*0.913*	*1.112*	*1.386*	*1.259*
Erzurum	4339	*0.450*	*0.546*	*0.677*	*0.616*	*0.654*	*0.796*	*0.990*	*0.899*	*0.924*	*1.125*	*1.401*	*1.272*
Ağrı	4050	*0.434*	*0.526*	*0.653*	*0.594*	*0.629*	*0.766*	*0.954*	*0.867*	*0.839*	*1.083*	*1.350*	*1.226*

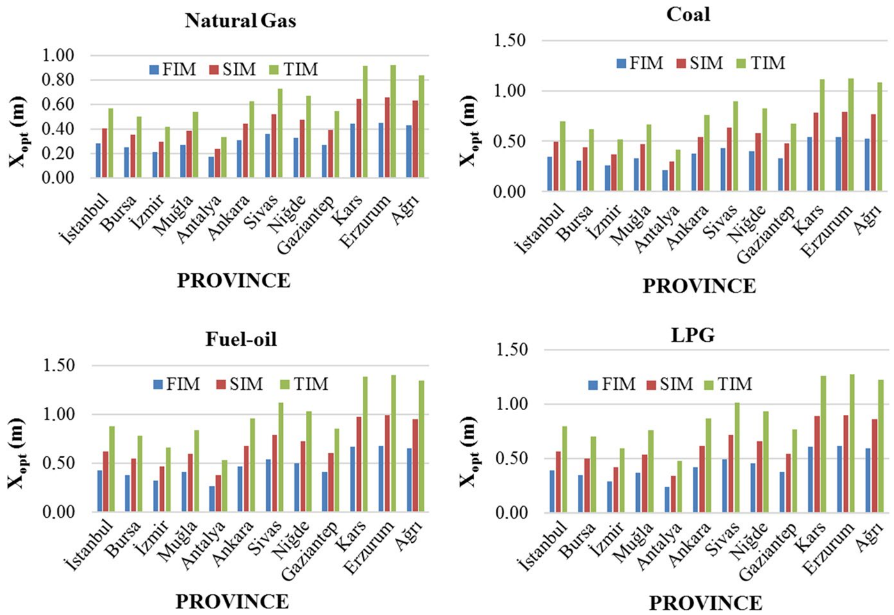

Fig. 6 The change of thickness of three different insulation materials according to the type of fuel used in the selected provinces

Table 11 Annual heating energy values for the unit surface area of non-insulated outer walls

Uninsulated Wall (Reference wall) $E_{year,H}$ (kJ·m^{-2}-year)					
Province	HDD	NG	Coal	Fuel–oil	LPG
İstanbul	1865	296,420	410,430	333,480	303,160
Bursa	1497	237,930	329,450	267,680	243,340
İzmir	1119	177,850	246,260	200,090	181,900
Muğla	1705	270,990	375,220	304,870	277,150
Antalya	788	125,250	173,420	140,900	128,090
Ankara	2169	344,740	477,330	387,830	352,580
Sivas	2862	454,890	629,840	511,750	465,230
Niğde	2467	392,110	542,920	441,120	401,020
Gaziantep	1751	278,300	385,340	313,090	284,630
Kars	4253	675,970	935,960	760,470	691,340
Erzurum	4339	689,640	954,890	775,850	705,320
Ağrı	4050	643,710	891,290	724,170	658,340

When Fig. 8 is examined, it is seen that the most suitable fuel type to be used for heating uninsulated buildings is natural gas and the costliest fuel type is fuel oil. It is seen that the cost of heating is directly proportional to the HDD number and the cost of fuel increases with the increase of the HDD number. Besides, by applying insulation to the exterior walls, the insulation costs of the exterior walls

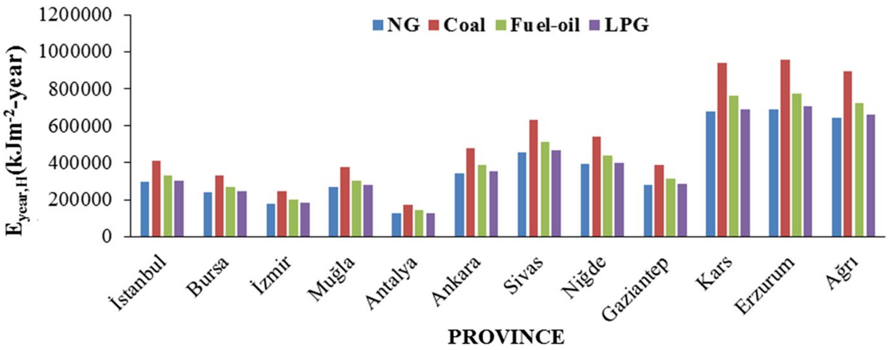

Fig. 7 Comparison of the heating energy requirements of the reference walls in the selected provinces by fuel type

in the selected provinces by considering each fuel type and the insulation material used were calculated using Equality 14 and are given in Table 14.

The comparison of the insulation costs for the cities that are considered to be suitable in practice for the insulation application is shown in Table 10 and is given in Fig. 9. In Fig. 9, it can be seen that the most suitable province where novel developed composite materials can be used as insulation elements in heating is Antalya (HDD = 788). For Kars, Erzurum, and Ağrı (HDD = 4253, 4339, and 4050, respectively) in the Eastern Anatolian region, the insulation materials cannot be applied in practice, whereas for Sivas (HDD = 2862) and Niğde (HDD = 2467), the first insulation material (k = 0.167 Wm^{-1} K^{-1}) can be applied for heating with natural gas. In addition, it is seen that the province that requires the highest insulation cost is Bursa (HDD = 1497) when the first insulation material (FIM) is used and Fuel–oil or LPG is used for heating. The lowest insulation cost is in Antalya when the first insulation material and natural gas is used for heating.

The payback period of the insulation cost values found for the provinces where novel produced composite materials will be applied is given in Table 15.

When Fig. 10 is examined, it is seen that in cities with a large number of HDD, the insulation cost payback period is less than cities with a smaller number of HDD. This can be explained by the fact that more heating energy is saved and the cost of the fuel used decreases due to the higher temperature difference between the exterior walls and the ambient air.

4 Conclusion

In Turkey, insulation is usually applied to buildings for heating. For this reason, in this study, the insulation thickness calculation was made only for the heated buildings. In calculations, three different insulation elements, partially produced from waste materials to provide an alternative to conventional insulation elements, were compared in terms of insulation thickness, net saving amount, payback period, and usability. Although the production costs of the new insulation elements produced

Table 12 Annual heating energy values for the unit surface area of insulated exterior walls according to X_{opt} values

Province	HDD	NG	COAL	FUEL–OIL	LPG
FIM $E_{year,H}$ (kJ·m^{-2}-year)					
İstanbul	1865	61,219	84,764	68,871	62,610
Bursa	1497	49,139	68,039	55,281	50,256
İzmir	1119	36,731	50,859	41,323	37,566
Muğla	1705	55,967	77,492	62,962	57,239
Antalya	788	25,866	35,815	29,099	26,454
Ankara	2169	41,655	57,676	46,862	42,602
Sivas	2862	93,945	13,008	10,569	96,080
Niğde	2467	80,979	11,213	91,102	82,820
Gaziantep	1751	57,477	79,583	64,661	58,783
Kars	4253	13,960	19,330	15,706	14,278
Erzurum	4339	14,243	19,721	16,023	14,566
Ağrı	4050	13,294	18,407	14,956	13,596
SIM $E_{year,H}$ (kJ·m^{-2}-year)					
İstanbul	1865	106,940	148,080	120,310	109,370
Bursa	1497	858,410	118,860	965,710	877,920
İzmir	1119	641,660	888,450	721,870	656,240
Muğla	1705	977,680	135,370	109,990	999,900
Antalya	788	451,860	625,650	508,340	462,130
Ankara	2169	727,670	100,750	818,630	744,210
Sivas	2862	164,110	227,230	184,630	167,840
Niğde	2467	141,460	195,870	159,150	144,680
Gaziantep	1751	100,410	139,020	112,960	102,690
Kars	4253	243,880	337,670	274,360	249,420
Erzurum	4339	248,810	344,500	279,910	254,460
Ağrı	4050	232,240	321,560	261,270	237,510
TIM $E_{year,H}$ (kJ·m^{-2}-year)					
İstanbul	1865	150,750	208,730	169,590	154,170
Bursa	1497	121,000	167,540	136,130	123,750
İzmir	1119	904,490	125,240	101,760	925,050
Muğla	1705	137,820	190,820	155,040	140,950
Antalya	788	636,940	881,920	716,560	651,420
Ankara	2169	102,570	142,020	115,400	104,900
Sivas	2862	231,340	320,310	260,250	236,590
Niğde	2467	199,410	276,100	224,330	203,940
Gaziantep	1751	141,530	195,970	159,230	144,750
Kars	4253	343,770	475,990	386,740	351,580
Erzurum	4339	350,720	485,620	394,560	358,690
Ağrı	4050	327,360	453,270	368,280	334,800

Table 13 Annual heating cost per unit surface area of uninsulated walls

$C_{A,H}$ ($\$m^{-2}$-year)					
Province	HDD	NG	COAL	FUEL–OIL	LPG
İstanbul	1865	13.753	19.637	29.444	24.659
Bursa	1497	11.039	15.763	23.634	19.793
İzmir	1119	8.251	11.782	17.666	14.795
Muğla	1705	12.573	17.953	26.918	22.543
Antalya	788	5.811	8.297	12.440	10.418
Ankara	2169	15.995	22.839	34.243	28.678
Sivas	2862	21.105	30.136	45.184	37.841
Niğde	2467	18.192	25.976	38.948	32.618
Gaziantep	1751	12.912	18.437	27.644	23.151
Kars	4253	31.363	44.782	67.145	56.233
Erzurum	4339	31.997	45.688	68.503	57.370
Ağrı	4050	29.866	42.645	63.940	53.549

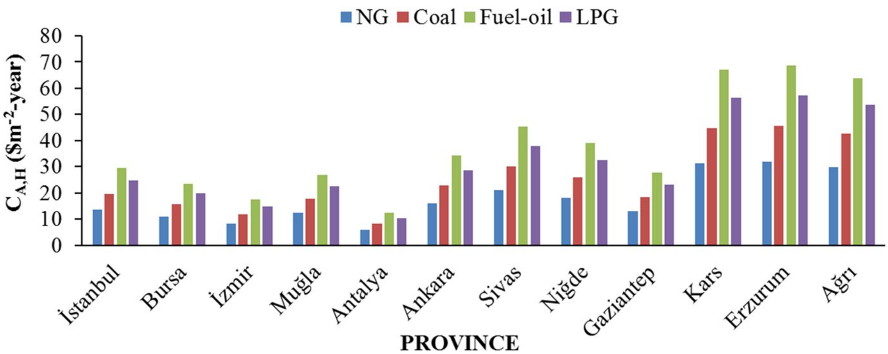

Fig. 8 Comparison of the annual heating cost per unit surface area of uninsulated walls

are quite low compared to traditional insulation materials, the thermal conductivity coefficients are much higher than conventional insulation materials. However, considering the features such as the new materials produced being lightweight construction materials and being produced from waste materials, especially non-combustible materials, they offer practical usage advantages. The results obtained from the study are presented below as items:

- The X_{opt} values calculated for the new materials produced are not only the insulation thickness but the total wall thickness excluding the interior and exterior plasters. The X_{opt} values determined vary between 0.170 and 1.401 m for the selected 12 provinces and four different types of fuels for which usability is considered. It has been accepted that X_{opt} values above 0.40 m cannot be applied in practice.

Table 14 Insulation cost of X_{opt} thickness insulated walls

PROVINCE	HDD	FIM	SIM	TIM
Naturel Gas $C_{ins, H}$ ($\$m^{-2}$-year)				
İstanbul	1865	36.738	44.561	46.715
Bursa	1497	32.409	39.127	40.959
İzmir	1119	27.365	32.791	34.243
Muğla	1705	34.918	42.262	44.288
Antalya	788	22.178	26.279	27.355
Ankara	2169	40.001	48.653	51.053
Sivas	2862	46.670	57.024	59.917
Niğde	2467	42.978	52.393	55.014
Gaziantep	1751	35.451	42.933	44.993
Kars	4253	57.954	71.192	74.923
Erzurum	4339	58.591	71.984	75.768
Ağrı	4050	56.446	69.289	68.806
Coal $C_{ins, H}$ ($\$m^{-2}$-year)				
İstanbul	1865	44.850	54.736	57.498
Bursa	1497	39.676	48.246	50.619
İzmir	1119	33.644	40.667	42.599
Muğla	1705	42.666	51.997	54.596
Antalya	788	27.443	32.901	34.366
Ankara	2169	48.750	59.631	62.681
Sivas	2862	56.719	69.641	73.275
Niğde	2467	52.312	64.108	67.420
Gaziantep	1751	43.303	52.800	55.440
Kars	4253	70.200	86.570	91.209
Erzurum	4339	70.954	87.516	92.209
Ağrı	4050	68.393	84.293	88.798
Fuel–oil $C_{ins, H}$ ($\$m^{-2}$-year)				
İstanbul	1865	56.004	68.750	72.332
Bursa	1497	49.673	60.786	63.911
İzmir	1119	42.289	51.524	54.087
Muğla	1705	53.339	65.395	68.782
Antalya	788	34.697	42.009	44.009
Ankara	2169	60.775	74.734	78.679
Sivas	2862	70.538	86.988	91.651
Niğde	2467	65.143	80.212	84.476
Gaziantep	1751	54.119	66.374	69.815
Kars	4253	87.061	107.723	113.611
Erzurum	4339	87.984	108.878	114.841
Ağrı	4050	84.838	104.940	110.659
LPG $C_{ins, H}$ ($\$m^{-2}$-year)				
İstanbul	1865	50.843	62.260	65.461
Bursa	1497	45.045	54.989	57.753
İzmir	1119	38.285	46.497	48.774

Table 14 (continued)

PROVINCE	HDD	FIM	SIM	TIM
Muğla	1705	48.399	59.191	62.213
Antalya	788	31.343	37.785	39.540
Ankara	2169	55.211	67.749	71.274
Sivas	2862	64.142	78.958	83.148
Niğde	2467	59.202	72.754	76.580
Gaziantep	1751	49.114	60.093	63.165
Kars	4253	79.261	97.933	103.246
Erzurum	4339	80.106	98.989	104.370
Ağrı	4050	77.220	95.381	100.540

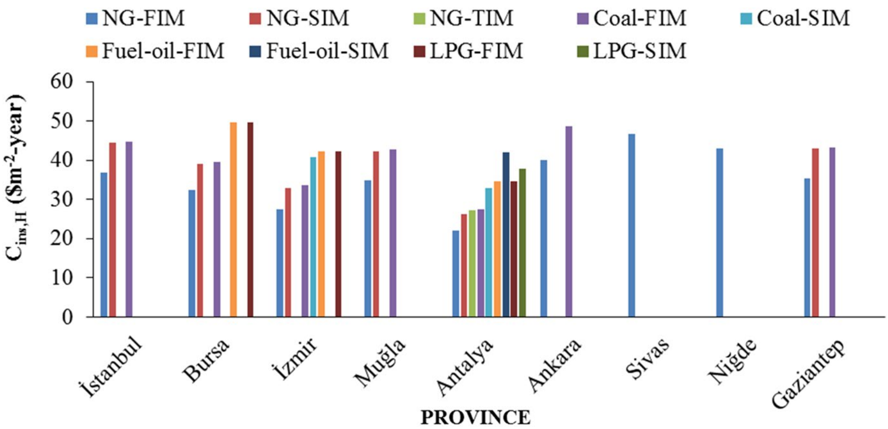

Fig. 9 Insulation costs of cities where insulation can be applied

- It has been determined that the first type of insulation material (FIM) produced is suitable for use with natural gas in provinces with HDD values between 1000 and 3000. In addition, it has been determined that the second type of material (SIM) produced is not suitable for buildings heated by fuel oil and the third type of insulation material (TIM) produced is suitable only for provinces heated with natural gas and with HDD values below 1000.
- It has been determined that the use of all three materials would not be practical in provinces with HDD values of 4050 and above.
- Antalya (HDD = 788) has been determined as the most suitable city to use the insulation materials produced.
- It has been determined that if the insulation materials are used in the provinces where they are accepted as suitable, the payback period varies between 2.5 and 6.5 years.

Table 15 Payback periods of walls insulated with X_{opt} thickness

PROVINCE	HDD	FIM	SIM	TIM
Naturel Gas $S_{PP,H}$ (year)				
İstanbul	1865	3.367	4.375	4.683
Bursa	1497	3.700	4.786	5.116
İzmir	1119	4.180	5.366	5.722
Muğla	1705	3.501	4.539	4.857
Antalya	788	4.811	6.106	6.491
Ankara	2169	3.152	4.107	4.401
Sivas	2862	2.787	3.648	3.914
Niğde	2467	2.978	3.889	4.170
Gaziantep	1751	3.331	4.490	4.805
Kars	4253	2.329	3.065	3.294
Erzurum	4339	2.308	3.038	3.265
Ağrı	4050	2.382	3.133	3.177
Coal $S_{PP,H}$ (year)				
İstanbul	1865	2.761	4.012	5.177
Bursa	1497	3.043	4.405	5.678
İzmir	1119	3.452	4.968	6.393
Muğla	1705	2.873	4.168	5.377
Antalya	788	3.999	5.707	7.324
Ankara	2169	2.581	3.758	4.853
Sivas	2862	2.276	3.325	4.299
Niğde	2467	2.435	3.552	4.589
Gaziantep	1751	2.840	4.122	5.317
Kars	4253	1.895	2.782	3.601
Erzurum	4339	1.878	2.757	3.569
Ağrı	4050	1.939	2.845	3.682
Fuel–oil $S_{PP,H}$ (year)				
İstanbul	1865	2.215	2.838	2.987
Bursa	1497	2.447	3.126	3.329
İzmir	1119	2.787	3.545	3.769
Muğla	1705	2.307	2.953	3.146
Antalya	788	3.248	4.104	4.355
Ankara	2169	2.067	2.653	2.829
Sivas	2862	1.818	2.340	2.497
Niğde	2467	1.948	2.503	2.670
Gaziantep	1751	2.280	2.918	3.109
Kars	4253	1.510	1.950	2.083
Erzurum	4339	1.496	1.932	2.064
Ağrı	4050	1.545	1.995	2.131
LPG $S_{PP,H}$ (year)				
İstanbul	1865	2.438	3.132	3.340
Bursa	1497	2.691	3.446	3.671
İzmir	1119	3.060	3.898	4.148

Table 15 (continued)

PROVINCE	HDD	FIM	SIM	TIM
Muğla	1705	2.539	3.257	3.472
Antalya	788	3.557	4.498	4.775
Ankara	2169	2.276	2.930	3.127
Sivas	2862	2.004	2.588	2.765
Niğde	2467	2.146	2.766	2.954
Gaziantep	1751	2.509	3.219	3.433
Kars	4253	1.667	2.160	2.310
Erzurum	4339	1.651	2.140	2.289
Ağrı	4050	1.705	2.209	2.362

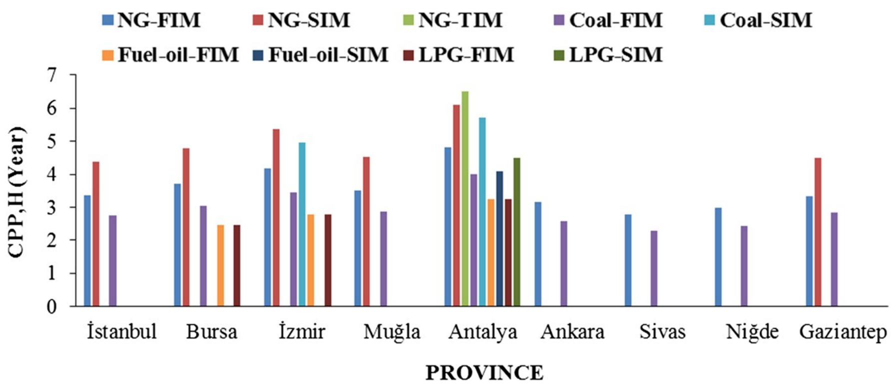

Fig. 10 Comparison of payback periods of walls insulated with X_{opt} thickness

According to the results obtained, X_{opt} change according to the fuel type and HDD values of the insulating materials examined showed a similar trend with the studies examined in the literature [1, 2, 5, 15]. Besides, in this study, it was determined that the insulation cost values varied between 22.841 and 114.841 $\$m^{-2}$ and the payback period between 2.5 and 6.5 years. When the results obtained were compared with the studies performed, it was determined in the studies conducted in the literature that the payback periods ranged between 1.9 and 6.1 years [2, 15, 16]. In this context, the payback periods were considered to be within the appropriate range. However, one of the most important features of this study is that the calculations made for the new types of insulation materials are not only the insulation thickness but also the total wall thickness except for interior and exterior plasters. Considering the reasons mentioned above and properties, such as convenience to apply during the construction phase, not requiring extra labor fee, sufficient mechanical properties, cheap production, and most importantly non-flammability, it is assumed that it is advantageous to use new types of insulation materials in the regions where they are applicable in terms of insulation.

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