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EVALUATING SMART INSULATING MATERIALS FOR ENERGY EFFICIENCY IN MULTI-STORY BUILDINGS IN ALEXANDRIA'S CLIMATIC ZONE, EGYPT

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ABSTRACT

This paper evaluates the efficiency of smart thermal insulation materials, including Aerogel, Phase Change Materials (PCM), and Vacuum Insulation Panels (VIP), in residential buildings in Alexandria, Egypt. Using the DesignBuilder simulation tool, it examines the impact of these advanced materials on energy consumption. The study conducts a comparative analysis to determine how each material reduces annual energy use. Simulation results show that Aerogel, PCM, and VIP reduce annual energy consumption by 6.52%, 4.87%, and 6.10%, respectively. A comprehensive analysis identifies Aerogel as the most effective option in the long term, improving energy performance while reducing environmental impact. These findings underline the importance of incorporating smart thermal insulation materials in the design and retrofitting of energy-efficient buildings. Furthermore, the study emphasizes the critical role of advanced materials in addressing the challenges of climate change and resource conservation. The findings highlight the potential of smart insulating materials for both new constructions and retrofitting existing buildings, promoting sustainable practices in the Egyptian building sector. This study provides valuable insights into the role of innovative materials in achieving energy efficiency and environmental sustainability in hot-arid climates.

KEYWORDS: Energy consumption, Sustainable architecture, Smart thermal insulation materials, Building performance.

1. INTRODUCTION

The continuous rise in energy consumption is a pressing global concern, significantly contributing to environmental issues such as climate change. According to the U.S. Energy Information Administration (EIA), the building sector accounts for approximately 40% of total energy consumption in the United States [1]. In Egypt, energy consumption has steadily increased over the past decade, rising from 104.1 billion kilowatt-hours (kWh) in 2010 to 159.7 billion kWh in 2020—a significant increase of 34.8% [2], as illustrated in Figure 1.

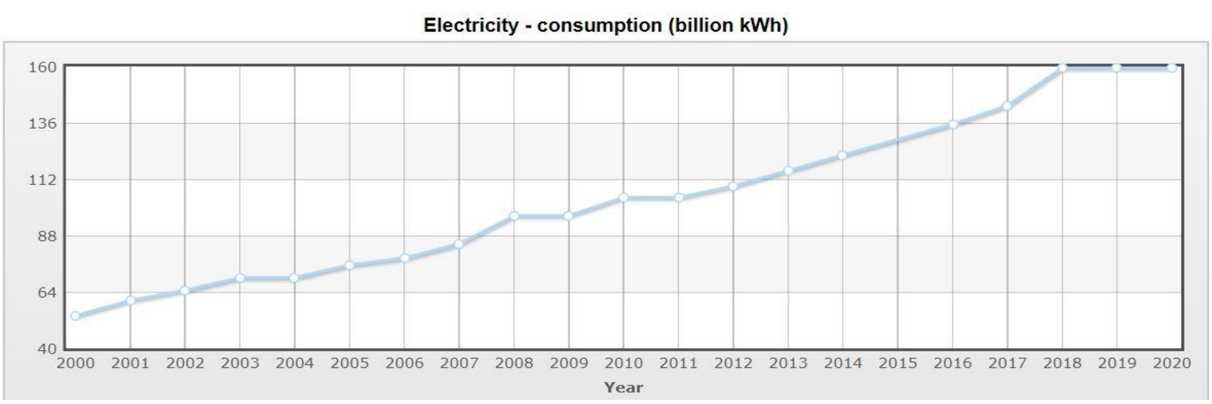

Figure1: Egypt Electricity consumption in billion (kWh) from 2000 to 2020 [2].

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Residential buildings, particularly multi-story structures with glazed façades, often suffer from low energy efficiency, leading to excessive internal heat gain during the hot summer months (June to September), as illustrated in Figure 2. This increased heat gain amplifies the demand for HVAC systems, resulting in higher energy consumption for cooling, contributing to the depletion of non-renewable energy sources, economic strain, and harmful emissions [3].

In response to these challenges, advanced materials—specifically smart thermal insulation materials—offer innovative solutions for enhancing energy efficiency in building envelopes. These materials improve thermal insulation performance while providing environmental benefits, making them a sustainable alternative to traditional insulation methods [3]. This paper explores the effectiveness of smart thermal insulation materials, including Aerogel, Phase Change Materials (PCM), and Vacuum Insulation Panels (VIP), in enhancing energy performance in residential buildings in Alexandria, Egypt.

Using the DesignBuilder simulation tool, this paper assesses the impact of these materials on annual energy consumption. By focusing on the integration of smart materials in the Egyptian context, the study highlights their potential to reduce energy usage and promote greener building practices in the region.

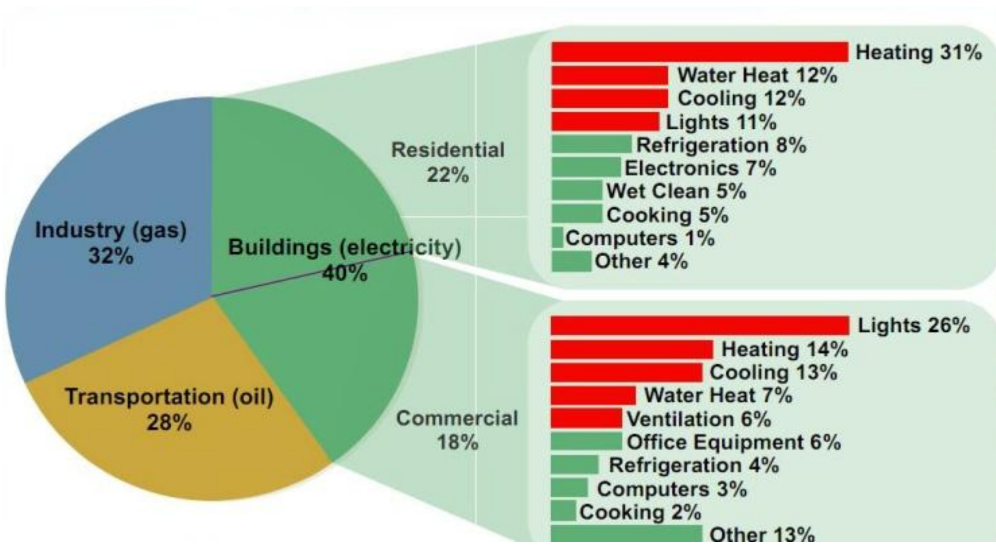

Figure 2: Energy consumption breakdown in buildings [4]

2. SMART INSULATION MATERIALS

This paper examines smart insulation materials, specifically aerogels, Phase Change Materials (PCMs), and Vacuum Insulation Panels (VIPs), chosen for their exceptional thermal performance and suitability for the Egyptian climate[5]. Aerogels provide outstanding thermal resistance in limited spaces, while PCMs effectively regulate temperature fluctuations by absorbing and releasing thermal energy. VIPs offer superior insulation with minimal thickness, enhancing energy efficiency. these materials represent innovative solutions for improving thermal comfort and reducing energy consumption in Egypt.

A. The Aerogel

Aerogel, discovered by Samuel Kistler in 1931, is a superior alternative to conventional insulation materials due to its exceptional thermal resistance, low thickness, and transparency, which enhances energy efficiency while maintaining aesthetic qualities [6]. Composed primarily of air and gel, aerogel has a porosity exceeding 90%, leading to its colloquial names "frozen smoke" or "blue smoke." As shown in Figure 3. With a thermal conductivity as low as 0.013 W/m·K, aerogels are among the best insulating materials available [7].

Figure 3: Aerogel 'puffed-up sand' or 'frozen smoke [8].

Table 1 summarizes the key physical properties of silica aerogels. A range of values is given for each property because the exact value is dependent on the preparative conditions and, in particular, on density.

Table 1: Physical properties of silica aerogels [8]

Properties	Value	Properties	Value
Density (kg/m³)	3–350 (most common ~100)	**Primary particle diameter (nm)**	2–5
Pore diameter (nm)	1–100 (~20 on average)	**Surface area (m²/g)**	600–1000
Porosity (%)	85–99.9 (typical ~95)	**Index of refraction**	1.0–1.05
Thermal conductivity (W/m·K)	0.01–0.02	**Thermal tolerance temperature (°C)**	500 (m.p > 1200)
Transmittance in 0.5–2.5 µm, 3.7–5.9 µm	0.80–0.95	**Coefficient of linear expansion (1/°C)**	$2.0–4.0 \times 10^{-6}$
Longitudinal sound speed (m/s)	100–300	**Tensile strength (kPa)**	16

In a notable application in 2012, a 10 mm layer of aerogel was installed in the solid walls of the Pentagon, resulting in significant energy savings of 122,796 kWh annually and a reduction of 22 kg in CO2 emissions per year[7].

B. Phase Change Materials (PCM)

Phase Change Materials (PCMs) are designed to absorb, store, and release significant amounts of energy as latent heat. They undergo phase changes—typically from solid to liquid and then to gas—at various temperatures depending on the specific PCM type. For example, Sodium Thiosulfate has a melting point of 48°C, and additives are often used to enhance its supercooling properties. This capability enables PCMs to absorb solar radiation and release energy upon solidification, making them highly effective for thermal management in buildings [9].Common types include paraffin wax and salt hydrates, known for their effective thermal management properties[10].

Physical Properties:

- Phase Change Temperature: Typically, between 20-30°C for paraffin-based PCMs.
- Latent Heat Storage: High capacity for thermal energy storage.
- Thickness: Typically integrated within wall systems or applied as a coating.
- Protection Layers: Often require encapsulation to prevent leakage and ensure safety.

Applications of PCM:

Projects integrating PCMs into building materials have shown up to 20% reduction in cooling energy consumption, highlighting their effectiveness in energy management [11].Some application areas for PCM in buildings are illustrated in Figure 4: No. 1: Latent heat store for space heating. No. 2: Plaster and compound systems with high heat storage capacity. No. 3: Transparent insulation and day lighting schemes. No. 4: Shading PCM compounding system. No. 5: PCM in gypsum products and paints. No. 6: PCM to buffer temperature variations in solar-air systems [12].

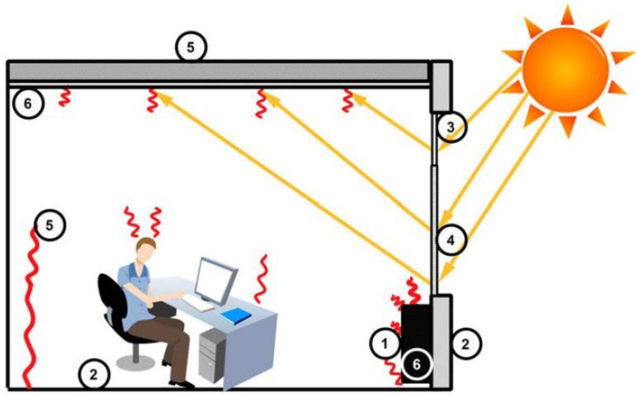

Figure 4: Application areas for PCM in buildings [12]

Benefits: Enhanced thermal comfort and energy efficiency.

PCMs help reduce heat gain in summer by reflecting solar radiation and minimizing latent heat, enhancing indoor thermal comfort, especially in hot and dry climates like Egypt [13]. During winter, PCMs release stored heat, maintaining comfortable indoor temperatures and reducing heating energy demands. This dual functionality makes them valuable for energy efficiency in regions with significant temperature fluctuations [14].

C. Vacuum Insulation Panel (VIP)

Initially developed for refrigeration, Vacuum Insulation Panels (VIPs) have been adapted for building applications due to their exceptional insulation performance. With thermal conductivity as low as 0.004 W/m·K—5 to 10 times lower than traditional materials like polystyrene or mineral wool—VIPs provide superior insulation owing to their rigid core and vacuum design [15]. The typical VIP is presented in Figure 5.

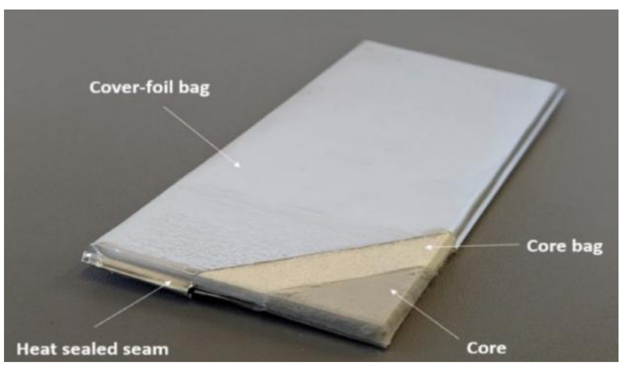

Figure 5: Vacuum insulation panel [16]

Physical Properties [17]:

- Density: Typically around 0.5 to 1.0 g/cm³.
- Thermal Conductivity: 0.004 - 0.008 W/m·K.
- Compressive Strength: High.
- Core Material: Composed of porous nanoscale materials (~100 nm).
- Protection Layers: Includes a core protection layer and a silver sealing layer.
- Thickness: Ranges from 10 mm to 40 mm, allowing for maximum thermal resistance without compromising the aesthetic value of interior spaces during renovations.[18].

3. METHODOLOGY

The study was conducted on a multi-story residential building in Alexandria Governorate, Egypt, with the primary objective of assessing the effectiveness of smart thermal insulation materials—specifically Aerogel, Phase Change Materials (PCM), and Vacuum Insulation Panels (VIP)—in reducing annual energy consumption.

A. **Insulation Material Assessment:** Three types of insulation materials were evaluated:

- **Aerogel**: Known for its low thermal conductivity and lightweight properties.
- **Phase Change Materials (PCM)**: Designed to absorb and release thermal energy, stabilizing indoor temperatures.
- **Vacuum Insulation Panels (VIP)**: Known for their excellent insulation properties with minimal thickness.

B. Building Specifications

The specifications of the residential building are outlined below. Key characteristics include:

- **Location:** Alexandria Governorate, Egypt
- **Building Type:** Multi-story residential
- **Total Floors:** Ground floor +10 typical floors residential
- **Total Area:** 277.4 m2
- **Floor height:** 3 meters
- **Annual Energy consumption:** 57,649 kWh/year

C. Climatic Classification

The building is situated in the Hot Desert Climate (Köppen Classification: BWh). According to the Housing and Building National Research Center (HBRC), Alexandria is classified within a local climatic region characterized by high temperatures and low humidity, with significant seasonal variations, hot summers, and mild winters. [19]

D. Research Methods

The study employed the following additional research methods:

- **Simulation Tool:** Energy simulations were conducted using Design Builder Software (version 6.0.1), which excels in evaluating and comparing building material alternatives to identify the most energy-efficient option for reducing energy consumption in existing buildings. [20].
- **Data Collection:** Monthly and annual energy consumption data were collected for each insulation material scenario, allowing for a robust analysis of energy savings.
- **Comparative Analysis:** A comprehensive simulation was conducted over an entire year to investigate the impact of smart thermal insulation materials on annual energy consumption. The performance of each insulation material was evaluated against a baseline (the existing building) using established energy simulation metrics.
- **Evaluation Metrics:** The effectiveness of each insulation material was assessed based on:
    - Annual Energy Consumption (kWh/year)
    - Annual Energy Savings (kWh/year)
    - U-value calculations to determine thermal performance

4. RESULTS

The base case model represents the existing building without any insulation enhancements. Each floor was modeled to accurately reflect the four elevations of the residential building, simulating the building envelope (external walls). The specifications of the existing external wall (Base Case) are illustrated in Table 2.

Table 2: the Base Case external walls specifications calculated by Design Builder software

	Layer	Thickness (mm)	Thermal conductivity (W/mk)	Specific Heat (j/kg-k)	Density (kg/m3)
1	**Cement plaster**	10	0.72	840	1760
2	**Masonry medium weight**	200	0.85	840	1650
3	**Cement plaster**	10	0.72	840	1760
Total thickness (mm)		220			
U-value (W/m2k)		1.464			

Monthly & annual energy consumption are illustrated in Figures 6 and 7.

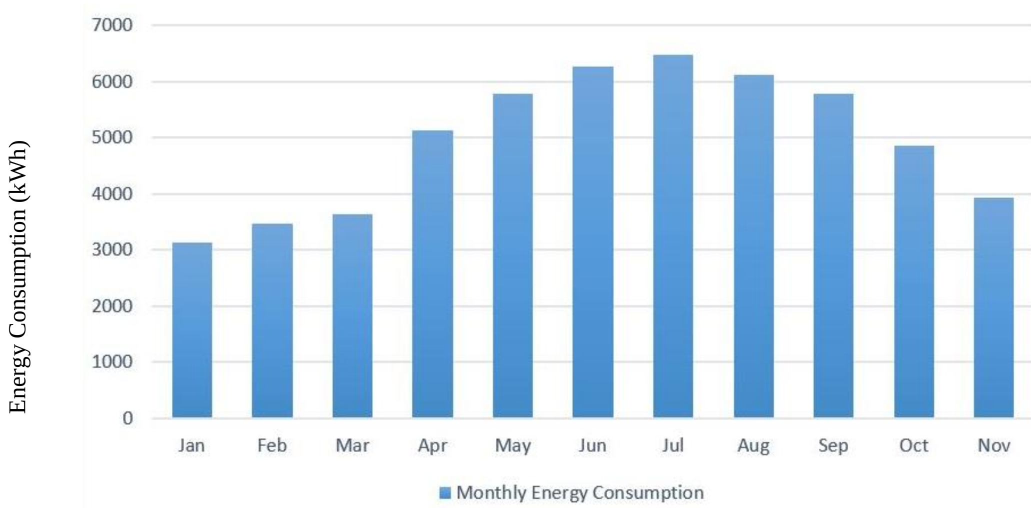

Figure 6: Monthly Energy Consumption for the base case

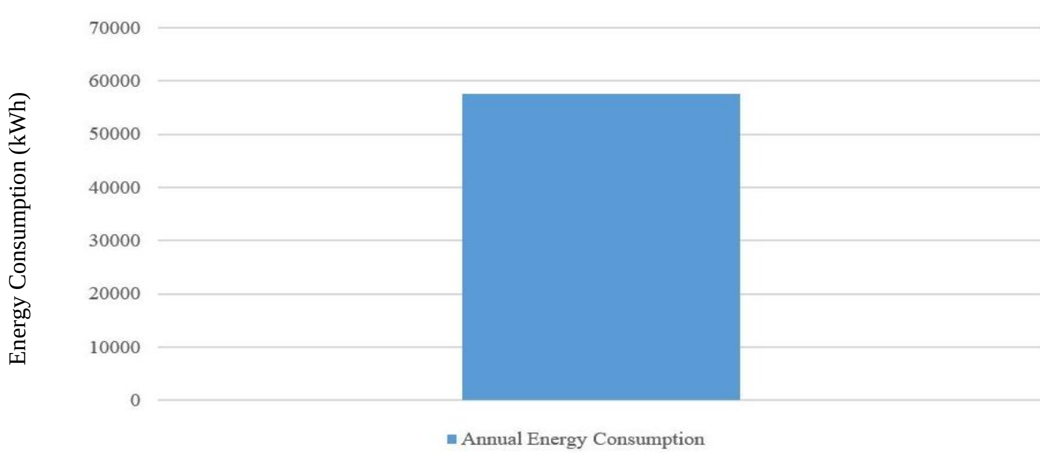

Figure 7: Annual Energy Consumption for the base case

3.4 Case 1 (Aerogel)

The simulation specifications for applying a 40mm aerogel layer are illustrated in Table 3.

Table 3: The specifications for Case 1 external walls were calculated using DesignBuilder software.

	Layer	Thickness (mm)	Thermal conductivity(W/mk)	Specific Heat (j/kg-k)	Density (kg/m3)
1	**Cement plaster**	10	0.72	840	1760
2	**Aerogel**	40	0.015	1000	160
3	**Masonry medium weight**	200	0.85	840	1650
4	**Cement plaster**	10	0.72	840	1760
Total thickness (mm)		260			
U-value		0.287			
R-value		≈ 0.905 m²·K/W			

Aerogel reduced the annual energy consumption to 53,891 kWh/year, approximately 6.52% of the total energy consumption, as illustrated in Figure 8.

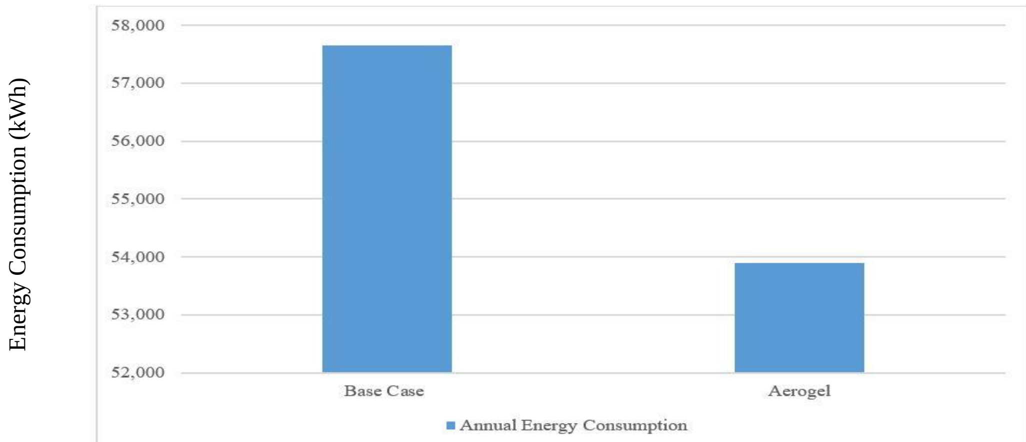

Figure 8: Comparison of the annual energy consumption between the Base Case and Aerogel.

A. Case 2 (PCM)

The simulation specifications for applying a 20mm PCM layer are illustrated in Table 4.

Table 4: The specifications for Case 2 external walls were calculated using DesignBuilder software.

	Layer	Thickness (mm)	Thermal conductivity (W/mk)	Specific Heat (j/kg-k)	Density (kg/m3)
1	**Cement plaster**	10	0.72	840	1760
2	**BioPCM (M51/Q23)**	20	0.2	1970	235
3	**Masonry medium weight**	200	0.85	840	1650
4	**Cement plaster**	10	0.72	840	1760
Total thickness (mm)		240			
U-value		1.080			
R-value		≈ 0.836 m²·K/W			

PCM reduced the annual energy consumption to 54,842 kWh/year, approximately 4.87% of the total energy consumption, as illustrated in Figure 9.

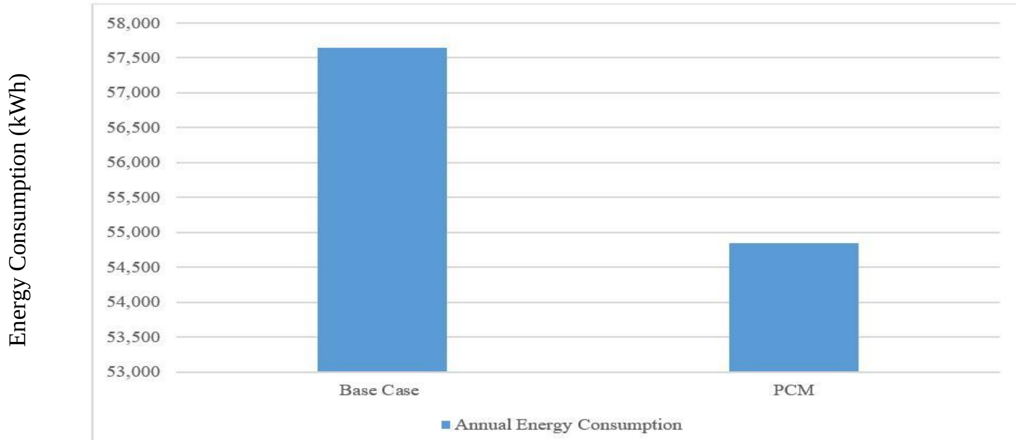

Figure 9: Comparison of the annual energy consumption between the Base Case and the PCM smart insulating material.

B. Case 3 (VIP)

The simulation specifications for applying a 50mm VIP layer are illustrated in Table 5.

Table 5: The specifications for Case 3 external walls were calculated using DesignBuilder software.

	Layer	Thickness (mm)	Thermal conductivity (W/mk)	Specific Heat (j/kg-k)	Density (kg/m3)
1	**Cement plaster**	10	0.72	840	1760
2	**VIP insulation (VACUPOR NT-B2)**	50	0.005	800.00	170
3	**Masonry medium weight**	200	0.85	840	1650
4	**Cement plaster**	10	0.72	840	1760
Total thickness (mm)		270			
U-value		0.092			
R-value		≈ 2.935 m²·K/W			

VIP reduced the annual energy consumption to 54,133 kWh/year, approximately 6.10% of the total energy consumption, as illustrated in Figure 10.

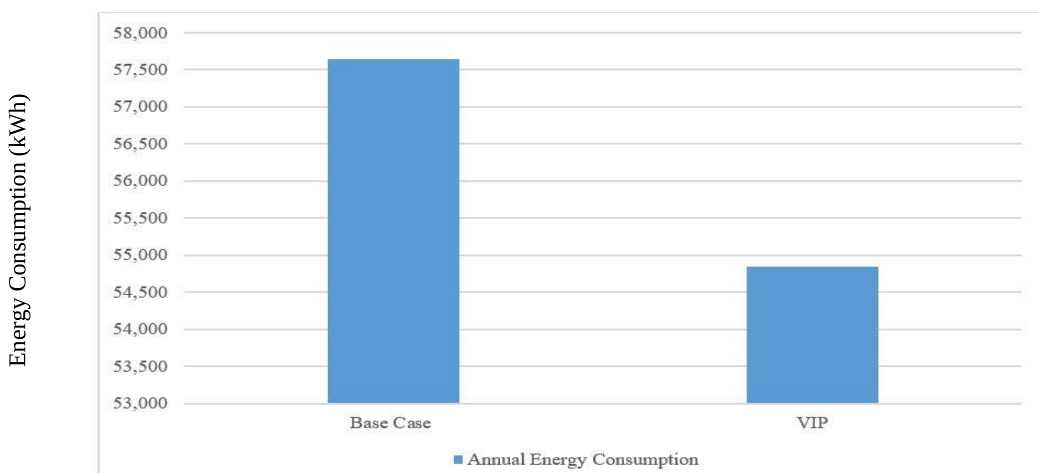

Figure 10: Comparison of the annual energy consumption between the Base Case and VIP.

C. Comparative Analysis of the Annual Energy Consumption of smart thermal insulation materials

Based on the simulation results, the comparative analysis of annual energy consumption for external wall thermal insulation materials, including Aerogel, PCM, and VIP, compared to the Base Case, is illustrated in Figure 11.

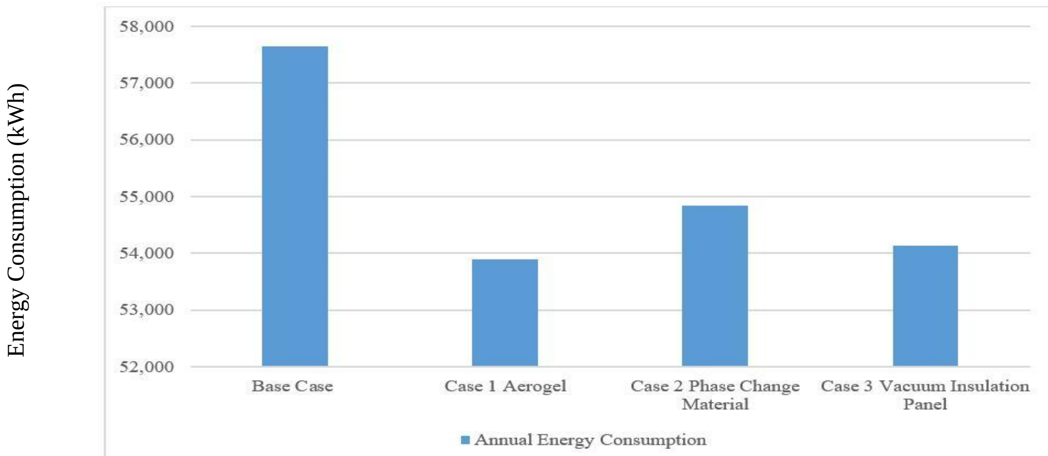

Figure 11: Annual energy consumption comparison of smart insulating materials with the Base Case.

- In Case 1, Aerogel reduced the Base Case U-value from 1.464 W/m²K to 0.287 W/m²K, with a total wall thickness of 260 mm. This resulted in a reduction of the annual energy consumption from 57,649 kWh/year to 53,891 kWh/year, representing a 6.52% decrease in energy use.
- In Case 2, PCM reduced the Base Case U-value from 1.464 W/m²K to 0.287 W/m²K, with a total external glass panel thickness of 240 mm. This reduced the annual energy consumption from 57,649 kWh/year to 54,842 kWh/year, achieving a 4.87% reduction in energy use.
- In Case 3, VIP reduced the Base Case U-value from 1.464 W/m²K to 0.092 W/m²K, with a total wall thickness of 270 mm. This led to a reduction in the annual energy consumption from 57,649 kWh/year to 53,133 kWh/year, reflecting a 6.10% decrease in energy use.

Based on the simulation results and comparative analysis, the most energy-efficient thermal insulating material is Case 1 (Aerogel), as it achieves the highest annual energy savings of 6.52%.

5. CONCLUSION

The study investigated the effectiveness of smart insulating materials as alternatives for the external walls of multi-story residential buildings in Egypt, a region characterized by a hot-arid climate. It evaluated the performance of Aerogel, Phase Change Materials (PCM), and Vacuum Insulation Panels (VIP) in reducing annual energy consumption. Simulation results indicated that these materials significantly impacted energy efficiency, with Aerogel, PCM, and VIP achieving reductions in annual energy consumption of 6.52%, 4.87%, and 6.10%, respectively.

Among the materials assessed, Aerogel emerged as the most effective in enhancing energy performance. Its integration into new constructions or retrofitting of existing buildings is strongly recommended, given its superior energy efficiency. Overall, this study underscores the potential of smart insulation technologies to improve building energy performance in hot-arid environments, paving the way for more sustainable architectural practices.

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تقييم المواد العازلة الذكية لكفاءة الطاقة في المباني متعددة الطوابق في منطقة الاسكندرية المناخية ,مصر

نادية سمير[1] , مينا بشوت[2]

الملخص

تُقيّم هذه الدراسة كفاءة المواد العازلة الذكية للحرارة، بما في ذلك الإيروجيل ومواد تغيير الطور (PCM) وألواح العزل بالفراغ (VIP)، في المباني السكنية بمدينة الإسكندرية، مصر. يتم استخدام أداة المحاكاة DesignBuilder لتحليل تأثير هذه المواد المتقدمة على استهلاك الطاقة. تعتمد الدراسة على تحليل مقارن لتحديد مدى فعالية كل مادة في تقليل استهلاك الطاقة السنوي. تُظهر نتائج المحاكاة أن الإيروجيل ومواد تغيير الطور (PCM) وألواح العزل بالفراغ (VIP) تُقلل من استهلاك الطاقة السنوي بنسبة 6.52% و4.87% و6.10% على التوالي. يكشف تحليل شامل أن الإيروجيل هو الخيار الأكثر كفاءة على المدى الطويل، حيث يُحسن الأداء الطاقي للمباني مع تقليل التأثير البيئي. وتُبرز هذه النتائج أهمية دمج المواد العازلة الذكية في تصميم المباني وتجديدها لتحقيق كفاءة الطاقة. علاوة على ذلك، تؤكد الدراسة على الدور الحاسم للمواد المتقدمة في مواجهة تحديات تغير المناخ والحفاظ على الموارد. تُسلط النتائج الضوء على إمكانات المواد العازلة الذكية لتطبيقها في المباني الجديدة وتجديد المباني القائمة، مما يدعم الممارسات المستدامة في قطاع البناء المصري. تُقدم هذه الدراسة رؤى علمية قيمة حول دور المواد المبتكرة في تحقيق كفاءة الطاقة والاستدامة البيئية في المناخات الحارة والجافة.

الكلمات الدالة: استهلاك الطاقة، العمارة المستدامة ، مواد العزل الحراري الذكية ، أداء المباني.

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