



Study the Effect of Transparent Paraffin Wax Gel Thickness on Window Thermal Insulation

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ABSTRACT

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hydrocarbon bonds, thermal conductivity, room window, amorphous structure

This paper involved using transparent paraffin wax to insulate the room's glass. Where the two panes of glass in the room's window were separated by translucent wax, which served as an insulating substance in the current investigation. Two windows measuring (73 × 28) cm² were included in the design of a thermally insulated room. A temperature reader data logger (Lutron BTM-4208SD) was used to capture data after the clear wax gel was applied to the room's windows. The study showed that in the winter, the translucent wax gel could remain stable at ambient temperature. Using some analysis, a structural investigation was performed to ascertain the gel's compositional and structural behavior. To find the effect of thermal insulation caused by the presence of the gel between two glass panes, three thicknesses (4, 6, and 8 mm) were applied. The results demonstrated that the gel might offer thermal insulation, and that this capability grows as the gel's thickness increases.

1. INTRODUCTION

Insulators are used in construction to decrease the amount of thermal energy transduction. Insulators are important for preserving suitable interior temperatures, increasing energy savings, and decreasing utility costs since they reduce heat dissipation. Insulating materials are designed to slow down the three thermal energy transfer mechanisms (conduction, convection, and radiation) by trapping air or creating barriers that resist heat flow [1, 2].

Motyl et al. [3] studied the heat conductivity of a transparent coating film applied to window glass. Different thicknesses were used in the study. The film under inspection was shaped using a polymer matrix that included metallic inclusions. So, they concluded that increasing the thickness of insulation leads to reducing energy cost. In modern building design, the imperative to minimize energy consumption has spurred intense research into advanced insulation materials, mainly those applicable to windows [3]. Windows, usually a significant source of heat loss and gain, exist as a serious area for development in building energy efficiency [4]. Traditional window designs often compromise between admitting light and providing acceptable thermal insulation [5]. This requires the development of materials that can settle these conflicting requirements, presenting both high transparency and real thermal resistance [6]. Comparing the performance of wax gel to ultra-efficient insulation materials such as aerogels and VIPs, these materials excel at reducing thermal conductivity to record levels compared to wax hydrocarbon structures. However, wax gel possesses a unique ability to store potential energy during its phase transformation, a characteristic not offered by conventional static insulators. Therefore, wax remains an economical option, combining transparent

insulation with internal temperature regulation, although it is less efficient in pure thermal resistance compared to aerogels.

Several studies have included adding materials to increase the thermal insulation of buildings and thus conserve energy. Some studies have included adding materials to increase the thermal insulation of buildings and thus conserve energy. Cuce et al. [7] and their colleagues conducted a comparative study and concluded that aerogel, as a transparent, heat-insulating material, is a promising material for building insulation.

The application of transparent wax gel as an insulating layer on room windows represents a promising avenue for enhancing energy efficiency in buildings [8]. The enhanced size will depend on the thermo-optical factors, like heat transfer coefficient, solar heat gain coefficient, and total transmittance of the window. Wax gels, characterized by a component finely dispersed within a liquid solvent, present a compelling combination of properties for potential application as a transparent insulation material in windows [9]. It features latent heat storage and optical transparency, allowing natural light to pass through clearly. It also boasts a low cost compared to advanced technologies and is easy to manufacture and install between glass layers. However, it suffers from chemical degradation, which may reduce its lifespan with continuous sun exposure, and low thermal resistance. When exposed to temperatures above or below its transition point, it loses its latent energy storage properties. Application scenarios include sustainable architecture, areas with fluctuating climates, and agricultural greenhouses.

Transparent wax gel is generally undocumented as a window insulator in literature or commercial products; that's why it has been used as an insulator applied to window glass to increase thermal insulation, which is often the area of thermal dissipation.

2. EXPERIMENTAL WORK

2.1 Materials

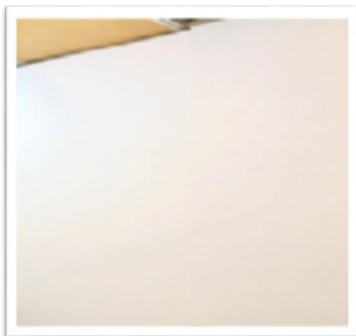
Paraffin gel wax is a semi-solid material composed of a specific ratio of paraffin wax and mineral oils or hydrocarbon compounds. This formulation results in a translucent or transparent gel-like consistency. The incorporation of oils not only alters the physical appearance but also enhances the thermal and mechanical properties of the wax, making it suitable for various functional and energy-related. Its specifications are listed in Table 1.

Table 1. Properties of gel wax [10]

| Appearance | Clear Gel (Colorless) |
|--------------------------------------|-----------------------|
| Melting point (°C) | 70–85 |
| Boiling point (°C) | >250 |
| Flash point (°C) | >250 |
| Density at 20°C (g/cm ³) | Approx. 0.86 |
| Specific heat of a solid | 2100 J/kg·K |
| Specific heat of liquid | 2500 J/kg·K |
| Heat of fusion | 220 kJ/kg |
| Thermal conductivity | 0.3 W/m·K |
| Solubility in water (% by weight) | Insoluble |
| Solubility in water (% by weight) | Odorless |

2.2 Experimental environment

A room with dimensions (3.35 × 2.40 × 2.80) m³ has been prepared in the Department of Materials/College of Engineering/Mustansiriyah University/Baghdad. Except for two windows on the left side, which are left uncovered as seen in Figure 1, the whole room was covered with polystyrene foam boards that were 5 cm thick in order to stop heat transmission. The temperature of the room was raised to 30 °C using a heater.



(a) On wall



(b) On window

Figure 1. Coverage polystyrene foam boards on one side of the room

2.3 Sample preparation

The paraffin wax gel was melted on a heater set to 60 °C in order to prepare the material for casting. A glass plate with dimensions of (73 × 28) cm² and 2 mm thick, about the same size as the window seen in Figure 2, was used for the casting process. To stop the molten wax from leaking, the plate was set inside a wooden frame. To monitor the temperature of the wax over the course of the temperature measurement, the temperature sensors (type K thermocouples) are affixed to the glass prior to the wax casting process. The two glass plates that contain the wax are then taken out of the wooden frame. The sample is then prepared for window placement.

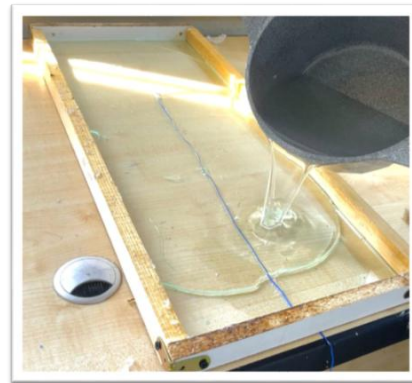


Figure 2. The process of pouring molten wax into the mold

2.4 Data logger

The Lutron BTM-4208SD — 12 Channels Temperature Recorder manufactured in Taiwan by Lutron Electronic Enterprise Co., Ltd. has the following specifications in Table 2.

Table 2. Specifications of Lutron BTM-4208SD temperature data logger [11]

| Specification | Details |
|----------------------------|---|
| Model | Lutron BTM-4208SD |
| Manufacturer | Lutron Electronic Enterprise Co., Ltd. |
| Country of Origin | Taiwan |
| Measurement Channels | 12 channels |
| Sensor Types Supported | Thermocouples: K, J, E, T, R, S types |
| Temperature Range (K-Type) | −100 °C to +1300 °C |
| Accuracy | ±(0.4% of reading + 1 °C) |
| Sampling Interval | Adjustable: 1 second to 8 hours |
| Display Unit | °C / °F (selectable) |
| Data Storage | SD memory card (up to 16 GB), CSV format |
| Interface | No PC interface required; data accessible via SD card |
| Display | Large LCD screen |
| Power Supply | 6 x AA batteries or 9V DC adapter |
| Software Requirement | No special software; data opened directly in Excel |

The temperature differences of the wax over various time periods were measured using this apparatus. Six of the device's twelve sensor inputs were utilized for measurement, as shown

in Figure 3. During the measurement period, which ran from 10:00 a.m. to 5:00 p.m. during the winter months when sunshine was present, the heater was utilized to keep the room temperature at 30 °C. Measurements were conducted without the heater after 5:00 p.m. to measure the wax material's capacity to retain and insulate heat.



Figure 3. The temperature of the wax was measured using a data logger device

3. RESULTS AND DISCUSSION

3.1 Experimental results

The experimental part commenced with an examination of both the internal and external laboratory conditions by identifying four key points (variables) that illustrate the relationship between room temperature and the external environment. The five different points were fixed in the locations as follows: (1) T-in: Represented the temperature inside the room. (2) T-wax: Represented the temperature of the glass (glass-wax-glass, where a temperature sensor was located directly on the surface of the glass inside the room). (3) T-near: Represented the temperature adjacent to the glass surface. (Where a temperature sensor was positioned 10 cm from the glass within the room). (4) T-out: Represented the temperature outside the room. (Where a temperature sensor was located outside the room, 10 cm from the window). (5) T-glass: Represented the temperature of the glass without a gel

wax.

The experiment commenced with the raising of the room temperature to 30 °C, achieved through the use of an electric heater over a duration of eight hours, beginning at 8:00 a.m. and concluding at 4:00 p.m. Following 4:00 p.m., the electric heater was deactivated, and the room was allowed to rest for 16 hours, resuming at 8:00 AM the next day. The same process was repeated the next day. Figure 4 illustrates the relationship between the temperatures recorded at the designated points (variables) and time. The temperature was observed without the application of the gel to the glass surface. After preparing the samples and sticking the gel on two windows separately (the space between the windows is 2 meters) in the laboratory. All laboratory parameters and environment were prepared, and sensors were set up to monitor the indoor air temperature, the wax temperature, the outdoor air temperature (5 cm from the window), and the data logger was activated. Recording started and continued for 48 hours. Over the course of 48 hours, the temperature change was recorded every 30 minutes. The data logger stores the readings. These measurements were taken for three different gel thicknesses: 4 cm, 6 cm, and 8 cm, as shown in Figure 5. The test and reading were repeated three times for each thickness used.

Figure 5 represents gel-free readings. There appears to be a convergence in the data curve, as the three readings (T-glass, T-in, T-out) are almost close together, indicating that there is a clear thermal conductivity between the variables (T-glass, T-in, T-out). In other words, the insulation is poor.

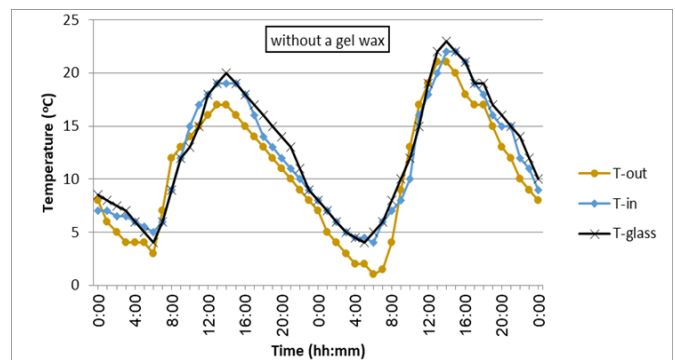


Figure 4. Temperature change over time for a window gel-free

Figure 5 shows the relationship between temperature and time for the variables (T-wax, T-in, T-near, T-out) after the gel wax is installed on the window. Here, a clear temperature contrast between the room and the outside environment, more than 10 °C, at specific times is observed. By reading the gel wax curve, this contrast can be understood. The work begins by raising the room temperature at 8:00 a.m., which is why the four readings (T-wax, T-in, T-near, T-out) are identical. After four hours, specifically starting at 12:00 p.m., the gel curve begins to rise as it gains and stores thermal energy, and often reaches its peak between 1:00 and 2:00 p.m. (average of two consecutive days). The gel's thermal insulation begins to take effect, so at this stage, a contrast is observed between the (T-out) and (T-in) readings. The repetition of the alkane chains is what led to the heat storage, as we mentioned in the Fourier transform infrared spectroscopy (FTIR) analysis. Alkanes are widely used as PCMs because they can absorb and release large amounts of latent heat at relatively constant temperatures. So, alkanes can store and release thermal energy efficiently [12].

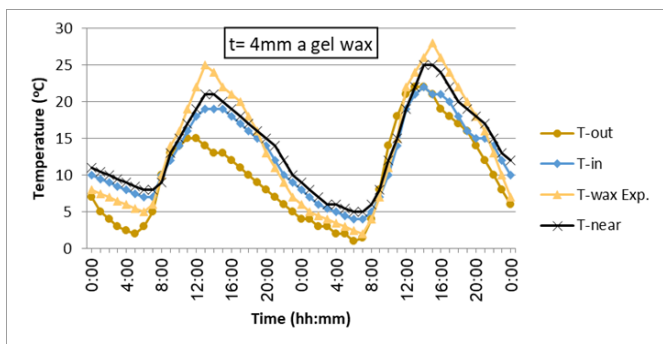


Figure 5. Temperature change over time for a window with a gel wax (4 mm)

The temperature difference between the inside of the room (T-in) and the outside environment (T-out) increases with increasing gel thickness, as is evident in Figures 6 and 7. Therefore, it is clear that the thickness of the gel plays a key part in insulating the room from the outside environment, and this is due to the insulating properties of the gel components, in addition to the gel's ability to store thermal energy.

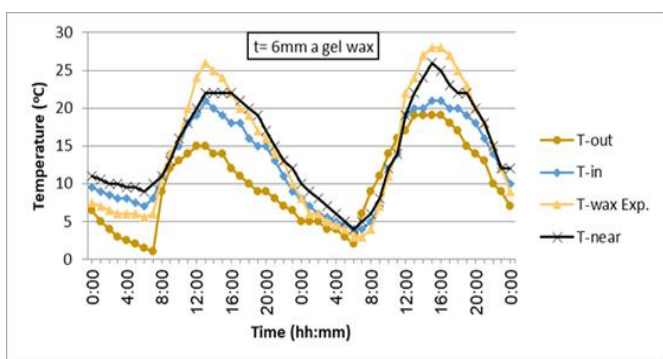


Figure 6. Temperature change over time for a window with a gel wax (6 mm)

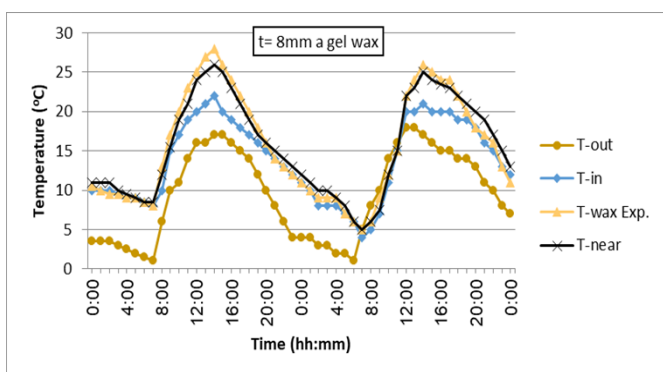


Figure 7. Temperature change over time for a window with a gel wax (8 mm)

Gel wax impedes the transfer of both thermal and electrical energy. So, thermal insulation of the gel is due to two main factors: molecular structure (hydrocarbon content, amorphous structure) and physical properties (low thermal conductivity). Gel wax consists of long-chain alkanes. The heat storage capacity of alkanes depends significantly on their long molecular chain. Longer chains generally have higher latent heat storage capacities, which lack free-moving electrons [13, 14]. So, the tightly bound electrons in atoms prevent electrical conduction. Moreover, in gel states, where molecular aggregation creates a dense network that traps electrons,

electron mobility is reduced by increasing van der Waals forces [15].

In the recent study, the degree-day method was used to estimate the heating load. Degree days are used extensively in applications that do not focus on the effect of heat transfer through building elements, but only on the effect of temperature difference across the building. The heating load by the degree-days method could be calculated in units of (J) by [2]:

$$H.L. = U A (T_B - T_{\infty}) \Delta t$$

where,

U: The overall heat transfer coefficient of the building ($1.35 \text{ W/m}^2\text{K}$) [2].

A: The total surface area of the building (m^2).

T_B : The constant base temperature required indoors ($^{\circ}\text{C}$). For the current study, the base temperature is 20°C .

T_{∞} : The average ambient temperature outdoors for an hour ($^{\circ}\text{C}$).

Δt : The time period (3600 s for each hour of heating).

$$A = 0.73 \text{ m} \times 0.28 \text{ m}$$

$$A = 0.2044 \times 2$$

$$A = 0.4088 \text{ m}^2$$

$$T_B = 20$$

$$T_{\infty} = \text{Base Temperature}$$

$$\Delta t = 3600 \text{ for one hour}$$

$$H.L. = U \times A (T_B - T_{\infty}) \Delta t$$

$$= 1.35 \times 0.4088 \times (20 - 10) \times 3600$$

$$= 19867.68 \text{ J}$$

3.2 Fourier transform infrared spectroscopy

The functional groups and molecular structure of the gel were examined using FTIR. FTIR has a number of benefits over other methods, including flexibility, non-destructiveness, and the capacity to offer insightful information on the composition and characteristics of materials. In the current study, FTIR with the mid-infrared region, $400\text{--}4000 \text{ cm}^{-1}$, was used to analyze the gel wax.

FTIR chart of gel illustrates a clear peak at 3421 cm^{-1} , which indicates that there are O-H-stretching modes from the alcohol group. This peak showed a shift to lower wave numbers, which is an indication of an increase in the mass of the atoms; therefore, lower wavenumber components in the O-H band correspond to shorter hydrogen bond components. A distinct broad peak appeared at 3469 cm^{-1} , corresponding to the O-H stretching vibration. This suggests the presence of traces of moisture or hydroxyl groups, which may result from environmental exposure or the use of formulation additives. These groups could have a minor effect on the wax's thermal response by promoting weak hydrogen bonding interactions, as shown in Figure 8. The peak at 3453 cm^{-1} is located within the range of $3200\text{--}3550 \text{ cm}^{-1}$ and is typically associated with O-H vibrational modes. Its appearance suggests possible moisture absorption from the atmosphere during sample preparation or storage, or the presence of impurities or additives that contain hydroxyl groups. The presence of the -OH group affects the physical properties of wax, potentially increasing its local polarity and making it more susceptible to moisture absorption, which may lead to a slight change in thermal properties over time. The peak at 2922 cm^{-1} in the FTIR spectrum typically results from C-H bond stretching vibrations in hydrocarbon chains, particularly in the methyl (-

CH₃) and methylene (–CH₂–) groups. In transparent wax, this peak primarily represents C–H bond stretching vibrations in the longitudinal chains of alkanes that form the basic structure of the wax. This peak typically appears as a sharp, distinct peak, indicating the presence of long unsaturated or saturated hydrocarbon bonds. The presence of this peak confirms the hydrocarbon character of the material and reflects its organic composition. These bonds also influence physical properties such as melting and hardness, contributing to the cohesion of the wax molecules. The important peak at 2953 cm⁻¹ represents asymmetric stretching vibrations of the C–H bond in the methyl groups (–CH₃). This indicates a long alkane structure, which is responsible for the hydrocarbon character of the wax, contributing to its chemical stability and insulating properties. While the peak at 2852 cm⁻¹ represents symmetric stretching vibrations of the C–H bond in the methylene groups (–CH₂–), this specifies the repetition of the alkane chains, which increases the melting point and heat storage properties. The peak of 1635 cm⁻¹ is highly likely caused by the bending of absorbed water (H–O–H bending) or oxidized wax tails. Its presence suggests that the material has been affected by moisture or the presence of polar impurities, which reduces long-term stability. The peak of 1616 cm⁻¹ is rare in pure waxes, but may indicate C = C bonds or minor surface oxidation effects. It may indicate the onset of thermal decomposition or the presence of very few unsaturated components, which affects the material's lifespan. The peak at 1460 cm⁻¹ in the FTIR spectrum indicates scissoring of the C–H bonds within the –CH₂– group, a spectral feature very common in waxy materials such as waxes, which contain long alkane chains (paraffinic chains). It indicates complete saturation, which gives the wax chemical stability and durability. The peak 1375 cm⁻¹ represents a methyl bend (–CH₃ bending, symmetric). It reflects the arrangement of the alkane groups and contributes to a compact structure, which improves viscosity and mechanical stability.

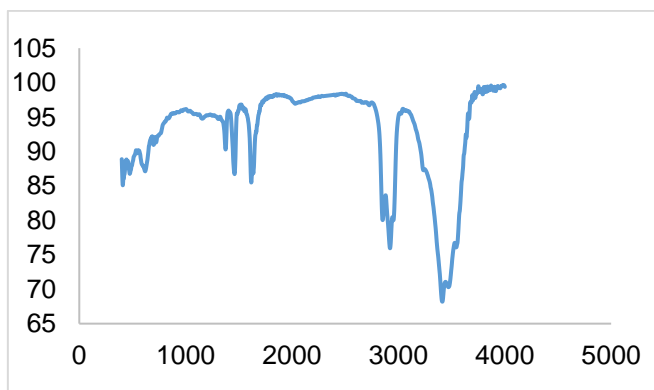


Figure 8. Fourier transform infrared spectroscopy (FTIR) analysis of a transparent gel

Chemically recorded peaks can be linked to gel wax components such as mineral oils and polymer gelling agents as follows:

1. Mineral Oils: Strong peaks in the range of 2852–2921 cm⁻¹ are attributed to stretching vibrations of the C–H bonds in alkanes, the main component of mineral oil used to soften wax and maintain its transparency.

2. Polymeric Gelling Agents: The peak at 1463 cm⁻¹, associated with the bending of the CH₂ and CH₃ groups, indicates the polymer structure that binds the oil to the wax to form the gel.

3. Oxidation and double bonds: The peak at (1616–1635 cm⁻¹) may not be due only to moisture, but may indicate the presence of carbon double bonds (C = C) or carbonyl groups resulting from chemical reactions between mineral oil and additives during the thermal manufacturing process.

3.3 X-ray diffraction test to analyze the crystalline structure of the sample

The X-ray diffraction (XRD) pattern of the transparent gel wax displays a broad, low-intensity peak centered around $2\theta \approx 20^\circ$, with no distinct sharp peaks observed throughout the scan range (10–80°). This feature is characteristic of an amorphous or poorly crystalline material, in which the atoms or molecular chains lack long-range periodic order. In gel waxes, which typically consist of a mixture of mineral oil (paraffinic hydrocarbons) and polymeric gelling agents (such as styrene-based copolymers), the molecular structure is largely disordered due to the flexible and entangled nature of the hydrocarbon chains, as shown in Figure 9 [16]. The broad hump in the XRD pattern is attributed to short-range ordering, where some local molecular alignment occurs over a few nanometers, but without sufficient periodicity to form Bragg diffraction peaks. This is consistent with the transparent optical behavior of gel wax: amorphous materials do not scatter light strongly, enabling light transmission and giving rise to visual clarity. Moreover, the amorphous structure plays a critical role in the thermal behavior of the material, including its phase change characteristics. The lack of crystalline domains allows the gel wax to melt and solidify over a broad temperature range rather than at a sharp melting point, which is advantageous in latent heat thermal energy storage (LHTES) systems [17].

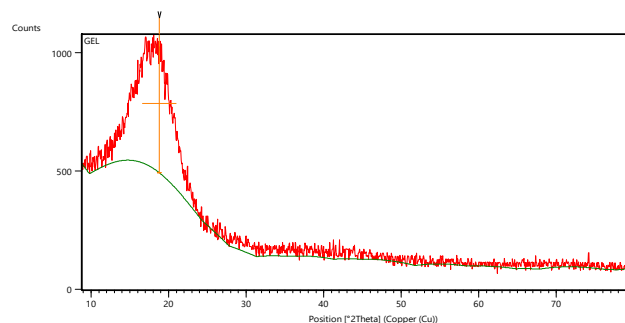


Figure 9. X-ray diffraction (XRD) for transparent gel

In summary, the XRD profile confirms the non-crystalline nature of the gel wax, which aligns with its molecular composition and functional properties as a phase change material (PCM). This behavior has been similarly observed in related studies of gel waxes used in candles and thermal systems [18]. The amorphous structure of gel wax, confirmed by XRD, directly affects the material's optical and thermal properties.

1. Effect on light transmittance (transparency):

* The amorphous structure is responsible for the gel's high optical clarity and transparency.

* Unlike crystalline materials, amorphous materials lack crystalline boundaries or long-range periodicity of atoms, preventing strong light scattering and allowing light to pass through easily.

* This characteristic allows natural light to enter the room

as if the dielectric were not present.

2. Effect on stability and thermal behavior:

* This structure plays a vital role in thermal properties, particularly in phase change processes.

* The absence of crystalline bands allows gel wax to melt and solidify over a wide range of temperatures rather than at a single sharp melting point, which is very useful in low-temperature latent energy storage (LHTES) systems.

* This non-crystalline structure, along with the hydrocarbon composition, contributes to the material's thermal insulation capacity.

3. Mechanical and Structural Properties:

* This random arrangement results from the flexible and intertwined nature of the hydrocarbon chains that make up the gel.

* This molecular entanglement creates a dense network that reduces electron movement, contributing to the material's effectiveness as a thermal and electrical insulator [19].

3.4 Surface morphology characterization of transparent gel wax using scanning electron microscopy

The scanning electron microscopy (SEM) micrograph of the transparent gel wax reveals a heterogeneous surface morphology with the presence of micro-voids and agglomerates distributed across the matrix. These microstructural features suggest a porous architecture that plays a critical role in thermal insulation. Micro-voids, in particular, act as thermal barriers by trapping air, which has inherently low thermal conductivity. This structural configuration disrupts heat transfer pathways and enhances the overall thermal resistance of the material, as shown in Figure 10. Such behavior is consistent with findings reported by Choi et al. [20], who demonstrated that increased porosity within polymer-based thermal adhesives significantly reduces their effective thermal conductivity due to interfacial resistance and localized air gaps that impede phonon transport. Therefore, the observed microstructure of the gel wax is indicative of its potential for enhanced thermal insulation performance [20].

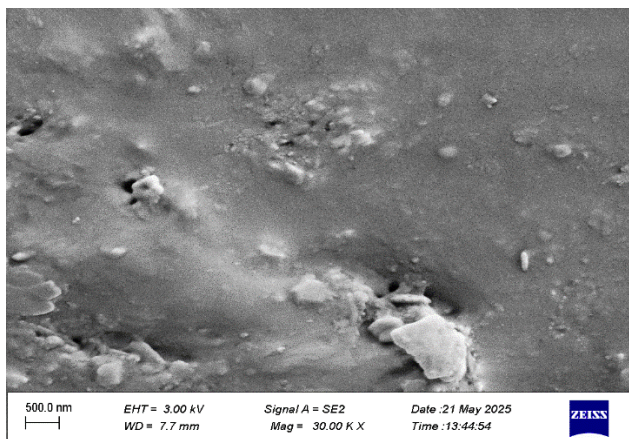


Figure 10. Scanning electron microscope (SEM) for transparent gel

4. CONCLUSION

The use of gel wax was studied experimentally to improve the investment of thermal energy used in buildings. From the results obtained, the following conclusions can be drawn:

Clear gel wax applied to building glass is able to maintain the room temperature by a significant amount compared to rooms without clear gel wax.

Clear gel wax maintains sufficient normal light radiation passing into the room by allowing light to enter the room naturally, as if it were not there due to its transparency.

Based on the thermometers, the thicker the transparent gel wax, the greater the amount of thermal storage (latent heat), which means an increase in thermal insulation and investment in the energy used.

A long alkane structure is responsible for the hydrocarbon character of the wax, contributing to its chemical stability and insulating properties.

The amorphous structure of the gel, which was confirmed by XRD analysis, also contributed to the thermal insulation.

The micro-structural features of transparent gel suggest a porous architecture that plays a critical role in thermal insulation.

Structural analysis of paraffin wax gel reveals good chemical stability thanks to its saturated alkane hydrocarbon chains, which provide natural resistance to water solubility and mechanical strength under normal operating conditions. However, FTIR indicates the presence of hydroxyl groups and carbon double bonds resulting from moisture absorption or surface oxidation. This suggests the potential for slight thermal degradation and deterioration of physical properties upon prolonged and direct exposure to UV radiation, which could eventually lead to a loss of transparency or a slight change in thermal efficiency unless the material is reinforced with chemical stabilizers.

5. COMMERCIAL PROSPECTS AND POSSIBLE DIRECTIONS FOR FUTURE IMPROVEMENT

The commercial potential of this research lies in providing a low-cost alternative to smart windows, targeting sustainable buildings and greenhouses that require a balance between lighting and temperature control. Future development directions include:

1. Durability: Adding chemically stabilized materials against oxidation and ultraviolet (UV) radiation to increase lifespan.
2. Efficiency: Incorporating transparent nanoparticles to improve thermal insulation without blocking light.
3. Flexibility: Modifying the chemical composition to suit operation in summer (higher temperatures).
4. Feasibility: Conducting economic studies to calculate the cost payback period based on actual energy savings.

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