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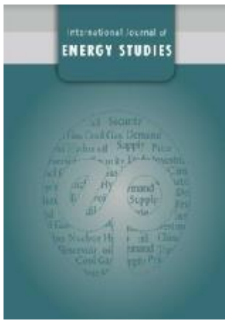

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Alternative heat insulation method for rigid construction walls

Abdullah Dağdeviren[a,*], Bahadır Acar[b], Murat Aydın[c]

[a]*Karabuk University, Technology Faculty, Energy Systems Engineering, 0000-0002-5418-4445*

[b]*Karabuk University, Technology Faculty, Energy Systems Engineering, 0000-0002-9494-6301*

[c]*Karabuk University, Technology Faculty, Industrial Design Engineering, 0000-0003-4654-8293*

*(*Corresponding Author: abdullahdagdeviren@karabuk.edu.tr)*

Highlights

- An alternative heat insulation methodology is presented for rigid construction walls.
- Various heat insulation materials are compared in terms of thermal conductivtiy and efficiency as well.
- The mathematical approach and experimental procedure are given to calculate the thermal conductivity coefficient.

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ABSTRACT

The purpose of heat insulation is to minimize the heat transfer between the interior and external environment. Besides, it helps to prevent the structure of the constructions from the harmful heat effects because of heat transfer. This study presents an alternative method to achieve heat insulation in concrete walls. 4 various heat insulation materials as wood shavings, fiberglass, granule rubber, and styrofoam were added into the concrete wall parts and an enclosed volume was created using those. The interior temperature of the enclosed volume increased using resistance and the temperature was measured with a thermocouple as well. In order to calculate the thermal conductivity of heat-insulated walls, measured temperature, power consumption, and surface area were used. As a result, it was shown that the wood shavings insulation in concrete had a lower thermal conductivity coefficient as 2,51 W/mK than others and much efficiency as well. In addition, the uncertainty of the thermal conductivity coefficient was calculated approximately about ± 0,204 for all type of walls. Besides, the presented methodology could help to prevent lacking energy resources and to save economical incomes.

Keywords: *Heat Insulation, Heat Transfer, Thermal Conductivity, Insulation Material, Insulation Method*

1. INTRODUCTION

Modern societies around the world have developed several methods to use and control energy resources effectively [1]. Energy consumption in Turkey has been increased dramatically by residence and industry requirements [2]. Among this increment, 30% of the total amount of energy is consumed in residences approximately. Besides, the majority of installed power is used by air conditioning systems in residences. This power consumption can be decreased by thermal insulation methods and thus, minimizing costs can be achieved as well. As the nature of heat transfer, losing heat in winter and gaining lost heat in summer makes it difficult to control energy consumption efficiently. Fossil fuels such as coal and natural gas, are generally used to get heated for sanitary living conditions in winter, and on the other hand, air conditioning systems are used to decrease the interior temperature of the residences in summer. The efficient energy consumption balance must be achieved precisely between those heating and cooling situations. Heat insulation applications have been started to use keeping the interior temperature of residence constant and minimizing the energy consumption in heating and cooling processes since the beginning of the 20th century [3]. In order to decrease energy consumption, precautions that prevent heat transfer should be taken for interior and external walls of the residence, windows and window frames, roofs, floor coverings, and pipings. The applied sheathing process according to the regulations and standards brings economizing on the costs and expenses for heating and cooling. Thanks to heat insulation techniques, the constant inner temperature of the residence is obtained at a low cost and more efficient as well. Also, the temperature differences between warm and cold interior temperatures in residences could not occur. So, the condensation is prevented and the humidity, mold, fungus, and black taints could not form. Moreover, fuel consumption, exhaust gases, and emissions are decreased by keeping the temperature constant in residences, thus, an effective contribution to the prevention of environmental pollution is performed. Although the constructions have been raised gradually, the heat insulation applications could not be performed according to the TS 825 standard regulations. Thus, energy consumption has been increased dramatically for the heating and cooling of residences. Besides, the amount of physically weak and unhealthy residences has become common. Although heat insulation is the most effective factor and stable solution for energy conservation, the problems caused by heat insulation applications noncompliance with TS 825 standard and suggestions for the solution of these problems have been developed [4]. Figure 1 shows the historical background of the regulations for heat insulation applications in Turkey.

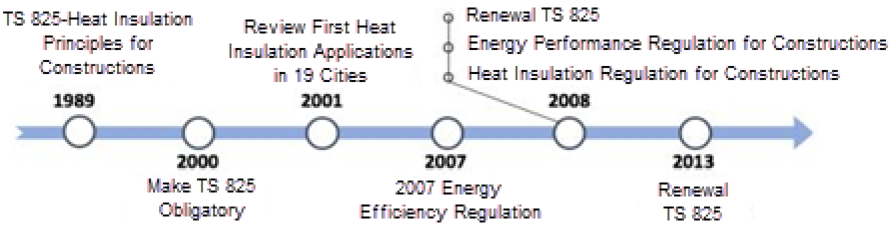

Figure 1. The historical background of the regulations for heat insulation applications in Turkey [4].

Because heat leakages are prevented by heat insulations, the heating and cooling expenses are diminished, and energy conservation is gained as well. The heat energy is produced to get heat in residence by exposing potential energy of various renewable and fossil fuel resources. This gained heat energy helps to keep the interior temperature insanitary living conditions [5]. The heat is transferred from the interior environment to the external environment because the external environment temperature is always lower than the interior temperature of the residence. Several methods of heat insulation are applied to minimize the degree of those heat losses. One of the essential heat insulations is to prevent heat losses caused by residence walls. When the heat insulation market was compared with the previous year, it grew about 20% in 2005, and end of this growth, it reached approximately about 5 million m3 volume. Although the rapid development in the heat insulation market, it is obvious that more applications must be performed when compared with AB countries and the USA. Per capita, insulation materials in those countries are about 5-15 times higher than Turkey's population. It is predicted that the monetary equivalent of energy conservation would be about 5 billion dollars if the proper heat insulation applications were performed according to the standard regulations in Turkey [1]. Ecological novel insulation materials have been in the market over the years. However, the general approach is to use traditional insulation materials widely rather than those. Many of the constructors have doubts whether the novel alternative insulation materials have better insulation performance and efficiency or not when compared with the traditional materials. Also, finding the scientific researches that support this idea is quite difficult [6]. Zach et al. [7] produced an alternative heat insulation material using sheep's wool and performed series of experiments to determine the effect on the structural and acoustic properties of the construction. They showed that developed insulation material using sheep's wool had comparable properties with the mineral and rock wool. Besides, they mentioned that developed insulation material showed better performance in some applications than traditional insulation materials. Besides, they observed that sheep's wool insulation material had less harmful in terms of ecological and sanitarian properties when it was compared with the mineral wool. Korjenic [8] studied the usage of jute, flax, and cannabis at the development of new insulation materials which were produced from renewable resources. They compared the thermal and mechanical properties of those with the traditional insulation materials. Charca et al. [9] investigated the thermal properties of grass feather which was a local and cheap insulation material, especially for rural dwellings. The thermal conductivity of developed insulation material varied between 0,047 and 0,113 W/(mK). Wei et al. [10] focused on the effect of high-frequency heating, board density, particle size, and ambient temperature on the properties of developed novel insulation material using rice straw. They showed that optimum physical and mechanical properties were achieved at a moisture content of 14% and board density of 250 kg/m^3. Besides, they determined that the thermal conductivity of developed insulation material was ranging from 0.051 to 0.053 W/(mK). Deque et al. [11] studied the evaluation of heat bridges in a computer environment based on the energy efficiency of constructions. They modeled heat transfer at the intersection of walls via Sisley computer software and integrated those models into Clim200 software. They achieved an additional sensitivity of 5% by comparing their modeling results with traditional heat transfer rules models for walls models, modeling of heat losses, and evaluation of heat losses of constructions. In the light of the above, several studies in the literature focused on alternative insulation materials in terms of developing novel materials. However, the present study exhibits a novel methodology that includes creating 4 different wall types by adding the same amount of various insulation materials directly into the concrete mixture and the heat insulation performances of those wall types as well.

2. MATERIAL AND METHOD

In the experiments, the first step was to make a rectangular shape enclosed volume using concrete flat parts for side, upper and lower sections. 4 flat parts with various insulation materials and 1 control flat part without any insulation material were produced for the front wall. Except for the front wall, the rest of the walls were produced pure concrete and during the experiments, only the front wall was changed.

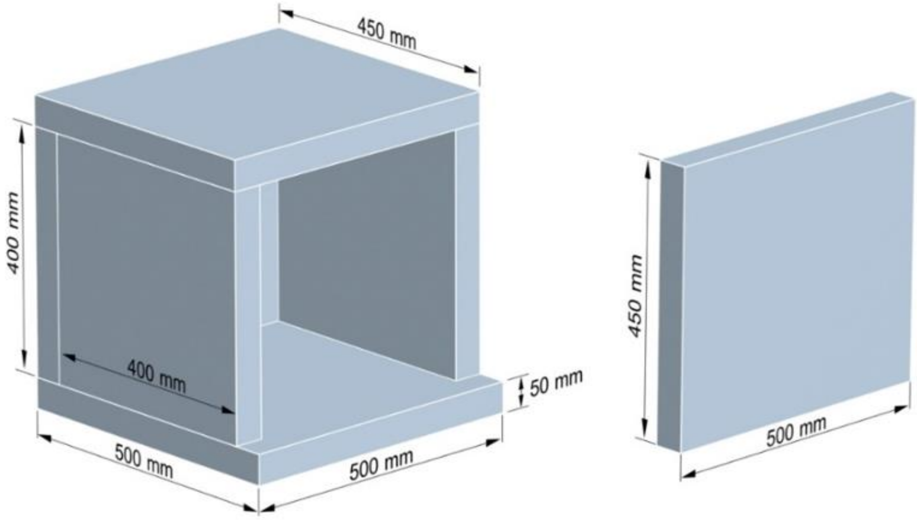

Figure 2. Dimensions of enclosed volume and various heat-insulated front parts.

Figure 3. Experimental setup.

The dimensions of the rectangular shape enclosed volume are shown in Figure 2. The flat parts bonded together and, in this way, enclosed volume was built. The volume of the enclosed room was about 0,064 m^3. Figure 3 shows the installed setup. As seen in Figure 4, to measure the interior temperature of the enclosed volume, a resistance and a thermocouple were mounted into it.

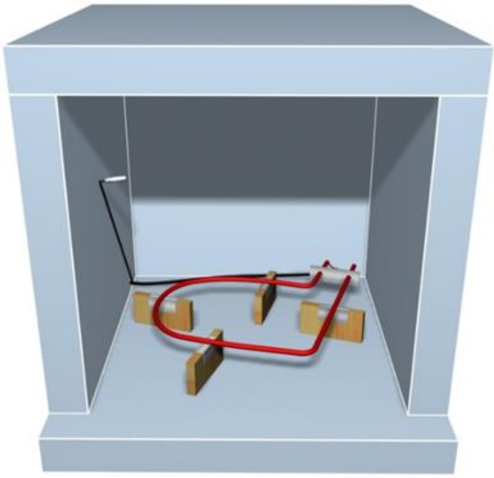

Figure 4. The location of resistance and thermocouple in the experimental setup.

The resistance with 750 W power was installed into the enclosed volume to increase the interior temperature. The thermostat control with thermocouple kept the inner temperature constant and controlled the heating process. To measure power consumption, a wattmeter instrument with ± 0,05 resolution was used. The thermal conductivity coefficients of the heat-insulated walls were calculated using the power consumption of the resistance.

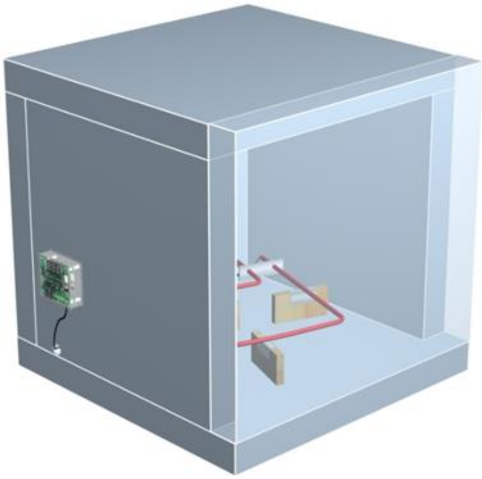

Figure 5. Installed experimental setup.

Figure 5 shows the installed experimental setup with the measurement instruments as a 3D model. As a first step, control flat parts without any insulating material were used to calculate heat losses as reference. After the control flat part, the experiments performed using heat-insulated flat parts with wood shavings, fiberglass, styrofoam, granule rubber respectively to measure heat losses. Figure 6 shows the various heat-insulated materials blended with the concrete. The experiments were conducted every other day because of keeping the flat parts at room temperature. At the beginning of each test, the experimental setup operated for 2 hours to achieve stable operating conditions. After this period, the wattmeter mounted to the setup. The surface temperatures of part were measured every 5 minutes via a thermocouple and the ambient temperature was recorded with a thermometer as well.

a) Wood shavings b) Fiberglass c) Styrofoam d) Granule rubber

Figure 6. Various heat-insulated materials for the front wall part.

Surface temperatures were measured using a multi-channel data logger with ±0,1 °C resolution. From the recorded surface temperatures, average surface temperatures were obtained. Power per unit surface was defined as the ratio of the total power consumption to the area of a surface. According to this approach, the thermal conductivity coefficient (k) was obtained by calculating the power consumption by the surface of the heat-insulated front flat part. The surface of the heat-insulated front flat part was heated up to 35°C and the temperature was kept constant at this temperature level utilizing an electronic thermostat instrument. The surface temperatures were measured with an infrared thermometer. Power consumption for the heat-insulated wall can be determined using Equation 1, a schematic view of the heat transfer mechanism is given in Figure 7.

$$PCHIW = \frac{TPC \times SHIW}{TSA} \tag{1}$$

In Equation 1, *PCHIW* defines power consumption for the heat-insulated wall (W), *TPC* defines total power consumption (W), *SHIW* defines the surface area of the heat-insulated wall (m^2), and *TSA* defines the total surface area of enclosed volume (m^2).

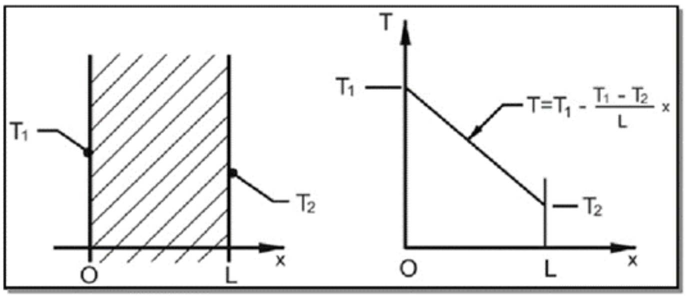

Figure 7. Schematic view of the heat transfer mechanism.

As one-dimensional heat transfer by conduction *T(x)* is a temperature distribution at x-direction,

$$T = T(x) \tag{2}$$

When the thermal conductivity is constant, a general form of the heat equation for a cartesian coordinate is defined as,

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{d^2T}{dz^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{dT}{dt} \tag{3}$$

The general form of the heat equation is simplified for one-dimensional, steady-state solutions without heat generation,

$$\frac{d^2T}{dx^2} = 0 \tag{4}$$

The general solution of this simplified heat equation is,

$$T = C_1 x + C_2 \tag{5}$$

To obtain the constants of integration, C_1, and C_2, boundary conditions must be introduced. Applying the boundary condition at $x=0$ to the general solution, C_2 is expressed as,

$$\int_{x=0} T = T_1 \qquad T_1 = 0 + C_2 \qquad C_2 = T_1 \tag{6}$$

Similarly, at $x = L$,

$$\int_{x=L} T = T_2 \qquad T_2 = C_1 L + C_2 \qquad C_1 = \frac{T_2 - T_1}{L} \tag{7}$$

Substituting into the general solution, the temperature distribution is then,

$$T = T_1 + \frac{T_2 - T_1}{L} x \qquad \frac{T - T_1}{T_2 - T_1} = \frac{x}{L} \tag{8}$$

Using Fourier's Law, temperature distribution and heat transfer rate, the heat flux is expressed for one-dimensional, steady-state solutions without heat generation as,

$$q'' = -k\frac{dT}{dx} = -k\frac{d}{dx}\left(T_1 - \frac{T_1 - T_2}{L} x\right) = k\frac{\Delta T}{L} \tag{9}$$

The heat flux represents the rate of heat transfer through a section of the unit area. The rate of heat loss through the area can be written as,

$$Q = q''A = k\frac{\Delta T}{L} A \tag{10}$$

From Equation 10, thermal conductivity coefficient is expressed using Equation 10 as,

$$k = \frac{Q}{A\frac{\Delta T}{L}} \tag{11}$$

In Equation 11, Q, k, A, L, ΔT defines the power (W), thermal conductivity coefficient (W/mK), area (m^2), wall thickness (m), temperature difference (°C) respectively.

3. RESULTS AND DISCUSSION

Table 1 shows the measured surface temperatures of the various heat-insulated walls using a thermocouple and average temperatures, and the line graph of the measured surface temperatures is given in Figure 8 as well.

Table 1. Measurement series of surface temperatures of various heat-insulated walls

	SURFACE TEMPERATURES (°C)				
Measurement Series	**Control Wall (without insulation)**	**Wall with Wood Shavings**	**Wall with Fibreglass**	**Wall with Styrofoam**	**Wall with Granul Rubber**
1	23,5	20,6	22,3	21,0	21,9
2	23,5	20,5	22,2	20,9	21,8
3	23,4	20,6	22,2	20,9	21,8
4	23,4	20,6	22,2	21,0	21,9
5	23,3	20,6	22,3	20,9	21,8
6	23,3	20,7	22,3	20,9	21,9
7	23,4	20,7	22,1	21,1	21,8
8	23,4	20,6	22,2	21,0	21,7
9	23,3	20,6	22,2	21,0	21,7
10	23,2	20,5	22,1	21,2	21,8
11	23,2	20,6	22,2	21,2	21,8
12	23,3	20,7	22,4	21,1	21,8
Average	**23,35**	**20,60**	**22,23**	**21,02**	**21,81**

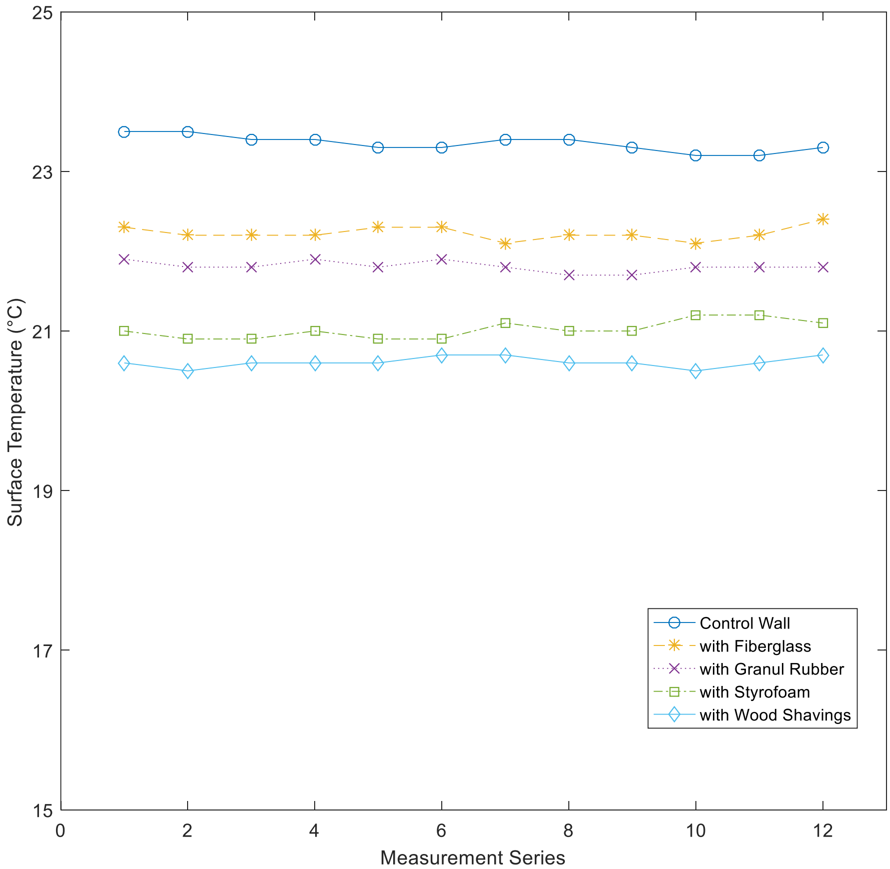

Figure 8. Line graph of the measured surface temperatures.

Using Table 1 measurement, thermal conductivities of various insulated walls were calculated as Equation 11. Equation 12, Equation 13, Equation 14, Equation 15, and Equation 16 show the calculation procedure of thermal conductivity coefficients for the control wall, the wall with wood shavings, the wall with fiberglass, the wall with styrofoam, and wall with granule rubber respectively.

Control wall without heat insulation,

$$k = \frac{Q}{A\frac{\Delta T}{L}} = \frac{87}{0,12\frac{(35-23,35)}{0,05}} = 3,09 W/m\cdot K \tag{12}$$

Wall with wood shavings,

$$k = \frac{Q}{A\frac{\Delta T}{L}} = \frac{87}{0,12\frac{(35-20,6)}{0,05}} = 2,51 W/m\cdot K \tag{13}$$

Wall with fiberglass,

$$k = \frac{Q}{A\frac{\Delta T}{L}} = \frac{87}{0,12\frac{(35-22,23)}{0,05}} = 2,83 W/m\cdot K \tag{14}$$

Wall with styrofoam,

$$k = \frac{Q}{A\frac{\Delta T}{L}} = \frac{87}{0,12\frac{(35-21,02)}{0,05}} = 2,58 W/m\cdot K \tag{15}$$

Wall with granule rubber,

$$k = \frac{Q}{A\frac{\Delta T}{L}} = \frac{87}{0,12\frac{(35-21,81)}{0,05}} = 2,74 W/m\cdot K \tag{16}$$

The calculated thermal conductivity coefficients are given in Table 2. Thermal conductivity is an important property of the material and is a measure of a material's ability to conduct heat. Many of the traditional insulation materials have lower thermal conductivity for this purpose. As seen in Table 2, blending heat insulation material with concrete helps to decrease the thermal conductivity coefficient. The control wall without insulating material is about 3,09 W/(mK). On the other hand, when the insulation material was added into concrete, it started to decrease and the highest decline was observed in wood shavings insulation material because wood particles dispersed homogeneously in concrete and not dissolved in concrete. Also, styrofoam heat-insulated materials exhibited the same behavior in terms of homogenous distribution and the thermal conductivity coefficient was very close to the wood shavings particles. Besides, from Table 2, it can be seen that the thermal conductivity coefficient decreases as long as the heat insulation particles do not dissolve completely and remain in large particle sizes in concrete.

Table 2. Thermal conductivity coefficients of various heat-insulated walls.

Types of Heat Insulated Wall	**Thermal Conductivity Coefficient [k]**
Control wall without heat insulation	3,09
Wall with wood shavings	2,51
Wall with fiberglass	2,83
Wall with styrofoam	2,58
Wall with granule rubber	2,74

The error values of measured magnitudes are determined in terms of suggested error limits of the manufacturer of the measurement instrument, calibration processes, and experiences from experiments studies. Although error analysis is a process to determine random errors, it is always difficult to separate constant errors and random errors from each other. Especially for the experimental study, uncertainty analysis is the common method to obtain a methodological approach about the precision and accuracy of the results [12]. The uncertainty analysis was conducted according to the Guide to the Expression of Uncertainty in Measurement [13], as seen in Equation 17.

$$u_f = \sqrt{\sum_{n=1}^{N}\left(\frac{\partial f}{\partial x_n}u_n\right)^2} \tag{17}$$

In Equation 17, overall uncertainty u_f for a value f (in our case, calculated thermal conductivity coefficients) is calculated using the Gaussian propagation of uncertainties where x_n are the independent variables (Q, total power; A, area; L, wall thickness; ΔT temperature difference), N is their number, and u_n is the uncertainty of the associated variable x_n.

When Equation 11 is rearranged, the thermal conductivity coefficient can be written as

$$k = \frac{Q}{A\frac{\Delta T}{L}} = \frac{Q \times L}{A \times \Delta T} = \frac{Q \times L}{w \times h \times \Delta T} \tag{18}$$

Equation 18, w and h expresses the width (m) and height (m) of the wall respectively. According to Equation 17, the terms of Equation 18 are the independent values for uncertainty analysis. If Equation 17 is modifying in terms of independent values, it would be defined as,

$$u_f = \sqrt{\left(\frac{\partial k}{\partial Q}u_Q\right)^2 + \left(\frac{\partial k}{\partial L}u_L\right)^2 + \left(\frac{\partial k}{\partial w}u_w\right)^2 + \left(\frac{\partial k}{\partial h}u_h\right)^2 + \left(\frac{\partial k}{\partial \Delta T}u_{\Delta T}\right)^2} \tag{19}$$

In terms of thermal conductivity coefficient, the Gaussian uncertainty can be written as (derived from Equation 19),

$$\frac{u_f}{k} = \sqrt{\left(\frac{u_Q}{Q}\right)^2 + \left(\frac{u_L}{L}\right)^2 + \left(\frac{u_w}{w}\right)^2 + \left(\frac{u_h}{h}\right)^2 + \left(\frac{u_{\Delta T}}{\Delta T}\right)^2} \tag{20}$$

In Equation 20, u_Q defines the uncertainty of the power consumption as ± 0,05 because of the resolution of the instrument, u_L, u_w, u_h defines uncertainty of the wall thickness, wall width, and wall height as ± 0,01 respectively because of the precise of the digital caliper, $u_{\Delta T}$ defines the uncertainty of the temperature difference ± 0,1 because of the resolution of the data logger. When Equation 19 is transformed according to the uncertainty of the associated values for average temperatures, it can be written as for all types of insulated walls in Equation 21, Equation 22, Equation 23, Equation 24, and Equation 25.

Control wall without heat insulation,

$$\frac{u_f}{k}=\sqrt{\left(\frac{0,05}{87}\right)^2+\left(\frac{0,01}{0,05}\right)^2+\left(\frac{0,01}{0,4}\right)^2+\left(\frac{0,01}{0,3}\right)^2+\left(\frac{0,1}{(35-23,35)}\right)^2}=\pm 0,204475 \quad (21)$$

Wall with wood shavings,

$$\frac{u_f}{k}=\sqrt{\left(\frac{0,05}{87}\right)^2+\left(\frac{0,01}{0,05}\right)^2+\left(\frac{0,01}{0,4}\right)^2+\left(\frac{0,01}{0,3}\right)^2+\left(\frac{0,1}{(35-20,6)}\right)^2}=\pm 0,204413 \quad (22)$$

Wall with fiberglass,

$$\frac{u_f}{k}=\sqrt{\left(\frac{0,05}{87}\right)^2+\left(\frac{0,01}{0,05}\right)^2+\left(\frac{0,01}{0,4}\right)^2+\left(\frac{0,01}{0,3}\right)^2+\left(\frac{0,1}{(35-22,23)}\right)^2}=\pm 0,204445 \quad (23)$$

Wall with styrofoam,

$$\frac{u_f}{k}=\sqrt{\left(\frac{0,05}{87}\right)^2+\left(\frac{0,01}{0,05}\right)^2+\left(\frac{0,01}{0,4}\right)^2+\left(\frac{0,01}{0,3}\right)^2+\left(\frac{0,1}{(35-21,02)}\right)^2}=\pm 0,204420 \quad (24)$$

Wall with granule rubber,

$$\frac{u_f}{k}=\sqrt{\left(\frac{0,05}{87}\right)^2+\left(\frac{0,01}{0,05}\right)^2+\left(\frac{0,01}{0,4}\right)^2+\left(\frac{0,01}{0,3}\right)^2+\left(\frac{0,1}{(35-21,81)}\right)^2}=\pm 0,204436 \quad (25)$$

Table 3. Uncertainty of thermal conductivity coefficients of various heat-insulated walls.

Thermal Conductivity Coefficient [k]	Unit	Uncertainty Values
3,09	W/mK	±0,204475
2,51		±0,204413
2,83		±0,204445
2,58		±0,204420
2,74		±0,204436

Table 3 shows the calculated thermal conductivity values for all wall types and the uncertainty analysis of those as well. As seen in Table 3, it is shown that the uncertainty for all wall types is calculated approximately about ± 0,204 which is in an acceptable range. Besides, it was observed that the uncertainty of thermal conductivity was slightly increased with the increasing of the thermal conductivity of coefficient and decreasing of the temperature differences (ΔT).

4. CONCLUSION

This study presents an alternative methodology to use heat insulation materials directly into concrete blocks. An enclosed concrete volume was designed and produced. Four various heat insulation materials were added to the concrete walls for enclosed volume. The surface temperatures, power consumptions were measured, and thermal conductivity coefficients were calculated as well. As a result;

- It was observed that the maximum efficiency was achieved using a wall with wood shavings because it had the lowest thermal conductivity coefficient among other types.
- The thermal conductivities are sorted from most efficient to the lowest as 2,51, 2,58, 2,74, 2,83, 3,09 W/(mK) for wood shadings, styrofoam, granule rubber, fiberglass, and control wall respectively.
- When the thermal conductivity coefficient of the control wall is compared with others, it is observed that the efficiencies of heat-insulated walls are higher than the control wall about 18,8%, 16,5%, 11,3%, 8,4% for wood shadings, styrofoam, granule rubber, fiberglass respectively.
- In general, it can be concluded that the heat losses, environmental pollution, and energy costs would be decreased compared with non-heat insulated construction if those heat-insulated wall types could be performed.
- According to the uncertainty analysis, the uncertainty of the thermal conductivity coefficient was calculated at approximately ± 0,204.

Declaration of Ethical Standards

The authors of the paper submitted declare/declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

Contribution of the Authors

Abdullah Dağdeviren: Methodology, Writing - Original Draft.

Bahadır Acar: Conceptualization, Methodology.

Murat Aydın: Writing - Review & Editing, Visualization.

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