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Experimental Investigation and Numerical Simulation on the Thermal Insulation Materials Using Recycled Thermoplastic Polymers

ALI F. AL-SHAWABKEH[1*], SALAMAH SAWALHEH[2], IBRAHIM I. IKHRIES[2], WAID OMAR[3]

[1]Physics and Basic Sciences Department, Faculty of Engineering Technology, AL-Balqa Applied University, Amman 11134 Jordan

[2]Mechanical Engineering Department, Faculty of Engineering Technology, Al-Balqa Applied University, Amman 11134 Jordan

[3]Chemical Engineering Department, Faculty of Engineering Technology, Al-Balqa Applied University, Amman 11134 Jordan

***Abstract**: In construction building, the optimum insulation material thickness determines the efficiency of energy consumption. In this paper, heat transfer and the temperature distribution of recycled polymers between construction building components are investigated using theoretical and simulation methods. It has been shown that when the thickness of all recycled polymers being studied is increased, insulation improves and energy consumption decreases, indicating that XPS is the best recycled plastic and the optimum thickness is 7 cm. In this work, experimental and numerical approaches have been used, to conduct a qualitative and quantitative analysis of the thermal performance of an external wall outfitted with new insulation materials, based on the most commercialized recycled thermoplastic polymers (Polyethylene RPE, Polyethylene terephthalate RPET, and Expanded Polystyrene RXPS) waste.*

***Keywords**: thermoplastic, polymer, thermal insulation, simulation, energy, heat transfer*

1. Introduction

In general, Jordanian residences and public structures have inadequate thermal insulation. According to recent figures, less than 30% of villas in Amman adhere to national building codes for thermal insulation, whereas 10-15% of apartments do. Smaller commercial flats, on the other hand, rarely follow building norms that govern thermal insulation, with only 5-10% of small apartments in Amman adhere to the rules. As a result, and as a result of the lack of sufficient thermal insulation, the majority of homes and commercial buildings have a thermally uncomfortable environment.

On a cold winter day in Amman, the temperature of the outer walls and roofing around the perimeter of the home can drop to 12°C, while the outdoor ambient temperature drops to roughly 0°C. To feel comfortable in such a situation, a typical household would need to elevate the temperature of inside spaces to around 25°C. Therefore, even when the heater is turned off for lengthy periods of time and at high temperatures, most people do not feel thermally comfortable. Pollution is at an all-time high in this situation, as the fuel used to generate energy sends greenhouse gases into the environment. All other methods, such as increasing the heating load, diversifying energy sources, or extending heating hours, are a waste of money, unhealthy, and pollute the environment even more [1].

Globally, 260 million tons of plastic garbage was generated in 2016 [2]. Landfilling accounted for 40% of the total, reflecting underutilized resources. Only 16 % of the waste generated was collected for recycling, with mechanical recycling accounting for the majority [3]. The thermal qualities of wall and insulation materials, as well as their configurations and dimensions, wall structure types, indoor thermal comfort conditions, and weathering parameters, all influence heat transfer [4].

The quality of a building's envelope has a significant impact on its energy usage. The thermal performance of external walls is an important aspect in improving theconstruction sector's energy efficiency and lowering greenhouse gas emissions. Furthermore, excessive use of virgin materials in

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**email: drshawabkeh@bau.edu.jo*

building materials depletes natural resources and adds to the environmental load [5,6]. As a result, replacing waste products for virgin resources tackles two major issues: waste generation and usage of virgin materials.

Thermal insulation is without a doubt one of the most effective techniques to reduce energy consumption due to both winter and summer heating and cooling. Insulation materials play a vital part in this scenario because proper material selection, thickness, and placement allow for good indoor thermal comfort and adequate energy savings. When constructing a building envelope, thermal qualities are vital, but they aren't the only factors to consider sound insulation, fire resistance, water vapor permeability, and the influence on the environment and human health must all be carefully examined [7]. For example, Daouas (2011) [8] used dynamic heat transfer and LCC analysis to determine the best insulation thickness for a single-layered brick wall with various orientations. He discovered that the optimal insulating thickness is 10.15 cm, with a maximum energy saving of 71%. His other work Saafi and Daouas (2018) looked at the effect of longwave radiation and color aging on the best insulation thickness for walls and roofs [9]. They discovered that depending on the environmental circumstances, both reduce the value of optimum insulation thickness. Furthermore, solar shading affects the ideal wall insulation thickness [10].

The reduction of heat transfers (the transmission of thermal energy between objects at various temperatures) between items in thermal contact is known as thermal insulation. It is possible to achieve this by the use of specially engineered technologies or processes, as well as the selection of appropriate item shapes and materials. However, various studies have emphasized the issue of exploitation waste materials in concrete because of the significant cost and energy consumption associated with converting waste materials to a usable material [11]. When polystyrene is used for both wall and roof insulation, Mohsen and Akash [12] found that considerable energy savings of around (76.8%) can be achieved. Those conclusions were reached in light of the fact that only 5.7 percent of people living in Jordan's urban areas had divider insulation, and none of the rooftops have been insulated.

Shilpi et al. [13] concluded that thermal comfort can be achieved for very low-cost buildings by using PET bottles as construction recycling materials, benefiting people who cannot afford to acquire and maintain heating and cooling equipment. According to a 15-year study conducted at the Oak Ridge National Laboratory, below-grade XPS insulation loses 10-44 percent of its thermal resistance [14]. Other installations subjected to high moisture conditions in colder climates had water-logged XPS insulation with even larger thermal resistance losses [15].

The cost of insulating material rises in direct proportion to its thickness [16,17]. As a result, determining the optimal point at which the total investment cost for insulating thickness and energy consumption may be minimized helps lower operation and construction expenses. The largest life cycle savings, however, might be realized by placing 6 cm of XPS layers to the roof and walls, which could save \$86.2 per m^2 [18].

Other researchers have used a simulation-based method to circumvent this type of input simplification in the equation-based method [19]. Sofrata and Salmeen [20] established a mathematical model for optimum insulation thickness that is more consistent and general. He also demonstrated how to use a flowchart to choose the appropriate insulation thickness. With enough computing power, it can make good use of these inputs and determine the operating energy consumption of buildings with remarkable precision.

In general, there are two techniques for calculating energy usage when it comes to space heating and cooling. The equation-based method is one option, while the simulation-based method is another. They discovered in the reference that using equations to calculate energy demand for space heating and cooling may not produce the intended accurate result [21-23]. This approach, however, uses assumptions to simplify the equations in computing heat transfer due to the computation constraints. From the cradle to the grave, the environmental impact of common building materials (such as concrete, hollow blocks, and common insulation materials) was primarily investigated in the early days [24-26].

In this article, we established strategies and systems based on an environmentally friendly environment that could still be built at very low prices, using waste materials such as plastic waste, while yet offering enough thermal comfort and being sustainable. The study discusses Jordan's housing improvement and occasional worth. At this time, we have more opportunities than ever before to use renewable energy sources such as solar and geothermal, and the development of renewable and opportunity energies is progressing. When you think that plastic was invented over a hundred years ago, it has become an integral part of our daily lives.

According to the goal of this research, it is necessary to investigate the respondents understanding of the usage of recycled plastic for sustainable building as well as for housing insulation projects.

2. Materials and methods

2.1. Identification of the goal and criteria

Stone, supported cement, concrete squares, mud, and other materials are common divider development materials in Jordan. Cement blocks are the most commonly used development materials in Jordan, accounting for roughly 63 percent of all structures; hence, lowering their warm conductivity will allow for a wider range of designs and result in significant energy savings from heating and air-conditioning. Applying thermoplastic materials in different areas of innovation is progressively clear because of their capacity to endure high mechanical and thermal [27].

The main purpose of this research is to determine how the thermal insulation of Jordanian housing blocks is affected by the expansion of many recycled thermoplastic materials of varied thicknesses. The goal of this organization, in addition to enhancing thermal insulation, is to assist blocks industrial facilities regionally and provincially in using some newly developed insulation materials in construction. This investigation found new techniques (designs) to combine recycled thermoplastics with ground cement tile material as layers (sandwich) to improve thermal insulation. Figure 1 indicates the existence cycle of a product from waste via manufacture to assembly.

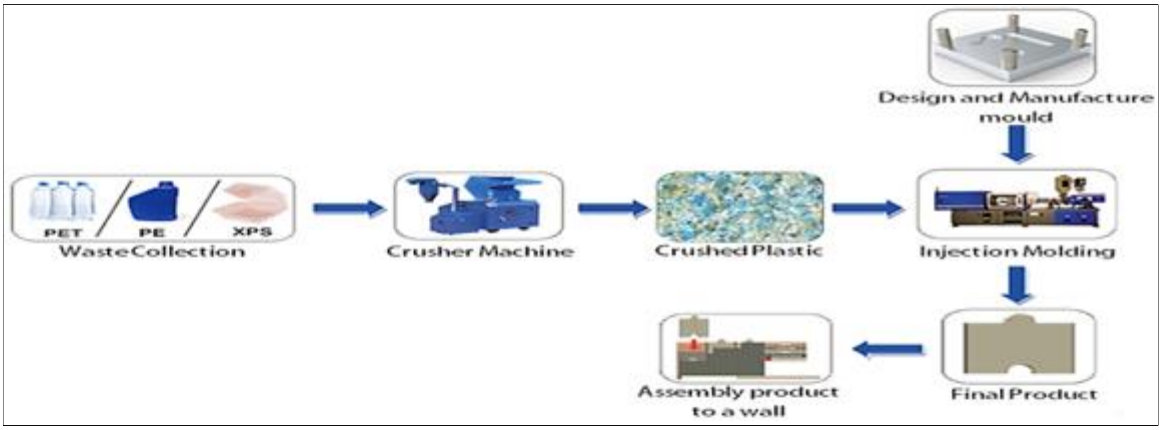


Figure 1. The life cycle of a product from waste through manufacture to assembly

2.2. Materials and experimental procedures

In this work, PET, PE, and XPS polymer waste were collected and crushed each polymer individually in a crusher machine to find new techniques (designs) to layer-recycled thermoplastics with ground cement tile material to improve thermal insulation capabilities. We develop the product, assess it using theoretical and simulation studies, then design and create the injection mold using Computer Numerical Control (CNC) equipment.

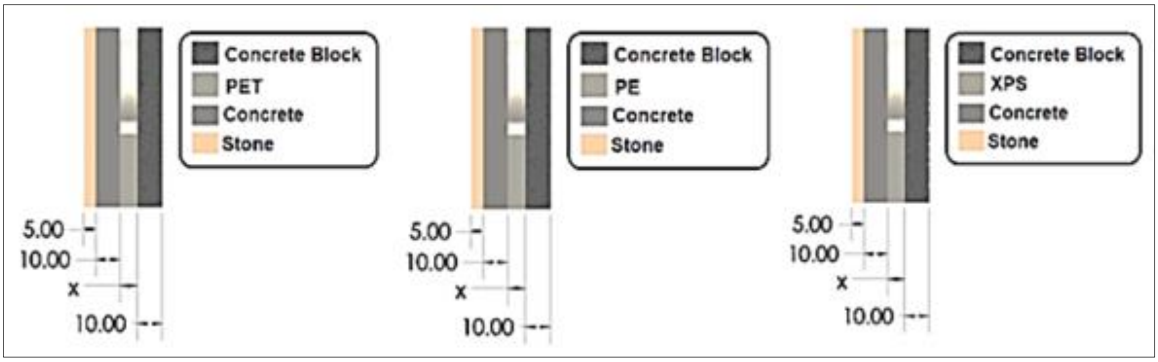


Figure 2. Standard wall construction with RPET, RPE, and RXPS insulation thickness

As a result, each of the three recycling polymers has its own mold installed on an injection molding machine to make the final product. As shown in Figures 2 and 3, the wall in this study was constructed using Stone, Concrete, and Concrete blocks, as well as a final product-recycled polymer sandwiched between Concrete and Concrete blocks, as well as a dowel with a plastic nail for additional mechanical fixture of the thermal insulation system with slabs of recycle polymer.

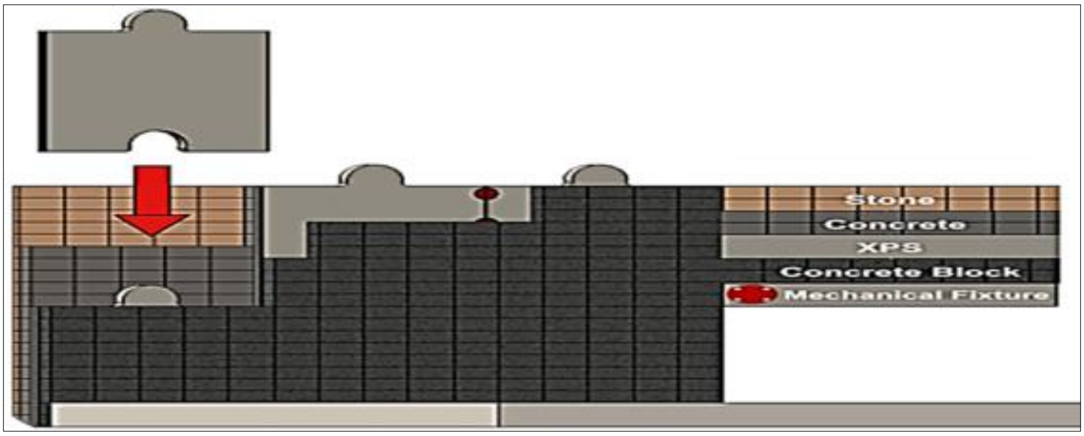


Figure 3. Installation and constriction including its final product

2.3. Theoretical consideration

We need to estimate heat transfer through a composite wall, by applying the heat transfer rate formula, as indicated in equation 1[28]:

$$\boldsymbol{q = \frac{(To - Ti)}{\frac{1}{ho} + \frac{l1}{k1} + \frac{l2}{k2} + \frac{l3}{k3} + \frac{l4}{k4} + \frac{1}{hi}}} \quad (1)$$

where:

T_o: Outside Temperature (K).
T_i: Inside Temperature (K).
l_1:Thickness of Stone (m).
l_2: Thickness of Concrete (m).
l_3: Thickness of Recycled Polymer (m).
l_4: Thickness of Concrete Block (m).
K_1: Thermal conductivity of Stone (W/m.K).
K_2: Thermal conductivity of concrete (W/m.K).
K_3: Thermal conductivity of Recycled Polymer (W/m.K).
K_4 : Thermal conductivity of concrete block (W/m.K).
h_o : Outside convection heat transfer coefficient (W/m^2.K).
h_i : Inside convection heat transfer coefficient (W/m^2.K).

We utilized equation (1) to compute overall heat transfer for seven specimens in this study assuming that this research was accomplished in August when To is 33°C, Ti is 22°C and ho 30 $W/m^2.K$ and hi 8.5 $W/m^2.K$ [29,30].

The temperature difference between the outside and interior of the wall is represented by the numerator of equation (1), while the thermal resistance of the wall to heat convection and conduction is represented by the denominator. In Figure 4, electrical circuits are depicted that are connected in series, with the resistance equal to the sum of outside convection, four wall conduction materials and inside convection resistance.

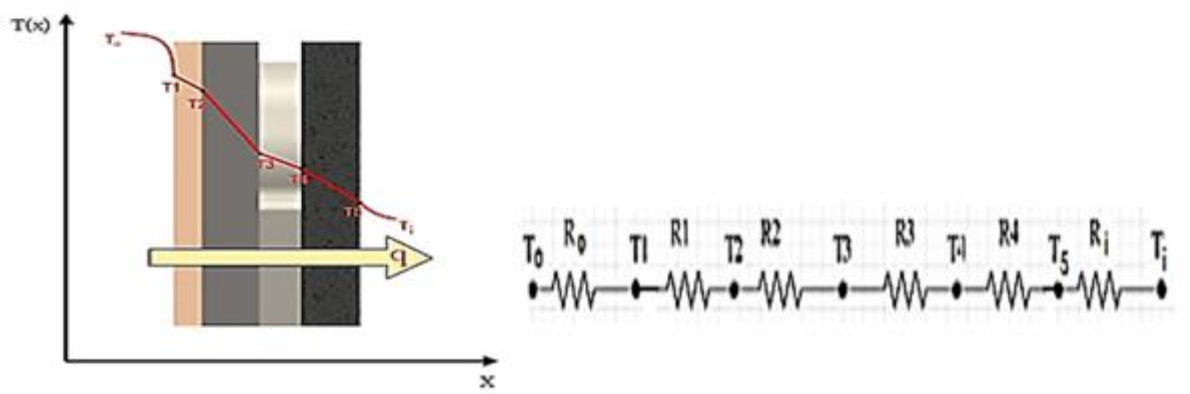
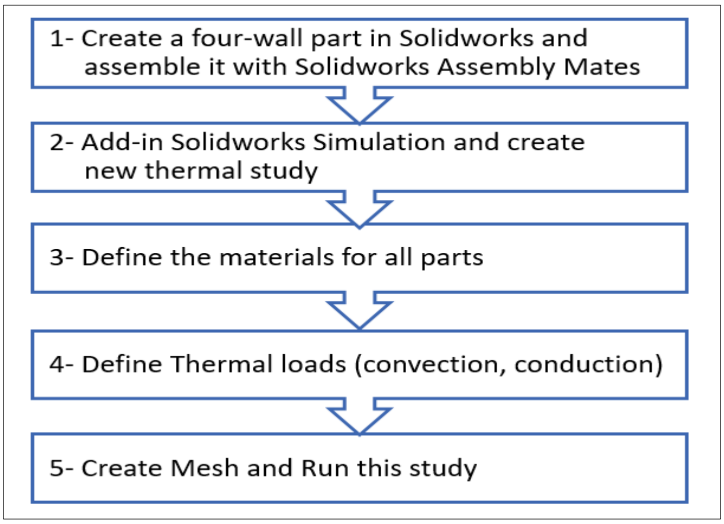


Figure 4. Thermal Distribution and Resistance of Insulated Wall Buildings

2.4. Thermal analysis simulation

Thermal analysis uses the SOLIDWORKS software to estimate the heat transmission in this investigation. It necessitates seasoned simulation users as well as top-notch CAD/CAE software. The SOLIDWORKS software was used in this study for design and simulation, with the practical approach shown in Figure 5. In computer-aided design, we design the components and assemble them with proper mates; in computer-aided engineering, we choose the materials for all parts, define part interaction, define thermal loads, and define mesh density and parameters. However, a drawback of CAD/CAE is that it necessitates the use of a strong computer processor. The most relevant material parameters employed in the investigation are listed in Table 1.



1- Create a four-wall part in Solidworks and assemble it with Solidworks Assembly Mates

2- Add-in Solidworks Simulation and create new thermal study

3- Define the materials for all parts

4- Define Thermal loads (convection, conduction)

5- Create Mesh and Run this study

Figure 5. The procedure steps for simulating thermal load in SOLIDWORKS

Table 1. Properties of RPE, RPET, and RXPS [31-33]

Materials Properties					
	Stone	**Concrete**	**RPET**	**RXPS**	**RPE**
Mass Density [kg/m^3]	2280	2450	1340	3598	949
Thermal Conductivity[W/(m·K)]	5.690	1.390	0.144	0.030	0.419
Specific Heat [J/(kg·K)]	879	936	1450	1500	1840

Figures 6a, b, and c illustrate a sample of temperature gradient and heat flux simulations for a 7 cm thickness of recycled polymers.

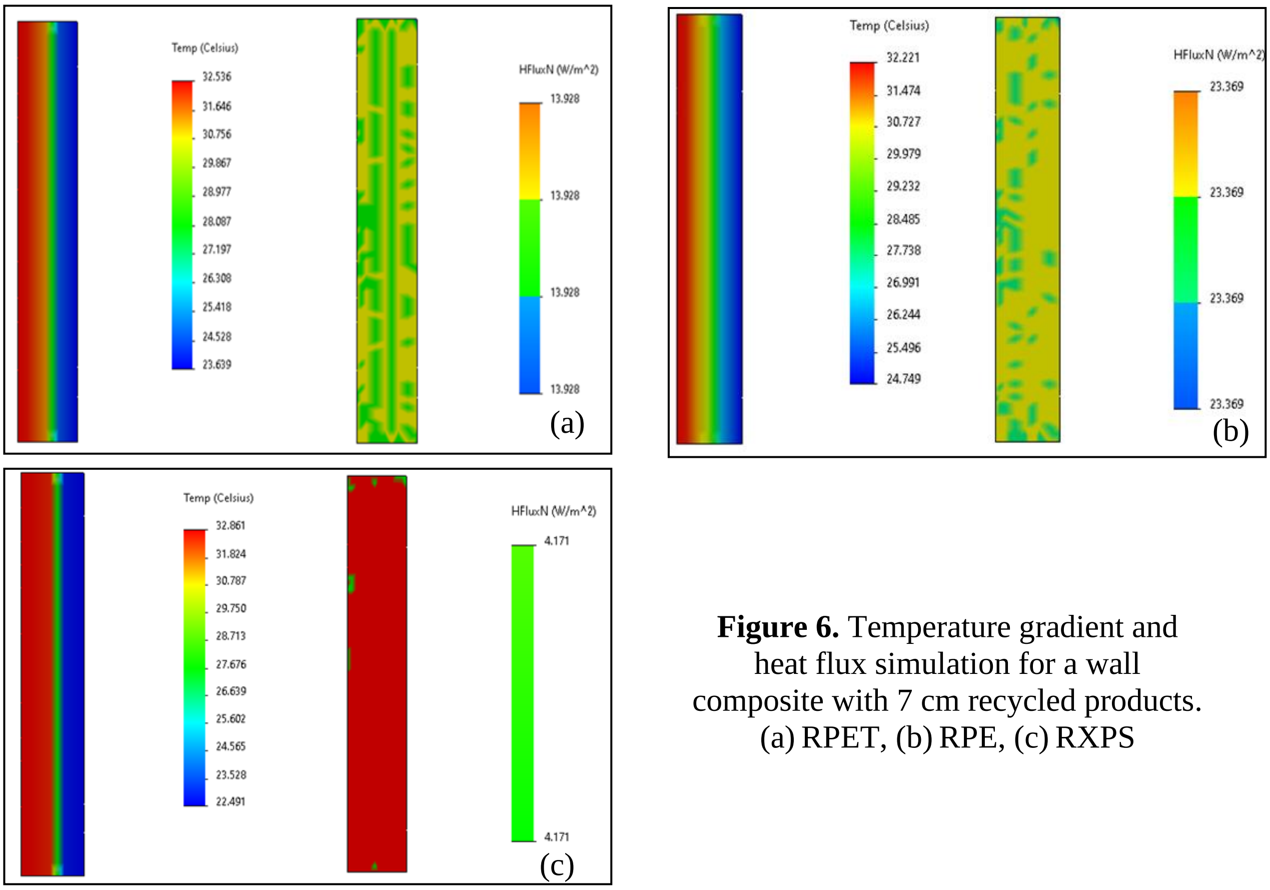


Figure 6. Temperature gradient and heat flux simulation for a wall composite with 7 cm recycled products. (a) RPET, (b) RPE, (c) RXPS

The temperature gradient outside the wall using the RPET product is 32.536°C and inside 23.639°C, RPE product is 32.221°C and inside 24.749°C, and RXPS product is 32.861°C and inside 22.491°C. The RPET product delivers 13.928 watts of heat flux, the RPE product 23.369 watts, and the RXPS product 4.171 watts, as shown in the figures above. After designing the injection mold in SOLIDWORKS, we export the cavity drawing file to MASTERCAM, which generates the GM code program using tool path strategies and transmits it to a CNC machine to be manufactured. Figure 7 depicts this situation. We put the injection mold in the injection machine and add recycled polymers separately according to the required production quantity.

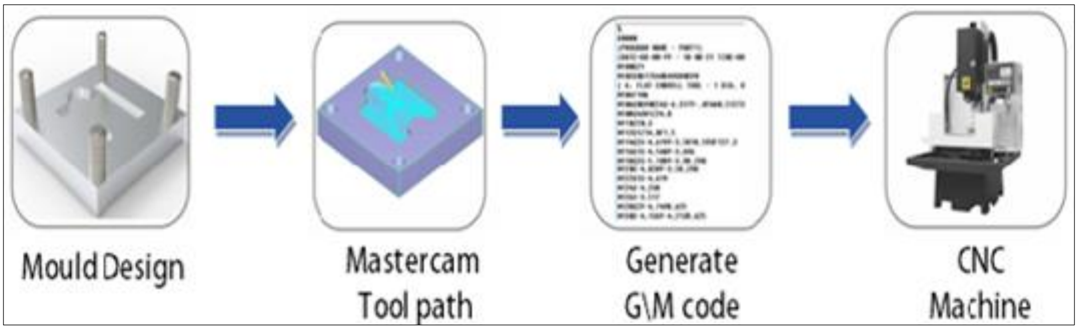


Figure 7. Illustrates the machining procedure for a mould manufacture

If Jordan's Average Efficiency Rate COP for heating and cooling is 5 [35], Equation (2) can be used to predict energy consumption for various optimum thicknesses of all recycled polymers in composite walls [34]:

$$\boldsymbol{E = \frac{q\,\Delta T}{COP}} \tag{2}$$

where:

ΔT: temperature gradient between the inside and outside (°C).
E: total annual energy consumption (kWh).
q: heat flux through the wall (W).
COP: coefficient of performance.

3. Results and discussions

The results of heat flux (q) and temperature gradient (ΔT) through the wall for recycled polymer were computed from the SOLIDWORKS software and are shown in Table 2. The wall thickness should be gradually increased to provide the best thermal insulation. RPET has a heat flux of 21.48 W at 3 cm thickness and 11.02 W at 10 cm thickness, RPE has a heat flux of 29.31 W at 3 cm thickness and 20.283 W at 10 cm thickness, and RXPS has a heat flux of 8.438 W at 3 cm thickness and 3.024 W at 10 cm thickness.

Table 2. Theoretical and simulation results for final product

	RPET				**RPE**				**RXPS**			
	Theoretical		Simulation		Theoretical		Simulation		Theoretical		Simulation	
X(cm)	q(W)	ΔT(°C)	q(W)	ΔT(°C)	q(W)	ΔT(°C)	q(W)	ΔT(°C)	q(W)	ΔT(°C)	q(W)	ΔT(°C)
3	21.480	7.756	21.485	7.756	29.310	6.574	29.310	6.574	8.438	9.726	8.438	9.726
4	18.920	8.144	18.919	8.143	27.560	6.839	27.560	6.839	6.720	9.985	6.720	9.985
5	16.900	8.448	16.900	8.449	26.010	7.074	26.010	7.074	5.583	10.160	5.583	10.160
6	15.270	8.694	15.271	8.694	24.620	7.283	24.620	7.283	4.775	10.280	4.775	10.280
7	13.928	8.897	13.928	8.897	23.370	7.472	23.370	7.472	4.171	10.370	4.171	10.370
8	12.802	9.067	12.800	9.067	22.421	7.642	22.421	7.642	3.700	10.440	3.700	10.440
9	11.845	9.212	11.845	9.212	21.217	7.797	21.217	7.797	3.330	10.497	3.330	10.497
10	11.020	9.336	11.000	9.336	20.283	7.940	20.283	7.940	3.024	10.543	3.024	10.543

The temperature gradient (ΔT) for RXPS polymers is 0.817°C, and for RPET and RPE is 1.58°C and 1.37°C, respectively, the RXPS value is roughly half that of RPET or RPE. Installing a recycled polymer reduces the heat transfer by decreasing thermal conduction and convection through the wall layers. Exceeding the thickness restriction increases production costs and component weight, causing the installation and fastening issues. As a result, we'll need more high-thickness materials to achieve significant insulating gains.

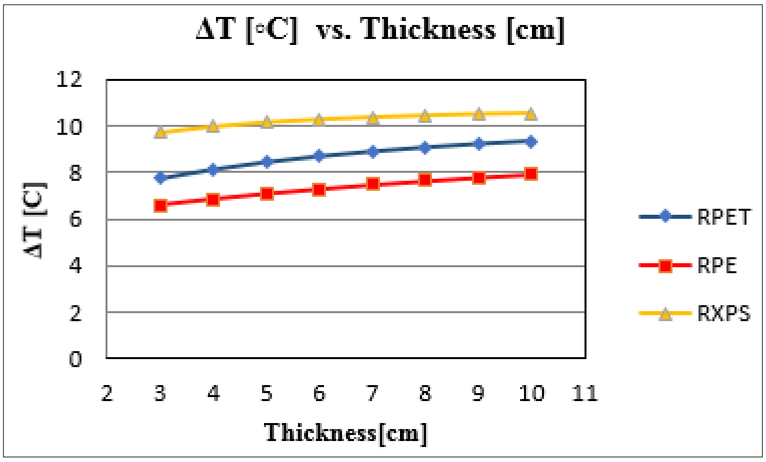


Figure 8. The dependence of ΔT of the thickness for RPET, RXPS and RPE

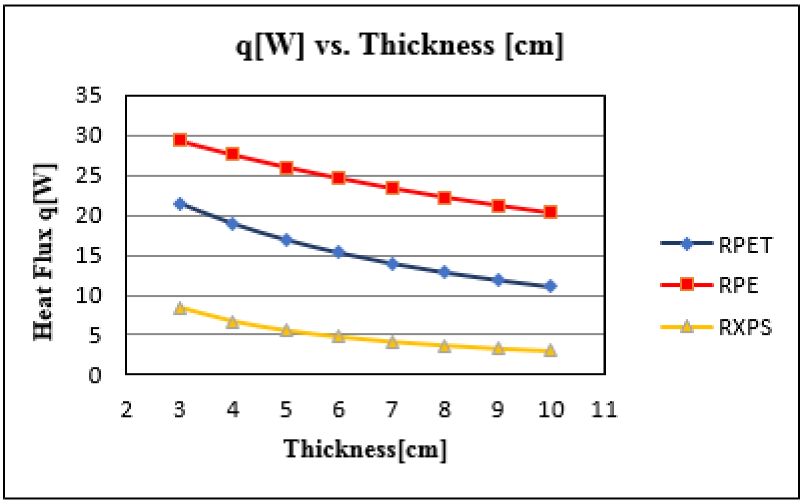


Figure 9. The dependence of the heat flux of the thickness for recycled polymers

RXPS polymers offer the best insulation from a range of 3 to 10 cm [at 3 cm = 8.438 W, 10 cm = 3.024W] compared to RPET [at 3 cm = 21.48 W, 10 cm = 11.02W] and RPE [at 3 cm = 29.31 W, 10 cm = 20.283W]. Generally, insulation is realized when the thickness is raised. When compared 3 cm and 4 cm, the variation in heat flux between 7 cm and 10 cm in RXPS is small. As a result, the optimum thickness of 7-cm RXPS is the best value.

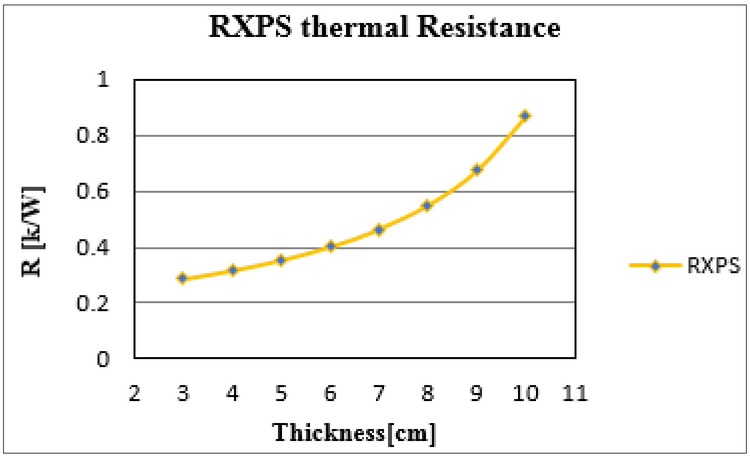


Figure 10. Dependence of the thermal resistance of the thickness for RXPS

The heat resistance (R) of RXPS improves exponentially as thickness increases, as shown in Figure 10. The relationship between thermal resistance and heat flux, according to the heat flow equation, is inverse; thus, increasing thermal resistance reduces heat flux and so enhances insulation.

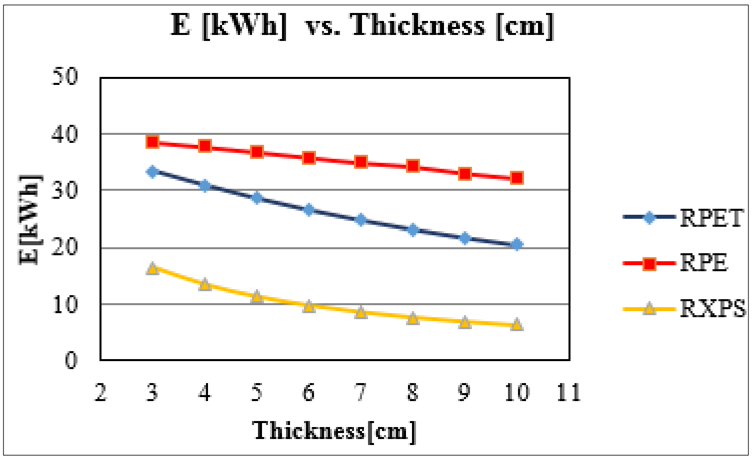


Figure 11. Dependence of the energy consumption of thickness for recycled polymers

At the polymer thickness range of 3 cm to 10 cm, RPET and RPE polymers consume more energy than RXPS. In comparison, at 3 cm thickness, the RPET is 33.32 kWh, the RPE is 38.54 kWh, and the RXPS is 16.41 kWh, whereas at 10 cm thickness, the RPET is 20.58 kWh, the RPE is 32.21 kWh, and the RXPS is 6.38 kWh. At a thickness of 10 cm, RXPS showed the best consumption result. The energy consumption of the optimal thickness (7 cm) of RPET is 24.78 kWh, RPE is 34.92 kWh, and RXPS is 8.65 kWh. The relative consumption percentage compared to RPE, while the energy consumption percent for RXPS is 75.2 % and for RPET is 29 %. RXPS is the best consumption percentage ratio.

The thermal properties of composite wall materials, as well as their configurations and dimensions, wall contruction types, and appropiate thermal conditions, all impact heat transfer. The thermal insulation layers don’t seal the space between each layer, which increases heat loss, especially as the buildings grow older. Thus, the idea of making thermal insulation layers that lock with each other came up, sealing that area and decreasing the chance of destroying performance during aging.

4. Conclusions

The key findings of this study are summarized as follows:

The thermal insulation building materials using recycled thermoplastic polymers were successfully designed and constructed by theoretical and simulation analysis.

The conclusions of the temperature gradient and heat flux simulated and estimated on paper suggest that this work is profitable.

The optimal thickness of recycled XPS is 7 cm because it consumes less energy than other recycled polymers at the same thickness and also has a lower production cost than 10 cm.

RXPS insulation was more effective at providing thermal energy efficiency in all models when compared to RPET and RPE insulation from 3 to 10 cm, maximum temperature gradients in the recycled XPS composite being 0.814°C.

In comparison to RPE, RXPS insulation consumes about 75.2 percent of the energy.

This research develops an opportunity and paves the way for future insulating building modifications utilizing recycled polymers.

Future work in simulation analysis will concentrate on investigating the impact of different recycled polymers' mechanical characteristics on the thickness of composite wall buildings.

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