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Selecting the Optimal Thermal Insulation Material for a Residential Building Envelope in Cairo in Consideration of The Thermal Comfort and Energy Consumption

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Abstract

As a result of the current global energy crisis, there is a universal tendency towards energy-saving in the housing sector. In Egypt, mega housing projects such as "Dar Misr" are established to provide apartments for middle-income families. The envelopes of those buildings play a significant role in the increased heat gain of indoor spaces. Therefore, this study aims to assess the thermal performance and calculate the energy savings of five thermal insulation materials available in the market; (Vermiculite, Rockwool, Phenolic Foam, Extruded Polystyrene (XPS), and Polyethylene). The assessment is for those materials installed in the apartment's external walls to find the optimal material that achieves the most extended annual indoor thermal comfort hours and the highest annual energy-saving. An apartment in a typical floor was modeled by DesignBuilder software to calculate the indoor thermal comfort hours and energy consumption for the five alternatives. The results show that thermal insulation materials inside the external walls are pivotal in reducing heat gains and extending comfort hours. The optimal insulation material is XPS which achieved thermal comfort for 33% of the year compared to 28% and 29% by the Phenolic Foam and Rockwool, respectively. Moreover, the XPS saved 9.27% of the annual energy consumption, which is the highest energy-saving ratio compared to Polyethylene (6.21%) and Vermiculite (2.4%).

Keywords: energy consumption; optimization; residential buildings; thermal comfort; thermal insulation; XPS.

Introduction

Since a comfortable home is a human goal, housing considers as an important need in human life. Housing is one of the main sectors of the Egyptian national development. In line with Egypt's strategy to achieve Vision 2030, the Ministry of Housing is implementing medium housing projects "Dar Misr", which aims to provide affordable housing units. In several locations in seven new cities with a total of 400 thousand housing units, Dar Misr projects are being built nowadays. Apartment areas are getting between 100 and 150 square meters (MHUC, 2020).

Thermal comfort is mainly associated with the temperature that the resident considers as comfortable to stay in. Indoor thermal comfort is achieved when occupants can do the intended activities

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without any hindrance, as well as it is essential for their well-being and productivity (Haruna, Musa, Tikau, & Yerima, 2014). The International Organization for Standardization (ISO 7730) as well as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) use the results of intensive research by Fanger (1970) to define thermal comfort as that condition of mind that expresses satisfaction with the thermal environment (Fanger, 1970).

The main components of the building (ceiling, walls, foundation, windows and doors) control the amount of heat gain, consequently, the thermal comfort (Menyhart & Krarti, 2017). The external walls are responsible for 25-30 % of the heat gain of the building (Abanda & Byers, 2016). Therefore, the thermal performance of the building envelope is a crucial aspect that needs to be studied by building researchers. Designing an efficient external wall with a thermal insulation is a necessary step to achieve the indoor thermal comfort (Makram, 2008).

Energy plays a significant role in the economic growth, therefore, the current global energy crisis restricts the sustainable development (Ding, Zhang, He, Huang, & Mao, 2019). Buildings consume about 30% of the global energy consumption (Mavromatidis et al., 2019). Thus, governments aim to improve energy efficiency in buildings (Ibrahim et al., 2019). Currently, the National Research Center for Housing and Construction (HBRC, 2009) has published energy efficiency symbols for the residential buildings. The housing sector in Egypt consumes around 41% of the total national energy consumption (CAPMS, 2019). The air conditioning system in buildings consumed 56% of the total energy consumed in buildings (El-Darwish & Gomaa, 2017). So any effective way to reduce energy demand for this type of building helps us cope with the very high costs of energy consumed.

Therein, the thermal insulation material is one of the most effective approaches to economize energy (Ni et al., 2020). Currently, organic Polymer Foam insulation board (Li, Zhang, Zhang, Ding, & Zhou, 2020), such as Extruded Polystyrene (XPS), is widely applied as a thermal insulation material in buildings due to its outstanding performance (Si et al., 2019).

Several studies discussed the optimization of the indoor thermal comfort and energy consumption by integrating the thermal insulation materials in the external walls. In 2018, Morsy et al. studied achieving the optimization of thermal comfort and energy consumption for an educational building in Cairo to find the relation between insulation materials and thermal comfort. The authors simulated a computational model to evaluate the thermal performance of eight thermal insulation materials with different thicknesses. Results showed that XPS and Polyurethane (0.026) using 6cm thickness were the most effective option that achieved the lowest energy consumption while 16cm thickness Celton was the best alternative in the thermal comfort (Fahmy, Morsy, Abd Elshakour, & Belal, 2018).

Akpinar and Demir calculated the optimal insulation thickness and energy saving based on life-cycle cost analysis in seven locations represented four climate zones in Turkey. Results indicated that insulation thicknesses varied between 0.002–0.049 m, with the amount of life-cycle energy saving as 0.629–21.047 $/m^2 and a payback period of 0.3-6.5 years depending on the type of fuel, insulation material and wall-type. Energy saving was great, and the thermal insulation was more effective for cities with higher degrees. The highest value was for the sandwich wall and XPS; whereas the thinnest insulation was for Expanded Polystyrene (EPS). (AKPINAR & DEMİR, 2018).

Expanded Polystyrene (EPS) and XPS are recommended by the National Agency for the renewable energy resource and energy efficiency development (ADEREE) to be used in roofs and external walls (ADEREE, 2020). In 2020, Lafqir et al claimed that the thermal insulation of the 4cm XPS ceiling in different climates of Morocco reduced the demand for heating and cooling by 10% and 30% respectively, compared to the uninsulated house. Consequently, by including minimum additional XPS thermal insulation layers on the roof and the external walls, the annual power demand for scenario 2 decreased to 42.61 kWh/m^2 year, below the limit, 46 kWh/m^2 year, 7.4% below performance-based

(RTCM) (Thermal Regulation for Construction) range requirements (Lafqir, Sobhy, Benhamou, Bennouna, & Limam, 2020).

XPS was found to be particularly commonly used for roof insulation in the construction industry in Saudi Arabia due to its reasonable costs, ease of manufacture, and installation, Al-Tamimi 2021, used XPS to assess the impact of thermal insulation on energy consumption. Two cases were modeled and compared to the non-insulated base case to investigate the effect of thermal insulation. Furthermore, simulation software was used for more investigations, such as the benefits of the cost of insulation using a life cycle cost model to find out when to stop adding insulation. The results show that energy cost savings vary from 5.6 $/m^2 to 9.7 $/m^2 depending on the city's climatic state. On the other hand, the most extended recovery period with 8.8 years in Meshit Thursday (mild climate), while the shortest period was 4.7 years (Al-Tamimi, 2021).

In 2022, Kazanci and Samanci designed a 100 m^2 single-family residential house to calculate the external wall's optimal insulation thickness, including a 20% window-to-wall ratio (WWR) for two different climate zones. The authors simulated four types of insulation material for the external walls due to its physical properties, which were available in the market. The result revealed that the XPS material was identified as the ideal alternative in the hot zone (KAZANCI & SAMANCI, 2022).

Based on the previous studies, it can be noticed that there are some research deficits regarding modeling thermal insulation materials for residential buildings by simulation software in the hot arid climate inside Egypt to achieve thermal comfort. Therefore, the main objectives of this study are to assess thermal comfort inside residential buildings using various thermal insulation materials available on the Egyptian market by DesignBuilder software and selecting the optimal insulation material among these alternatives. This research also introduces the solution to save energy for middle-income citizens in the medium housing project.

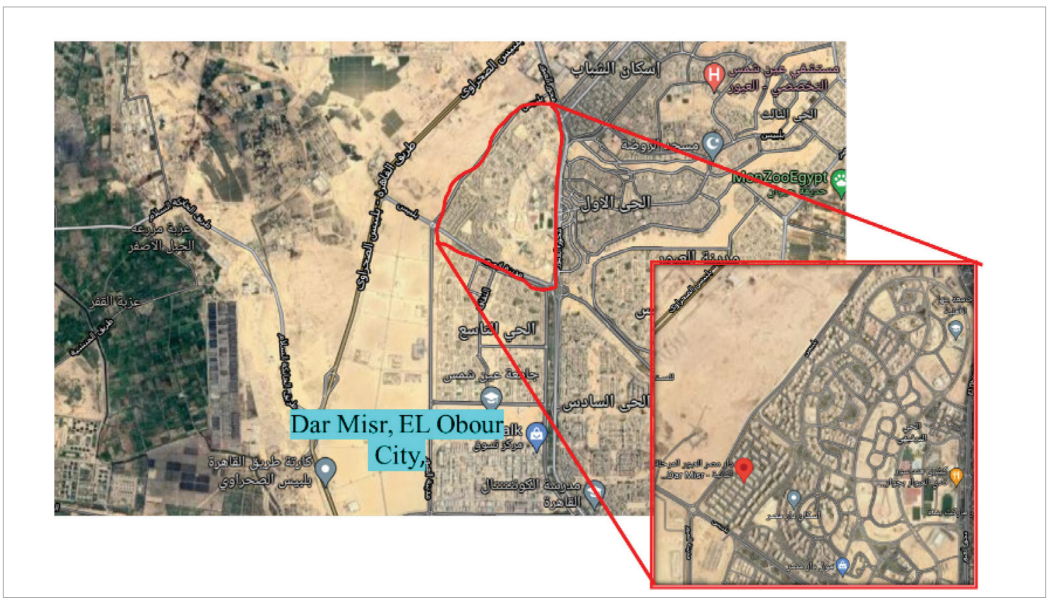
Study Area

Egypt is a large country of about one million square kilometers, located between 22°N to 31° 37´N latitude and 24° 57´E to 35°45´E longitude. Egypt has a variety of climatic zones ranging from hot desert, to semi-hot climate zone in the north coast (Mahdy & Nikolopoulou, 2014).

The location of 'Dar Misr, Al Obour City, Cairo, Egypt', considered one of the public residential buildings of middle-income residents, was selected as a case study (Fig. 1).

Fig. 1

Dar Misr Layout, EL Obour City, Cairo



The residential building is 570 m^2 and consists of ground and five typical floors. There are four apartments in the floor. As a simulation model, an apartment of a total area (130 m^2) and a clear height of 3 meters, as shown in **Fig. 2** consists of a reception and dining space, three bedrooms, a kitchen, a bathroom, a toilet and terraces.

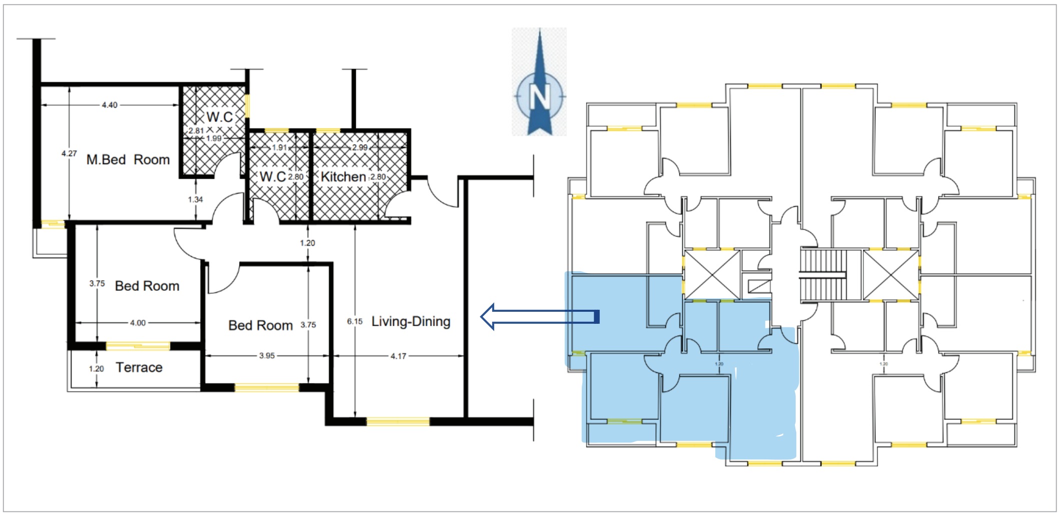


Fig. 2
Flat of total area (130m^2), Dar Misr (modified after Auto-CAD)

Methodology

Simulation tools

Simulate an apartment in Building Type A as shown in **Fig. 3** using DesignBuilder v6.5 software, which allows to build three-dimensional model, and select the structure and finishing materials of the building. Moreover simulating, the thermal performance and energy consumption of each apartment.

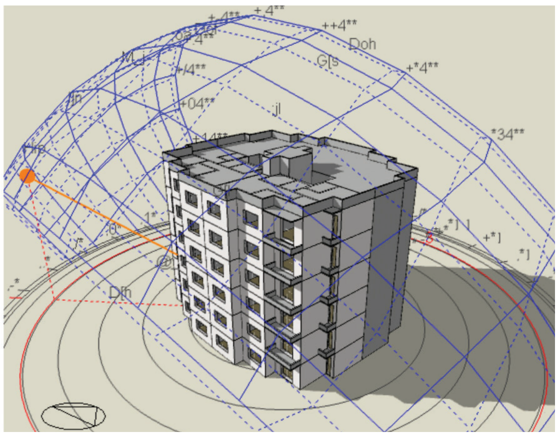


Fig. 3
3D model of Building Type (A) (modified after DesignBuilder).

Physical model characteristics

The simulation is based on weather file data from Climate Consultant 6.0 every hour, considering the acquisition of solar energy, thermal conduction, and convection between zones of different temperatures. The input data is verified by the Egyptian building Code, as shown in (**Table 1**):

Table 1
Specifications of the building envelope layers

Constructions	Layers of the building envelope	
External wall	**Outermost layer** Plaster (lightweight)	Thickness (m) 0.005
	Cement/plaster/mortar- plaster	0.02
	Brickwork Outer	0.25
	Cement/plaster/mortar- plaster	0.02
	Innermost layer Acrylic	0.001

Selection criteria of insulation material

Choosing the insulation materials from that available in the Egyptian market depends on nine parameters, including; durability, cost, pressure force, absorption and transport of water vapour, fire resistance, ease of application and thermal conductivity (Mahlia & Iqbal, 2010).

The simulation is conducted to compare the thermal and energy performance of five insulation alternatives. The characteristics of the selected insulation materials are shown in Table 2. Thermal properties are obtained from the Egyptian Residential Energy Code to improve energy efficiency (EREC) and Egyptian specifications for thermal insulation work items , also the thicknesses of insulation materials are the optimal thicknesses obtained in earlier research. (Al-Homoud, 2005) (Si et al., 2019).

Table 2

Performance characteristics of different insulation

No.	Insulation type	Density (kg/m3)	Thermal conductivity (W/m-K)	Compressive strength (N/mm^2)	Thickness (mm)
1	Vermiculite	100	0.065	0.35	4.8 mm
2	Rockwool (board)	72	0.045-0.05	0.14	50 mm
3	Phenolic foam	35-200	0.018-0.023	0.5 - 5	60 mm
4	Extruded polystyrene (XPS)	28-40	0.027-0.033	0.276	70 mm
5	Polyethylene (board)	30 - 40	0.02-0.027	0.2 - 0.1	4 mm

The specifications for external wall constructions used are presented in Table 3. In Fig. 4, the layers of the selected insulation materials are shown, as well as the base case.

Table 3

External walls main characteristics with insulation material

Case	Insulation type	External Walls
Base Case	without insulation	wall of red-brick.
Alternative -1	Vermiculite	**Vermiculite** insulation painting, and changing the colors of external finishing walls to lighter colors.
Alternative -2	Rockwool (board)	wall of red-brick with additional 50 mm of **Rockwool** thermal insulation layer.
Alternative -3	Phenolic foam	Double wall of half red-brick with additional internal 60mm of **Phenolic foam** thermal insulation layer.
Alternative -4	Extruded polystyrene (XPS)	Double wall of half red-brick with additional internal 70mm of **XPS** thermal insulation layer.
Alternative -5	Polyethylene (board)	Double wall of half red-brick with additional internal 4mm of **Polyethylene** thermal insulation layer.

Thermal comfort measures

There are six factors, environmental and personal parameters, that affect thermal comfort status. These factors may be independent of each other, but together contribute to an employee's thermal comfort, including (Table 4): Air temperature, air velocity, relative humidity and average radioactive temperature. In addition, personal factors including the clothing insulation and the metabolic rate also affect human thermal comfort. According to EREC, climatic conditions to assess people's thermal comfort are (EREC, 2008):

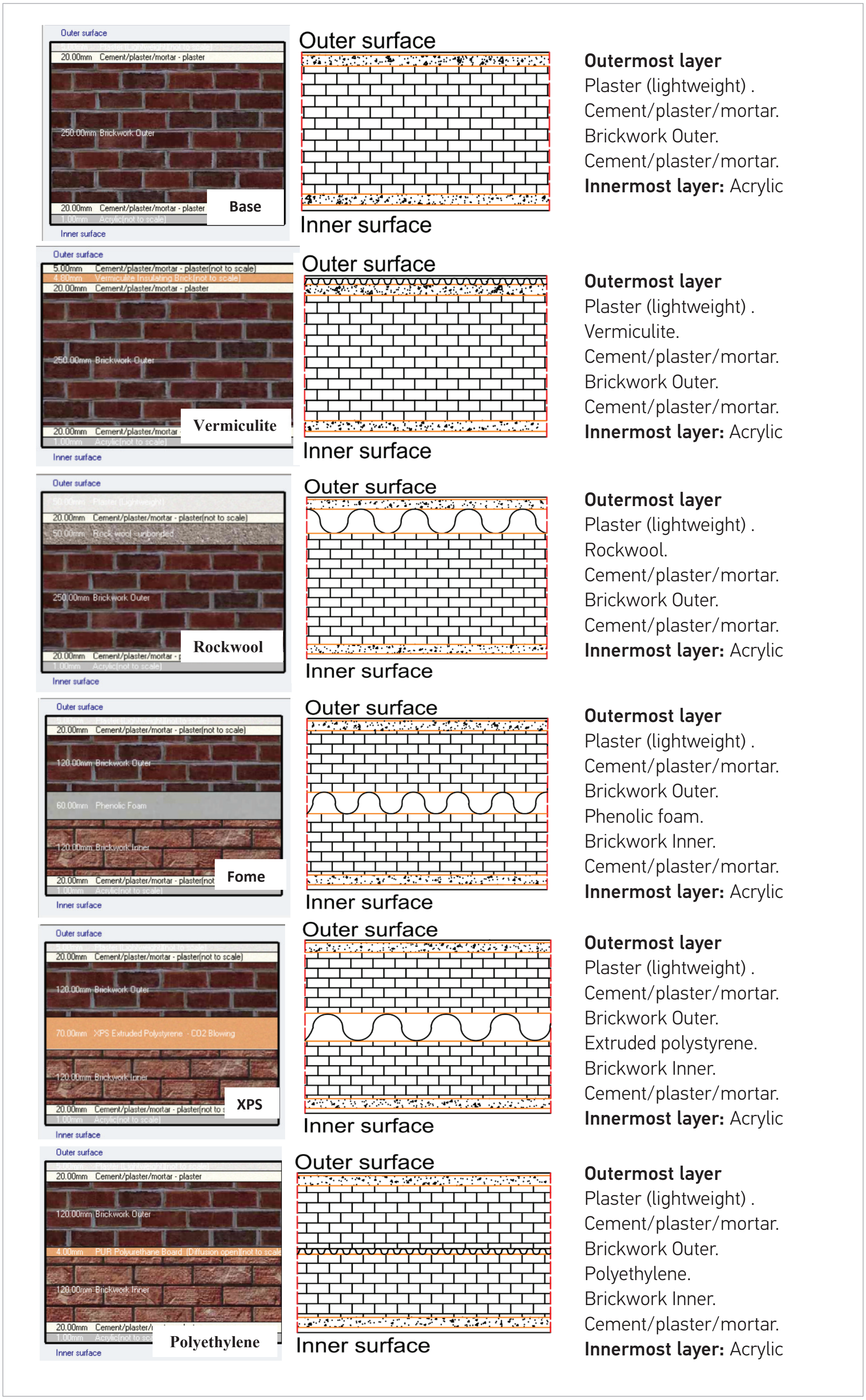


Fig. 4
Wall sections used

Table 4

EREC Thermal comfort measures

Element	Minimum	Maximum
Air Temperature	21.8° c.	30° c.
Relative Humidity	20 %.	50 %.
Air velocity	0.5 m / sec.	1.5 m / sec.

Results and Discussion

Energy-conscious building design consists in controlling the thermophysical characteristics of the building envelope such as thermal transmittance (U-value). U-value is one of the practical criteria when considering thermal performance and energy conservation issues. Attention is paid to simulating the thermal performance of all alternatives accepted in the Egyptian Building Energy Code and previous studies in various countries, indicating their greater impact on energy saving and thermal comfort leading to results and ultimately obtaining the optimal insulating material. Table 5 shows the U-value of the five alternatives which are simulated by DesignBuilder. Whilst the non-insulation base case recorded the highest U-value (1.68 W/m^{2}K), XPS has the lowest value (0.37 W/m^{2}K).

Table 5

Thermal transmittance (U-value) for different insulation materials

Case	Base Case	Alternative -1	Alternative -2	Alternative -3	Alternative -4	Alternative -5
		Vermiculite	Rookwool	Phenolic foam	XPS	Polyethylene
U-Value (W/m2K)	1.68	1.60	0.51	0.46	0.37	1.25

Impact on thermal comfort analysis

Thermal comfort is measured in terms of the number of hours of discomfort. The shortest discomfort period is the best scenario in which the suitable thickness is used in building construction to achieve optimal thermal comfort. The results of each material effect on thermal comfort are displayed first, and measurements of the walls' air temperature and surface temperature were made for a year without using air conditioning units or fans.

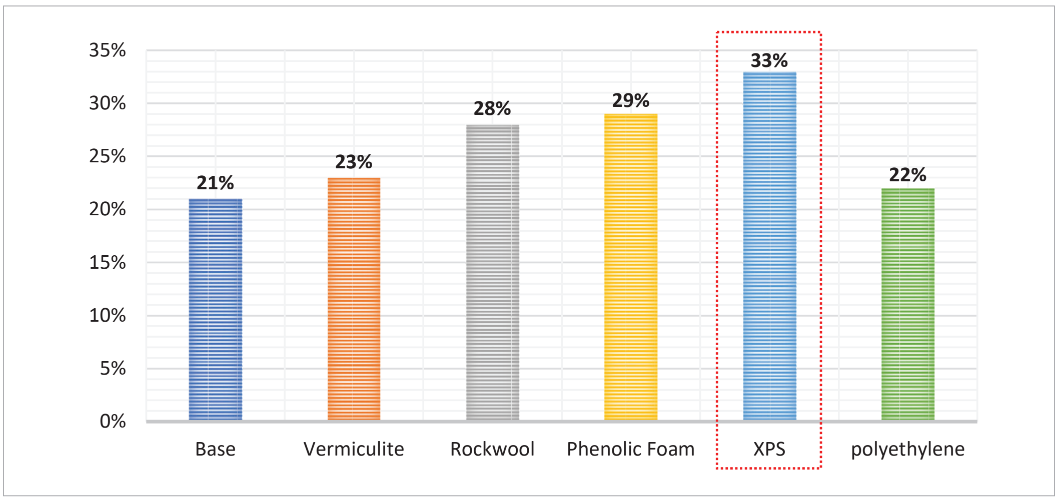


Fig. 5

Indoor thermal comfort percentage for base case and alternatives

Fig. 5 shows that simulation results of the base case study in the comfort zone were about 1853 thermal comfort hours from 8760 hours over the year (21%). The use of polyethylene has almost no impact on the thermal comfort inside the building, while using vermiculite had a slight effect, as the thermal comfort period increased to reach 23%. Whilst applying the rockwool and foam as insulation material recorded 28% and 29%, respectively. With XPS insulation, the thermal comfort period reached 33%. Therefore, XPS is the optimal insulation material that achieves thermal comfort compared to the other alternatives. The performance characteristics of XPS insulation and other types are shown in Table 2.

Impact on Energy consumption

This study focuses on the annual energy consumption of an apartment for separate single-family of 130 m². The energy consumption calculations include lighting, air conditioning, and equipment. The overall energy consumption is measured in kWh. The output was analyzed and compared mainly to the base case considering the annual energy consumption.

It is observed in Fig. 6 that while the monthly energy consumption went down to the lowest values in the winter period, especially in November (310.27 kWh), total energy consumption increased in May, June, July, August, September, and October due to increased solar radiation in these months. The monthly energy consumption peaked at 732.18 kWh in August, and the total yearly energy consumption reached 5445.12 kWh of the base case model, also showing that energy consumption in the summer period was the highest. Therefore, since its beginning, the study focused on cooling techniques, and simulation showed that heating loads were not as critical as cooling loads in a hot arid climate like Cairo.

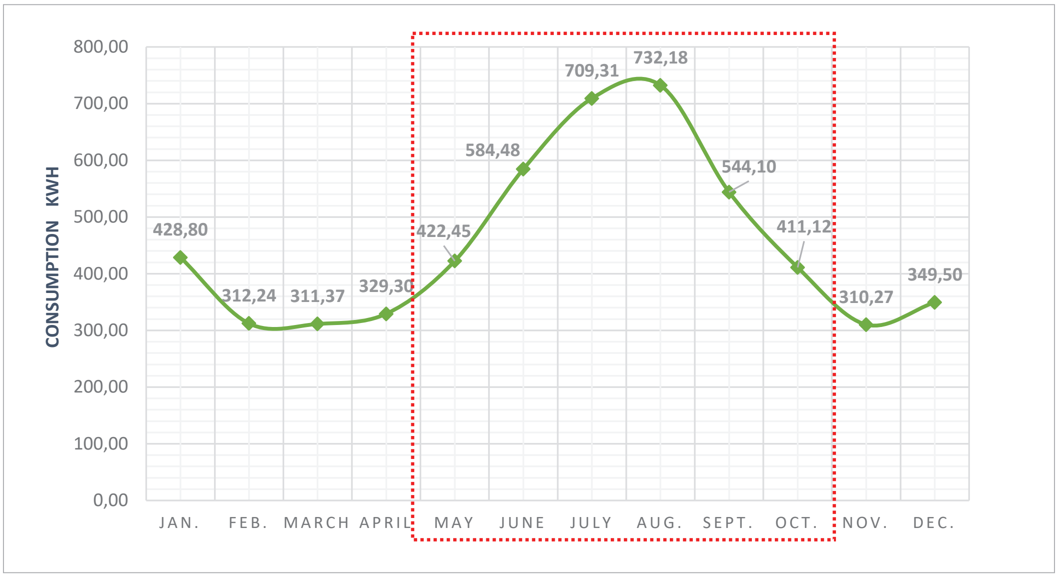
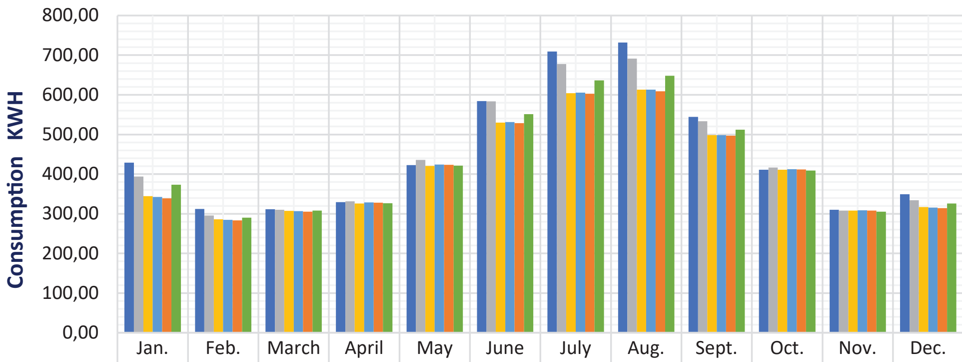


Fig. 6
base case simulation results show monthly energy consumption for base case and maximum energy consumption from May to October (cooling period)

As shown in Fig. 7, alternatives, Vermiculite, Rock Wool, Phenolic Foam, XPS, and Polyethylene, perform better than the base case during the year. The base case has the maximum annual energy consumption (about 5445 kWh). After installing the thermal insulation materials in the external walls, it was found that the five thermal insulation alternatives reduced the energy consumption during the year in varying proportions. XPS is considered the most thermal insulation for energy saving inside the building, primarily through the summer months, as its total annual energy consumption was around 4940kWh. It is also noted that this yearly consumed energy in the building has the minimum consumption compared to the other alternatives.

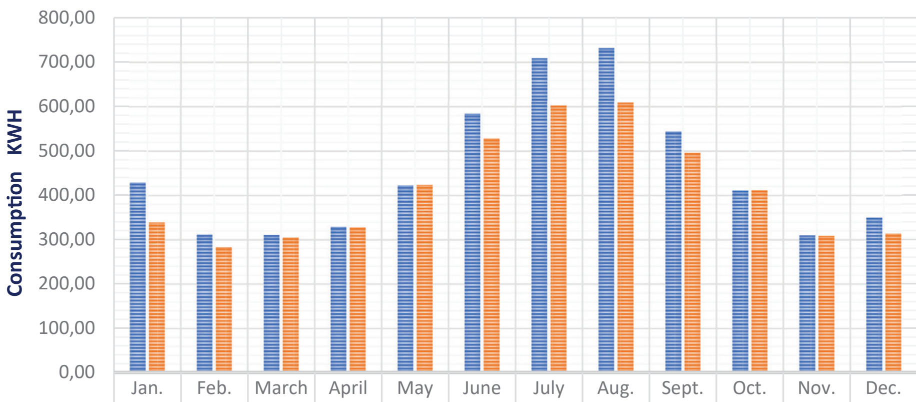
After reaching the optimal insulation, it is found that the results of the proposed compared to the previous model achieved energy saving towards thermal comfort. The annual energy consumed by the base case model for thermal energy was 5445.12 kWh/y and after optimizing the XPS insulation became 4940.3 kWh/y. Fig. 8 shows the monthly energy consumption of thermal energy for the base case and new proposed model. This saved energy by 9.27 %. These results show that regarding the total energy demand, how the optimal design of the proportions of the building insulation material is vital.



	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Base Case	428,80	312,24	311,37	329,30	422,45	584,48	709,31	732,18	544,10	411,12	310,27	349,50
Vermiculite	393,86	295,8	310,28	331,37	435,78	583,71	677,37	691,37	533,11	416,69	308,03	334,49
Rockwool	344,26	285,76	307,16	325,95	420,69	530,15	604,43	612,77	498,45	411,25	308,22	316,66
Phenolic Foam	342,28	284,45	306,49	328,33	424,3	531,02	605,35	612,75	498,49	412,25	308,85	315,96
XPS	338,99	283,21	305,34	327,78	423,7	528,65	602,55	609,17	496,65	411,52	308,2	314,16
Polyethylene	373,01	290,06	308,25	326,35	421,13	551,27	636,59	647,89	511,89	408,93	305,33	326,11

Fig. 7

Total annual energy consumption for base case and alternatives



	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Base Case	428,80	312,24	311,37	329,30	422,45	584,48	709,31	732,18	544,10	411,12	310,27	349,50
optimized insulation	338,99	283,21	305,34	327,78	423,7	528,65	602,55	609,17	496,65	411,52	308,2	314,16

Fig. 8

Monthly total energy consumption for previous situation (Base case) and new proposal model (model optimized insulation)

Conclusions

This study demonstrates the detailed analysis of indoor thermal comfort and the impact of insulating materials on energy consumption for a residential flat (130 m^2) in Egypt's hot arid climate during the year. Using DesignBuilder software, five available thermal insulation materials (Vermiculite, Rock Wool, Phenolic Foam, Extruded Polystyrene (XPS) and Polyethylene) for the building envelope were simulated. Simulation results of the current design show that the base case study construction prototype achieved 21% of thermal comfort recommendations during the year. Results also indicate that all types of insulation materials substantially impact achieving more hours of indoor thermal comfort. By modifying the current case study using the wall's thermal insulation strategies, extruded polystyrene material (XPS) was the optimal insulating material that yearly obtains indoor thermal comfort area by 33% of thermal comfort recommendations without using air conditioning units or fans. The study shows that the insulation wall system has a significant impact on reducing energy consumption and reducing discomfort hours in the building. XPS is the optimal alternative for residential buildings to minimize annual energy consumption. While the total annual energy consumed by the thermal energy base case model was 5445.12 kWh/y, after optimization it became 4940.3 kWh/y with a saving ratio of 9.72%.

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Availability of data and material. Providing the data for this modeling study by Egyptian building Code and Egyptian Residential Energy Code to improve energy efficiency (EREC).

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