HASAN KALYONCU UNIVERSITY
INSTITUTE OF GRADUATE EDUCATION
CIVIL ENGINEERING DEPARTMENT

INVESTIGATION OF ALTERNATIVE MATERIALS FOR THERMAL INSULATION IN CONCRETE BUILDINGS

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M.SC THESIS

Supervisor
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HASAN KALYONCU ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ
İNŞAAT MÜHENDİSLİĞİ ANABİLİM DALI

BETON BİNALARDA ISI YALITIMI İÇİN ALTERNATİF MALZEMELERİN ARAŞTIRILMASI

Mehmet Fatih YILMAZ

YÜKSEK LİSANS TEZİ

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Özet

Dünya genelinde artan nüfus ile birlikte enerji tüketimi de hızla yükselmektedir. Türkiye özelinde değerlendirildiğinde, toplam enerji tüketiminin yaklaşık %31'inin konutlarda gerçekleştiği göz önünde bulundurulduğunda, binalarda enerji verimliliğini artırmaya yönelik çalışmaların önemi açıkça ortaya çıkmaktadır. Bu doğrultuda yürütülen bu çalışmada, Gaziantep ilinde yaygın olarak kullanılan farklı yalıtım malzemelerinin genleştirilmiş polistiren (EPS), taş yünü, kenevir ve aerogel gibi ısı transferi üzerindeki etkileri, termal performansları ve geleneksel yöntemlere alternatif oluşturma potansiyelleri incelenmiştir. Çalışma kapsamında, Hasan Kalyoncu Üniversitesi yerleşkesinde beş adet benzer özelliklere sahip deney odası inşa edilmiştir. Bu odalardan biri yalıtımsız kontrol odası olarak bırakılırken, diğer dört oda farklı yalıtım malzemeleri ile kaplanmıştır. Yalıtımlı ve yalıtımsız deney odalarından iç ve dış ortam sıcaklıkları düzenli olarak ölçülmüştür. Ölçümler sırasında güneş ışınım şiddeti, bağıl nem ve rüzgâr hızı sabit tutulmuştur. Elde edilen veriler doğrultusunda, mevcutta yaygın olarak kullanılan yalıtım malzemeleri ile yenilikçi yalıtım malzemelerinin ısıl iletkenlik performansları karşılaştırmalı olarak değerlendirilmiştir.

Bu tez beş bölümden oluşmaktadır. Birinci bölümde çalışmanın amacı, kapsamı ve önemi açıklanmıştır. İkinci bölümde, sıcak iklimlerde kullanılan organik ve inorganik ısı yalıtım malzemelerine yönelik literatür taraması yapılmıştır. Üçüncü bölümde deney düzeneği, malzeme özellikleri ve veri toplama yöntemi detaylandırılmıştır. Dördüncü bölümde deneysel bulgular sunulmuş ve değerlendirilmiştir. Beşinci ve son bölümde ise genel sonuçlar özetlenmiş ve ileriye dönük önerilere yer verilmiştir.

Anahtar Kelimeler: Yalıtım, Alternatif Malzemeler, Geleneksel Malzemeler, Termal Performans, Beton Binalar

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Abstract

With the increasing global population, energy consumption is rapidly rising. In Türkiye, considering that approximately 31% of total energy consumption occurs in residential buildings, the importance of enhancing energy efficiency in buildings becomes evident. This study investigates the impact of various insulation materials, such as expanded polystyrene (EPS), stone wool, hemp, and aerogel, on heat transfer, their thermal performance, and their potential to serve as alternatives to traditional methods. Within the scope of this study, five experimental rooms with similar characteristics were constructed on the campus of Hasan Kalyoncu University. One of these rooms was left as an uninsulated control room, while the other four were covered with different insulation materials. The indoor and outdoor temperatures of both insulated and non-insulated experimental rooms were measured regularly. During the measurements, solar radiation intensity, relative humidity, and wind speed were kept constant. Based on the collected data, the thermal conductivity performance of commonly used insulation materials was compared with that of innovative insulation materials.

This thesis consists of five chapters. In the first chapter, the purpose, scope and importance of the study are explained. In the second chapter, a literature review is made on organic and inorganic thermal insulation materials used in hot climates. In the third chapter, the experimental setup, material properties and data collection method are detailed. In the fourth chapter, experimental findings are presented and evaluated. In the fifth and last chapter, general results are summarized and forward-looking suggestions are given.

Keywords: Insulation, Alternative Materials, Traditional Materials Thermal Performance, Concrete Buildings

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İÇİNDEKİLER

SYMBOLS AND ABBREVIATIONS

SYMBOLS

T: Temperature

R: Thermal resistance

λ: Thermal conductivity

U: Overall heat transfer coefficient

Q: Heat transfer rate

A: Surface area

t: Time

ΔT: Temperature difference

RH: Relative humidity

ABBREVIATIONS

EPS: Expanded Polystyrene

U-value: Overall Heat Transfer Coefficient

ASTM: American Society for Testing and Materials

TS EN ISO: Turkish Standard, European Standard, International Organization for Standardization (Türk Standardı, Avrupa Standardı, Uluslararası Standardizasyon Örgütü)

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CHAPTER 1

1. INTRODUCTION

Throughout history, energy has always been a fundamental need for the sustainability of human life. Today, with the rapid development of countries and increased access to modern energy resources, especially in developing countries, global energy demand is constantly increasing. This has made energy one of the most critical and strategic elements of today (Report, 2014).

Türkiye is a country that meets most of its energy needs through imports. Increasing energy consumption creates a serious burden on the country both in terms of environmental impacts and economic dimension. In this context, thermal insulation is one of the leading methods to be applied to increase energy efficiency. Thermal insulation can significantly reduce total consumption by preventing energy loss in buildings (İzoder & Su, 2017).

While per capita energy consumption on a global scale has increased by only 5% in the last 25 years, this rate has exceeded 100% in Türkiye. In 1990, the country was able to meet about 50% of its energy needs with its own resources, whereas today this ratio has fallen below 30% (Sezer, 2005). Approximately 33% of Türkiye's energy consumption takes place in industry, 20% in transportation, 5% in agriculture and 1% in other sectors. However, approximately 85% of the energy consumed is used for heating purposes. This clearly shows that residential buildings have the largest share in energy consumption. Therefore, thermal insulation applications are of great importance to reduce energy losses and increase energy efficiency in residential buildings.

In terms of energy consumption, Türkiye consumes much more energy compared to countries located further north and with colder climates. For example, while the amount of natural gas consumed by a 100 m^2 house in countries such as Germany or the USA is approximately 280 m^3 in winter, a house of the same size consumes approximately 1800 m^3 natural gas in Türkiye. These comparisons show that life can be sustained with much less energy without reducing living comfort; however, in the current situation, about five times more energy is consumed due to inefficient use of energy resources. Likewise, in the summer months, too much electricity is consumed for cooling purposes, indicating that energy waste continues throughout the year (Aşkadar, 2006).

Since the residential sector accounts for a significant portion of the country's total energy expenditures, ensuring energy efficiency in this area is among the priority issues. As Türkiye aims to become a member of the European Union, it strives to reach the same level as technologically and economically developed countries. However, the inefficiency in the current energy consumption structure constitutes an important obstacle in achieving this goal. Factors such as urbanization, industrialization and population growth increase energy consumption day by day; however, inefficient use of energy both increases energy imports and causes environmental problems (Yalçın, 2012).

In this context, various structural and technical methods have been developed that can be applied to increase energy efficiency in dwellings. These methods include thermal insulation, preventing the formation of thermal bridges, reducing heat losses from windows, cutting the contact of the air-conditioned indoor environment with the outside air, using shading elements and preferring double door systems at building entrances (Yılmazoğlu, 2011).

It is known that these practices not only save energy and fuel, but also make significant contributions to human health and environmental sustainability. Reducing the amount of energy consumed reduces harmful gas emissions, which in turn reduces environmental impacts and creates healthier and more comfortable living spaces (Sezer, 2005).

On the other hand, heat transfer, which is one of the main causes of energy losses, is caused by the temperature difference between outdoor and indoor conditions. Heat transfer is inevitable from the cold outdoor environment to the indoor spaces where energy is spent for heating in winter and from the hot outdoor environment to the cooled indoor spaces in summer. This situation once again reveals the necessity of implementing effective thermal insulation measures in buildings (Candan, 2007).

Energy efficiency in sustainable buildings located in hot climates can be significantly enhanced by minimizing the transmission of external heat into indoor spaces and by limiting the loss of cooling energy during summer periods. In such regions, over 50% of the building envelope is directly exposed to solar radiation, with external walls constituting a major portion of these sunlit surfaces. The remaining parts of the envelope are typically subjected to elevated temperatures in shaded conditions. Consequently, substantial amounts of external heat are transferred into the building's interior through the external walls. (Khabaz, A. 2023).

The residential sector is one of the sectors with the highest share in energy use for air conditioning (heating and cooling). Therefore, even a small energy efficiency improvement in this sector has the potential to have a great impact on reducing the total energy consumption and carbon footprint of the country (Gölcü, Dombaycı & Abalı, 2006). Increasing the level of insulation in houses within the framework of energy policies is important not only for economic gains but also for environmental sustainability. For this reason, in this study, conventional insulation systems used in existing buildings and alternative thermal insulation systems that can provide higher efficiency are investigated and evaluated comparatively. Understanding the main sources of heat losses is of great importance for the development of effective insulation strategies. In a typical four-story building, approximately 25% of the total heat loss is due to the roof, 60% to the exterior walls and 15% to the floors. With the increase in floor height, the wall surface area also increases, and accordingly, wall-induced heat losses increase even more (Dikici & Kocagül, 2019).

TS 825 Standard for Thermal Insulation Rules in Buildings, which is an important step in the implementation of thermal insulation standards in Türkiye, has become mandatory for new projects. This standard aims to improve the uncomfortable indoor conditions encountered in uninsulated buildings and shows that insulation application provides an economic return within an average of 3 to 4 years. This increases users' interest in insulation applications and encourages energy efficiency investments (Dikici & Kocagül, 2019).

The assessment of thermal comfort is an important criterion in determining the success of insulation applications. Parameters such as temperature, air velocity and relative humidity should be taken into account to evaluate indoor conditions. These parameters can roughly represent the thermal condition of the environment and provide insight into the level of thermal comfort (Ünver, Adıgüzel, Adıgüzel, Çivi & Roshanaei, 2020).

Thermal comfort encompasses not only physical comfort but also environmental conditions that affect individuals' mental state and work productivity. In this context, the term “comfort range” defines the optimum environmental conditions necessary for individuals to live healthy, productive and peaceful lives in enclosed spaces (Al-Sanea, Zedan & Al-Hussain, 2012). The main physical parameters considered in the evaluation of thermal comfort are room temperature, indoor surface temperature, relative humidity and air movement speed (Öztürk, 2011). These variables directly affect the environmental comfort level of individuals and play a guiding role in determining the insulation strategies to be applied in buildings.

According to various air conditioning standards, acceptable room temperatures should be between 21-22 °C in summer and 20-21 °C in winter (İşbilir, 2009). However, not only air temperature but also indoor surface temperatures have a critical effect on thermal comfort. Therefore, it is ideal that the difference between indoor temperature and indoor surface temperatures should not exceed 2-3 °C. If this difference exceeds 6 °C, individuals experience discomfort by being exposed to cold or hot surfaces, which can cause both psychological and physiological disorders (Usta, 2009).

Table 2

Comfort Assesment According To The Difference Between Indoor (Ti) And Indoor Surface (Ty) Temperatures (Usta, 2009)

Ti - Ty Difference (°C)	Comfort Assessment
0–2	Ideal comfort
2–4	Acceptable level of comfort
>4	Uncomfortable indoor environment

It is known that thermal comfort is critical not only for health but also for work efficiency. A study on the relationship between room temperature and individuals' performance shows that temperature conditions have a direct impact on work efficiency (Seppänen, et al., 2006).

Figure 1

Relationship Between Room Temperature and Operating Efficiency (Seppänen et al., 2006)

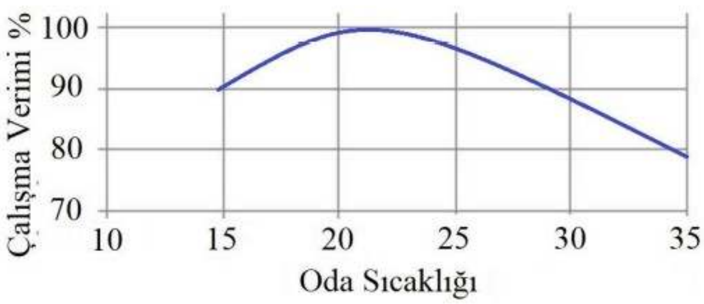


Figure 1 shows the effect of room temperature on human work efficiency. According to the data, working efficiency first increases as the room temperature increases, peaking at around 21-22 °C, and then decreases as the temperature continues to rise. This suggests that both low and high temperature conditions negatively affect individual performance. Especially at ambient temperatures below 15 °C and above 27 °C, there is a noticeable decrease in efficiency. Keeping the indoor temperature within a certain range is therefore critical not only for comfort but also for user efficiency.

Failure to balance indoor and surface temperatures in buildings not only negatively affects the comfort of individuals, but also leads to serious energy losses. In buildings where the thermal transition is not well managed, the desired internal temperature cannot be maintained, resulting in unnecessary energy use. Thus, not only the interior of the building but also the exterior environment is heated, causing waste of resources and increasing the amount of harmful gases released into the atmosphere (Sezer, 2005).

1.1. The Purpose of the Research

The primary objective of this study is to experimentally compare the thermal performance of different insulation materials in reinforced concrete buildings under hot climate conditions and to determine the most suitable material in terms of energy efficiency. In this context, four different insulation materials, including traditional (EPS and stone wool), innovative (aerogel), and natural (hemp) materials, were applied in test rooms with identical physical properties. Over a period of nine days, under stable environmental conditions, the indoor-outdoor temperature differences were monitored and evaluated. This study aims to determine the capacity of each material to both retain heat and balance indoor temperatures. Based on the results, scientific data on sustainable, economical, and environmentally appropriate insulation materials have been presented. The findings are expected to guide material selection for improving the thermal performance of building envelopes in hot climate regions.

1.2 The Importance of the Research

The primary aim of this research is to experimentally compare the thermal performances of different building materials under hot climate conditions and provide optimal insulation solutions for improving energy efficiency. The growing demand for energy and the need for sustainable building design necessitate the scientific evaluation of the thermal properties of building envelopes. In this context, EPS, stone wool, aerogel, and hemp-based insulation materials were applied in standard reinforced concrete test rooms, and the effects of these materials on temperature transitions were analyzed using time series data. The study not only evaluates the thermal protection capacities of the materials but also examines critical parameters such as the stability of indoor temperatures, the temperature differences (ΔT) with the outdoor environment, and the materials' responses at different times of the day. Through this, the aim is to create a scientific foundation for material selection that will both ensure user comfort and minimize energy consumption from the perspective of building physics. Furthermore, the study is expected to contribute to the development of environmentally friendly and cost-effective insulation strategies for residential and low-rise building projects in hot climate regions. This will be an important step toward achieving energy savings, reducing greenhouse gas emissions, and meeting sustainable urbanization goals.

1.3. The Structural Analysis

The experimental study conducted in this research was evaluated not only in terms of thermal performance but also in terms of the structural integrity and stability of the building envelope where the insulation materials were applied. All the test rooms used in the experimental setup were designed and constructed according to the TS 500 (2000) standard for reinforced concrete systems. The structural elements (foundation, walls, and roof slab) were constructed with similar dimensions and concrete properties to prevent thermal differences resulting from material changes from affecting the structural comparison (Çölhan, 2001). The load-bearing capacity of the building components, their resistance to vertical and horizontal loads, and their interaction with the applied insulation materials were analyzed. As indicated in the literature, insulation materials are generally placed outside the load-bearing system, and it is preferred that these materials do not impose a significant load on the structure (Dikici & Kocagül, 2019). In regions with high temperatures, the insulation systems used on the exterior facades of reinforced concrete buildings play a significant role in maintaining indoor thermal comfort and improving energy efficiency. Studies conducted in areas with dominant hot climate conditions, such as Saudi Arabia, have brought attention to the search for specialized solutions against heat transfer in the design of exterior walls and roofs of reinforced concrete buildings (Khabaz, 2018; Khabaz, 2023). In this context, it was observed that hemp-based natural insulation and low-density aerogel added minimal load to the structural system. In contrast, high-density insulation products such as stone wool require careful application in terms of installation techniques and surface connection systems (Ünal & Işık, 2020). As a result, none of the insulation materials used during the study negatively affected the structural integrity of the test rooms, and no physical degradation such as cracking, settling, or deformation was observed. This confirms the assumption underlying the research, which is that "the change in insulation material only affects thermal performance." Therefore, the structural equivalency condition was met, and the reliability of the experimental comparisons was supported (Usta, 2009).

1.4. Assumptions

This study is based on the following assumptions to ensure the consistency and applicability of the analyses and evaluations:

1. The thermal properties of the insulation materials (such as thermal conductivity, density, and specific heat capacity) are assumed to be accurate as reported by manufacturers or referenced in the scientific literature under standard conditions.
2. The structural and thermal characteristics of the concrete walls and roofs used in the analysis are assumed to represent typical features of low- to mid-rise concrete buildings commonly found in hot climate regions.
3. Climatic data used in the study, including outdoor temperature, solar radiation, and relative humidity, are considered to be representative of a typical hot winter period and are assumed to remain stable throughout the analysis.
4. Heat transfer is considered to occur only through conduction and radiation. Convective heat transfer effects (due to natural or mechanical ventilation) are excluded from the scope of the analysis.
5. It is assumed that insulation materials maintain their thermal performance over time without physical degradation, chemical change, or installation defects.
6. Installation quality is assumed to be ideal, and no performance loss due to workmanship or construction errors is taken into account.
7. The influence of occupant behavior, internal heat gains from equipment, and variations in HVAC system performance are excluded from the simulation or calculation processes.
8. The numerical methods or simulation tools used are assumed to provide reliable and sufficiently accurate results for comparative performance analysis.

1.5. Limitations

The scope of this study is defined by the following limitations:

1. Structural elements such as foundations, slabs, interior walls, and roof systems are excluded from the analysis. The study is limited solely to experimental analyses conducted on external wall components.
2. The insulation materials evaluated in this research are restricted to a specific selection of organic and inorganic alternatives; not all insulation materials available on the market were considered.
3. The study focuses exclusively on winter season and cold climate conditions. Since the experimental data were collected in January, effects related to summer temperatures and cooling demands were not included in the analysis.
4. Heat transfer analyses were carried out under steady-state (static) external climatic conditions. Daily temperature variations, wind effects, and seasonal fluctuations throughout the year were not taken into account.
5. Properties such as fire resistance, acoustic performance, and environmental impacts (e.g., carbon footprint, recyclability) of the insulation materials were excluded from the evaluation. The analysis focused solely on thermal performance.
6. Occupant behavior (such as window opening and appliance usage) and internal heat gains were not considered. The study was conducted based on the assumption of ideal indoor environmental conditions.
7. It was assumed that the physical and chemical properties of the insulation materials remain stable over time, and that their thermal performance does not degrade throughout their service life.
8. The calculation and/or simulation methods used in this study rely on certain simplifications and assumptions, and thus may not fully reflect all the dynamic interactions present in real-world applications.

1.6. Originality and Contribution

The originality of this study lies in the comparative investigation of different types of insulation materials (organic and inorganic) used in concrete buildings, specifically focusing on winter conditions and the thermal performance of external wall components. Unlike many studies in the literature that primarily concentrate on summer seasons and cooling demands, this thesis evaluates the heat retention performance of insulation materials under cold climate conditions through experimental data.

The performance of the materials was tested under real climatic conditions, integrating experimental applications with field conditions. This approach goes beyond theoretical data obtained in laboratory environments and enables the development of practical recommendations for insulation applications.

Furthermore, the study aims to provide more suitable insulation solutions for reinforced concrete residential buildings located in Turkey's hot regions from an energy efficiency perspective. This contributes to the goals of reducing heat loss, decreasing fuel consumption, and lowering carbon emissions, thereby supporting sustainability targets.

Additionally, this thesis reveals the potential of some alternative insulation materials that are relatively less examined in the literature, offering a scientific reference for decision-makers in material selection and building design processes. Additionally, this thesis reveals the potential of some alternative insulation materials that are relatively less examined in the literature, offering a scientific reference for decision-makers in material selection and building design processes.

1.

CHAPTER 2

2. LITERATURE REVIEW

Energy efficiency in buildings has gained significant importance in today's world, particularly in line with sustainability goals. As part of this focus, building materials and design strategies have been reconsidered within the construction sector. In particular, in hot climate zones, the high amount of energy expended to maintain indoor comfort has made it essential to delve deeper into concepts such as thermal insulation, thermal comfort, and the thermal properties of building envelopes. In this context, studies available in the literature provide the scientific foundations of fundamental topics such as thermal energy flow, temperature control, and the performance of insulation materials. This section explains the key concepts related to these topics and establishes the theoretical framework for the study based on the existing literature.

2.2. Heat and Temperature

Heat is a form of energy that is disordered (microscopic) or in transition due to temperature differences. The operation of various devices we use in nature and daily life is a physical example of heat transfer. Today, the theory of heat transfer is advancing rapidly due to the development of analytical solution techniques and the availability of super-fast computers. This progress is largely driven by the limited knowledge of heat transfer, which is primarily based on experimental foundations. Developments in experimental methods and the resolution of differences between theory and experimentation have played a significant role in this advancement (Yeşilata, 2019).

Likewise, heat is a form of energy that moves from a hotter area to a colder one in an environment with different temperatures. During this transfer, resistance to heat is shown depending on the thermal conductivity coefficients and thicknesses of materials between spaces. (Özer, 2006). Heat can be generated from mechanical energy or friction. An example of this is the heating of a drill bit. Heat generated from chemical reactions: Heat energy is produced when substances like oil, coal, or wood burn. Heat generated from electrical energy: Electrical current passing through a resistor produces heat energy. An example of this is an electric stove. Heat generated from radiation: The heating of the Earth's crust occurs when sunlight is absorbed. Heat from atomic energy: When an atom is split, particles produce a large amount of energy. (Ünal, 2002).

Heat Transfer occurs in three ways:

Conduction (Heat Transfer): This is the process of heat passing through solid objects. Heat transfer data can be used to determine how heat moves through stationary gases and liquids. The heat transfer capacity establishes a specific property for materials as a fixed value. The heat transfer coefficient (λ) is the amount of heat passing through a unit area (1 m²) and a unit thickness (1 m) in one unit of time (1 hour), in the direction parallel to the area. The temperature difference between two perpendicular surfaces is 1°C. The unit is kcal/m·h·°C = 1.163 W/m·K (Ekinci, 2003).

Convection: Heat transfer occurs through the molecular movement of the substance. The molecular structure of the material also affects heat transfer. (Özer, 1984).

Radiation: Heat transfer in the form of electromagnetic waves is called radiation. Objects at high temperatures emit their energy through electromagnetic waves. The Sun is an example of this. (Özer, 1984).

2.2.1. Thermal insulation

Since ancient times, humans have built shelters to protect themselves from adverse weather conditions, extreme heat, and cold, aiming to lead a comfortable life. As humanity has developed and the quality of life in the places where we live has improved, various heating and cooling systems, products of advanced technology, have begun to be used. At present, the application of "Thermal Insulation" in buildings, which make up our living spaces, is of great importance to ensure more comfort and less energy consumption. Thermal insulation can be defined in various ways. It refers to the restriction of heat loss and gain caused by temperature differences to prevent energy loss. In other words, thermal insulation prevents hot or cold air from escaping a building to the external environment. In buildings, thermal insulation is used to reduce energy consumption and prevent heat loss. Heat transfer through areas with high heat loss, such as walls and roofs, can be prevented through insulation. (Bektaş, 2018).

To better understand the importance of thermal insulation, we need to address some key concepts. These include energy efficiency, thermal comfort, and air pollution. Efficient use of energy involves limiting the energy required for heating and cooling. By using energy efficiently, desired savings can be achieved. The primary form of comfort needed for people to be happy, peaceful, and productive is the internal environment of the building. Places where individuals come together, such as shopping malls, schools, and hospitals, must provide a comfortable environment both in residential buildings and other spaces. Air pollution is a significant issue that threatens both the environment and human health. Harmful gases are released into the atmosphere as a result of the consumption of energy sources. Proper thermal insulation applications reduce energy consumption, resulting in less harmful gas emissions to the environment. (Çölhan, 2001).

In the 1970s, external thermal insulation, also known as facade insulation, became a key component of heat insulation in developed countries. Türkiye introduced exterior thermal insulation materials in 1991 through imported products. In the early 1990s, heat-loss windows, also known as double-glazed windows, contributed to significant heat loss in exterior joinery. In the initial years, the thickness of thermal insulation was around 3 centimeters, but it increased to 8–16 centimeters according to the application of the relevant standard (TS 825) and calculation rules based on the specific region. Today, 85% of buildings in Türkiye still lack thermal insulation. The 10th Development Plan of the Turkish Prime Ministry aims to increase the proportion of insulated buildings from 15% to 26% by 2018. (Yaman, et al., 2015).

2.2.2. The importance of thermal insulation

Thermal insulation includes all measures taken to reduce the amount of energy used in heating and cooling processes in buildings, solve environmental problems, and reduce air pollution. These measures protect buildings against external climate conditions and help maintain indoor temperatures at desired levels. By meeting the requirements of building physics, the structure extends its service life and reduces operational costs. (Koçu, 2000).

Extreme temperatures, cold, and rain, which vary according to the seasons, are factors that affect indoor temperatures in buildings. Temperature fluctuations in the external environment, which alter the indoor temperatures of homes and workplaces, also impact the quality of life. The temperature of the environment in which a person lives or works can lead to health issues, which, in turn, affect work productivity. Thermal comfort helps individuals live in a temperature-healthy environment. Thermal comfort affects a person's physical and mental health, human physiology, and quality of life. (Bayer, 2006).

Thermal insulation reduces heating and cooling costs and energy consumption by reducing heat transfer. Properly applied insulation with the right thickness not only saves energy but also protects against extreme heat in summer and cold in winter. It prevents condensation on walls and ceiling surfaces, reduces wall thickness, resulting in gains per unit area, decreases air pollution, reduces emissions causing the greenhouse effect, and ensures fuel savings during the building's use. (İşbilir, 2009). For these reasons, investment in thermal insulation pays off in a short time. Given that much of the fuel used for heating in Türkiye is imported, thermal insulation provides foreign exchange savings. (Karakoç et al., 1999).

Türkiye is classified into four degree/day regions. In cities located in the 1st-degree day zone, external temperatures can reach 40 to 45°C during the summer months. In these cities, thermal insulation reduces heating costs in winter and cooling costs in summer. Cooling processes are three to six times more expensive than heating. Sufficient insulation reduces heat flow in an environment where the external temperature is higher than the internal temperature. This minimizes the operation of the cooling system, resulting in energy savings. (Şengül et al., 2005).

Thermal insulation reduces heat loss and gain, saves energy, protects the environment, controls thermal comfort, and reduces noise. Additionally, it prevents condensation on building components and reinforced concrete surfaces, increasing the efficiency of heating and cooling systems and protecting structures from external effects. A careful selection of insulation materials ensures both climatic and acoustic comfort, as well as fire safety. (Candan, 2007).

2.2.2.1. Importance of thermal insulation in terms of energy consumption

In buildings with thermal insulation, both operational and initial investment costs decrease over time. As a result of correctly applied insulation, energy and fuel savings are achieved, with a consumption reduction of around 50%. Thermal insulation not only saves energy used for heating but also for cooling during hot weather. (Kibici, 2016). In buildings with thermal insulation, the need for heating and cooling is reduced, leading to lower energy consumption and mitigating potential environmental damage. (Kibici, 2016). Thermal insulation prevents the formation of thermal bridges in buildings. (Bektaş, et al., 2017). With proper insulation, the amount of energy consumed decreases annually. (Bektaş, et al., 2017).

2.2.2.2. The importance of thermal insulation for human health

The greatest benefit of thermal insulation is the user's health. The temperature of the environment significantly affects work productivity. Thermal comfort in the working environment impacts physical and mental productivity. Indoor air quality and thermal comfort are characteristics of an environment where individuals feel comfortable and are not exposed to health problems arising from thermal conditions. Air quality and humidity directly affect human health. (Kozak, & Kozak, 2015). Walls and curtain walls without thermal insulation may condense due to diffusion, leading to material degradation. These walls may experience sweating, mold growth, black stains, peeling of plaster and paint, and uneven heat distribution, with areas near windows being warmer. These factors make the environment dangerous to health. Additionally, summer colds and other diseases can result from air conditioning systems that are overused to cool spaces in the summer. (Özen, 2016). The high surface temperature of steam and hot water installations helps prevent burns and injuries caused by accidents. (Sontay, 2019).

2.2.2.3. The importance of thermal insulation for the end user

Thermal insulation creates more comfortable and healthier living spaces due to balanced temperature differences in the insulated areas. (Yücesoy et al., 2024). In a heated environment, warm air moves toward the cooler areas. In an uninsulated or poorly insulated space, the surface temperature is lower, and warm air moves toward cold surfaces, such as windows. This movement creates air currents, which are undesirable for comfort. Thermal insulation is applied to increase the surface temperature of the walls, as the inner surface temperature is crucial for comfort. This results in a better environment and less fuel consumption. (Kozak, & Kozak, 2015). The ideal room temperature for a person sitting without physical activity, in normal clothing, is between 20°C and 21°C during winter. In the summer, the outdoor temperature is between 22°C and 24°C. When the air temperature is high in the summer, individuals should wear lighter clothes, as the body's surface temperature remains constant, even though the surrounding temperature may be higher. During winter, the average room temperature is about 21–22°C for still air conditions. This is applicable for environments with still air. In buildings, there should be a comfort range of 2–3 degrees between the room air temperature and the inner wall surface temperature. In uninsulated buildings, this difference is larger, causing air movement inside. (Özen, 2016).

2.2.2.4. The impact of thermal insulation on initial investment and operating costs

Buildings with thermal and installation insulation will have lower investment and operating costs due to the use of smaller capacity boilers, air conditioners, cooling towers, radiators, radiator pipes, valves, and other materials during construction or later stages. (Özen, 2016). Adequate protection against heat effects, such as sweating on surfaces and freezing of pipe installations, reduces operational, maintenance, and repair costs. (Ekinci, 2003).

2.2.2.5. The effect of thermal insulation on the structural health of buildings

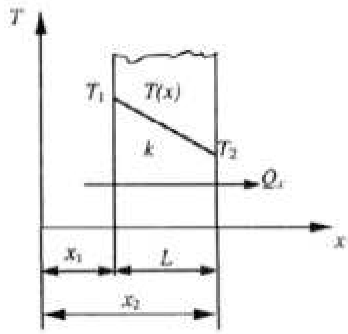
The thermal insulation of a building is crucial for its structural health. Exposure to sunlight causes expansions in buildings, and when these expansions reach a certain point, the building begins to crack. Cracks can severely damage buildings and cause water permeability at various points. (Kozak, & Kozak, 2015). Insulation prevents the corrosion of reinforcement within concrete, preserving its strength capacity. Therefore, it can be said that insulation directly prevents corrosion. Thermal insulation reduces corrosion risk by decreasing condensation on exterior walls and roofs, while waterproofing protects the reinforcement from corrosion. (Bektaş, 2018).

2.2.3. Heat transfer (Conduction)

Heat energy results from the movement of molecules in the environment. In environments where heat energy is generated, it should generally not be used. Therefore, heat energy must be distributed in many different ways. The movement of molecules continues as long as the energy source is not interrupted. Heat energy spreads everywhere. Heat transfer occurs when there is a temperature change near a system or between two systems. (Altınışık, 2006). Heat transfer is a vector quantity with a specific magnitude, direction, and orientation. Fourier's law of heat distribution can be used to calculate the amount of heat passing through a plane with two surfaces at different temperatures. Figure 2 shows the physical condition of heat transfer through a plane. (Halıcı, & Gündüz, 1998).

Figure 2

One-dimensional heat conduction in a plane (Halıcı, & Gündüz, 1998)



In the case of a plane wall, the heat flux in the x-direction is expressed in equation as follows:

$$qx = -k\frac{dT}{dX}$$

Heat flux, $qx = \frac{w}{m^2}$ refers to the amount of heat passing in the x-direction through a unit surface perpendicular to the heat transfer direction in one unit of time.

This amount is directly proportional to the temperature gradient $\frac{dT}{dX}$ is the thermal conductivity coefficient, measured in $\frac{W}{mK}$ and it is related to the material properties of the wall. The negative sign indicates that the heat transfer occurs in the direction of decreasing temperature. (Yüncü & Kakaç, 1999).

In these equations, T (°C) represents temperature, and L (m) represents the thickness of the wall. As shown in Figure 2, in steady-state conditions where the temperature distribution is linear, the temperature gradient is expressed as:

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L}$$

The heat flux can thus be expressed as:

$$qx = -k \frac{T_2 - T_1}{L}$$

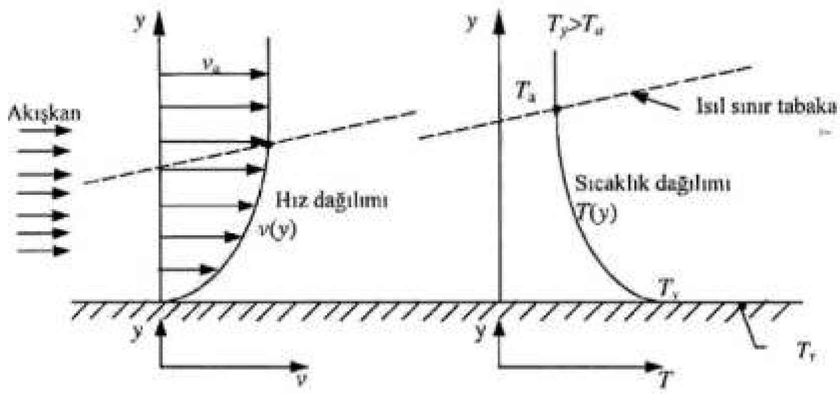
This equation represents the amount of heat passing through a unit surface in one unit of time, i.e. the heat flux. It is understood that the heat passing through a flat surface with surface area A (m^2) in one unit of time is equal to the heat flux multiplied by the area. (Yüncü & Kakaç, 1999).

2.2.4. Convection

Convection is the process of heat transfer that occurs between a solid surface and a fluid in an environment. The thermal boundary layer, where the temperature varies, is the location of heat transfer by convection.

Figure 3.

Velocity and temperature distributions on the plate (Altınışık, 2006)



In 1701, Newton described heat transfer between a surface at temperature Ty and a fluid at temperature Ta, as shown in Figure 3. This relationship is expressed as:

$q = h\,(T\,y - T\,a)$

In this case, the heat flux by convection, q (W/m²), is directly proportional to the difference in temperature between the surface and the fluid, $(T\,y - T\,a)$. This is known as Newton's Law of Cooling, where h (W/m²·K) is the heat transfer coefficient for convection. This value depends on the surface geometry, the type of fluid flow, and certain thermodynamic and potential properties of the system (Halıcı & Gündüz, 1998).

2.2.5. Radiation

Heat energy transferred through electromagnetic waves is called "radiation" or "thermal radiation." In this context, the term radiation refers to the thermal radiation emitted by an object due to its temperature. Hot objects, at high temperatures, emit heat energy in the form of electromagnetic waves. Therefore, unlike conduction and convection, this type of heat transfer does not require a medium. The best example of this is the heat energy that reaches Earth from the Sun. (Yüncü & Kakaç, 1999).

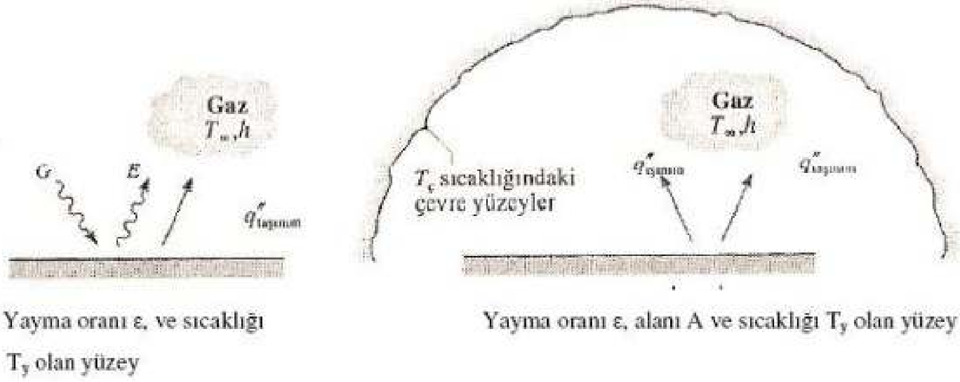
In space, the most effective method of heat transfer is radiation. As shown in Figure 4, when heat transfer via radiation is considered, it is observed that the heat emitted by a surface is not solely derived from the thermal energy emitted by the surface itself. The energy radiated per unit time per unit area (W/m²) is expressed as the emissive power E E of the surface. The upper limit of emissive power is determined by the Stefan-Boltzmann law:

$$E_{b} = \sigma T_y^4$$

Here, $T\ y$ T y represents the absolute temperature (K) of the surface, and σ σ is the Stefan-Boltzmann constant (= 5.67 × 10 − 8 W/m 2 · K 4 σ=5.67×10 −8 W/m 2 ·K 4). Surfaces of this type, with ideal heat emission capacity, are called black surfaces.

Figure 4

Heat Exchange by Radiation: (A) On A Surface (B) Between A Surface And Surrounding Surfaces (Öztürk, & Yavuz, 1995)



The heat flux emitted by a surface is less than the heat flux emitted by a black body under the same conditions. This relationship can be explained by the following equation:

$$E_{b} = \varepsilon \sigma T_y^4$$

In this equation, ϵ represents the ratio of the heat flux emitted by the specified surface to the heat flux emitted by a black surface under the same temperature conditions. This is referred to as the emissivity. For black surfaces, this coefficient is considered as "1," and for white surfaces, it is considered as "0." (Yüncü, H., & Kakaç, S., 1999).

If a black surface at temperature $T\ 1$ is in contact with another black surface at temperature $T2$, the heat transfer (Q) is expressed as:

$$Q = A\sigma(T_1^4 - T_2^4)$$

However, if one of the surfaces is not black (ε ≠ 1), the equation becomes:

$$Q = \varepsilon A\sigma(T_1^4 - T_2^4)$$

This equation holds true in this case.

2.2.6. Factors to consider when selecting thermal insulation materials

There is a wide variety of thermal insulation materials available today, derived from both synthetic processes and the processing of naturally occurring raw materials. These materials can differ in their interior compositions as well as their physical and mechanical properties. Under the category of evaluation criteria, the significance of these distinctions, which are crucial in the selection process of thermal insulation materials, is examined systematically.

2.2.7. Density (kg/m³)

Density is defined as the ratio of the mass of a material to the volume it occupies. The unit of measurement is kilograms per cubic meter (kg/m³). Materials characterized by low density typically exhibit high porosity and volumetric voids, making the importance of density especially prominent in the context of thermal insulation. This results in a decrease in the overall thermal conductivity of the material. In contrast, a solid material with high density tends to have high thermal conductivity, facilitating more efficient heat transfer. The presence of smaller, more numerous, and uniformly distributed pores within the material increases its thermal insulation properties, as the air trapped within these pores has lower conductivity compared to the surrounding material. (TSE, 2015).

2.2.8. Thermal conductivity coefficient (λ) (W/m·K)

In general, thermal insulation materials should have low thermal conductivity. The lower the thermal conductivity of a material, the less heat passes through it. Therefore, the thermal conductivity coefficient (λ) is an important factor. Thermal conductivity is measured in W/m·K and represents the amount of heat transferred through a 1m x 1m x 1m cube of material with a 1 K temperature change from one side to the other. (Pfundstein, et al., 2008).

In fiber-based thermal insulation products, the integrity of the fibers plays a significant role. In foam insulation materials, the size, location, and gases within the cellular voids are crucial. Furthermore, the moisture content of a material affects its thermal conductivity. Compared to foam materials with a closed-cell structure exposed to moisture, fiber-based insulation materials exhibit a more rapid increase in thermal conductivity.

Factors influencing thermal conductivity in insulation materials include:

- Material density
- Raw material type
- Moisture content
- Temperature
- Gases contained in the material
- Natural structure of the material
- Fine structure of the material

2.2.9. Vapor diffusion resistance (μ)

There is always a certain level of water vapor present in building elements and the air. Water vapor molecules constantly move in different directions. Due to the fine structures of building materials, resistance is shown against these movements. When comparing the vapor impermeability of one millimeter of thermal insulation material to that of one meter of air, the water vapor resistance factor (μ) is a dimensionless value. The manufacturing method and cell structure affect the vapor diffusion resistance of materials. Fiber insulation materials are very vulnerable to water vapor, while foam insulation materials are much more resistant. (Hegger et al., 2013). Ideally, thermal insulation materials are expected to have high vapor diffusion resistance. When thermal insulation materials are impermeable to water vapor, $\mu = \infty$ μ=∞ (infinite), and when they allow water vapor to pass, $\mu = 1$ μ=1. (Akelçi, 2016).

2.2.10. Water absorption rate (%)

For thermal insulation materials to maintain their function and effectiveness, they must remain free from water and moisture. Otherwise, the material loses its expected insulation ability, as the dry, stagnant air voids within the material are filled with water or moisture. This results in the failure to meet the desired insulation values. (Toydemir, et al., 2000). Water has ten times the thermal conductivity of air, which is why the absorption of water and moisture is harmful to thermal insulation materials. (Özer, 2006). The water absorption coefficient relative to the volume of the material is an important criterion in material selection.

2.2.11. Fire resistance

Thermal insulation materials can be either flammable or non-flammable, as their raw materials may be organic, inorganic, or synthetic. Ideal properties for such materials include being flame-resistant, not emitting smoke, not releasing toxic gases, and being non-combustible, while also being suitable for the temperature limits required by the place of use. (Toydemir, et al., 2000). The fire resistance of insulation materials is tested with samples having the highest thickness, density, and organic content. (EOTA, E., 2013).

2.2.12. Compression resistance (kPa)

Compression resistance refers to the durability of thermal insulation materials against two-way loads (static and dynamic), also known as mechanical strength. A reduction in thickness beyond a certain value in thermal insulation materials leads to unacceptable degradation of the material's basic properties. Even if the material carries a load, it can no longer fulfill its primary function. Therefore, when thermal insulation materials undergo 10% deformation (a 10% reduction in thickness), compression stress is essential. (Volo İnşaat Malzemeleri Sanayi, 2015). Additionally, in materials with a fibrous structure, the strength and properties of the fibers are crucial. Long-term compression resistance is also important in this context. In certain special roofs, thermal insulation materials are expected to have high compression resistance, particularly under raft foundations and in industrial buildings. Compression resistance may decrease at high temperatures. (Pfundstein, et al., 2008).

2.2.13. Specific heat

Specific heat (c) refers to a material's capacity to retain heat based on its mass. The specific heat of thermal insulation materials is calculated using the calorimetric method. The fine structure and density of the material determine its heat resistance capacity. Materials with high density heat up for longer periods because of their higher specific heat and greater heat retention capacity. Since the total specific heat values of building components are high, indoor air quality is particularly better during the summer. (Pfundstein, et al., 2008).

2.2.14. Thermal resistance and thermal transmittance

Thermal resistance is the physical quantity obtained by dividing the material thickness by the thermal conductivity. (İzoder, 2014). This value is not specific to the material. It is used to calculate the total thermal resistance of each layer in a building component. The equation below is used to calculate the thermal resistance of the layers in building components:

$$\mathbf{R = d/\lambda}$$

Where:

R is the thermal resistance value (m²·K/W)

d is the thickness of the material (m)

λ is the thermal conductivity coefficient of the material (W/m·K)

As shown in the equation below, the thermal resistance ($\frac{1}{U}$) is obtained by summing the thermal resistance of the inner and outer surface resistances along with the material's total thermal resistance. Therefore, the higher the thermal resistance of a thermal insulation material, the better its insulating properties. The total thermal transmittance coefficient ( ) of a building component is found by taking the arithmetic inverse of the total thermal resistance value. This value represents the amount of heat flow between the surface and the air that causes a 1K temperature difference per 1 m² of area in one second.

$$\frac{1}{U} = R_i + \mathbf{R} + R_e$$

Where:

$\boldsymbol{U}$ is the thermal transmittance coefficient (W/m²·K)

R_i is the surface thermal resistance of the inner layers (W/m²·K)

$\boldsymbol{R}$ is the total thermal resistance of the material (W/m²·K)

R_e is the surface thermal resistance of the outer layer (W/m²·K) (TS 825, Binalarda Isı Yalıtım Kuralları, 2013).

2.3. Thermal Insulation

When examining the legislation related to thermal insulation of buildings in Türkiye, we encounter the following key regulations related to our subject matter: TS 825 “Rules for Thermal Insulation in Buildings” Energy Efficiency Law No. 5627 Building Energy Performance Regulation (2008)

2.3.1. TS 825 “rules for thermal insulation in buildings”

2.3.1.1. General definition of TS 825

The "TS 825 Rules for Thermal Insulation in Buildings" regulation officially recognized the rules for thermal insulation in Türkiye in 1970. By using the TS 825 "Rules for Thermal Insulation in Buildings" standard, the net heating energy requirements in buildings can be calculated, and the maximum allowable heating energy in buildings can be determined. The initial version of the standard, which was aimed at aligning with European Union standards, came into effect on April 29, 1998. It was revised by the Turkish Standards Institute's Engineering Services Specialization Committee, TK30 Energy and Energy Systems Technical Committee, and the revision TS 825: 2008 + T1: 2009 + T2: 2009 was approved as a Turkish Standard at the TSE Technical Board meeting on December 18, 2013. (Turkish Standards Institute, 2013). The purpose of creating this standard was to control the amount of energy consumed for heating buildings, define the standard calculation method and values to be used for heating energy calculations. (Turkish Standards Institute, 2013). In a study conducted by Usta, S. (2009), the changes in heat losses, heat gains, and energy consumption required for heating were calculated in a house where thermal insulation had not been previously applied, after applying TS 825-compliant thermal insulation. The study concluded that heat losses in buildings vary according to the volume of the building, the dimensions of the structural elements used, and the thermal transmittance properties. Depending on the insulation applied, heat savings of 20-75% were achieved, and reductions in energy consumption led to a decrease in harmful gas emissions, thus positively affecting environmental health. (Usta, S., 2009).

2.3.1.2. Analysis of regional profiles according to TS 825

Annual heating energy requirement (Qı, year) refers to the amount of heat energy that a heating system must provide to the heated environment over the course of a year (TSE, T., 2013). The TS 825 calculation is based on simplifying degree-day calculations. In degree-day calculations, different values are taken for each day, and these values are reduced to degree-day regions, and monthly and seasonal average values are determined for the calculation (Ulaş, A., 2010). In the annual heating energy calculation, elements such as the building's exterior walls, windows, roof, floor, and floor areas in contact with the external environment are considered. Then, the U-values for each of the building components are calculated separately. Additionally, it is assumed that there will be no condensation and no thermal bridges, and necessary precautions are taken. (TSE, T., 2013). During the design of the building components, the thermal transmittance coefficients specified in TS 825 must meet the desired minimum U-values for the region where the structure is located. According to the Energy Performance Regulation, when the transparency of the heat-losing surfaces in buildings is 60% or more, a thermal transmittance value 25% lower than the values recommended in TS 825 is required. (Building Energy Performance Regulation, 2008). The upper limit values for building components have been determined based on degree-day regions. These values are not mandatory but are recommended. The table presents the maximum U-values recommended for exterior walls, roofs, floors, and windows based on the regions.

Table 2

Heating Energy Values for the Largest and Smallest Atop / Vbrüt Ratios (TSE, 2013)

		for A/V < 0,2	for A/V > 1,05	
1st Region	An related to Q1. DG =	13,8	44,9	kWh/m2,year
	Vbrüt related to Q1. DG =	4,4	14,4	kWh/m3,year
2nd Region	An related to Q2. DG =	28,5	82,3	kWh/m2,year
	Vbrüt related to Q2. DG =	9,1	26,3	kWh/m3,year
3rd Region	An related to Q3. DG =	38,4	100,9	kWh/m2,year

	Vbrüt related to Q3. DG =	12,3	32,3	kWh/m3,year
	An related to Q4. DG =	50,4	122,3	kWh/m2,year
4th Region	Vbrüt related to Q4. DG =	16,0	38,8	kWh/m3,year
5th Region	An related to Q5. DG =	62,8	148,2	kWh/m2,year
	Vbrüt related to Q5. DG =	20,0	47,4	kWh/m3,year

Table 3

Calculation of Q Limited by Regions and Intermediate Atop /Vbrüt Ratios TSE, T. (2013)

1st Region	related to An	Q1. DG =	36,7 x A/V + 6,0	kWh/m2,year
	related to Vbrüt	Q1. DG =	11,9 x A/V + 1,9	kWh/m3,year
2nd Region	related to An	Q2. DG =	63,7 x A/V + 14,9	kWh/m2,year
	related to Vbrüt	Q2. DG =	20,3 x A/V + 4,7	kWh/m3,year
3rd Region	related to An	Q3. DG =	74,2 x A/V + 22,4	kWh/m2,year
	related to Vbrüt	Q3. DG =	23,2 x A/V + 7,4	kWh/m3,year
	related to An	Q4. DG =	83,4 x A/V + 31,0	kWh/m2,year
4th Region	related to Vbrüt	Q4. DG =	27,1 x A/V + 9,8	kWh/m3,year
5th Region	related to An	Q5. DG =	88,7 x A/V + 30,6	kWh/m2,year
	related to Vbrüt	Q5. DG =	24,5 x A/V + 12,1	kWh/m3,year

In Türkiye, energy efficiency in buildings is a crucial aspect of both environmental sustainability and cost reduction. A key component in assessing energy needs for buildings, especially in terms of heating requirements, is the concept of degree-days. Degree-days represent the amount of energy required to maintain a desired indoor temperature, taking into account external temperature fluctuations. The classification of regions based on degree-days helps in determining the thermal insulation requirements for buildings, as well as guiding the implementation of appropriate energy-saving measures. Below is an overview of the degree-day regions for various cities in Türkiye, classified according to their geographic and climatic conditions. This classification is essential for understanding regional differences in heating energy needs, which directly impact building insulation standards and energy efficiency regulations.

Degree-Day Regions for Cities (TSE, 2013)

Region 1:

Adana, Hatay, Mersin, Antalya, Izmir

Cities in Region 2, but considered in Region 1 for certain municipalities: Bodrum (Muğla), Dalaman (Muğla), Fethiye (Muğla), Marmaris (Muğla), Gökova (Muğla), Datça (Muğla), Köyceğiz (Muğla), Milas (Muğla)

Region 2:

Aydın, Bursa, Giresun, Muğla, Sinop

Other cities: Ayvalık (Balıkesir), Çanakkale, Istanbul, Osmaniye, Şırnak, Adıyaman, Denizli, Kilis, Ordu, Şanlıurfa, Amasya, Diyarbakır, Kocaeli, Rize, Samsun, Trabzon, Balıkesir, Düzce, Kahramanmaraş, Tekirdağ, Yalova, Zonguldak, Sakarya, Siirt, Manisa, Mardin, Gaziantep, Edirne, Bartın, Batman

Cities in Region 3: Hopa (Artvin), Arhavi (Artvin)

Cities in Region 4: Abana (Kastamonu), Bozkurt (Kastamonu), Çatalzeytin (Kastamonu), İnebolu (Kastamonu), Cide (Kastamonu), Doğanyurt (Kastamonu)

Region 3:

Afyon, Aksaray, Ankara, Artvin, Bilecik, Bingöl, Bolu, Burdur, Çankırı, Çorum, Elazığ, Eskişehir, Iğdır, Isparta, Karabük, Karaman, Kırıkkale, Kırklareli, Kırşehir, Konya, Kütahya, Malatya, Nevşehir, Niğde, Tokat, Tunceli, Uşak

Cities in Region 1: Pozantı (Adana), Korkuteli (Antalya)

Cities in Region 2: Merzifon (Amasya), Dursunbey (Balıkesir), Ulus (Bartın)

Cities in Region 4: Tosya (Kastamonu)

Region 4:

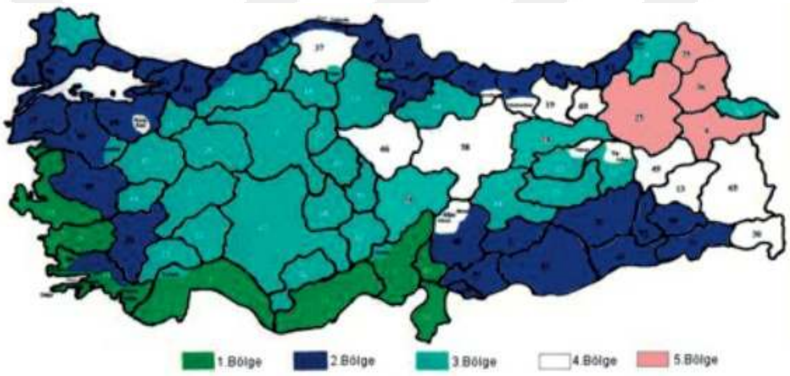
Bayburt, Bitlis, Erzincan, Gümüşhane, Kastamonu, Muş, Kayseri, Hakkari, Yozgat, Sivas, Van

Cities in Region 2: Keles (Bursa), Uludağ (Bursa), Şebinkarahisar (Giresun), Afşin (Kahramanmaraş), Göksun (Kahramanmaraş), Elbistan (Kahramanmaraş), Mesudiye (Ordu)

Cities in Region 3: Kiği (Bingöl), Pülümür (Tunceli), Solhan (Bingöl)

Figure 5

Cities According to Degree-Day Regions TSE, T. (2013)



2.4. Law No. 5627 on Energy Efficiency

The objective of the law is to ensure the efficient use of energy, prevent waste, reduce the economic pressure of energy costs, and protect the environment by increasing the efficiency of energy resources and energy use. The law outlines measures for improving energy efficiency, the assistance that will be provided within this framework, administrative penalties for violations, and various regulations including education and awareness-raising efforts. Under the law, incentive programs include Efficiency-Improvement Projects (VAP) support in industrial establishments, optional agreements with industrial businesses, treasury incentives, and support from the Ministry of Renewable Energy in line with recommendations and KOSGEB (Small and Medium-Sized Enterprises Development Organization) aids for SMEs. (RAPORU, O. 2012). The law also specifies that investments created to increase energy efficiency in industrial enterprises will benefit from investment incentives, and that training, work, and consultancy services provided for small and medium-sized enterprises to meet efficiency targets will be supported. (Keskin, T., 2007).

2.5. General Definition of Building Energy Performance Regulation (BEP)

The purpose of the Energy Performance Regulation (BEP) is to determine calculation rules for assessing the total energy use of a building, considering external climate conditions, internal space requirements, local conditions, and cost-effectiveness, to classify buildings in terms of primary energy and carbon dioxide (CO2) emissions, determine the minimum energy performance requirements for new buildings and existing buildings undergoing significant renovations, evaluate the feasibility of renewable energy sources, control heating and cooling systems, limit greenhouse gas emissions, establish performance criteria and implementation principles for buildings, and ensure environmental protection. (BEP Regulation, 2008). Building

Thermal Insulation Principles

When calculating the thermal insulation of buildings, the following rules must be followed: The building's annual heating energy requirement must be lower than the limit value defined in the TS 825 standard. For buildings to be constructed in contiguous order, the heating energy requirement must take into account that the walls of adjacent buildings are considered as exterior walls. The surfaces of building components separating the building from the outside air, ground, or areas with low indoor temperatures must be insulated according to the minimum thermal insulation conditions in the TS 825 standard. Every surface forming the exterior cladding of the building should be insulated in such a way that no thermal bridges are formed, including walls, floors, balconies, consoles, ground, ceilings, roofs, and window-wall junctions. In existing buildings where thermal bridges cannot be prevented, heat loss due to thermal bridges formed on the surfaces transferring heat is calculated according to TS EN ISO 10211-1, TS EN ISO 10211-2, TS EN ISO 14683, or TS EN ISO 6946 standards to determine the annual heating energy requirement. Independent sections between different users in the building must have insulation with a thermal transmittance coefficient no greater than 0.80 $W/m^2 \cdot K$ in walls, floors, and ceilings. (BEP Regulation, 2008).

2.5.1. Thermal insulation project requirement

In the thermal insulation project: Heat losses, heat gains, gain/loss ratio, gain utilization factor, and the monthly and annual heating energy requirements must be presented in tabular form, based on examples in the "Building Specific Heat Loss" and "Annual Heating Energy Requirement" tables in the TS 825 standard. The calculated annual heating energy requirement (Q) must be proven not to exceed the boundary value derived from the annual heating energy (Q_I) formula in the TS 825 standard. For buildings used for purposes other than residential, if the temperature difference between the sections exceeds 4°C and if the annual heating energy requirement for multiple sections is calculated, the boundaries of these sections must be drawn schematically, with the dimensions of the boundaries and the temperature values of the sections specified. The thermal transmittance coefficients (U values) for the building's heat-losing surfaces, such as external walls, ceilings, and floors, their material arrangement and thicknesses, as well as the areas of the walls, ceilings, and floors, must be clearly specified. The types of glass and frames used in window systems, the window areas for each direction, and the U values must also be specified. The type of ventilation must be defined, and if mechanical ventilation is used, calculations and results should be included in the project report. The condensation that may occur on the building's heat-losing surfaces must be checked according to the TS 825 standard, and necessary drawings and calculations must be presented in the project report. For major repairs, renovations, or additions in existing buildings or independent sections, the heating degrees specified in the TS 825 standard should be considered for the sections to be applied. (BEP Regulation, 2008).

2.6. Thermal Insulatıon By Applıcatıon Type

The thermal insulation materials used in buildings minimize heat transfer, and therefore, selecting the right insulation materials for buildings can result in significant energy and cost savings. Below, some of the types of insulation materials and their application principles in building sections are examined.

Table 4

Heat Loss Areas and Their Ratios in Buildings (Altinişik, 2006)

	Multistory Buildings	Single-story Buildings
Exterior Walls	40%	

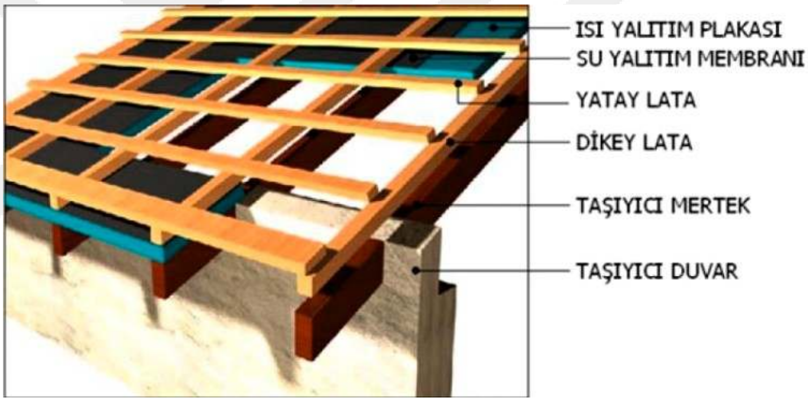
Windows	30%
Roof	7%
Basement	6%
Floor	
Air Leakage	17%

2.6.1. Roof insulation

Roof insulation materials can be applied in three basic ways: between rafters, on top of rafters, and under rafters.

Figure 6

Roof Insulation (Ünver, et al. 2020)



2.6.2. Window insulation

Single-glazed units are being replaced by double or triple-glazed units with heat-solar control coatings and heat control coatings. The use of heat-solar control coated glass units significantly reduces the heat loss from windows compared to standard double-glazed units. Ünver, Ü., et al. (2020).

2.6.3. Exterior wall insulation

Thermal insulation must be provided on the exterior or interior parts of the building's outer walls. Care should be taken to ensure that there are no gaps between insulation boards. During summer, there is an approximately 17-18°C difference between the inner surface temperature of insulated walls and uninsulated walls (Cengel, 2002).

2.6.4. Floor insulation

Floor insulation is applied in areas such as floors in contact with the ground, hollow concrete ceilings, intermediate floors, and the upper parts of unheated spaces. Key points to be considered during this application include ensuring that the concrete surface of the floor is smooth, clean, and free of dust and debris. The insulation material should also demonstrate sufficient resistance to compressive stress. (Ünver, et al. 2020).

2.7. Thermal Insulatıon Materials

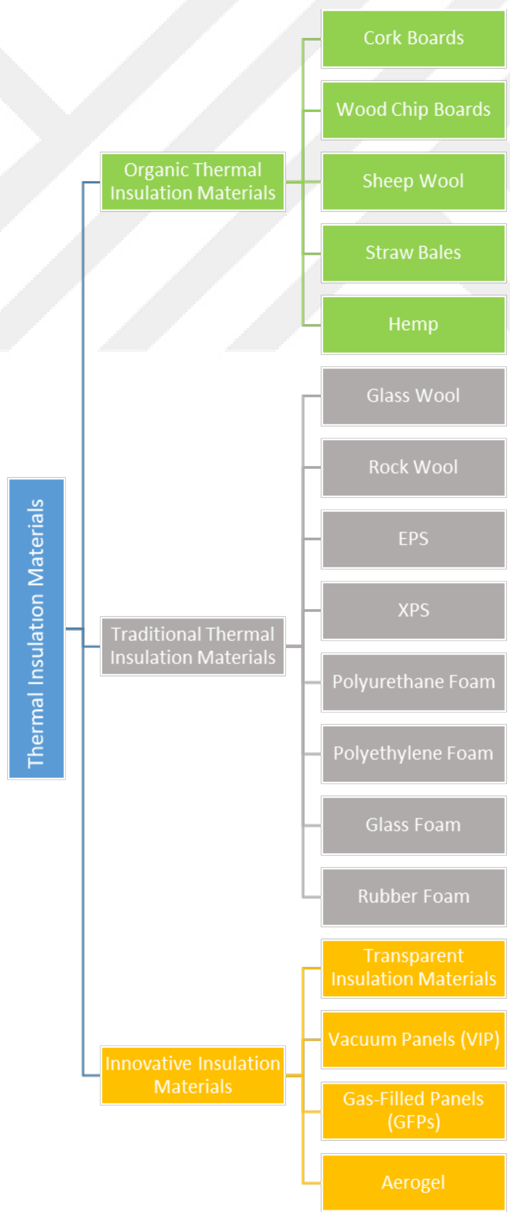
The use of natural and fossil fuels in heating and construction material production processes increases greenhouse gas emissions, raising carbon emissions. The production of construction materials and the heating of buildings contribute to CO2 emissions, which make up 30% of total carbon emissions. Thermal insulation is one of the most effective ways to create a healthier ecosystem by reducing the emissions of gases and waste released into the environment and decreasing carbon emissions. Therefore, the importance of thermal insulation is increasingly recognized in reducing heat losses and ensuring appropriate comfort conditions. Mıhlayanlar, E., Kartal, S., & Erten, Ş. Y. (2017). The thermal insulation capacity of a material is generally assessed using thermal conductivity (λ) or thermal transmittance (U-value). Thermal conductivity defines the rate of heat transfer through a unit cross-sectional area of a material in the direction perpendicular to the temperature gradient, expressed in W/mK. Thermal transmittance, on the other hand, indicates the rate of heat transfer through a material per square meter for a temperature difference of 1 Kelvin, expressed in $W/m^2 \cdot K$. (Karabulut, 2022). Thermal insulation is not only achieved by covering the building's envelope with suitable insulation materials. Energy savings also depend on several factors, such as the arrangement of the site plan during the design phase, the size of window areas, and the presence of adjacent buildings. Heating the interior naturally using solar energy, without consuming natural resources and fuels, is also linked to the positioning and facades that allow sunlight penetration. The width of the south-facing facade and larger window areas, along with the length of the north-facing facade and smaller window areas, play an essential role in reducing heat losses. By applying thermal insulation: Natural resource consumption decreases. Waste sent to the environment decreases. Economic savings are achieved. Comfortable indoor environments are created. Structural integrity is maintained (minimizing damage caused by thermal movement). Sound, fire insulation, and vapor impermeability are provided (Schiavoni, et al., 2016).

2.7.1. Classification of thermal insulation materials

To evaluate the sustainability of insulation materials, commonly used inorganic materials are classified as 'Traditional,' organic materials derived from alternative sources as 'Organic,' and innovative technologies that are not widely used today but offer efficiency and technological advances as 'Innovative.' These categories allow for the assessment of insulation materials from a sustainability perspective. (Ayçam et al., 2010).

Figure 7

The Classification of Thermal Insulation Materials



2.7.2. Traditional thermal insulation materials

Traditional thermal insulation materials are among the most preferred insulation options today due to their economic advantages and ease of application. However, the environmental impacts of these materials are negative. They lead to the consumption of limited natural resources during production processes and cause environmental pollution. (Ayçam et al., 2010).

2.7.2.1. Glass wool

Glass wool is a material obtained by transforming the inorganic raw material silica sand into fiber form at temperatures between 1200°C and 1500°C. It is a domestically produced thermal and sound insulation material. Depending on its intended use, it is produced in various sizes and densities, in forms such as blankets, boards, pipes, and loose forms, along with coatings and additives. Over time, it does not suffer from deterioration, decay, mold, corrosion, or rust; it is also resistant to damage from insects and microorganisms. As a roof blanket, it can be used in all types of wooden trusses, metal roofs, and sandwich roofs (Özer, 2006).

The formaldehyde gas emitted by glass wool is carcinogenic. The spread of formaldehyde and similar gases can cause irritation of the respiratory tract, such as in the ears, nose, and throat (Ayçam et al., 2010).

Glass wool comes in two main types: with or without Bakelite. Bakelite-containing glass wool, which is yellow due to its phenol-formaldehyde content, can be produced in sheet or blanket form. Its density ranges between 10-130 kg/m³. Bakelite glass wool is resistant up to 250°C, while the non-Bakelite version can withstand up to 550°C. The non-Bakelite glass wool, which is typically used for insulating pipes, boilers, and tanks, is white and is sewn onto materials such as corrugated cardboard and chicken wire (Onaylı, 2002).

Glass wool can be produced either with aluminum foil or glass cloth coating, or without any coating, depending on the application. In cases where glass wool cannot be used in sheet or blanket form due to uneven surfaces, loose glass wool is preferred. Depending on the need and intended use, glass wool can be applied in thicknesses of 2-5 cm in sheet form and 8-14 cm in blanket form (Dere, 2011).

Glass wool can be produced by different methods, including:

- Rod drawing method
- Drum chamber method
- Nozzle drawing method
- Nozzle blowing method
- Centrifugal method
- Combined centrifugal and stretching method.

Glass wool blankets are frequently preferred in ceiling installations due to their economical nature and ease of application (İZODER, Association of Thermal, Sound, and Water Insulation Contractors, 2003).

The operating temperature range of glass wool is between -50°C and +250°C. Its fire resistance class is designated as A1 or A2. The thermal conductivity coefficient ranges from 0.035 to 0.050 W/m·K, and its water vapor diffusion resistance factor (μ) is 1. The volume water absorption rate ranges from 3% to 10%. It is not affected by the ultraviolet rays of the sun (Kaynak, 2022).

Glass wool products, produced in various sizes and technical specifications with different coatings, are used in thermal and sound insulation and acoustic adjustments. According to the German Standard DIN 4102, these products are classified as "A" fireproof materials, enhancing their fire safety. (Dağsöz, 1991).

Glass wool is characterized by its low pyrolysis property. This material's flame-retardant low pyrolysis property forms a layer on its surface that prevents the spread of flames (Stec, & Hull, 2011).

Table 5

Physical Properties of Glass Wool (Özer,2006)

Density (kg/m³)	**14 - 100**
Thermal Conductivity (λ) (W/m·K)	0.04
Temperature Resistance (°C)	-50 / +250
Water Absorption (%) by Volume	3 - 10 (for 5 cm thickness)
Water Vapor Diffusion Resistance Factor	1

(µ)

Glass wool is used in closed attic spaces and placed on floors. No material should cover the laid blanket, and in the case of aluminum foil-coated blankets, the foil-coated surface should face the hot side during installation (Özer, 2006).

In cases where there is a direct wooden roof structure in the attic, it is possible to apply thermal insulation between the wooden rafters. The thickness of the insulation placed between the rafters should vary according to the different climate regions in Türkiye. For instance, thicker insulation should be preferred in very cold climates. Therefore, during the design phase, the thickness of the insulation material to be used should determine the rafter thickness, and the blanket should be compressed to prevent thickness loss (İşbilir, 2009).

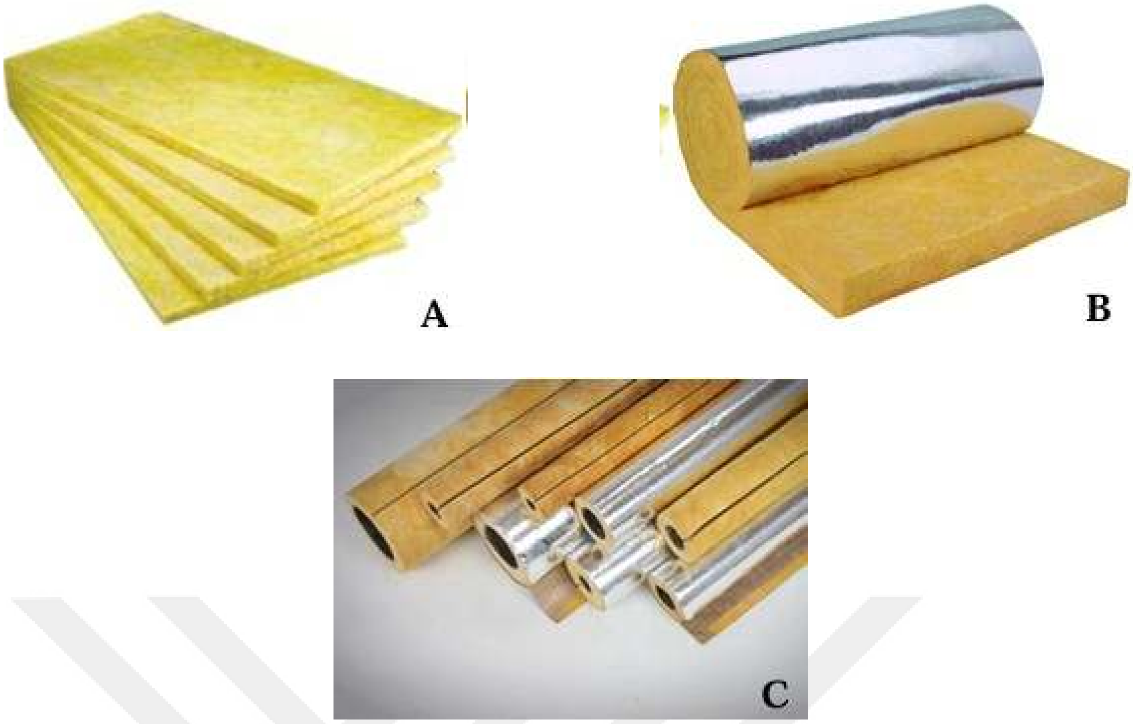
Figure 7

Application of Glass Wool on Closed Attic Surface (Karasu,& Büyüklü, 2003)

Examples of glass wool produced in different forms according to the purpose of use are shown in Figure 7.

Figure 8

The Types of Glass Wool



The materials have been shown in Figure 8, which represents A: Sheet Glass Wool, B: Foil-coated Blanket Glass Wool, C: Foil-coated Pipe Glass Wool (Dindar, 2024).

2.7.2.2. Rock wool

Rock wool, which has an open porous structure, is produced by passing basalt and diabase stones through fine screens and converting them into fibers using the centrifugal method at a temperature range of 1350-1400°C. During the fiber production process, the raw material is mixed with limestone and melted at 1600°C. The molten rock is then dropped onto a rapidly rotating disk, forming fibers approximately 5 microns in diameter. The density of the material varies between 30-200 kg/m³, depending on the application area. The properties of rock wool, such as tensile and compressive strength, change in direct proportion to the material's density. According to the TS 825 standard, the thermal conductivity coefficient of rock wool ranges from 0.035 to 0.050 W/mK. It is a non-combustible material, classified as A1 or A2. (Yaman et al., 2015)

Due to its open porous structure, rock wool is significantly affected by ambient temperature and humidity levels, which can change its insulation performance over time. In environments with high relative humidity, water vapor settles in the pores of rock wool, which can reduce its insulation performance. (Donavska et al., 2020)

The material maintains its performance within the continuous maximum usage temperature range of -50/+750°C. In TS 825, Appendix 5, the thermal conductivity value is determined to be 0.040 W/mK, and the water vapor diffusion resistance factor is μ=1. Rock wool is produced in a density range of 30-200 kg/m³. Its water absorption rate ranges between 2.5% and 10% by volume, and its mechanical strength ranges between 1.5 - 6.5 tons/m² (Bayer,2006)

Table 6

Physical Properties of Rock Wool (Özenç, 2007)

Density (kg/m³)	30 - 150
Thermal Conductivity (λ) (W/m·K)	0.04
Temperature Resistance (°C)	650 - 1000
Water Absorption (%) by Volume	2-3% (for 5 cm thickness)
Water Vapor Diffusion Resistance Factor (μ)	1
Compressive Strength (kg/m²)	Non-load bearing
Hygroscopic Equilibrium Moisture	≤ 0.2

Rock wool and glass wool insulation materials are 100% dimensionally stable and do not change their dimensions under the influence of temperature and humidity. They do not lose their physical properties over time, and they do not encounter negative issues such as deterioration, decay, mold formation, corrosion, and rust. Additionally, they are not damaged by insects or microorganisms. They have no hygroscopic and capillary properties. Their melting temperature is ≥1000°C. The ease of cutting and the ability to use each piece without waste provide advantages in application. Bayer, G. (2006)

Rock wool, which can be brown or gray, has a thickness of 2.5-10 cm when used in sheet form and 3-12 cm when used in blanket form. Depending on the intended use, rock wool can be applied either with or without coatings. If the surface to be insulated is not smooth, loose rock wool is preferred.

Rock wool is frequently used in cladding production due to its thermal, sound, and fire resistance properties. Calcium and sulfur-based rock wool is available in different forms, including sheets, blankets, and pipe forms (Dindar, 2024)

Examples of rock wool produced in different forms according to its intended use are shown in Figure 9.

Figure 9

Types of Rock Wool

A **B**

A: Sheet Rock Wool, B: Blanket Rock Wool, C: Foil-coated Pipe Rock Wool (Dindar, 2024)

Figure 10

Exterior Wall Sheet Rock Wool Application (Personal Archive)

2.7.2.3. EPS (expanded polystyrene foam)

EPS, an expanded polystyrene foam board, is a closed-cell, typically white-colored thermoplastic material used as a structural building material. This insulation material is produced by evaporating pentane added to polystyrene beads. Due to its low density, EPS has limited acoustic properties, and its density ranges from 15 to 30 kg/m³, making it suitable for thermal insulation purposes. 98% of EPS consists of trapped air, while 2% is polystyrene. Its thermal conductivity ranges from 0.035 to 0.040 W/m·K, and its fire resistance class is classified as D or E. Some manufacturers release hydrochlorofluorocarbons (HCFC) during the production process, and the high energy requirements are considered as some of its negative features. (Ayçam et al., 2010)

Table 7

Physical Properties of EPS (İşbilir, 2009)

Density (kg/m³)	10 - 40
Thermal Conductivity (λ) (W/m·K)	0.029 – 0.046

Temperature Resistance (°C)	-180 / +100
Thermal Expansion Coefficient (1/°C)	9010^-5 – 710^-3
Water Vapor Diffusion Resistance (µ)	80 - 225
Compressive Strength (N/mm²)	0.0006 – 0.35
Shear Strength (N/mm²)	0.008 – 0.29
Bending Strength (N/mm²)	0.013 – 0.7
Elastic Modulus under Pressure (N/mm²)	0.38 - 3

EPS insulation applications on the exterior walls of buildings provide insulation for reinforced concrete surfaces such as columns, beams, lintels, and shear walls, preventing the formation of thermal bridges. Additionally, it is the most effective solution for preventing physical changes like expansion and contraction caused by temperature fluctuations by providing protection against atmospheric conditions. By preventing thermal bridges, EPS reduces overheating in summer and minimizes the risk of condensation within the sections (Özer, 2006)

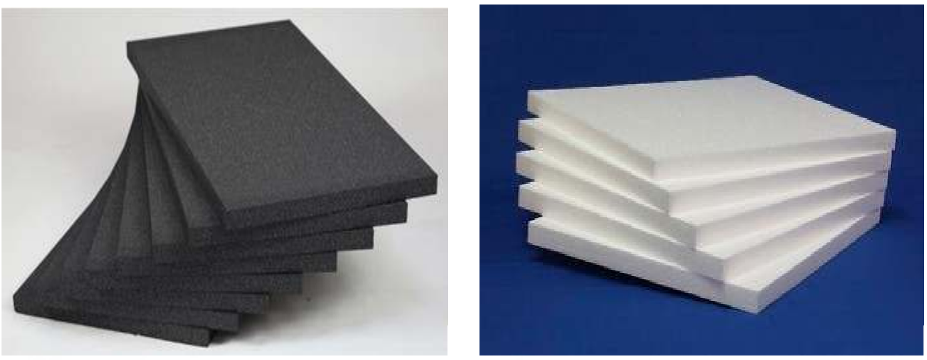
EPS is structurally a small and densely porous insulation material. Through the expansion of polystyrene beads and the trapping of stagnant air within them, the thermal conductivity, vapor permeability, water absorption capacity, and sound permeability of EPS are positively affected (Dere, 2011) Also, EPS, as a thermal insulation material, is classified in fire class D or E. (T.C. Ministry of Environment and Urbanization, 2015)

Like other plastic materials, EPS softens when it reaches a specific temperature. It is resistant to pressure and does not show brittleness. It has high bending resistance in thermal insulation. It is extremely lightweight, making it easy to transport and apply. However, it is sensitive to some chemicals and ultraviolet rays from the sun. It does not harbor insects or microorganisms. As an economic insulation material, it stands out for its cost-effectiveness. (Özer, 2006) Due to the petrochemical raw materials used in its production, the manufacturing process of EPS requires high energy consumption. (Ülker, 2009)

Despite this, the blowing agent (pentane) used in its production does not damage the ozone layer or contribute to climate change. EPS, with its breathable structure, allows vapor passage, making it a healthier insulation material compared to XPS. (Kandemir, et al., 2019)

Figure 11

Carbonized and Non-Carbonized EPS Visuals (Dindar, 2024)



A **B**

2.7.2.4. XPS (extruded polystyrene foam)

XPS insulation material is produced using polystyrene raw material through the extrusion method. Production can vary in size and technical specifications based on the intended use. It is available in the market for thermal insulation purposes. Since its cells are fully closed, it does not allow water to enter. It has no capillary absorption. It has high compressive strength and is classified as E according to TS EN 13501-1 standard. Production continues under the Owens Corning USA Hydrovac License. Additionally, it is manufactured in facilities that are certified with ISO 9001 Quality Assurance, ISO 14001 Environmental Management, and OHSAS 18001 Occupational Health and Safety Management System by BVQI (Kocagül, 2013)

Table 8

Physical Properties of XPS Insulation Material (İşbilir, 2009)

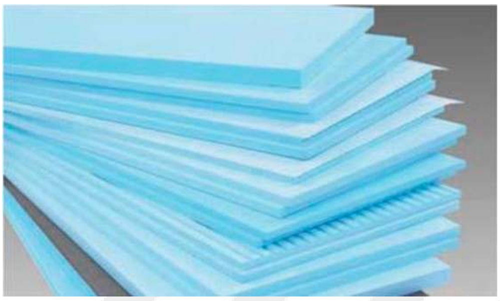
Density (kg/m^3)	**25 - 48**
Thermal Conductivity (λ) (W/m·K)	0.03
Temperature Resistance (°C)	-50 / +75
Thermal Expansion Coefficient (1/°C)	0.07
Water Vapor Diffusion Resistance (μ)	80 - 225
Compressive Strength (N/mm^2)	0.15 – 0.35

Shear Strength (N/mm²)	60
Bending Strength (N/mm²)	60

XPS insulation material is shown in Figure 12.

Figure 12

XPS Insulation Material (Kaynak, 2022)



2.7.2.5.Polyurethane foam

Polyurethane is composed of two separate chemical components, polyol and isocyanate. It reacts with air and hardens when exposed to it. It is a thermal insulation material that can be used in the form of sheets, sandwich panels, and spray application methods (Evcil, 2000).

Polyurethane is a foam-based plastic type formed by the combination of two chemicals, polyol and isocyanate, which expands and hardens when exposed to air. It finds wide application due to its lack of joints, ability to apply without forming thermal bridges, and its ease in handling complex details. Thermal insulation boards are produced by injecting a polyurethane raw material mixture into a mold, where it expands and fills the mold (Ünal, 2002).

95% of the cells in polyurethane have a closed-cell structure. It is resistant to light acids, gasoline, diesel, alkalis, and seawater. Its resistance to chemicals increases its variety of usage areas. Polyurethane's initial thermal conductivity value is very low; however, over time, this value increases by 15%. Being a petroleum-based product, it is flammable. The material has a very low water absorption capacity (Karakoç et al., 1999)

Polyurethane foam's properties, such as compressive, tensile, and breaking strength, density, cell shapes, and arrangements, vary and are generally high. It does not undergo dimensional changes under external forces. When the lifespan of polyurethane ends, it cannot be recycled due to its thermoset nature, and it cannot be reused while maintaining its functionality (Ülker, 2009).

Polyurethane foams are obtained by combining the polyol system with isocyanate in specific ratios and expanding this mixture with a blowing agent. Depending on the application area, polyurethane can expand up to 100 times its original liquid volume. Its thermal conductivity ranges from 0.025 to 0.040 W/m·K, and it is classified in fire resistance classes D, E, or F (Yaman et al., 2015)

Table 9.

Physical Properties of Polyurethane Foam (İşbilir, 2009)

Density (kg/m³)	30 - 40
Thermal Conductivity (λ) (W/m·K)	0.035
Temperature Resistance (°C)	-200 / +110
Water Absorption (by Volume %)	3 - 5
Water Vapor Diffusion Resistance (μ)	300 - 100

Figure 13

Polyurethane Foam Insulation Material (Akelçi, 2016)

Figure 14.

Application of Polyurethane Foam Insulation Material (Kaynak, 2022)

2.7.2.6. Polyethylene foam

Polyethylene-based materials are porous, plastic materials produced from polymers. Polyethylene foam, which has a closed-cell structure and is obtained through the extrusion method, is an insulation material that stands out for its durability, reliability, economy, and ease of use. It is free from toxic gases, chemically neutral, and odorless. Polyethylene-based materials have low density, an elastic structure, and low thermal conductivity. Additionally, they have high water and vapor resistance and excellent impact resistance (Karakoç, 1999). Polyethylene foam has a wide temperature range for usage and is a non-flammable, self-extinguishing insulation material. (Altınışık, 2006).

The thermal conductivity coefficient (λ) must be equal to or less than 0.040 W/m·K, and the water vapor diffusion resistance factor (μ) is greater than 5000. The temperature resistance varies between -45°C and +80°C. The material is ductile with a closed-cell structure. Ultraviolet rays from the sun can damage this insulation material. According to British Standard BS 476, it falls into classes 0 and 1 (Kocagül, 2013). Table 10 shows the physical properties of polyethylene foam.

Table 10.

Physical Properties of Polyethylene Foam (Kocagül, 2013)

Density (kg/m³)	30 - 40
Thermal Conductivity (λ) (W/m·K)	0.040
Temperature Resistance (°C)	-45 / +80

Water Absorption (by Volume %)	0.4
Water Vapor Diffusion Resistance (μ)	5000

Figure 15

Types of Polyethylene Foam


A


B

Polyethylene Foam A (Yıldırım, 2021).

Polyethylene Foam B (Kocagül, 2013).

2.7.2.7. Rubber foam

Rubber foam comes in different sizes and technical specifications, including pipe and sheet variants. It is available on the market for thermal insulation and condensation control. The thermal conductivity coefficient (λ) is equal to or less than 0.038 W/m·K. The water vapor diffusion resistance factor (μ) is greater than values between 3000 and 7000. The temperature resistance varies between -60°C and +1050°C. The material has a ductile structure with a closed-cell architecture. Ultraviolet rays from the sun can damage this insulation material. It is classified in classes 0 and 1 according to British Standard BS 476. Its production is licensed by Armacell GmbH and is manufactured in facilities certified with ISO 9001 Quality Management System and OHSAS 18001 Occupational Health and Safety Management System by BVQI. (Kocagül, 2013).

Table 11.

Physical Properties of Rubber Foam (Kocagül, 2013)

Density (kg/m³)	**30 - 40**
Temperature Resistance (°C)	-60 / +1050

Water Vapor Diffusion Resistance (μ)	3000 - 7000

2.7.2.8. Glass foam

Glass foam is produced by melting glass at high temperatures, cooling it into fine powder, and passing it through furnaces at 1000°C after adding carbon. The product from the furnaces is then molded into pipe or sheet forms in the final annealing ovens. The resulting glass foam is very hard and brittle, with a surface that can easily become dusty due to friction. It is pressure-resistant, has 90-95% porosity, and does not allow water or vapor to pass through.

This material does not allow animals to nest, grow, or seeds to germinate. Additionally, it does not have undesirable properties such as rotting, mold, or harboring pests (Akelçi, 2016).

The usable temperature range of glass foam varies from -260 to +430 ºC. The thermal conductivity value at +20 ºC has been calculated as 0.052 W/m·K, and the water vapor diffusion resistance factor is 10,000. According to BS476 standards, it is classified as a non-combustible material (Class 0). It has no water absorption properties, and does not exhibit hygroscopic or capillary characteristics. Its density ranges from 100-200 kg/m³, while its pressure resistance ranges from 48-880 tons/m² (Bayer, 2006).

Table 12.

Physical Properties of Glass Foam

Density (kg/m³)	**100 - 200**
Temperature Resistance (°C)	-260 / +430
Thermal Conductivity (λ) (W/m·K)	0.052
Water Vapor Diffusion Resistance (μ)	10,000
Water Absorption (by Volume %)	Does Not Absorb

Table 13

Glass Foam Insulation Material (Bayer, 2006).

2.7.3. Organic thermal insulation materials

Organic materials that have developed as alternatives to traditional thermal insulation materials have many positive features in terms of sustainability. All organic insulation materials are produced from renewable plant and animal sources, using low energy consumption. Non-toxic natural additives are used during the production process. They do not cause health issues and can decompose completely in nature. In other words, they do not contain toxic or synthetic chemicals. The use of organic insulation materials helps reduce environmental problems caused by the production and use of traditional insulation materials. (Ayçam et al., 2010)

2.7.3.1. Cork boards

Cork, which has a heterogeneous structure and a variable thermal conductivity coefficient from sample to sample, is available in various forms in the market, such as sheets, tiles, and panels. Additionally, cork can be mixed with a binder or cement mortar and applied as plaster or screed to contribute to thermal insulation. Among its general properties are ease of gluing, nailing, and cutting, as well as its non-decaying feature. Moreover, cork is hygroscopic and resistant to chemical substances, but it is sensitive to halogens, ammonia, and ether oils. Cork boards with improved durability can be produced by adding a binder, such as bitumen, under pressure. These types of cork boards have fire-resistant properties, are nearly waterproof, and do not harbor pests (Evcil, 2000).

Natural cork is obtained from the bark of a tree species growing along the coasts of North Africa and Mediterranean islands. This product is completely natural and has a granular structure. Cork, which exhibits a porous structure, is collected from nature, cleaned, and processed into granules. The granules are pressed and expanded with high-temperature steam, reducing their density by 50 - 75% (Akelçi, 2016).

The example of the cork board made from expanded cork granules is shown in Figure 16.

Figure 16

Expanded Cork Board (Akelçi, B 2016)

Cork boards, which are not affected by the sun's UV rays, easily allow moisture to pass through. Therefore, they cannot be used on surfaces with moisture problems. Cork boards have a highly flexible structure and are pest-free (Akelçi, 2016). Cork thermal insulation boards were commonly used in the construction of cold storage facilities in the past. However, due to the reduction of cork tree plantations and the development of modern synthetic insulation materials, they are rarely preferred for insulation purposes today (Özer, 1984).

The operating temperature of cork boards ranges from -180 to +110 ºC. The thermal conductivity value is calculated to be between 0.04 – 0.055 W/mK, and the water vapor diffusion resistance factor is between 10-35. These boards exhibit hygroscopic properties, meaning they absorb moisture from the air. They have no water absorption capability. The fire class is determined as Class 3 according to the BS476 standard. Their densities range from 80-500 kg/m³, and the pressure strength is listed as N/A (Bayer, 2006).

Table 14

Physical Properties of Cork Board

Density (kg/m³): 80 – 500
Temperature Resistance (°C): -180 / +110

Thermal Conductivity Value (λ) (W/m.K): 0.04 – 0.055

Water Vapor Diffusion Resistance Factor (μ): 10 – 35 (Bayer, 2006).

2.7.3.2. Wood chip boards

Wood chip boards are thermal insulation materials produced by pressing wood chips with a binder into board form. Wood chips are fine long strips of wood obtained by processing wood, lumber, and waste in special machines (Özer, 2006) A commonly used and known brand is Heraklit, which is also a producer's name (Ünal, 2002). These boards are resistant to both pressure and bending, and they also provide sound insulation. They are unaffected by UV rays from the sun, but as they are organic, they can be damaged by various insects and organisms (Bayer, 2006) The maximum operating temperature for wood chip boards is +110 ºC. The thermal conductivity value ranges between 0.09-0.15 W/mK, and the water vapor diffusion resistance factor is between 2-5. The fire class is determined as Class 1 according to the BS476 standard. The density of the boards ranges from 360-570 kg/m³. The water absorption is 10% by volume, and the pressure strength is 20 tons/m² (Bayer, 2006). An example of the board made from wood chips is shown in Figure X.

Figure 17

Example of Wood Chip Board (Akelçi, 2016)

Figure 18

Example 2 of Wood Chip Board (Kocagül, 2013).

Physical properties of wood chip board insulation material has been shown as below:

Table 15

Physical Properties of Wood Chip Board (İşbilir, 2009).

Density (kg/m³):	360 – 570
Temperature Resistance (°C):	+110
Thermal Conductivity Value (λ) (W/m.K):	0.09 – 0.15
Water Vapor Diffusion Resistance Factor (µ):	2 – 5
Water Absorption by Volume (%):	10

2.7.3.3. Sheep wool

Sheep wool is a renewable, sustainable, and recyclable material that does not harm human and environmental health and has increasing popularity. Compared to traditional insulation materials, it does not pose a risk to human health or skin. Wool fibers exceeding 30 micrometers in thickness do not pose a health risk, as cancerous fibers typically range from 1 to 4 micrometers. Additionally, insulation materials made from sheep wool do not continuously release harmful gases (such as nitrogen oxides, formaldehyde, etc.) that are emitted during the production or use of other materials. Wool insulation does not release toxic gases during combustion as it contains no chemical additives and does not require adhesive. When these insulation materials reach the end of their life, they easily decompose in nature and turn into fertilizer without harming the environment (Ayçam et al., 2010)

2.7.3.4. Straw bales

Thermal insulation applications made with straw bales are systems where wheat, rice, rye, and oat straw bales are used as load-bearing elements and building insulation. Straw bales are not only easy to access but are also renewable agricultural waste materials that are economical and easy to use (Ayçam et al., 2010)

In our country, straw is a material that can be harvested once a year and is abundant during certain periods. In areas where grain production occurs, straw from rice, oats, wheat, and barley are left unused and usually burned for disposal. However, if applied correctly, it is possible to build energy-efficient and well-insulated structures with this material (Eryıldız, D. I., et al., 2000).

2.7.3.5. Hemp

Hemp is an industrial plant that can be used in various sectors today. The importance and use of hemp globally have been steadily increasing in recent years. This has led to a diversification of hemp's applications and the emergence of many hemp-based production items in the industry. The industrial sectors focused on hemp include food, construction, textiles, pharmaceuticals, composite materials, and cosmetics. The formation of these sectors has also led to developments and increases in hemp agriculture and cultivation areas. (Ranalli & Venturi, 2004).

Hemp fibers from the stalks, when combined with cement and lime, form a material known as hempcrete. Hempcrete, a natural building material, is increasingly being preferred worldwide. Furthermore, the ability to produce hygienic and antimicrobial products from this plant provides a significant advantage in terms of competition and marketability. Specially designed houses and organic boards produced with hemp are now feasible. Hemp-based materials are particularly preferred for houses in tourist areas and structures in special camping sites. There are various examples of materials made from hemp used in the production of these structures (Yılmaz, & Yazici, 2022).

The thermal conductivity of hemp insulation material ranges from 0.038 to 0.060 W/m.K. Its density ranges from 20 to 90 kg/m³, and its specific heat capacity ranges from 1.6 to 1.7 kJ/kg K (Arslan, et al., 2018).

The industrial hemp-based insulation material is not only a natural product but also produced with 40% less energy than rock wool. This hemp-based material offers environmentally friendly features, making it ideal for healthy living conditions. Additionally, hemp blocks, due to their light structure, do not add significant weight to the construction. The most important products made from hemp stalks include insulation boards and wall blocks (Gizlenci, 2019).

Hemp is increasingly preferred in the construction sector as an insulation material instead of petroleum-based materials. Besides being healthy due to its natural structure, it is also durable and long-lasting. Compared to existing insulation materials, it can last much longer in terms of durability and strength. Thanks to its compliance with international fire standards, it can be used for all types of buildings. Buildings constructed with hemp insulation boards are highly effective in terms of both thermal and acoustic insulation (Gizlenci, 2019) Hemp-based insulation board is shown in Figure 19.

Figure 19

Hemp Insulation Board (Gizlenci, et al. 2019)

Figure 20

Hemp insulation board, (Personal archive)

Hemp insulation boards, while a relatively new product in Türkiye, have been used for many years globally and are primarily preferred as a plant-based insulation material. These boards, produced from recycled hemp fibers and stalks, provide a highly healthy, natural, eco-friendly, and sustainable insulation solution.

There is currently no standard established for hemp insulation materials. It is produced using the fibers and remaining parts of the hemp plant after harvesting. Depending on the desired outcome, boric acid may be added to provide fire retardant properties, metakaolin for increased durability, or bitumen to reduce water permeability. Hemp has a high moisture retention capacity, and as the moisture level increases, the thermal performance of the material decreases. Therefore, the material must be protected against moisture, pests, and water (Kaynak, 2022).

In tests conducted on samples made with hemp fibers, gravel, and a binder, the lowest thermal conductivity value measured for the material with a density of 82 kg/m³ was 0.039 W/m.K. (Kaynak, 2022). There are many advantages to using hemp as an insulation material. These include:

- Sustainability
- Recyclability
- Eco-friendliness
- Low cost
- Flame resistance and electrical insulation properties
- Moisture exchange without damaging thermal conductivity
- High acoustic performance
- Absorption of moisture and bacteria through its volatile organic components (VOC)
- Consistently high thermal performance in all seasons
- Resistance to microorganisms, pests, and decay

The thermal insulation performance of hemp is higher than many other insulation materials. According to EN ISO 10456, the thermal insulation performance of glass wool is around 670 J/kg, while rock wool insulation material has a value of 860 J/kg. For hemp-based products, this value is approximately 1600 J/kg. (Kaynak, 2022).

Table 16

Physical Properties of Hemp Insulation Material (Arslan, et al., 2018).

Property	**Value**
Density (kg/m³)	20 - 90
Temperature Resistance (°C)	+110
Thermal Conductivity Coefficient (λ) (W/m.K)	0.038 – 0.060

Property	Value
Specific Heat (kJ/kg K)	1.6 – 1.7

2.7.3.6. Innovative insulation materials

As an alternative to traditional insulation materials with adverse environmental effects, innovative insulation materials developed using technology and having low thermal conductivity coefficients are being researched and produced. Although these materials appear disadvantageous due to their high cost, efforts continue to make them a part of the insulation sector (Ayçam et al., 2010).

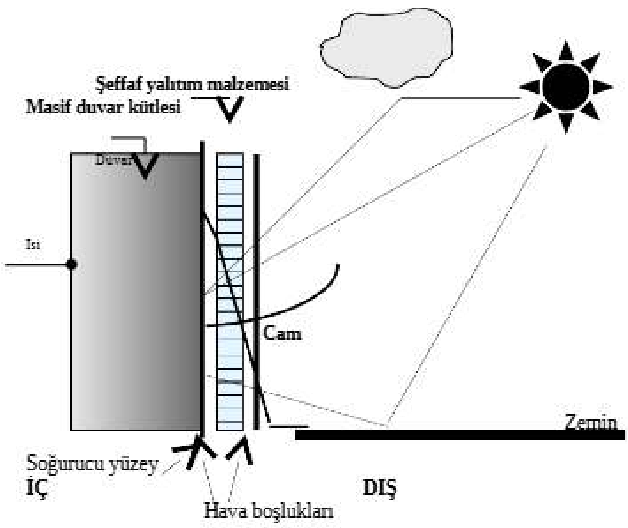
2.7.3.7. Transparent insulation materials

Transparent insulation materials were first used in solar collectors to increase thermal insulation and energy efficiency. These materials have been used on the outer surfaces of buildings to provide insulation from solar heat and energy savings. Their main applications include walls and windows. These structures can be described as having a core body with layers and gaps between them. The various types of transparent sections, the characteristics of the gap structure, and the materials in the gap allow for the development of transparent insulation materials with different performance characteristics (Forrest, 1990).

Transparent insulation materials allow short-wavelength infrared radiation to pass through while being opaque to long-wavelength infrared radiation (Gilani, 1992). A shell system with a transparent insulation system applied is shown in Figure 21.

Figure 21.

A shell system with a transparent insulation system applied (Wood & Jesch, 1993).



2.7.3.8. **Vacuum panels (VIP)**

Vacuum Insulation Panels (VIP) are insulation materials that provide much higher performance than traditional insulation materials. Compared to traditional insulation materials (max: 0.04 W/mK), VIPs (max: 0.004 W/mK) provide ten times more effective thermal insulation. VIPs are made by placing a porous core material in a vacuum-sealed outer envelope, either with a gas-absorbing material or on its own (Dursun, et al., 2008).

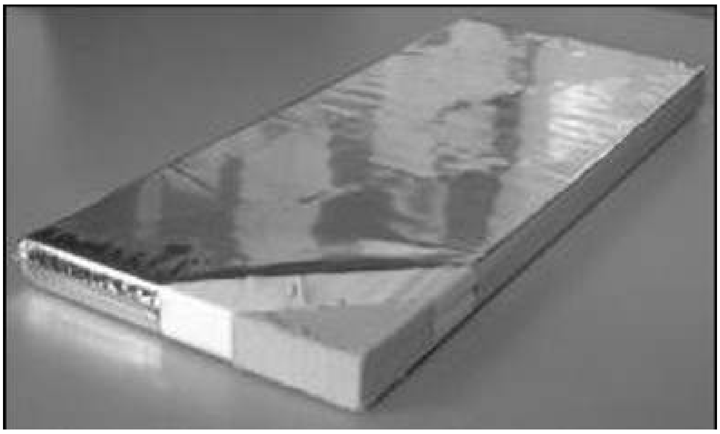
Developed vacuum insulation panels offer high thermal insulation properties and significantly reduce energy consumption. However, VIP systems are not well known, and due to their high cost, they are used in limited applications for building insulation. To become more common in the construction industry, economic VIPs with more affordable core materials should be developed. These panels can be more effectively used in areas with high energy needs and costs (Bayrakçı, et al., 2011.) Examples of applications of VIPs include:

- Ceiling, floor, and side wall applications
- Building exterior applications
- Roof and ceiling gap applications
- Window insulation applications
- Ready prefab concrete panel applications (Bayrakçı, et al., 2011)

Core, inner envelope, and outer envelope view of a vacuum panel insulation system is shown in Figure 22.

Figure 22.

Core, Inner Envelope, And Outer Envelope View of a Vacuum Panel Insulation System (Bayrakçı, H., et al., 2011).



2.7.3.8. **Gas-filled panels (GFPs)**

Gas-filled panels (GFPs) consist of a gas (a barrier) placed between reflective layers of a barrier envelope. This gas can be air or a denser gas, used to reduce thermal transport and conduction. A low-emission barrier is used to contain the gas and reduce heat transfer from radiation, while a low-emission barrier structure is also added to reduce internal gas convection and radiation (Baetens, et al., 2010).

Gas-filled panels (GFPs) are considered high-performance thermal insulation solutions for building applications, as their thermal conductivity can be reduced to as low as 10 mW/m K. However, prototype air-filled and argon-filled panels have thermal conductivities of 46 and 40 mW/m K, respectively, which are slightly higher than traditional building insulation materials (Baetens, et al., 2010).

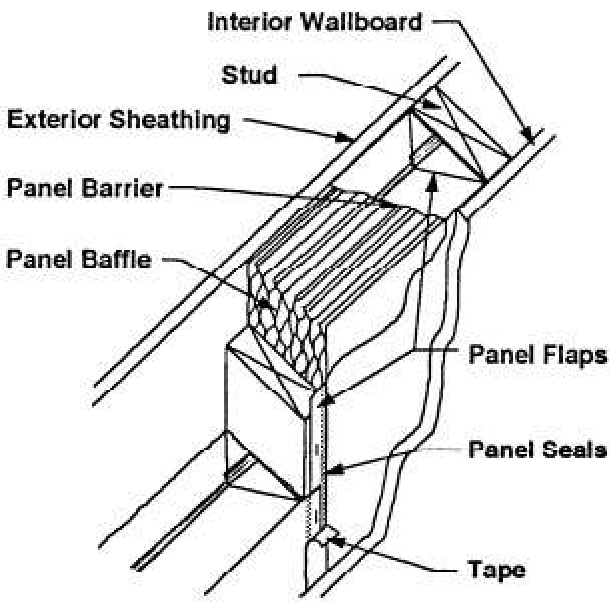
Special gas-filled insulation materials known as GFPs are produced by placing low thermal conductivity gases inside honeycomb-structured reflective panels, as shown in Figure X. These panels can be filled with various gases, such as krypton, argon, or air, for use in roofs and walls (Ayçam et al., 2010).

Gas-filled panel insulation system stud wall assembly shown in Figure X.

Figure 23.

Figure 23

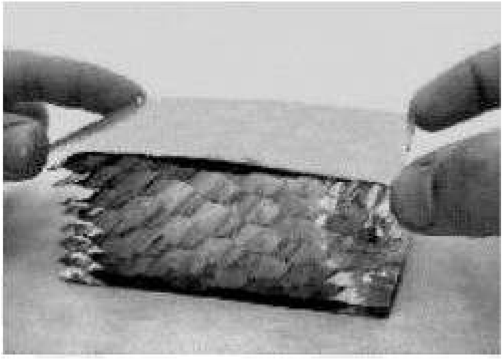
Installation of Gas-Filled Panels On a Stud Wall (Griffith, 1995).



Gas-filled thermal insulation panel is shown in Figure 24.

Figure 24.

Gas-Filled Thermal Insulation Panels (Kaynak, B., 2022).



2.7.3.9. Aerogel

The first aerogel was developed in the 1930s by Samuel Stephens Kistler. Kistler produced aerogels from various materials, including tungsten oxide, iron oxide, tin oxide, cellulose, cellulose nitrate, gelatin, agar, and rubber (Gurav, et al., 2010). The idea of using aerogel blankets for thermal insulation was first introduced globally in 1997. Since 2004, it has begun to be applied in commercial and industrial fields (Coffman, et al., 2010). Today, aerogels are used in a variety of fields, including building construction, industrial applications, aerospace, acoustic insulation, catalysts, chemical sensors, fuel cells, sports equipment, and textiles (Hrubesh, 1998).

Aerogels come in various forms, such as granules, monoliths, sheets, and blankets. Granule and monolithic aerogels are synthesized using the sol-gel method, while aerogel sheets and blankets are made by adding fibers, particles, and opacifiers. The brittle structure of granules and monolithic aerogels limits their application areas. To reduce brittleness and increase mechanical integrity, aerogels are typically reinforced with supporting fiber structures, which is why they are often used as flexible thermal insulation blankets (Hasan, et al., 2017). Silica aerogels are used in blanket form within fiber structures. A key characteristic of aerogels is their resistance to moisture. Silica aerogel blankets, due to this moisture resistance, exhibit hydrophobic properties, providing protection against mold. Their resistance to water and moisture makes them suitable for use in building and pipe insulation (Thorne-Banda, & Miller, 2011).

Since 2008, aerogel insulation materials have increasingly been used for building insulation applications in the construction sector. This rise in usage reflects growing social and political awareness of climate change, as well as the effectiveness of using thinner materials for thermal insulation and energy savings (Levy & Zayat, 2015.)

Some silica aerogel products is shown in Figure 25 .(Alan, S., 2022).

Figure 25

Some Silica Aerogel Products

Tarım Mak. Ve Aletleri San. Ve Tic. Ltd. Şti. (2024), which is an aerogel manufacturer, the physical properties of aerogel products which received via email are shown in Table 17.

Table 17

The Features of Aerogel Types

Product Name	Thickness (mm)	Thermal Conductivity (λ) (W/m.K)	Density (kg/m³)	Temperature Resistance (°C)
Aerogel LT200ALU	0.5-10.0	15.0	130	-200 / +100
Aerogel HT650	0.5-10.0	21.0	180	-50 / +650

Technical data of aerogel products from the manufacturer, personal communication, 31 October 2024 is shown in Table 18.

Table 18

Technical Data of Aerogel

TECHNICAL DATA	VALUES	UNIT	TEST METHOD
Roll width	1500	mm	
Roll thicknesses	3 / 6 / 10	mm	
Panel thicknesses	10/20/30/40/50/60	mm	
Thermal conductivity (λ_D) at 10°C	0,016	W/m·K	UNI-EN 13162:2015
Permeability to water vapor	0,07	m	
Commitment limit temperatures	-200 +650	°C	
Compressive strength (for a deformation of 10%)	30	KPa	ASTM 165
Specific heat	1.000	J/kgK	ASTM E 826
Nominal density	200 ± 30	kg/m³	
Fire reaction class	A_2		EN 13501-1
Dimensional stability	<1%		EN 1604
Perpendicular tensile strength	>17	KPa	EN 1607
Concentrated load resistance	>2550	N	EN 12430
Color	White		

2.7.4. Properties sought in thermal insulation materials

In order for thermal insulation materials to provide the expected performance, they must have a high porosity, low density, and low water absorption rate. It has been observed that building components designed based solely on thermal conductivity do not yield the desired results. Besides thermal insulation, the importance of moisture flow and condensation events has necessitated seeking different properties in insulation materials. The material must have sufficient resistance to vapor diffusion, which reduces the impact of vapor and is expected to have high thermal storage capacity to be less affected by temperature changes (Ekinci, 2003).

The selection of insulation materials depends not only on insulation performance but also on other technical characteristics. The material’s properties, such as moisture resistance, fire resistance, lightweight structure, ease of assembly, resistance to rust and corrosion, as well as pressure resistance, resistance to water and moisture, chemical resistance, and fire class, vary depending on the position and application of the building component. These factors directly affect the overall performance of the insulation system. As observed in Kulaksızoğlu’s studies, in Türkiye, the usage distribution of insulation materials is as follows: 33% glass wool, 11% EPS, 18% XPS, 11% rock wool, 8% polyurethane, and 1% other materials (Şimşek, 2019).

Beyond traditional insulation materials, the use of nanotechnology products such as aerogel, vacuum insulation panels, and transparent insulation materials on exterior surfaces allows for high performance to be achieved with thinner structures.

(Papadopoulos, 2005). The raw materials used in the production of insulation materials are very important; insulation materials produced with raw materials that are dependent on imports and have high costs will also be expensive. The main raw material for mineral wool-based insulation materials is sand, and in these materials, üleksit, a by-product of boron, which holds an important place in our country, is used. The increase in the use of mineral wool in buildings, industry, and the private sector will increase our consumption of boron ore and contribute positively to the national income (Yener, 2005). Thermal insulation is applied in areas of construction where the highest heat loss occurs, such as roofs, floors, exposed cantilevers, and facades. The selection of insulation materials requires considering specific properties depending on the type and location of the building component. These properties include:

- High thermal retention capacity
- Sufficient tensile strength
- Pressure resistance
- Resistance to water and moisture
- Resistance to chemical effects
- Fire class
- Dimensional stability
- Biological resistance
- Non-decay
- Durability
- Porosity
- Low unit weight
- Chemical composition
- Performance in temperature
- Appropriate vapor permeability for conditions
- Harmlessness to the environment and ecosystem
- Health safety
- Low energy consumption
- No maintenance required and recyclability after use (Toydemir, et. al., 2000).

2.7.4.1. Performance evaluation of thermal insulation materials

The properties of materials such as compressive strength, resistance to water and moisture, flexibility against chemical substances, and fire classification can vary depending on the spatial orientation and location of the architectural component designed for application, which significantly impacts the expected performance. According to Kulaksızoğlu's research, in the Turkish construction sector, 33% glass wool, 11% expanded polystyrene (EPS), 18% extruded polystyrene (XPS), 11% rock wool, 8% polyurethane, and 1% other materials are used. It has been determined that glass wool, rock wool, XPS, EPS, and polyurethane foam, with thermal conductivity values specified in TS EN 12667 and TS 415 EN 12939 standards, are widely used insulation materials in construction due to their availability and important market share (Şimşek, 2019). Unlike traditional thermal insulation materials, the use of nano-technological products such as gas-filled panels, vacuum panels, and aerogel in exterior wall insulation of buildings has resulted in higher thermal performance with thinner insulation materials (Papadopoulos, 2005). Unlike the currently used traditional thermal insulation materials, nano-technology insulation materials have a very low application frequency due to high costs, difficulties in procurement, and insufficient knowledge and expertise. However, for this thesis, aerogel blankets have been used for experiments and compared with traditional insulation materials. During the thesis research, thermal performance comparisons of rock wool, EPS, hemp, and aerogel thermal insulation materials were made.

2.7.5.2. Thermal conductivity coefficient

There is a relationship between thermal conductivity and density in EPS thermal insulation material, which is inversely proportional. That is, as the density increases, the thermal conductivity value decreases. When the density of EPS insulation material is between 15-45 kg/m³, the thermal conductivity ranges between 0.029 to 0.046 W/m.K. In rock wool insulation material, when the density is between 30-150 kg/m³, the thermal conductivity value is 0.04 W/m.K. In hemp insulation material, with a density of 20-90 kg/m³, the thermal conductivity value is between 0.038 and 0.060 W/m.K. In aerogel insulation blankets, when the density is between 200 ± 30 kg/m³, the thermal conductivity value is 0.016 W/m.K. It is well known that CFCs, which damage the ozone layer, have the lowest thermal conductivity. As the transition to HCFCs occurs, the damage to the ozone layer decreases, but the product's thermal conductivity increases, contributing to the greenhouse effect causing climate change. Since the use of

HCFCs is banned, alternative blowing agents such as HFCs or CO2 must be used. However, the use of these gases also leads to an increase in thermal conductivity (Bayer, 2006).

2.7.5.3. Compressive strength

The compressive strength at 10% deformation for mineral wools ranges between 1.5 to 6.5 tons/m². The compressive strength at 10% deformation for EPS is between 5-15 tons/m². Bayer, G. (2006). For hemp insulation boards, the compressive strength at 10% deformation ranges from 1.7 to 3.36 tons/m². Mocan, M., et al., 2025. For aerogel insulation blankets, the compressive strength at 10% deformation is 3.05 tons/m².

2.7.5.4. Vapor diffusion resistance value

The resistance to vapor diffusion exhibited by the surface of one meter of all thermal insulation materials is called the vapor diffusion resistance coefficient, and it is compared to the vapor diffusion resistance of air. To prevent potential damage caused by water vapor in the material's structure, materials with high vapor diffusion resistance should be preferred, or vapor barriers should be used on surfaces facing heated volumes (Şimşek, 2019). Mineral wool has a very low vapor resistance and is equivalent to air (μ=1). The vapor resistance of EPS varies widely (μ=20–250) (Bayer, 2006). In hemp insulation boards, the vapor diffusion resistance was found to be in the range of μ = 1.10 – 2.74 according to a study conducted at Bath University. Asghari, N., & Memari, A. M. (2024). In aerogel insulation blankets, this value is $\mu \leq 5$.

2.7.5.5. Fire class

The behavior of thermal insulation materials under temperature is divided into two main categories: their ability to catch fire and spread flames across the structure, and the emission of toxic gases during combustion. Rock wool maintains its integrity up to 750°C, while glass wool retains its integrity up to 250°C. Although their integrity begins to degrade above 250°C, these materials are fire-resistant, non-flammable, and do not emit toxic gases. This indicates that materials classified as Class A according to fire regulations are suitable for use on facade surfaces above 6.50 meters, window edges below 6.50 meters, and surfaces up to 1.5 meters high from the ground and on roofs. Plasters and coatings have a positive effect in delaying ignition. The temperature of these surfaces can rise to 475°C after 25 minutes of exposure to flame. Uygunoğlu, T., et al., 2015. This temperature causes deformation in glass wool. However, no degradation is observed on rock wool surfaces at the same temperature. Uygunoğlu and colleagues found that plastered white EPS had a higher burning height than XPS, while gray EPS showed the least burning. The use of low-density EPS and XPS insulation materials in composite form delays ignition and provides additional time for evacuation. Zhang, Y., et al., 2015. EPS and XPS, produced using petroleum-based polystyrene raw materials, have maximum usage temperatures of around 75-80°C. Due to their disadvantages, their use in buildings, especially in adjacent or multi-story buildings with high fire risk, is restricted by regulations. In Türkiye, the use of these materials has been limited by the Fire Protection Regulation published in the Official Gazette at the end of 2002. According to the DIN 4102 standard, these materials are classified as combustible. Although fire retardant additives improve their fire classification to some extent, they do not make them completely non-combustible. Rock wool, on the other hand, is classified as a Class A non-combustible material according to DIN 4102 and provides superior fire performance with a maximum usage temperature of 750°C. Bayer, G. (2006). In aerogel insulation blankets, this class is classified as A_2 according to EN 13501-1.

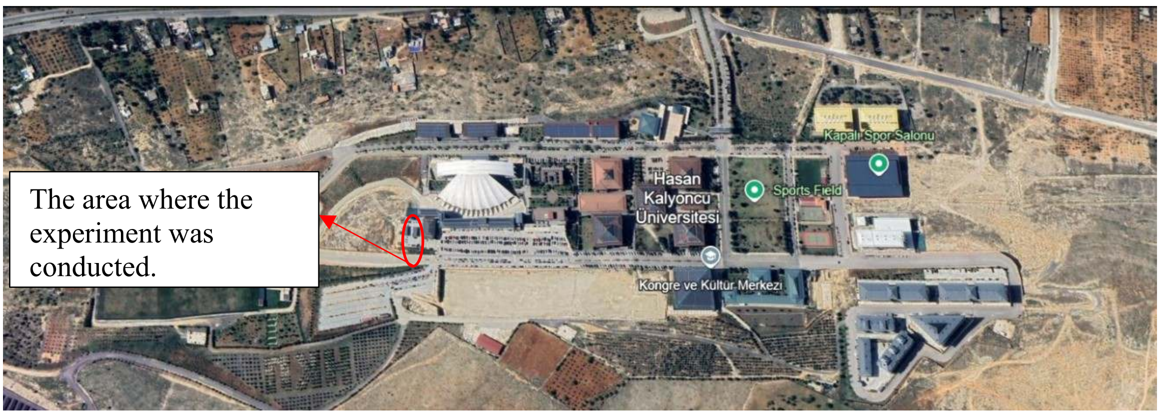
CHAPTER 3

3. MATERIALS AND METHODS

In this section of the thesis, the experiment conducted, the materials used, the methodology, and technical analyses will be discussed. A comparative experimental analysis was carried out between currently used products in thermal insulation and potential alternative materials. The experiment was performed on an open field at Hasan Kalyoncu University campus in Şahinbey district, Gaziantep, Türkiye, where there is no shading. To conduct the experiment, five homogeneous 1 m^3 structures were constructed using pumice blocks, and insulation was applied using different materials with similar technical properties. One of the test rooms was left without insulation, and the remaining four were insulated using different thermal insulation materials. These materials, in order, were carbonized EPS, rock wool, aerogel fleece, and hemp insulation boards. The experiment was carried out for a period of 9 days in January, the coldest month of the year, based on Gaziantep's long-term meteorological data. Measurements were taken three times daily, according to the hours specified for the coldest and hottest times of the day. The measurements were performed at 07:30 (just before sunrise), 13:30 (the hottest time of the day), and 19:00 (after sunset). The purpose of conducting the experiment during this period was to evaluate and compare the performance of the insulation materials in cold weather. Thermometers with probes were placed inside all structures to allow for measurements. Additionally, one thermometer was placed outside the test rooms to measure the outdoor air temperature.

Figure 26.

Hasan Kalyoncu University (Google Earth, 2025).



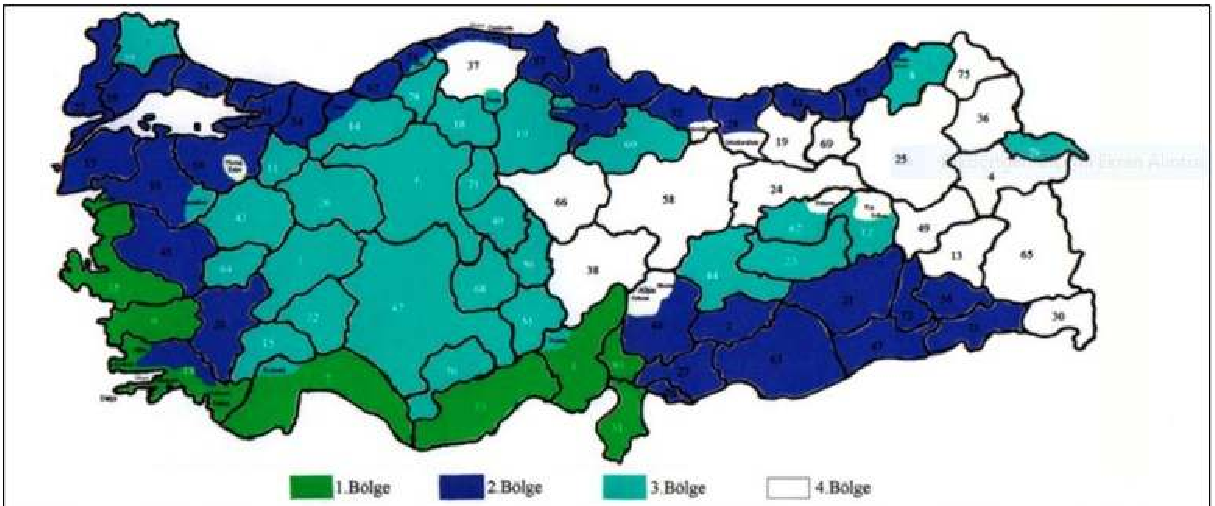
3.1. Area and Location of the Study

Gaziantep is located between the ancient civilizations of Mesopotamia and the Mediterranean, where the roads connecting the South and Mediterranean to the East, North, and West converge. Due to its strategic location, Gaziantep has been a settled and frequently visited area since prehistoric times. Gaziantep is Türkiye's 6th largest city and the largest province in the Southeastern Anatolia Region. It is considered a metropolitan city due to its population, economic structure, tourism potential, and metropolitan status. The city is situated at the intersection of the Mediterranean and Southeastern Anatolia regions. Its coordinates are between 36° 28' and 38° 01' east longitude and 36° 38' and 37° 32' north latitude. With an area of 6222 km², Gaziantep covers approximately 1% of Türkiye's land area. The terrain in Gaziantep is typically hilly and rugged. The province experiences a mixed climate of both Mediterranean and Continental climates due to its location. The hottest months are June, July, August, and September, while extremely cold weather can be expected in December, January, and February. The highest and lowest temperatures recorded in Gaziantep are 42°C and -13°C, respectively. From June to September, the region experiences the least rainfall, while December and February bring the most precipitation (Özbadem, S. E., 2014).

According to TS 825, Türkiye is divided into degree-day zones. Gaziantep, the selected study area, is located in the 2nd degree-day zone.

Figure 27

Climate Zones According to TS 825 (Turkish Standards Institute, 2008)

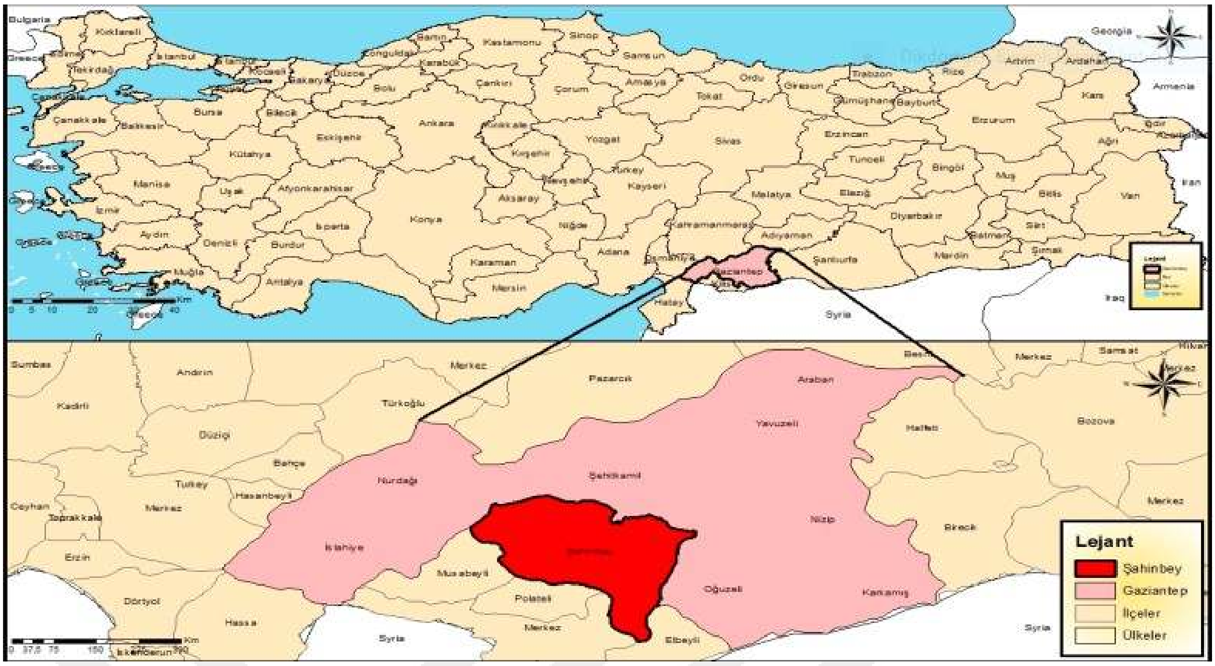


01- ADANA	10- BALIKESİR	19- ÇORUM	28- GİRESUN	37- KASTAMONU	46- K.MARAŞ	55- SAMSUN	64- UŞAK	73- ŞIRNAK
02- ADIYAMAN	11- BİLECİK	20- DENİZLİ	29- GÜMÜŞHANE	38- KAYSERİ	47- MARDİN	56- SİİRT	65- VAN	74- BARTIN
03- AFYON	12- BİNGÖL	21- DİYARBAKIR	30- HAKKARİ	39- KIRKLARELİ	48- MUĞLA	57- SİNOP	66- YOZGAT	75- ARDAHAN
04- AĞRI	13- BİTLİS	22- EDİRNE	31- HATAY	40- KIRŞEHİR	49- MUŞ	58- SİVAS	67- ZONGULDAK	76- IĞDIR
05- AMASYA	14- BOLU	23- ELAZIĞ	32- ISPARTA	41- KOCAELİ	50- NEVSEHİR	59- TEKİRDAĞ	68- AKSARAY	77- YALOVA
06- ANKARA	15- BURDUR	24- ERZİNCAN	33- İÇEL	42- KONYA	51- NİĞDE	60- TOKAT	69- BAYBURT	78- KARABÜK
07- ANTALYA	16- BURSA	25- ERZURUM	34- İSTANBUL	43- KÜTAHYA	52- ORDU	61- TRABZON	70- KARAMAN	79- KİLİS
08- ARTVİN	17- ÇANAKKALE	26- ESKİŞEHİR	35- İZMİR	44- MALATYA	53- RİZE	62- TUNCELİ	71- KIRIKKALE	80- OSMANİYE
09- AYDIN	18- ÇANKIRI	27- GAZİANTEP	36- KARS	45- MANİSA	54- SAKARYA	63- ŞANLIURFA	72- BATMAN	81- DÜZCE

The experimental study will be conducted in the Şahinbey district of Gaziantep.

Figure 28

Location Map of Gaziantep Province



3.2. Field Experiment

In the field experiment, five homogeneous test rooms were constructed using pumice blocks, measuring 39x19x19 cm, as shown in Figure X.

Figure 29.

Pumice block homogeneous test rooms A, B, C, D

A

B

C

The technical details of the pumice blocks used for wall construction are provided in Table 19.

Table 19.

Technical details of the pumice blocks used in wall construction (Okyap, 2025)

Size (cm)	39 x 19 x 19
Dry Weight (kg)	16.0 – 17
Dry Unit Weight (kg/m³)	1200
Thermal Conductivity (W/m·K)	0.45
Compressive Strength (N/mm²)	5
Fire Class	A1

No openings, such as doors or windows, were left in the constructed test rooms, and a completely sealed system was created to prevent air or light transmission. After the construction of the test room walls, plaster was applied to all surfaces, as shown in Figure 30.

Figure 30

Application of rough plaster to homogeneous test rooms made of pumice blocks A-B


A


B

After the rough plaster application, the surfaces were cleaned to remove factors that would prevent adhesion, such as mortar residues and dust, before applying the insulation. Following the cleaning, the test rooms were insulated sequentially with carbonized EPS, rock wool, aerogel fleece, and hemp insulation materials. When applying the insulation, the first step was to apply the adhesive evenly across the surface of the carbonized EPS boards. The boards were then installed staggered, ensuring that no gaps were left to avoid the formation of thermal bridges. After applying the boards, two layers of board plaster were applied. Then, a minimum of 160 g/m² plaster reinforcement mesh was applied, with each layer overlapping by 10 cm, ensuring the integrity of the structure and preventing the formation of thermal bridges. Finally, the last layer of plaster was applied.

Figure 31

Application Procedure


A


B


C

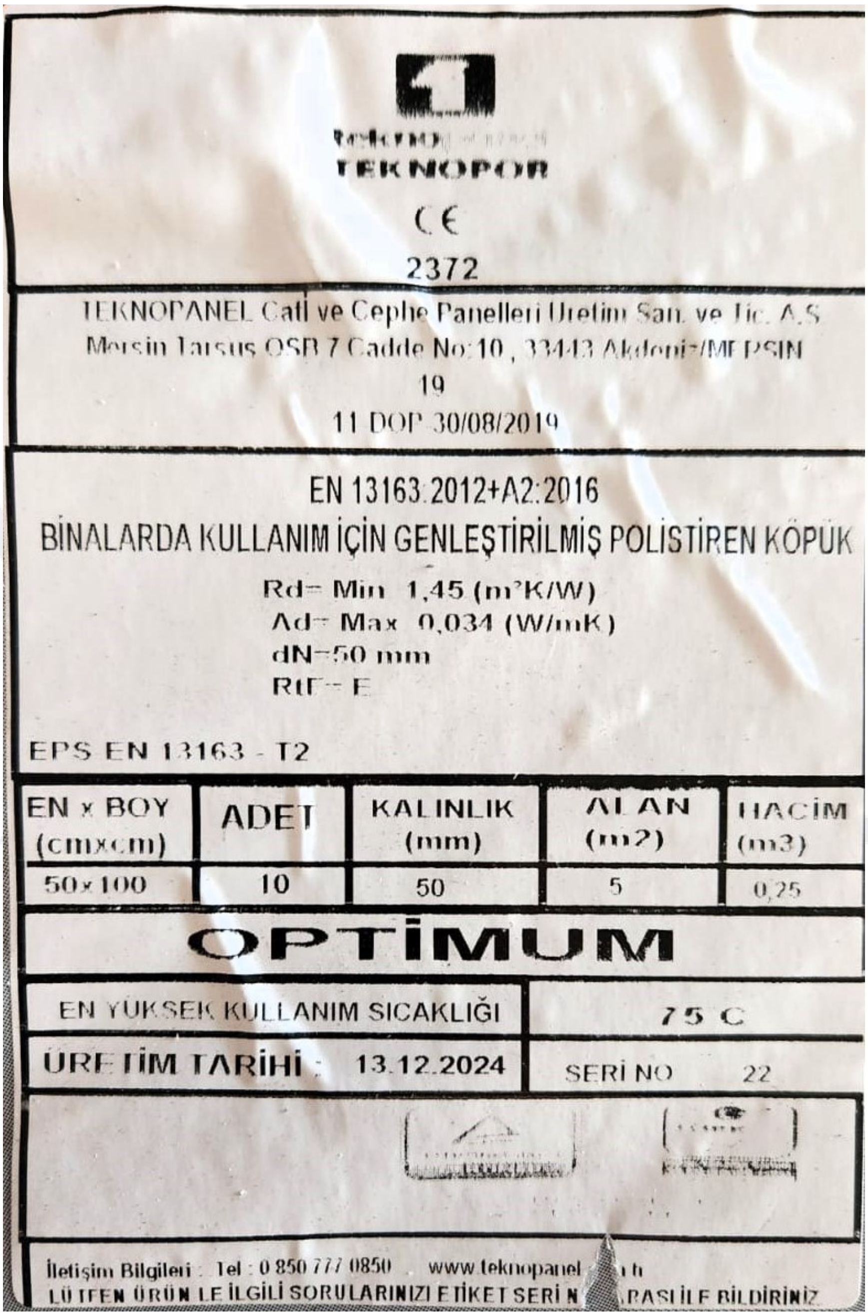

D

Application of carbonized EPS thermal insulation boards over rough plaster on pumice block test rooms A-B-C-D.

The technical properties of the carbonized EPS insulation board used are shown in Figure 32.

Figure 32.

Technical Specifications of the Carbonized EPS Insulation Board Applied to the Pumice Block Test Rooms



The technical properties of the selected EPS insulation board are as follows, according to EN 13613-T2 standard: width 500 mm, length 1000 mm, thickness 50 mm, thermal conductivity value 0.034 (W/m.K), density 15-20 kg/m³, and fire class E. In the second test room, rock wool insulation boards were used. When applying the insulation, the first step was to apply the adhesive evenly across the surface of the rock wool boards. The boards were then installed staggered, ensuring that no gaps were left to avoid the formation of thermal bridges. After applying the boards, two layers of board plaster were applied. Then, a minimum of 160 g/m² plaster reinforcement mesh was applied, with each layer overlapping by 10 cm, ensuring the integrity of the structure and preventing the formation of thermal bridges. Finally, the last layer of plaster was applied. After the rough black plaster work was finished in the experimental room, rock wool thermal insulation board sheathing was applied as shown in Figure X.

Figure 33

Application of Rock Wool Insulation Boards Over Rough Plaster on Pumice Block Test Rooms A-B-C-D

A

B

 C

 D

Figure 34.

Technical Specifications of the Rock Wool Insulation Board Applied to The Pumice Block Test Rooms.

The technical properties of the selected rock wool insulation board are as follows, according to EN 13162:2012 + A1:2015 standard: width 600 mm, length 1200 mm, thickness 50 mm, thermal conductivity value 0.035 (W/m.K), density 70-80 kg/m³, and fire class A1. In the third test room, aerogel insulation blankets were used. This material has a different characteristic: as a hydrophobic nanotechnology product, the surface of the product prevented water-based cementitious adhesives from adhering. To overcome this issue, when applying the aerogel insulation blankets, the first step was to apply the adhesive evenly across all surfaces of the test room. Then, the aerogel insulation blankets were applied across the entire surface. Care was taken to ensure no gaps were left, thus preventing thermal bridges. After the application of the blankets, nails were used for fixing. Then, a minimum of 160 g/m² plaster reinforcement mesh was applied, with each layer overlapping by 10 cm, ensuring the integrity of the structure and preventing the formation of thermal bridges. Two layers of board plaster were then applied, followed by the final coat of plaster. This approach increased the adhesion of the plaster due to the hydrophobic surface.

Figure 35

Application of Aerogel Insulation Blankets Over Rough Plaster On Pumice Block Test Rooms A-B-C

A

B

C

Table 20.
Technical Specifications of the Aerogel Insulation Blanket Applied Over Rough Plaster on Pumice Block Test Rooms

TECHNICAL DATA	VALUES	UNIT	TEST METHOD
Roll width	1500	mm	
Roll thicknesses	3 / 6 / 10	mm	
Panel thicknesses	10/20/30/40/50/60	mm	
Thermal conductivity (λ_8) at 10°C	0,016	W/m·K	UNI-EN 13162:2015
Permeability to water vapor	0,07	m	
Commitment limit temperatures	-200 +650	°C	
Compressive strength (for a deformation of 10%)	30	KPa	ASTM 165
Specific heat	1000	J/kgK	ASTM E 826
Nominal density	200 ± 30	kg/m³	
Fire reaction class	A_2		EN 13501-1
Dimensional stability	<1%		EN 1604
Perpendicular tensile strength	>17	KPa	EN 1607
Concentrated load resistance	>2550	N	EN 12430
Color	White		
TECHNICAL DATA	**VALUES**	**UNIT**	**TEST METHOD**

Rol width	1500	mm
Roll thichnesses	**3 / 6 / 10**	**mm**

The technical specifications of the selected aerogel insulation blanket are as follows, according to EN 13162:2015, ASTM 165, ASTM E 826, EN 13501-1, EN 1604, EN 1607, and EN 12430 standards:

- Width: 1500 mm

- Length: Free length
- Thickness: 10 mm
- Thermal conductivity (λ): 0.016 (W/m·K)
- Density: ~170 kg/m³
- Fire resistance class: A2

In the fourth test room, hemp insulation boards were used. The application process was as follows: First, an even layer of adhesive was applied across the entire surface of the hemp insulation boards. Then, the boards were applied staggered to prevent any gaps, ensuring that no thermal bridges were formed. After the boards were attached to the surface, two layers of board plaster were applied. A plaster reinforcement mesh with a minimum weight of 160 g/m² was then applied, with each layer overlapping by 10 cm, ensuring the integrity of the structure and preventing thermal bridges. Finally, the last layer of plaster was applied. Once the rough plaster application on the constructed test room was complete, the hemp insulation board application was carried out, as shown in

Figure 36

Application of Hemp Insulation Boards on Rough Plastered Pumice Block Homogeneous Test Rooms A-B-C-D-E-F-G

A


B


C


D


E

 F  G

The technical specifications of the selected hemp insulation board are as follows, according to ISO13786 standards:

- Width: 500 mm
- Length: 500 mm
- Thickness: 50 mm
- Thermal conductivity (λ): 0.075 (W/m·K)
- Density: ~ 355 kg/m³
- Temperature resistance: 90–120 °C
- Fire resistance class: A2 (IsoHemp, 2025).

In the fifth test room, after the pumice wall application, only rough plaster was applied and left as is. A comparison of thermal performance was made between the surface with insulation materials and the one without insulation.

The final state of the constructed test rooms is shown in Figure 37.

Figure 37

Final Appearance of the Test Rooms Made of Pumice Blocks, Each Insulated with Different Thermal Insulation Materials.

No applications that could affect the thermal performance, such as roofing or painting, were made in any of the experimental rooms. Four of the experimental rooms were covered with different thermal insulation materials, while one room was left with just a rough plaster finish.

CHAPTER 4

4. RESULTS AND DISCUSSIONS

In this chapter, the findings obtained from the experimental studies are analyzed and evaluated. Changes in the indoor temperatures of the test rooms, which were covered with different insulation materials, are presented comparatively. Based on these data, the thermal performances of the materials have been examined. The results obtained are interpreted by comparing them with studies in the existing literature, and conclusions regarding the selection of insulation materials in hot climate conditions are drawn. Additionally, the effectiveness of the applied systems in terms of energy efficiency is discussed.

4.1. Temperature Experiment

During the temperature experiment, temperature measurements were taken three times a day over a period of 9 days, both for each individual test room and for the external environment temperature, at the same hours each day. A probe thermometer was used to measure both the internal and external temperatures, and six of the same devices were used for all the test rooms and the external environment temperature measurements.

Figure 38 shows the temperature measuring thermometer used for the measurements. The graph of the measurements taken throughout the experiment is shown below.

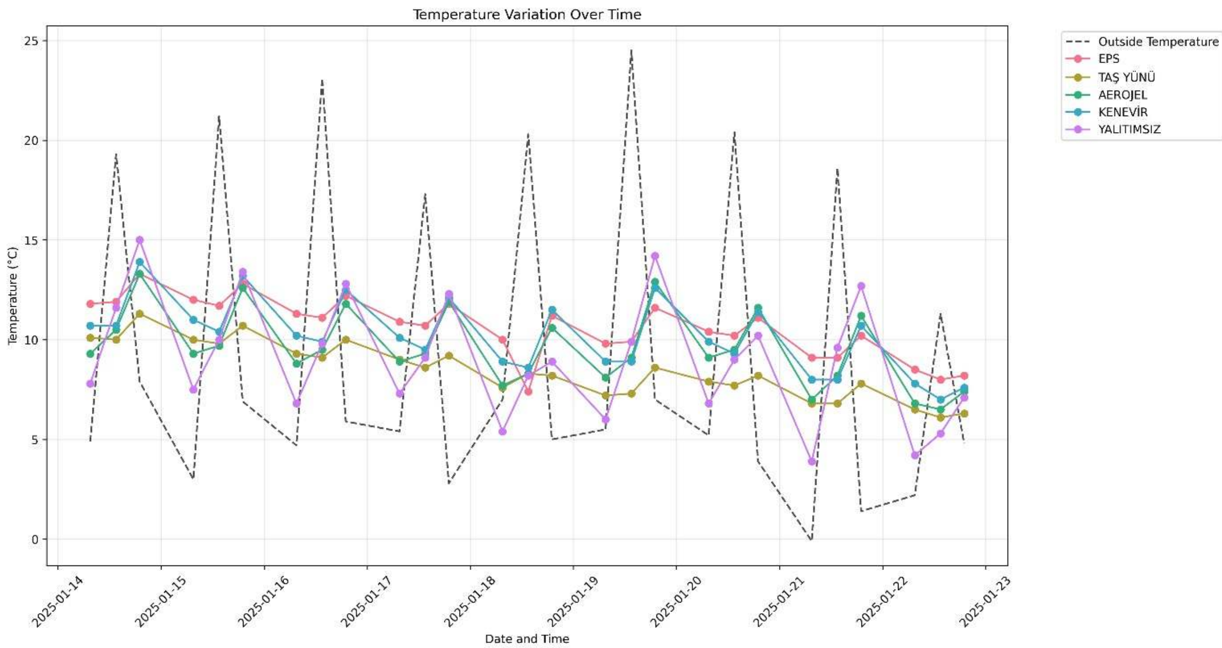
Figure 38.

Thermometer

The graph of the measurements taken during the experiment is shown below.

Figure 39

Historical Graph of General Measurements



4.2. External Temperature Experiment

During the 9-day experiment period, the external temperature was measured and recorded at the predetermined times of 07:30, 13:30, and 19:00.

Table 21

External Temperature According to Time of the Day and Dates

Date	Time	Temperature °C	Time	Temperature °C	Time	Temperature °C
14.01.2025		4,5		19,3		7,9
15.01.2025		3,0		21,2		6,9
16.01.2025		4,7		23,1		5,9
17.01.2025		5,4		17,3		2,8
18.01.2025	07:30	7	13:30	20,3	19:00	5
19.01.2025		5,5		24,5		7
20.01.2025		5,2		20,4		3,9
21.01.2025		-0,1		18,6		1,4
22.01.2025		2,2		11,3		4,8

In the context of this study, external temperatures in Gaziantep were measured on three different time intervals: morning (07:30), afternoon (13:30), and evening (19:00). The data collected is crucial in observing how internal temperatures are influenced by external conditions in the experimental environment.

- **Morning Measurements (07.30):**

During the morning hours, the temperatures generally remained low, with the highest recorded temperature of 7.0°C on January 18th and the lowest of -0.1°C on January 21st. The average temperature during this period was approximately 4.2°C.

- **Afternoon Measurements (13:30):**

Measurements taken during the afternoon, when solar radiation was at its peak, showed a significant rise in temperatures. The temperature ranged between 11.3°C and 24.5°C, with the highest temperature recorded on January 19th and the lowest on January 22nd. The average afternoon temperature was approximately 19.6°C.

- **Evening Measurements (19:00):**

In the evening, temperatures again decreased, with recorded values ranging from 1.4°C to 7.9°C. The lowest temperature during the evening was recorded on January 21st, and the highest on January 14th. The average evening temperature was approximately 5.4°C.

This data is significant for analyzing how exterior temperature fluctuations influence the internal temperatures of the experimental rooms across different times of day.

4.3. EPS Internal Temperature Measurements

One of the experimental rooms constructed was insulated with "EPS" (Expanded Polystyrene) thermal insulation material. During the 9-day experiment, temperature measurements were taken at designated times—morning (07:30), afternoon (13:30), and evening (19:00)—and recorded for further analysis.

- **Morning Measurements:**

One of the experimental rooms was insulated with "EPS" (Expanded Polystyrene) thermal insulation material. During the 9-day experiment, temperature measurements were taken at designated times—morning (07:30), afternoon (13:30), and evening (19:00)—and recorded for further analysis. In the morning, internal temperatures ranged from 8.5°C (January 22) to 12°C (January 15), with an average temperature of approximately 10.6°C. In the same time period, external temperatures ranged from -0.1°C to 7°C, with an average of about 4.2°C. This result shows that even when external temperatures were considerably low in the morning, the EPS material was effective in maintaining a noticeably warmer internal environment.

- **Afternoon Measurements:**

During the afternoon measurements, temperatures in the EPS room ranged from 7.4°C (January 18) to 11.9°C (January 14), with an average temperature of 10.0°C. Meanwhile, external temperatures fluctuated between 11.3°C and 24.5°C, with an average value of 19.6°C. An interesting observation here is that although external temperatures rose, the internal temperature increased in a controlled manner. This indicates that EPS material not only reduces heat loss but also limits overheating.

- **Evening Measurements:**

In the evening at 19:00, temperatures in the EPS-insulated room were measured between 8.2°C (January 22) and 13.3°C (January 14), with an average temperature of approximately 11.3°C. During the same period, external temperatures ranged from 1.4°C to 7.9°C, with an average of around 5.4°C. This shows that EPS material effectively maintains heat retention even in the evening.

These measurements suggest that EPS insulation provides consistent thermal performance across different times of the day, ensuring a stable internal environment regardless of fluctuating external conditions.

Table 22.

EPS Insulated Experimental Room Internal Temperature Measurement

Date	Time	Temperature °C	Time	Temperature °C	Time	Temperature °C
14.01.2025	07:30	11,8	13:30	11,9	19:00	13,3
15.01.2025		12		11,7		12,8
16.01.2025		11,3		11,1		12,2
17.01.2025		10,9		10,7		11,8
18.01.2025		10		7,4		11,2
19.01.2025		9,8		9,9		11,6
20.01.2025		10,4		10,2		11,1
21.01.2025		9,1		9,1		10,2
22.01.2025		8,5		8		8,2

4.4. Rock Wool Insulated Experimental Room Temperature Measurements

One of the constructed experimental rooms was insulated using "Rock Wool" as the thermal insulation material. Over the course of the 9-day experiment, temperature measurements were taken at three different times each day: 07:30 in the morning, 13:30 at noon, and 19:00 in the evening. These measurements were recorded to analyze the thermal performance of the rock wool insulation material.

- **Morning Measurements:**

During the morning hours, the indoor temperature ranged from 6.5°C (January 22) to 10.1°C (January 14), with an average temperature of approximately 8.2°C. Meanwhile, the outdoor temperature during the same time period remained around an average of 4.2°C. This indicates that the rock wool insulation was able to maintain the indoor temperature approximately 4°C higher than the outside temperature during the morning hours.

- **Afternoon Measurements:**

At noon, the indoor temperatures ranged from 6.1°C (January 22) to 10°C (January 14), with an average of approximately 8.0°C. During this period, the outdoor temperature averaged at 19.6°C. The significant difference between the indoor and outdoor temperatures shows that the rock wool insulation effectively limited heat transfer into the room, helping maintain a more stable indoor environment despite the increase in outdoor temperatures due to solar radiation.

- **Evening Measurements:**

In the evening (19:00), the temperature ranged from 6.3°C (January 22) to 11.3°C (January 14), with an average of 9.0°C. The outdoor temperature during this time averaged around 5.4°C. This indicates that the rock wool insulation contributed to maintaining heat in the indoor environment, providing a temperature difference of about 3-4°C between the inside and outside temperatures in the evening.

These findings demonstrate that the rock wool insulation performed effectively in maintaining a more stable and warmer indoor environment across different times of the day, even as outdoor temperatures fluctuated.

Table 23

Rock Wool Insulated Experimental Room Internal Temperature Measurement

Date	Time	Temperature °C	Time	Temperature °C	Time	Temperature °C
14.01.2025	07:30	10,1	13:30	10	19:00	11,3
15.01.2025		10		9,8		10,7
16.01.2025		9,3		9,1		10
17.01.2025		9		8,6		9,2
18.01.2025		7,6		8,3		8,2
19.01.2025		7,2		7,3		8,6
20.01.2025		7,9		7,7		8,2
21.01.2025		6,8		6,8		7,8
22.01.2025		6,5		6,1		6,3

4.5. Aerogel Mat Insulated Experimental Room Temperature Measurements

One of the experimental rooms was insulated with "Aerogel" thermal insulation material. During the 9-day experiment, temperature measurements were taken at designated times—morning (07:30), afternoon (13:30), and evening (19:00)—and recorded for further analysis.

- **Morning Measurements:**

The internal temperatures during the morning ranged from 6.8°C (January 22) to 9.3°C (January 14 and 15), with an average temperature of approximately 8.4°C. In the same period, external temperatures remained at an average of 4.2°C. This indicates that aerogel insulation was effective in maintaining internal temperatures about 4°C higher than external conditions during the morning hours.

- **Afternoon Measurements:**

In the afternoon, internal temperatures ranged from 6.5°C (January 22) to 10.5°C (January 14), with an average of 9.2°C. Despite external temperatures averaging 19.6°C during this period, the internal temperatures remained relatively low. This suggests that the aerogel material effectively resisted the transmission of heat from solar radiation into the interior, demonstrating its ability to limit heat gain.

- **Evening Measurements**:

In the evening (19:00), internal temperatures ranged from 7.4°C (January 22) to 13.3°C (January 14), with an average temperature of approximately 11.5°C. External temperatures during the same period averaged 5.4°C. Given this difference, it can be concluded that aerogel insulation significantly contributed to heat retention within the experimental room, particularly during the evening. The ability to maintain internal temperatures with a difference exceeding 6°C compared to the external environment reflects the high effectiveness of the aerogel material due to its low thermal conductivity.

Table 24.

Aerogel Mat Insulated Experimental Room Internal Temperature Measurement

Date	Time	Temperature °C	Time	Temperature °C	Time	Temperature °C
14.01.2025		9,3		10,5		13,3
15.01.2025		9,3		9,7		12,6
16.01.2025		8,8		9,5		11,8
17.01.2025		8,9		9,3		11,9
18.01.2025	07:30	7,7	13:30	8,3	19:00	10,6
19.01.2025		8,1		9,1		12,9
20.01.2025		9,1		9,5		11,6
21.01.2025		7		8,2		11,2
22.01.2025		6,8		6,5		7,4

4.6. Hemp Insulated Experimental Room Temperature Measurements

Temperature measurements in the experimental room insulated with "Hemp" thermal insulation material were conducted three times daily—morning (07:30), afternoon (13:30), and evening (19:00)—from January 14 to January 22, 2025.

- **Morning Measurements:**

Internal temperatures during the morning ranged from 7.8°C (January 22) to 11°C (January 15), with an average temperature of 9.4°C. During the same period, external temperatures averaged around 4.2°C. It was observed that hemp insulation maintained internal temperatures approximately 5.2°C higher than the external environment in the morning. This demonstrates the material's effectiveness in limiting heat loss during low temperatures.

- **Afternoon Measurements:**

In the afternoon, internal temperatures ranged from 7°C (January 22) to 10.7°C (January 14), with an average temperature of 9.3°C. External temperatures during this period averaged approximately 19.6°C. The fact that internal temperatures remained lower compared to the external environment indicates that hemp insulation played a limiting role in transmitting heat from solar radiation, showing resistance to heat transfer.

- **Evening Measurements:**

In the evening (19:00), internal temperatures ranged from 7.6°C (January 22) to 13.9°C (January 14), with an average temperature of 11.2°C. External temperatures during the same period averaged around 5.4°C. Therefore, hemp insulation was able to maintain internal temperatures approximately 5.8°C higher than the external environment in the evening.

Table 25

Hemp Insulated Experimental Room Internal Temperature Measurement

Date	Time	Temperature °C	Time	Temperature °C	Time	Temperature °C
14.01.2025		10,7		10,7		13,9
15.01.2025		11		10,4		13,2
16.01.2025		10,2		9,9		12,5
17.01.2025		10,1		9,5		12,1
18.01.2025	07:30	8,9	13:30	8,6	19:00	11,5
19.01.2025		8,1		8,9		12,6
20.01.2025		9,9		9,3		11,4
21.01.2025		8		8		10,7
22.01.2025		7,8		7		7,6

4.7. Temperature Measurements of the Uninsulated Experimental Room

One of the experimental rooms was constructed without any insulation ("Uninsulated"). Temperature measurements were taken at three different times of the day—morning (07:30), afternoon (13:30), and evening (19:00)—during the 9-day experimental period.

- **Morning Measurements:**

In the morning, the internal temperatures ranged from 3.9°C (January 21) to 7.8°C (January 14), with an average temperature of 6.2°C for this period. During the same time frame, external temperatures averaged approximately 4.2°C. Therefore, in the uninsulated room, the internal temperatures were only about 2°C higher than the external environment in the morning. This indicates that heat losses were not minimized, and external conditions directly affected the internal temperature.

- **Afternoon Measurements:**

At noon, the internal temperatures varied between 5.3°C (January 22) and 11.6°C (January 14), with an average of 9.2°C. During the same period, external temperatures averaged 19.6°C. The internal temperatures being about 10.4°C lower than the external temperatures suggests that the lack of insulation prevented solar heat gains from being effectively reflected into the indoor environment.

- **Evening Measurements:**

In the evening, internal temperatures ranged from 7.1°C (January 22) to 15°C (January 14), with an average of 11.9°C. At the same time, external temperatures averaged 5.4°C. The internal temperature was about 6.5°C higher than the external temperature in the evening. This difference is believed to be related to the temporary storage of accumulated heat by the building materials and its slow release during the evening hours.

Table 26

Uninsulated Experimental Room Internal Temperature Measurement

Date	Time	Temperature °C	Time	Temperature °C	Time	Temperature °C
14.01.2025	07:30	7,8	13:30	11,6	19:00	15
15.01.2025		7,5		10		13,4
16.01.2025		6,8		9,8		12,8
17.01.2025		7,3		9,1		12,3
18.01.2025		5,4		8,2		8,9
19.01.2025		6		9,9		14,2
20.01.2025		6,8		9		10,2
21.01.2025		3,9		9,6		12,7
22.01.2025		4,2		5,3		7,1

4.8. Regression-Based Thermal Insulation Efficiency Analysis

In the following analyses, the effects of different insulation materials (EPS, Stone Wool, Aerogel, Hemp) on the internal room temperature in comparison to external environmental temperatures are presented. Each graph shows the relationship between external environment performance on the x-axis and internal room behavior on the y-axis. The red dashed lines represent the regression accuracy for each material, while the gray dashed line represents the reference line $y = x$, which assumes that the internal temperature is equal to the external temperature. The reference line $y = x$, theoretically shows that the internal temperature matches the external temperature. If the measurements fall below this line, the internal environment is cooler than the external environment. Conversely, if the measurements are above this line, the internal environment is warmer than the external environment. The regression slope indicates the impact of a 1°C increase in external temperature on the internal room temperature.

The smaller the slope, the less the internal temperature is affected by the external temperature, indicating better insulation efficiency.

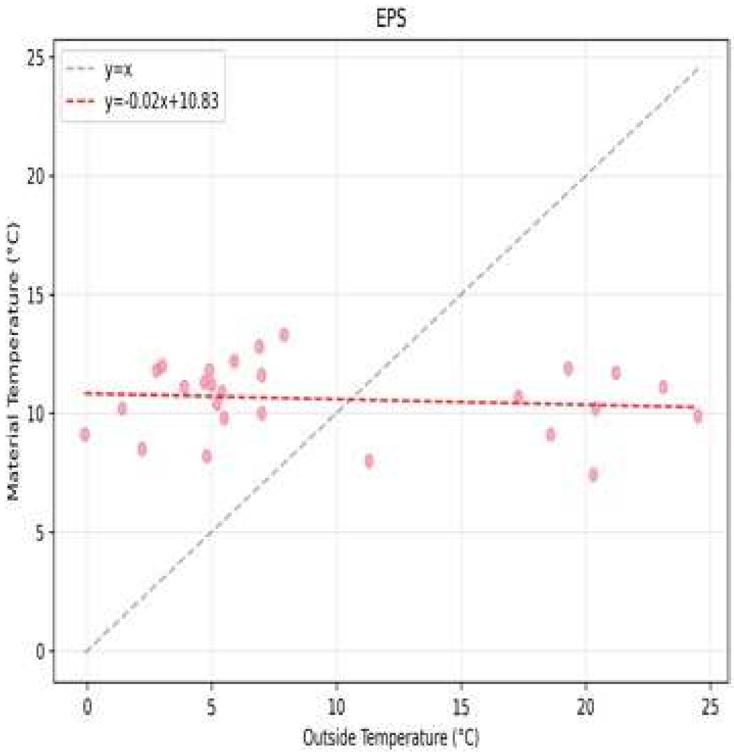
4.8.1. EPS insulated room regression analysis

Regression equation: $y = -0.02x + 10.83$

The slope is very close to zero and negative, indicating that internal temperatures remain almost constant, even if the external temperature changes. This shows that the EPS insulation performs excellently, almost completely isolating the internal environment from external temperature fluctuations.

Figure 40

EPS Insulated Room Regression Analysis



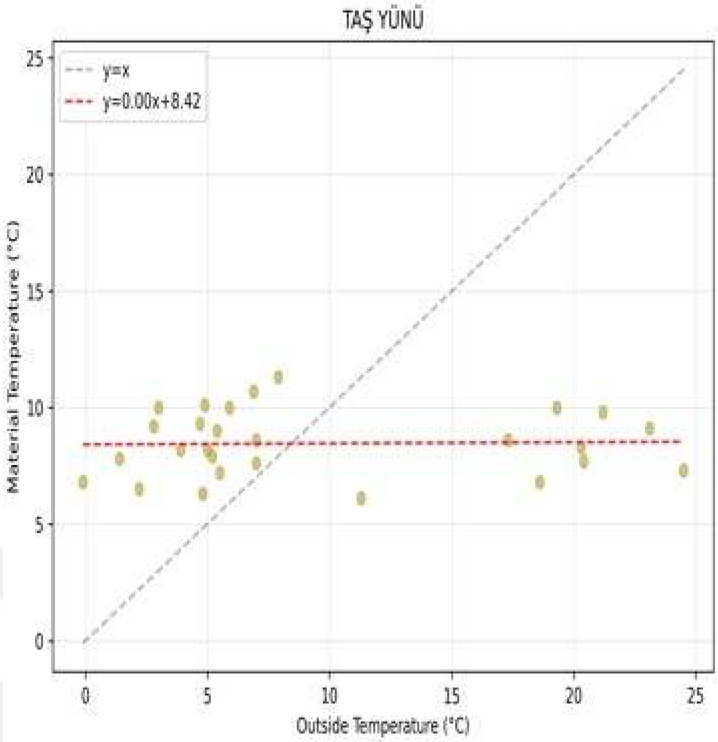
4.8.2. Stone wool insulated room regression analysis

Regression equation: $y = 0.00x + 8.42$

The slope is extremely close to zero (rounded to exactly zero), indicating a stable internal temperature (approximately 8.4°C). This demonstrates that Stone Wool is nearly unaffected by external temperatures, confirming its effectiveness as an insulation material.

Figure 41

Stone Wool Insulated Room Regression Analysis



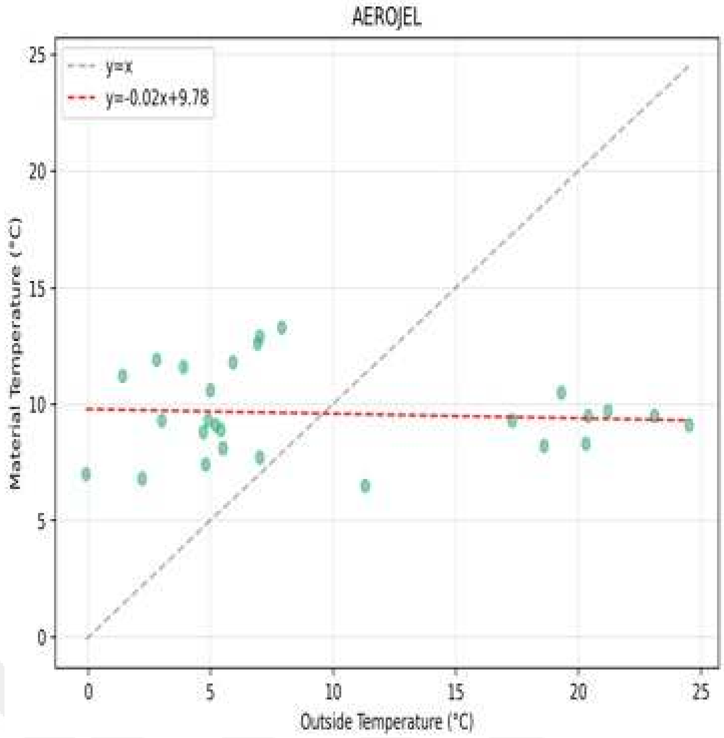
4.8.3. Aerogel insulated room regression analysis

Regression equation: $y = -0.02\ x + 9.78$

The negative and low slope indicates that as external temperatures increase, the internal temperature decreases slightly. This unique behavior suggests that aerogel may have a high capacity for retaining internal heat, but it still performs well as an insulation material, largely independent of external temperature fluctuations.

Figure 42

Aerogel Insulated Room Regression Analysis



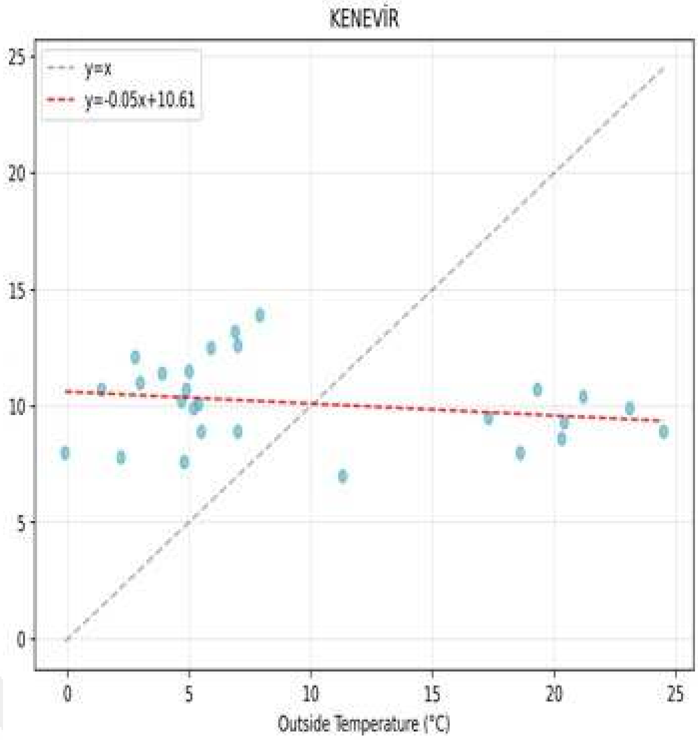
4.8.4 Hemp insulated room regression analysis

Regression equation: $y = -0.05\ x + 10.61$

The slope is somewhat higher and negative compared to the other materials, indicating that hemp insulation is more affected by external temperature changes. However, it still provides good insulation performance. As a natural material, it provides a satisfactory level of thermal performance.

Figure 43

Hemp Insulated Room Regression Analysis



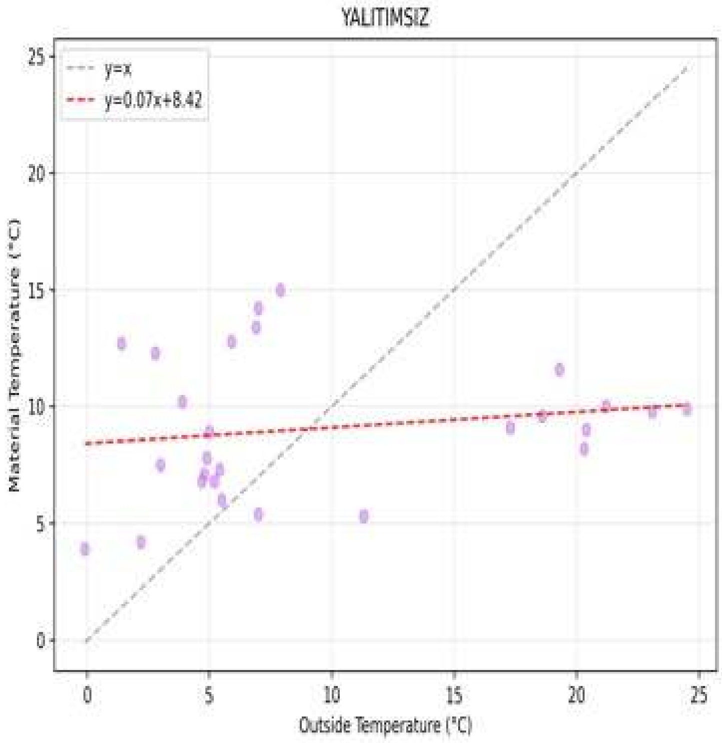
4.8.5. Uninsulated Control room regression analysis

Regression equation: $y = 0.07\ x + 8.42$

The slope is significantly higher compared to all other materials. This indicates that external temperature has a much greater impact on the internal environment, reflecting substantial heat loss. The uninsulated control room performs poorly in terms of thermal comfort, with internal temperatures directly influenced by external temperature fluctuations.

Figure 44

Uninsulated Control Room Regression Analysis



4.8.6. Overall regression analysis

As seen in the table X, **EPS**, **stone wool**, and **aerogel** successfully isolate indoor temperatures from external factors and maintain a stable internal temperature. **Hemp**, as a natural alternative, provides good results. The **uninsulated** structure, being exposed to external weather conditions, is insufficient in providing thermal comfort.

As a result of all these analyses, the regression values and insulation performances of the materials are presented in the table below:

Table 27

Materials, Regression Slopes and Insulation Performances

Material	Regression Slope	Insulation Performance
Stone Wool	0.00	Very Good
EPS	-0.02	Very Good
Aerogel	-0.02	Very Good
Hemp	-0.05	Good
Uninsulated	0.07	Poor

4.9. Temperature difference (ΔT) analysis

This section examines the level of thermal protection provided by different insulation materials against external environmental conditions through the ΔT parameter (ΔT = Internal Temperature - External Temperature), which reflects the temperature difference between internal and external environments. The study covers five different building components: EPS, stone wool, aerogel, hemp, and an uninsulated control. Temperature data for each material was regularly recorded over a nine-day period in January, at morning (07:30), noon (13:30), and evening (19:00) hours. The ΔT value was determined by calculating the difference between internal and external temperatures for each measurement. This way, the materials' ability to retain heat inside and their insulation level against external temperature fluctuations were evaluated. High ΔT values indicate more effective insulation, while low ΔT values suggest that the external temperature has more influence on the internal environment. This analysis is especially significant in evaluating the contribution of materials to energy efficiency under cold climate conditions.

4.9.1. Cold conditions (external temperature <10°C)

EPS showed the best performance, maintaining the highest internal temperature (ΔT = +6.27°C). Uninsulated Control unexpectedly outperformed Stone Wool (ΔT = +4.38°C vs. +3.96°C). This can be explained by the heat retention in the evening hours. Aerogel and Hemp performed at a moderate level (ΔT = +5.27°C and +5.98°C).

4.9.2. Warm conditions (external temperature >10°C)

Stone Wool kept the internal environment coolest (ΔT = -11.37°C). EPS ranked second (ΔT = -9.56°C), while Aerogel and Hemp showed similar performance (ΔT ≈ -10.6°C). Uninsulated Control provided the least effective cooling (ΔT = -10.39°C).

4.9.3. Stability

The fluctuations over time in internal temperature are a critical factor in determining the stability of an insulation material. In this study, stability was analyzed using the standard deviation of internal temperatures. A lower standard deviation value indicates a more consistent and comfortable internal temperature. Based on the findings, Stone Wool stands out with the lowest standard deviation (σ = 1.38°C), making it the most stable material. This is followed by EPS (σ = 1.47°C), Hemp (σ = 1.76°C), and Aerogel (σ = 1.85°C). The Uninsulated Control has the highest standard deviation (σ = 2.97°C), which indicates the most temperature fluctuations in the internal environment. These findings highlight the importance of both the presence of insulation and the type of material in achieving effective temperature control.

Table 28

Temperature Analysis and Stability of Different Insulation Materials

Material	Total Average Temperature (°C)	Total Standard Deviation	Total Min. Temperatur e (°C)	Total Max. Temperature (°C)	Stability
External Temp	9,6	7,520585375	-0,1	24,5	
EPS	10,6	1,470701521	7,4	13,3	2.
Stone Wool	8,5	1,380085682	6,1	11,3	1.
Aerogel	9,6	1,851592574	6,5	13,3	4.
Hemp	10,1	1,756539808	7	13,9	3.
Uninsulate d	9,1	2,966104816	3,9	15	5.

4.9.4. Material performance summary

Stone Wool provides the most stable internal environment with the lowest standard deviation (σ = 1.38°C). EPS follows closely with a value of σ = 1.47°C. Hemp and Aerogel show higher variability in temperatures (σ = 1.76°C and 1.85°C). The Uninsulated Control has the highest deviation (σ = 2.97°C), which directly indicates poor insulation performance and significant temperature fluctuations.

Table 29.

Performance and Stability Comparison of Insulation Materials

Material	Avg. ΔT (Cold)	Avg. ΔT (Warm)	Stability (σ)	Notes
EPS	+6.27°C	-9.56°C	1.47°C	Best heat retention performance in cold conditions.
Stone Wool	+3.96°C	-11.37°C	1.38°C	Provides the most stable internal environment and is most effective in hot conditions.
Aerogel	+5.27°C	-10.60°C	1.85°C	Provides moderate insulation, but with more variable temperatures.
Hemp	+5.98°C	-10.41°C	1.76°C	A sustainable option with good results but lower stability.
Uninsulated	+4.38°C	-10.39°C	2.97°C	Least effective, with high

	temperature fluctuations.

CHAPTER 5

5. CONCLUSION

In this section, the findings obtained from the experimental study are presented and interpreted in detail. The thermal performance of different insulation materials applied to concrete test chambers was evaluated based on the measured indoor temperatures over a nine-day period under natural climatic conditions. The results were analyzed by comparing the internal temperature values of insulated and uninsulated chambers at regular intervals, taking into account the fluctuations in outdoor temperature. The performance differences between EPS, stone wool, aerogel, and hemp-based insulation materials were examined both individually and comparatively. These findings were also discussed in the context of current literature, including recent studies focusing on thermal insulation efficiency in hot climates. The aim is to assess the suitability of the selected materials for use in concrete buildings exposed to high temperatures, and to identify the most effective insulation strategies for enhancing indoor thermal comfort and energy efficiency.

5.1. Results

Observations made in the uninsulated control experimental room show that internal temperatures are directly affected by external environmental conditions and that heat control could not be achieved. Especially in the morning and afternoon, when internal temperatures were low, it indicates that heat losses were high and thermal comfort was insufficient. Even during the midday, when solar radiation is at its peak, there was no significant difference between the internal and external temperatures, indicating that the building could not sufficiently take advantage of its passive heat gain potential.

In this context, the importance of thermal insulation in ensuring thermal comfort and increasing energy efficiency is once again validated. The obtained data demonstrate that uninsulated structures are inadequate in maintaining internal temperatures, especially under cold weather conditions, and highlight the need for structural insulation measures to provide comfort conditions.

The daily temperature variations show a trend of low temperatures in the morning, high in the afternoon, and a decrease in the evening. This situation stands out as an important parameter directly affecting the interaction between the internal and external temperatures of buildings. Especially the low temperatures observed in the morning can lead to rapid heat loss in uninsulated structures, while the increasing temperatures in the afternoon may lead to overheating problems in surfaces exposed to direct sunlight. In this context, the temperature differences, which can reach up to 15°C during the day, create an ideal foundation for comparing the performance of different insulation materials in the experimental environment.

The -0.1°C external temperature recorded on January 21st in the morning provides critical data for studying the behavior of the experimental system under low-temperature conditions. Similarly, the 24.5°C value recorded at noon on January 19th provides an important example for evaluating the building shell's response to solar heat gains under high-temperature conditions. The obtained external temperature data serve as a fundamental reference in assessing the performance of existing insulation materials and evaluating the applicability of innovative solutions.

The obtained data show that EPS material consistently maintains higher internal temperatures compared to external conditions across all time periods. Even on days when external temperatures dropped below 0°C in the morning, the internal temperature remained between 9-12°C, demonstrating the effectiveness of EPS in thermal insulation. When external temperatures exceeded 20°C during the afternoon, the internal temperatures remained limited, which highlights EPS's ability to delay heat transfer. This is of significant importance in both reducing heat losses and preventing overheating from solar radiation.

Experiments show that the temperature data obtained in a room insulated with EPS demonstrate that this material creates an effective thermal barrier against both cold and hot air conditions. This indicates that EPS can be used as a cost-effective and efficient insulation solution to increase energy efficiency in residential buildings.

The obtained temperature data demonstrate that stone wool is effective in reducing heat losses in the morning and evening. During the morning when external temperatures were low, it managed to keep the internal temperature at higher levels, demonstrating its effective thermal resistance. However, despite the high external temperatures in the afternoon, the internal temperature did not increase in parallel, showing that stone wool is resistant to heat transfer from the sun, thus preventing excessive overheating of the internal space.

Compared to other insulation materials, stone wool provided lower internal temperatures than EPS. This situation may arise from the slower heat transfer process and higher density of stone wool, resulting in more balanced heat distribution. Additionally, with its advantages such as sound insulation and fire resistance, stone wool can be considered a versatile insulation solution.

Stone wool is evaluated as an effective insulation material that can be preferred in climate conditions where thermal comfort needs to be kept stable.

Aerogel, one of the materials with the lowest thermal conductivity, has shown in the experimental data that this property is effective in practice. During the morning and evening, especially when external temperatures were low, aerogel insulation managed to keep the indoor temperature at high levels. Despite high external temperatures in the afternoon, the internal space remained relatively cool, indicating that this material has a low heat transfer rate.

Studies show that aerogel is highly effective in reducing heat loss and limiting incoming heat. In this context, aerogel is considered an innovative material that could be preferred in applications that require high levels of insulation, providing superior thermal performance in terms of energy efficiency and indoor comfort.

Hemp-based natural insulation materials provide a significant advantage in terms of environmental sustainability, and the thermal performance supported by experimental data yields satisfactory results. It has been observed that it is effective in maintaining indoor temperatures during low external temperatures, especially in the morning and evening. Despite high external temperatures during the afternoon, the internal temperatures remained relatively stable, demonstrating that hemp provides effective protection against solar heat gain.

However, compared to high-performance synthetic or mineral-based insulation materials such as aerogel or stone wool, it has shown modest performance. Despite this, due to its eco-friendly structure, renewable source availability, and capacity to provide adequate thermal insulation, hemp has the potential to be preferred in environmentally conscious building designs.

5.2 Recommendations

In this study, the thermal performance of five different building materials (EPS, stone wool, aerogel, hemp, and uninsulated control) was comparatively evaluated. The external temperature conditions in January represented cold winter conditions. The temperature measurements, conducted three times daily over nine days, helped us understand the ability of insulation materials to maintain internal temperatures, their behavior in heat exchange with the external environment, and their stability in temperature changes.

The results obtained help evaluate the effectiveness of the insulation materials used in current applications and provide guidance for new applications related to energy efficiency and sustainability.

The study shows that EPS material provides the best performance in maintaining internal temperatures under cold conditions, meaning it has a high capacity to retain heat in cold weather. Stone wool, on the other hand, has emerged as the most effective insulation material in maintaining a cool interior during midday measurements when temperatures rise. Additionally, it performed better in hot climate conditions during hours of high solar radiation. Aerogel and hemp provided moderate performance; although hemp is a natural and sustainable resource, its thermal efficiency is limited. The uninsulated control example showed significant temperature fluctuations in both low and high-temperature conditions, indicating its insufficient energy efficiency.

When evaluating stability, stone wool had the lowest internal temperature standard deviation, indicating a more balanced and comfortable environment. EPS also showed high stability, but aerogel and hemp, being more sensitive to internal temperature changes, could negatively impact comfort and energy consumption. Uninsulated structures caused the highest fluctuations in internal temperatures, largely reflecting any changes in external conditions.

Given these results, future research should focus on:

- **Climate-Based Approach to Material Selection**: The overall performance of an insulation material should consider not only the material itself but also the climatic characteristics of the region and daily temperature changes. While stone wool may be more effective in hot areas, EPS may be more effective in cold areas.
- **Long-Term and Seasonal Analyses**: The results of this study are based on winter conditions. Applying the same methodology in spring, summer, and autumn will reveal the performance across different seasons and help develop more comprehensive, climate-based insulation strategies.
- **Energy Consumption Integration**: Maintaining internal temperature is critical for both thermal comfort and energy consumption. Therefore, it is recommended

that the impact of insulation materials on energy consumption be analyzed experimentally.

- **Sustainability and Ecological Impact**: The use of natural insulation materials like hemp, their environmental impact, production costs, and carbon footprints could be a separate research topic.
- **Microclimate and Comfort Conditions**: The behavior of insulation materials in temperature values, moisture control, air permeability, and vapor diffusion should be examined to analyze the holistic effect on indoor environmental quality.

In light of all this, the study has demonstrated the thermal behavior of different insulation materials in the fields of building physics, energy efficiency, and comfort. The data obtained can assist in material selection based on scientific foundations during the building design process. This area of research will be significantly improved by increasing experimental data, using larger sample groups, and applying multi-parameter performance analyses.

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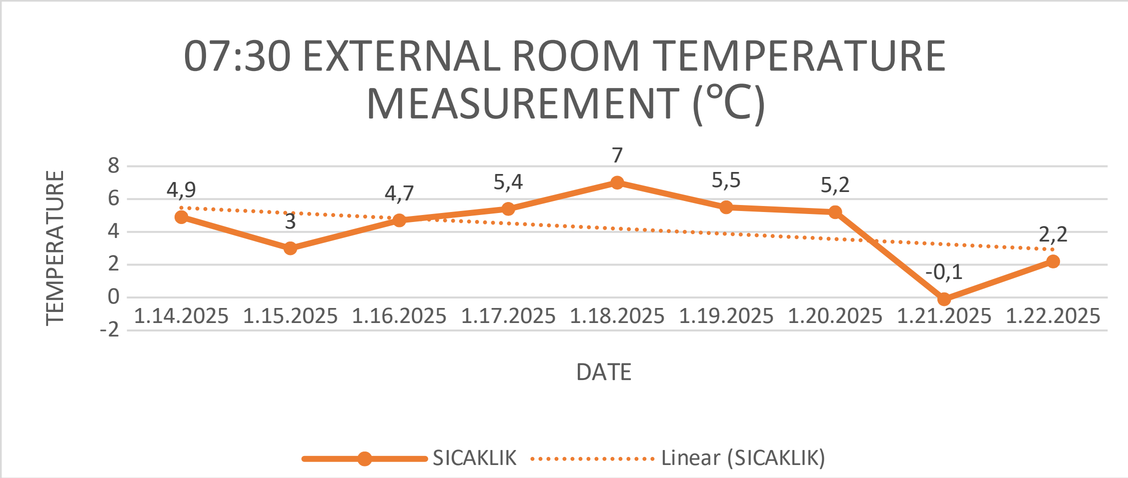
APPENDICES

APPENDIX -1 Daily External Temperature Measurements at 07:30 Between 14–22 January 2025.

MATERIAL	DATE	TEMPERATURE (°C)	TIME
EXTERNAL TEMPERATURE (°C)	14.01.2025	4,9	07:30
EXTERNAL TEMPERATURE (°C)	15.01.2025	3	07:30
EXTERNAL TEMPERATURE (°C)	16.01.2025	4,7	07:30
EXTERNAL TEMPERATURE (°C)	17.01.2025	5,4	07:30
EXTERNAL TEMPERATURE (°C)	18.01.2025	7	07:30
EXTERNAL TEMPERATURE (°C)	19.01.2025	5,5	07:30
EXTERNAL TEMPERATURE (°C)	20.01.2025	5,2	07:30
EXTERNAL TEMPERATURE (°C)	21.01.2025	-0,1	07:30
EXTERNAL TEMPERATURE (°C)	22.01.2025	2,2	07:30

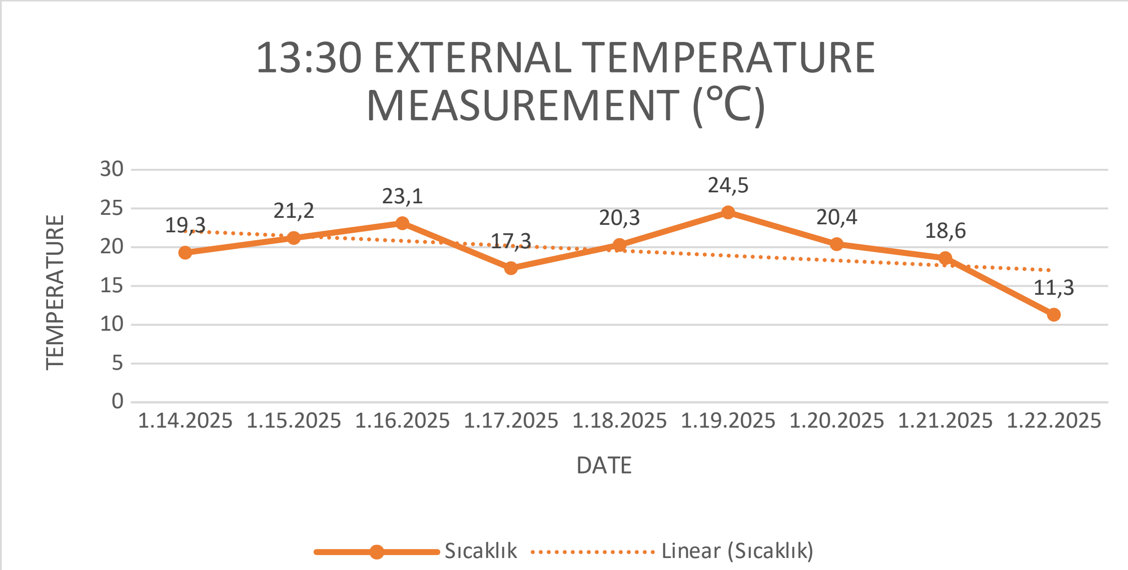
APPENDIX -2 Line Graph Showing External Room Temperatures at 07:30 Between January 14–22, 2025.



APPENDIX -3 Daily External Temperature Measurements at 13:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
EXTERNALTEMPERATURE (℃)	14.01.2025	19,3	13:30
EXTERNALTEMPERATURE (℃)	15.01.2025	21,2	13:30
EXTERNALTEMPERATURE (℃)	16.01.2025	23,1	13:30
EXTERNALTEMPERATURE (℃)	17.01.2025	17,3	13:30
EXTERNALTEMPERATURE (℃)	18.01.2025	20,3	13:30
EXTERNALTEMPERATURE (℃)	19.01.2025	24,5	13:30
EXTERNALTEMPERATURE (℃)	20.01.2025	20,4	13:30
AUTDOOR TEMPERATURE (℃)	21.01.2025	18,6	13:30
AUTDOOR TEMPERATURE (℃)	22.01.2025	11,3	13:30

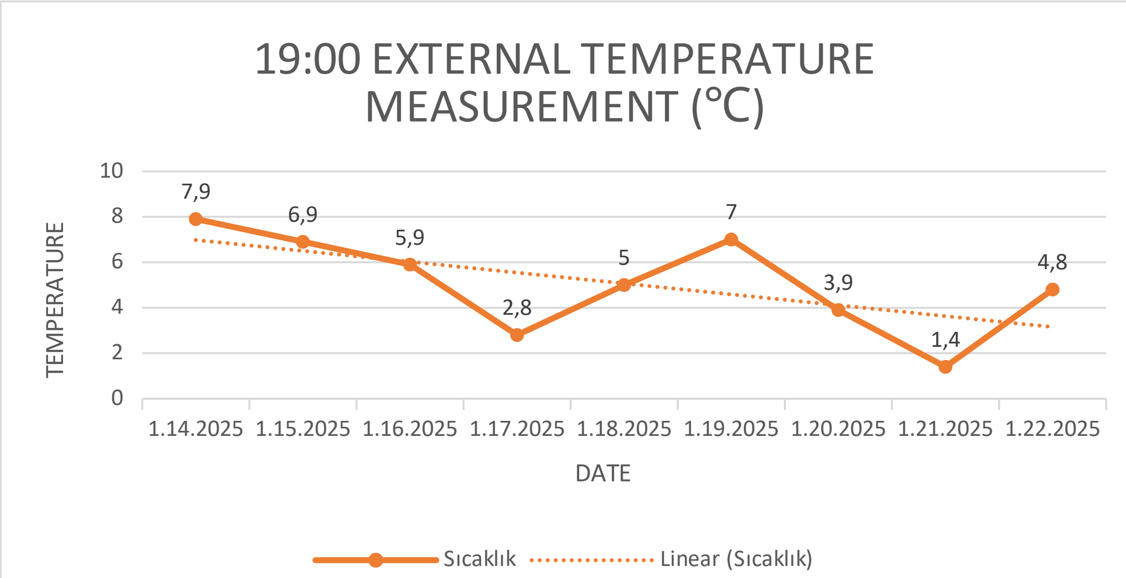
APPENDIX -4 Line Graph Showing External Room Temperatures at 13:30 Between January 14–22, 2025.



APPENDIX -5 Daily External Temperature Measurements at 19:00 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
EXTERNAL TEMPERATURE (℃)	14.01.2025	7,9	19:00
EXTERNAL TEMPERATURE (℃)	15.01.2025	6,9	19:00
EXTERNAL TEMPERATURE (℃)	16.01.2025	5,9	19:00
EXTERNAL TEMPERATURE (℃)	17.01.2025	2,8	19:00
EXTERNAL TEMPERATURE (℃)	18.01.2025	5	19:00
EXTERNAL TEMPERATURE (℃)	19.01.2025	7	19:00
EXTERNAL TEMPERATURE (℃)	20.01.2025	3,9	19:00
EXTERNAL TEMPERATURE (℃)	21.01.2025	1,4	19:00
EXTERNAL TEMPERATURE (℃)	22.01.2025	4,8	19:00

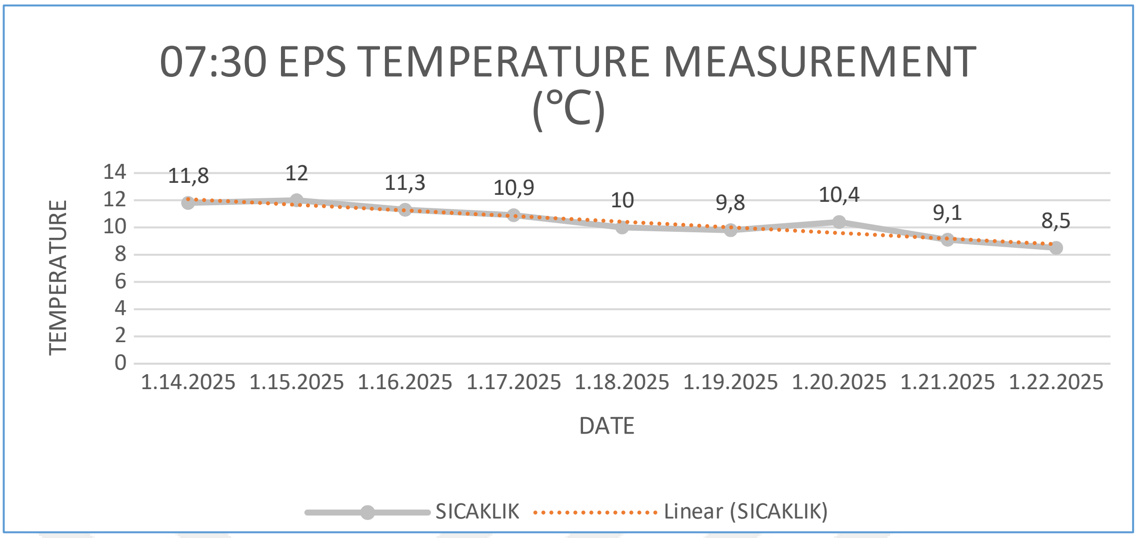
APPENDIX -6 Line Graph Showing External Room Temperatures at 19:00 Between January 14–22, 2025.



APPENDIX -7 Daily EPS Temperature Measurements at 07:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (°C)	TIME
EPS	14.01.2025	11,8	07:30
EPS	15.01.2025	12	07:30
EPS	16.01.2025	11,3	07:30
EPS	17.01.2025	10,9	07:30
EPS	18.01.2025	10	07:30
EPS	19.01.2025	9,8	07:30
EPS	20.01.2025	10,4	07:30
EPS	21.01.2025	9,1	07:30
EPS	22.01.2025	8,5	07:30

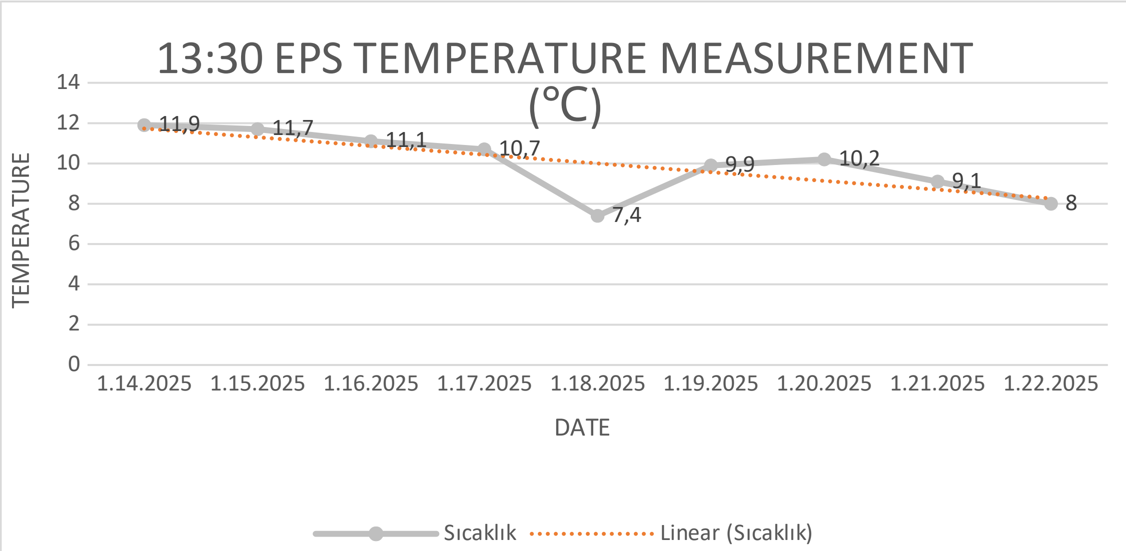
APPENDIX -8 Line Graph Showing External Room Temperatures at 07:30 Between January 14–22, 2025.



APPENDIX -9 Daily EPS Temperature Measurements at 13:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
EPS	14.01.2025	11,9	13:30
EPS	15.01.2025	11,7	13:30
EPS	16.01.2025	11,1	13:30
EPS	17.01.2025	10,7	13:30
EPS	18.01.2025	7,4	13:30
EPS	19.01.2025	9,9	13:30
EPS	20.01.2025	10,2	13:30
EPS	21.01.2025	9,1	13:30
EPS	22.01.2025	8	13:30

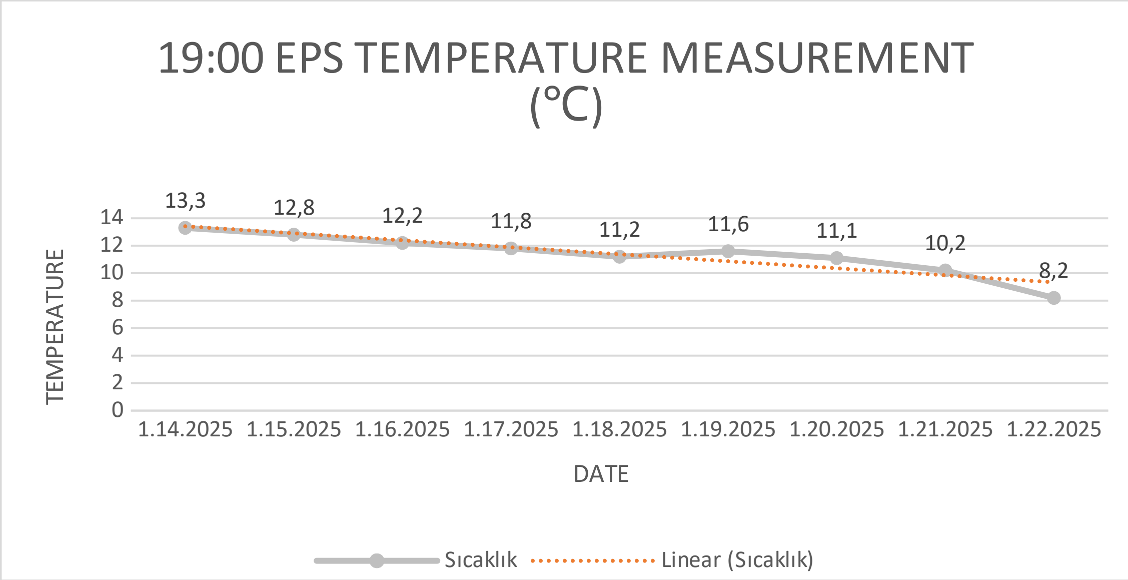
APPENDIX -10 Line Graph Showing EPS Room Temperatures at 13:30 Between January 14–22, 2025.



APPENDIX -11 Daily EPS Temperature Measurements at 19:00 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (°C)	TIME
EPS	14.01.2025	13,3	19:00
EPS	15.01.2025	12,8	19:00
EPS	16.01.2025	12,2	19:00
EPS	17.01.2025	11,8	19:00
EPS	18.01.2025	11,2	19:00
EPS	19.01.2025	11,6	19:00
EPS	20.01.2025	11,1	19:00
EPS	21.01.2025	10,2	19:00
EPS	22.01.2025	8,2	19:00

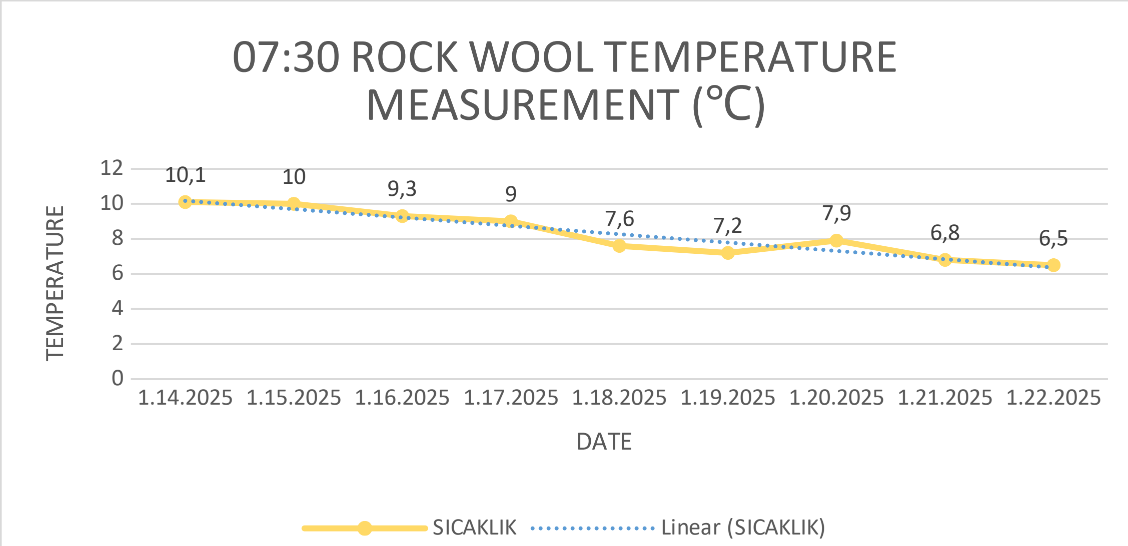
APPENDIX -12 Line Graph Showing EPS Temperatures at 19:00 Between January 14–22, 2025



APPENDIX -13 Daily Rock Wool Temperature Measurements at 07:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (°C)	TIME
ROCK WOOL	14.01.2025	10,1	07:30
ROCK WOOL	15.01.2025	10	07:30
ROCK WOOL	16.01.2025	9,3	07:30
ROCK WOOL	17.01.2025	9	07:30
ROCK WOOL	18.01.2025	7,6	07:30
ROCK WOOL	19.01.2025	7,2	07:30
ROCK WOOL	20.01.2025	7,9	07:30
ROCK WOOL	21.01.2025	6,8	07:30
ROCK WOOL	22.01.2025	6,5	07:30

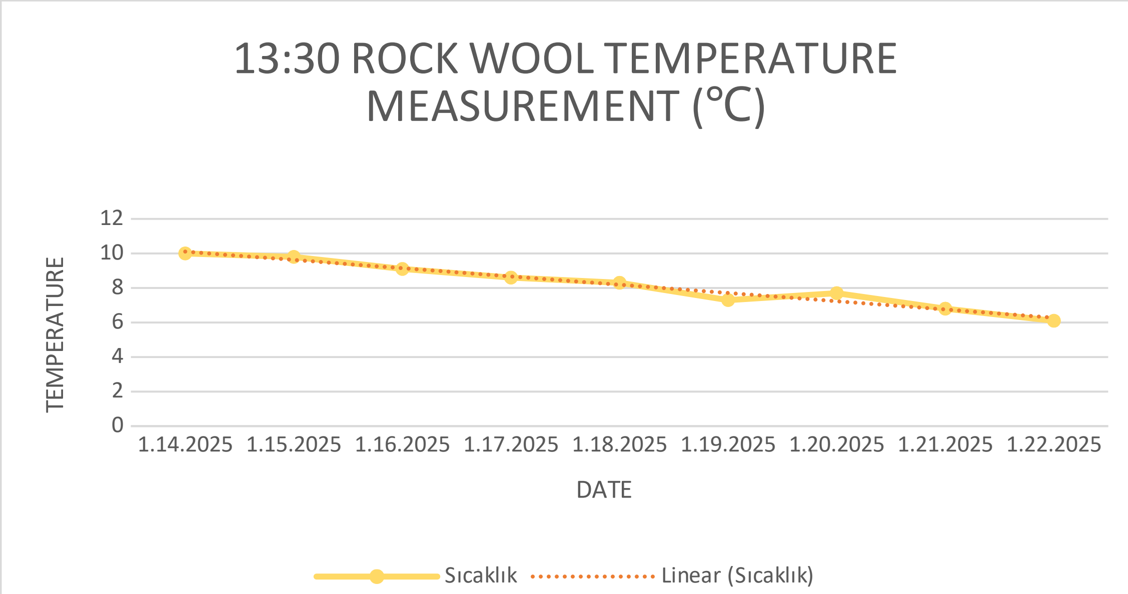
APPENDIX -14 Line Graph Showing Rock Wool Temperatures at 07:30 Between January 14–22, 2025.



APPENDIX -15 Daily Rock Wool Temperature Measurements at 13:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
ROCK WOOL	14.01.2025	10	13:30
ROCK WOOL	15.01.2025	9,8	13:30
ROCK WOOL	16.01.2025	9,1	13:30
ROCK WOOL	17.01.2025	8,6	13:30
ROCK WOOL	18.01.2025	8,3	13:30
ROCK WOOL	19.01.2025	7,3	13:30
ROCK WOOL	20.01.2025	7,7	13:30
ROCK WOOL	21.01.2025	6,8	13:30
ROCK WOOL	22.01.2025	6,1	13:30

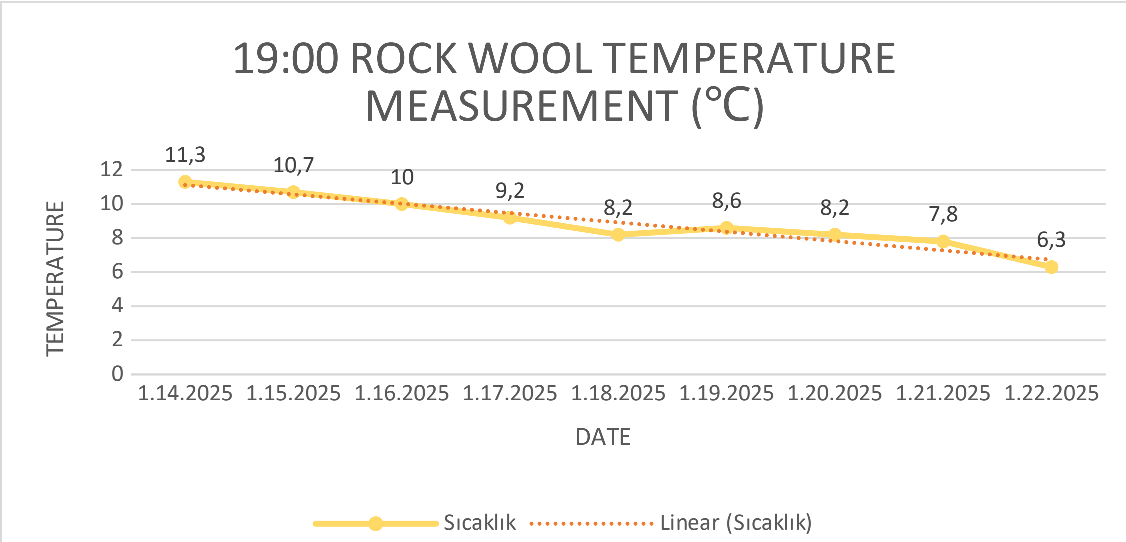
APPENDIX -16 Line Graph Showing Rock Wool Temperatures at 13:30 Between January 14–22, 2025.



APPENDIX -18 Daily Rock Wool Temperature Measurements at 19:00 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
ROCK WOOL	14.01.2025	11,3	19:00
ROCK WOOL	15.01.2025	10,7	19:00
ROCK WOOL	16.01.2025	10	19:00
ROCK WOOL	17.01.2025	9,2	19:00
ROCK WOOL	18.01.2025	8,2	19:00
ROCK WOOL	19.01.2025	8,6	19:00
ROCK WOOL	20.01.2025	8,2	19:00
ROCK WOOL	21.01.2025	7,8	19:00
ROCK WOOL	22.01.2025	6,3	19:00

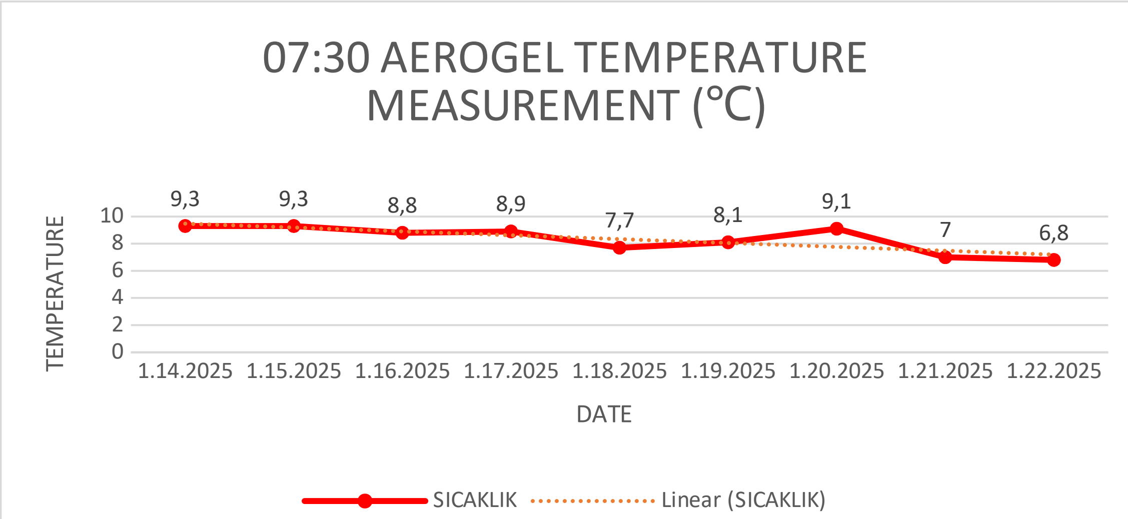
APPENDIX -19 Line Graph Showing Rock Wool Temperatures at 19:00 Between January 14–22, 2025.



APPENDIX -20 Daily Aerogel Temperature Measurements at 07:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
AEROGEL	14.01.2025	9,3	07:30
AEROGEL	15.01.2025	9,3	07:30
AEROGEL	16.01.2025	8,8	07:30
AEROGEL	17.01.2025	8,9	07:30
AEROGEL	18.01.2025	7,7	07:30
AEROGEL	19.01.2025	8,1	07:30
AEROGEL	20.01.2025	9,1	07:30
AEROGEL	21.01.2025	7	07:30
AEROGEL	22.01.2025	6,8	07:30

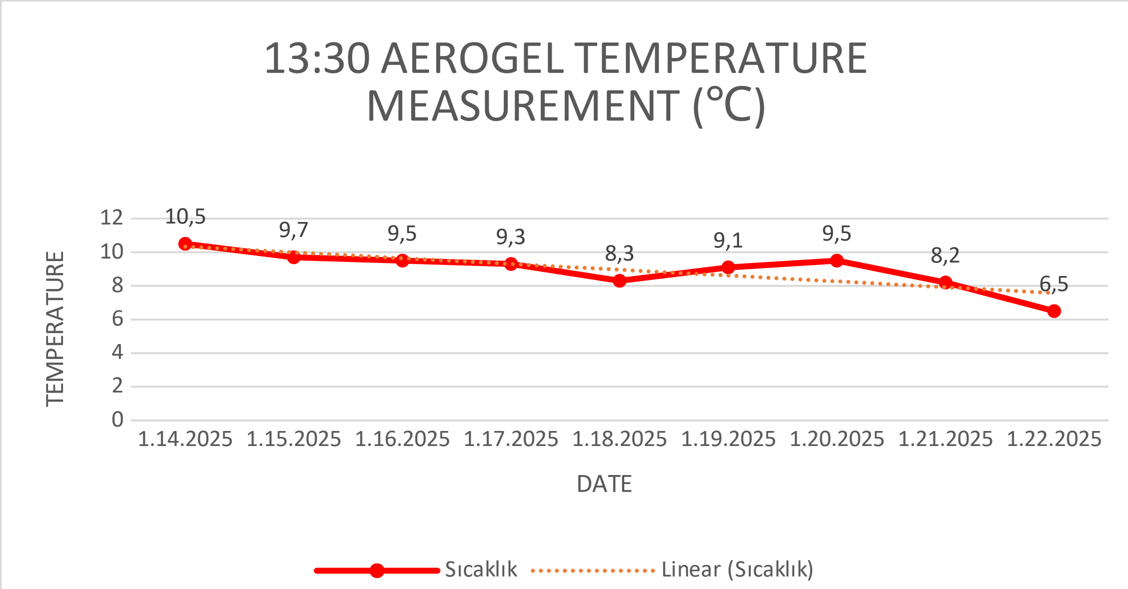
APPENDIX -21 Line Graph Showing Aerogel Temperatures at 07:30 Between January 14–22, 2025.



APPENDIX -22 Daily Aerogel Temperature Measurements at 13:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (°C)	TIME
AEROGEL	14.01.2025	10,5	13:30
AEROGEL	15.01.2025	9,7	13:30
AEROGEL	16.01.2025	9,5	13:30
AEROGEL	17.01.2025	9,3	13:30
AEROGEL	18.01.2025	8,3	13:30
AEROGEL	19.01.2025	9,1	13:30
AEROGEL	20.01.2025	9,5	13:30
AEROGEL	21.01.2025	8,2	13:30
AEROGEL	22.01.2025	6,5	13:30

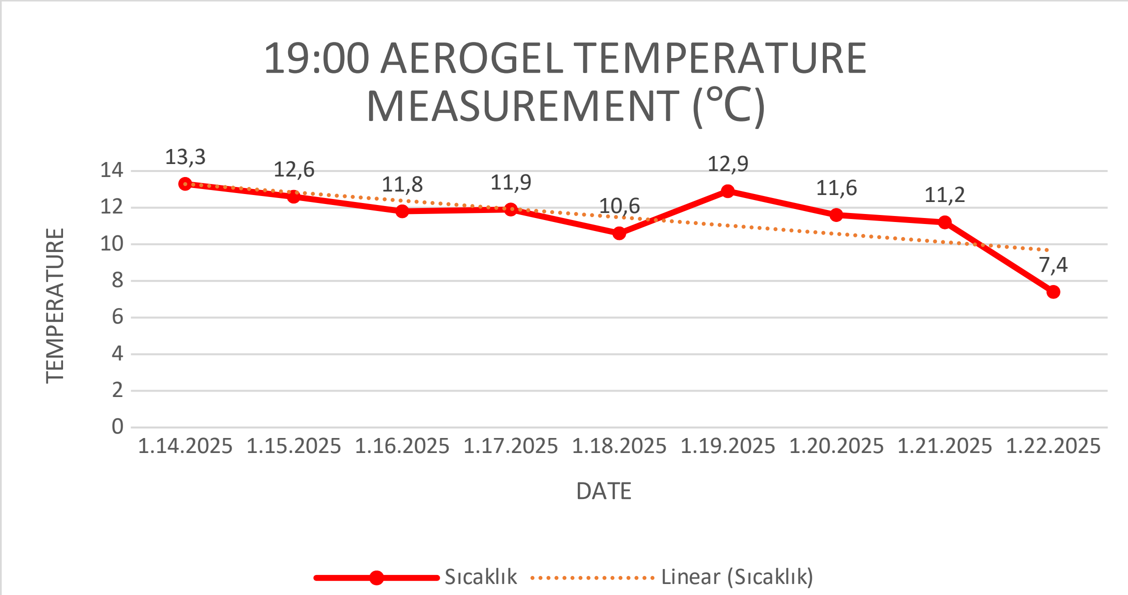
APPENDIX -23 Line Graph Showing Aerogel Temperatures at 13:30 Between January 14–22, 2025.



APPENDIX -24 Daily Aerogel Temperature Measurements at 19:00 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (°C)	TIME
AEROGEL	14.01.2025	13,3	19:00
AEROGEL	15.01.2025	12,6	19:00
AEROGEL	16.01.2025	11,8	19:00
AEROGEL	17.01.2025	11,9	19:00
AEROGEL	18.01.2025	10,6	19:00
AEROGEL	19.01.2025	12,9	19:00
AEROGEL	20.01.2025	11,6	19:00
AEROGEL	21.01.2025	11,2	19:00
AEROGEL	22.01.2025	7,4	19:00

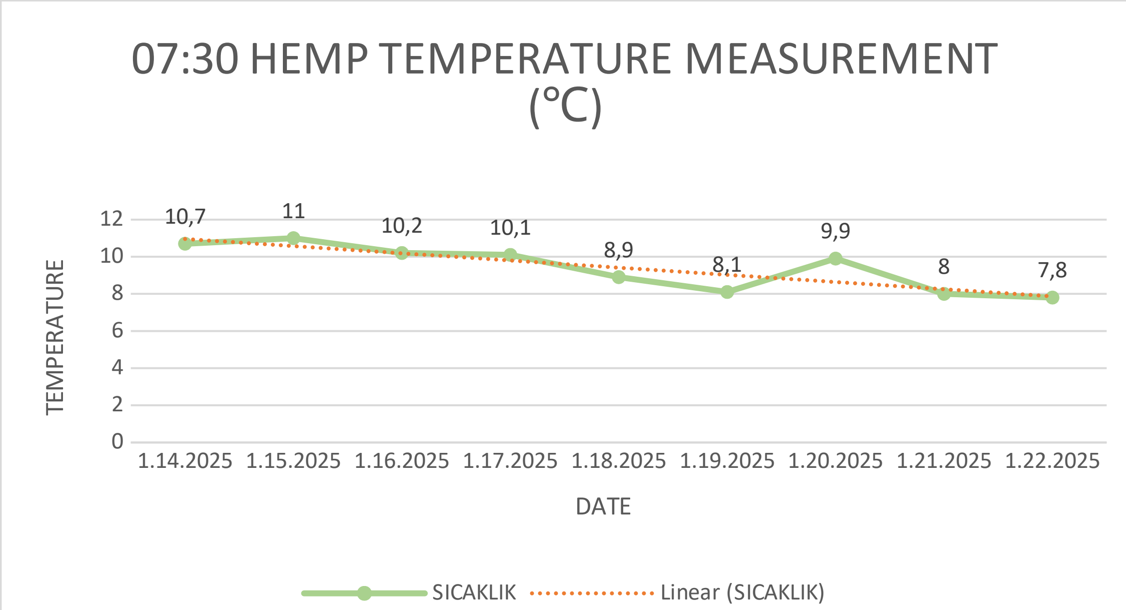
APPENDIX -25 Line Graph Showing Aerogel Temperatures at 19:00 Between January 14–22, 2025.



APPENDIX -25 Daily Hemp Temperature Measurements at 07:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
HEMP	14.01.2025	10,7	07:30
HEMP	15.01.2025	11	07:30
HEMP	16.01.2025	10,2	07:30
HEMP	17.01.2025	10,1	07:30
HEMP	18.01.2025	8,9	07:30
HEMP	19.01.2025	8,1	07:30
HEMP	20.01.2025	9,9	07:30
HEMP	21.01.2025	8	07:30
HEMP	22.01.2025	7,8	07:30

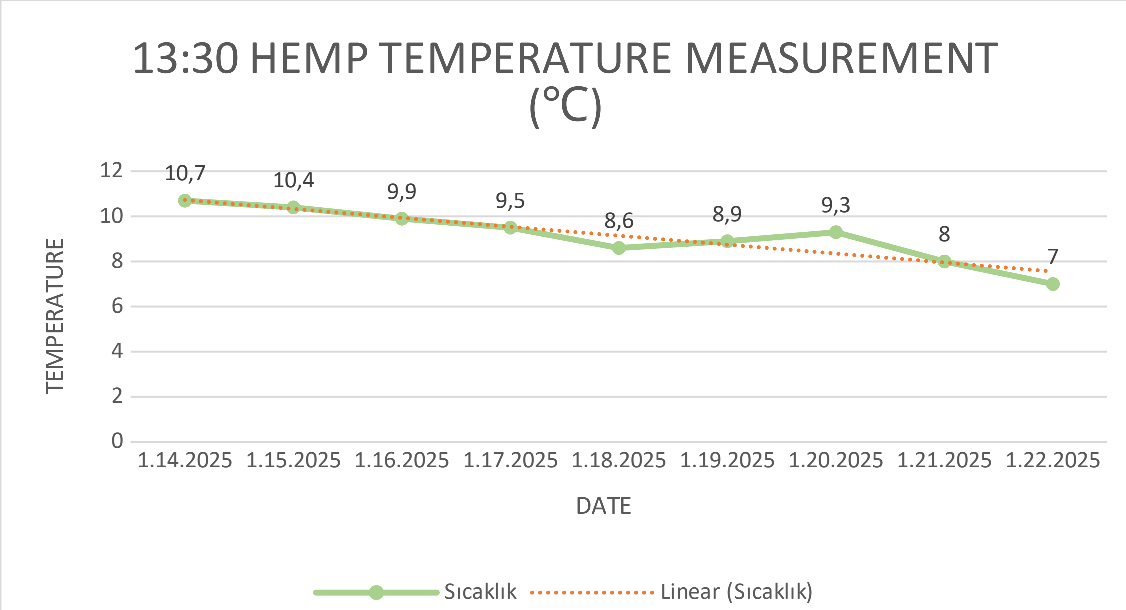
APPENDIX -26 Line Graph Showing Hemp Temperatures at 07:30 Between January 14–22, 2025.



APPENDIX -27 Daily Hemp Temperature Measurements at 13:30 Between 14–22 January 2025

MATERIAL	DATE	TEMPERATURE (℃)	TIME
HEMP	14.01.2025	10,7	13:30
HEMP	15.01.2025	10,4	13:30
HEMP	16.01.2025	9,9	13:30
HEMP	17.01.2025	9,5	13:30
HEMP	18.01.2025	8,6	13:30
HEMP	19.01.2025	8,9	13:30
HEMP	20.01.2025	9,3	13:30
HEMP	21.01.2025	8	13:30
HEMP	22.01.2025	7	13:30

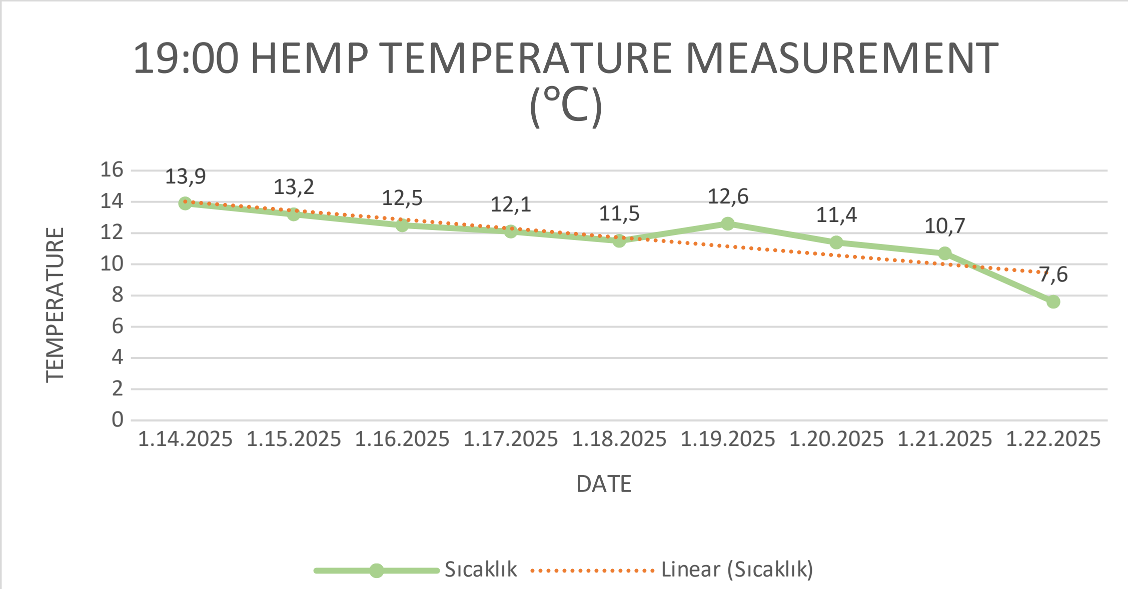
APPENDIX -28 Line Graph Showing Hemp Temperatures at 13:30 Between January 14–22, 2025



APPENDIX -29 Daily Hemp Temperature Measurements at 19:00 Between 14–22 January 2025.

MATERIAL	DATE	TEMPERATURE (℃)	TIME
HEMP	14.01.2025	13,9	19:00
HEMP	15.01.2025	13,2	19:00
HEMP	16.01.2025	12,5	19:00
HEMP	17.01.2025	12,1	19:00
HEMP	18.01.2025	11,5	19:00
HEMP	19.01.2025	12,6	19:00
HEMP	20.01.2025	11,4	19:00
HEMP	21.01.2025	10,7	19:00
HEMP	22.01.2025	7,6	19:00

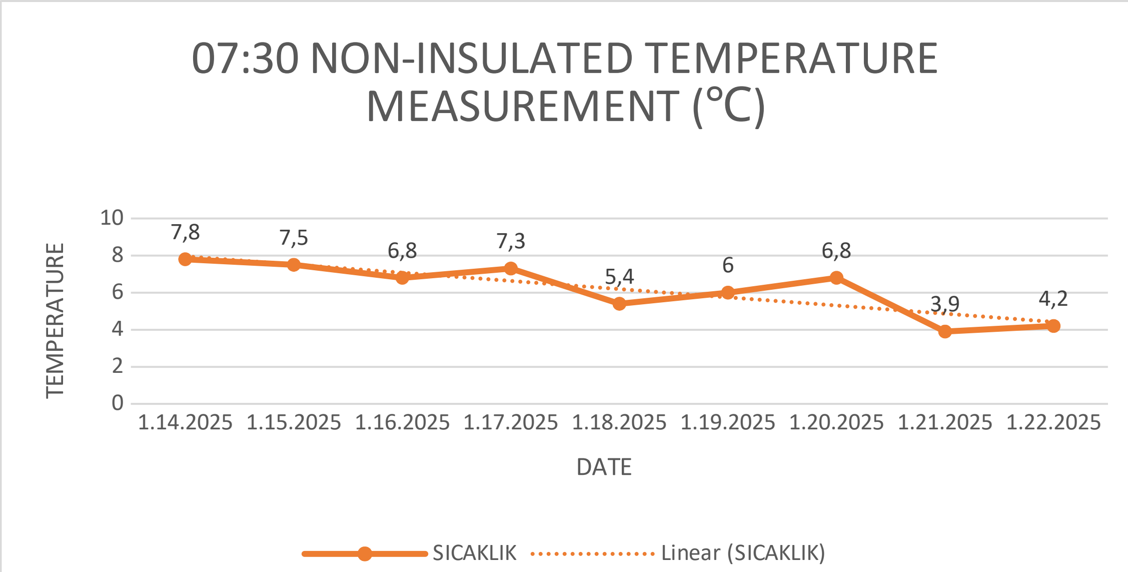
APPENDIX -30 Line Graph Showing Hemp Temperatures at 19:00 Between January 14–22, 2025



APPENDIX -31 Uninsulated Temperature Measurements at 07:30 Between 14–22 January 2025.

MATERIAL	DATE	TEMPERATURE (°C)	TIME
UNINSULATED	14.01.2025	7,8	07:30
UNINSULATED	15.01.2025	7,5	07:30
UNINSULATED	16.01.2025	6,8	07:30
UNINSULATED	17.01.2025	7,3	07:30
UNINSULATED	18.01.2025	5,4	07:30
UNINSULATED	19.01.2025	6	07:30
UNINSULATED	20.01.2025	6,8	07:30
UNINSULATED	21.01.2025	3,9	07:30
UNINSULATED	22.01.2025	4,2	07:30

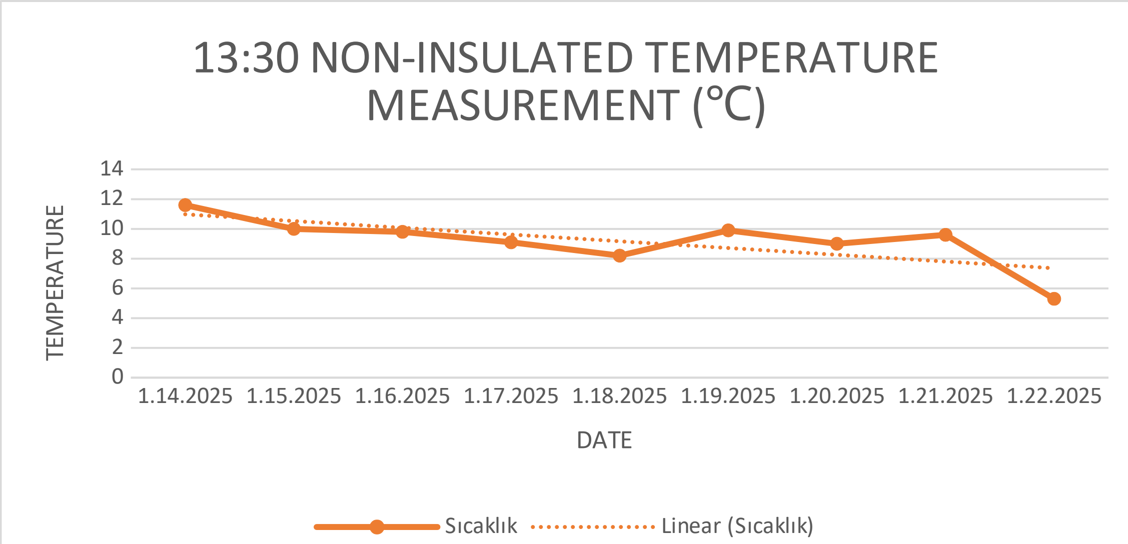
APPENDIX -31 Line Graph Showing Uninsulated Temperatures at 07:30 Between January 14–22, 2025



APPENDIX -32 Uninsulated Temperature Measurements at 13:30 Between 14–22 January 2025.

MATERIAL	DATE	TEMPERATURE (°C)	TIME
UNINSULATED	14.01.2025	11,6	13:30
UNINSULATED	15.01.2025	10	13:30
UNINSULATED	16.01.2025	9,8	13:30
UNINSULATED	17.01.2025	9,1	13:30
UNINSULATED	18.01.2025	8,2	13:30
UNINSULATED	19.01.2025	9,9	13:30
UNINSULATED	20.01.2025	9	13:30
UNINSULATED	21.01.2025	9,6	13:30
UNINSULATED	22.01.2025	5,3	13:30

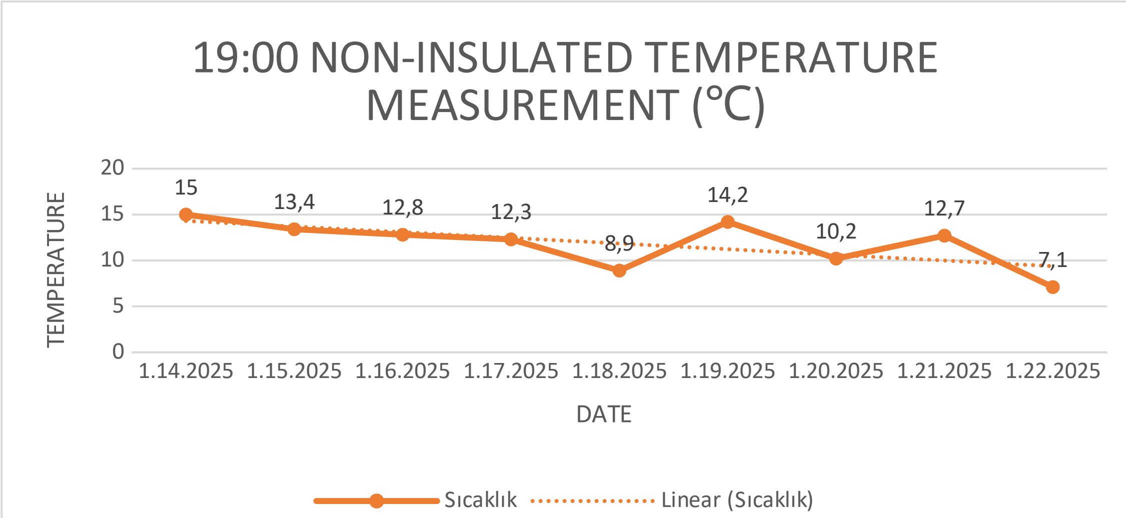
APPENDIX -33 Line Graph Showing Uninsulated Temperatures at 13:30 Between January 14–22, 2025



APPENDIX -34 Uninsulated Temperature Measurements at 19:00 Between 14–22 January 2025.

MATERIAL	DATE	TEMPERATURE (°C)	TIME
UNINSULATED	14.01.2025	15	19:00
UNINSULATED	15.01.2025	13,4	19:00
UNINSULATED	16.01.2025	12,8	19:00
UNINSULATED	17.01.2025	12,3	19:00
UNINSULATED	18.01.2025	8,9	19:00
UNINSULATED	19.01.2025	14,2	19:00
UNINSULATED	20.01.2025	10,2	19:00
UNINSULATED	21.01.2025	12,7	19:00
UNINSULATED	22.01.2025	7,1	19:00

APPENDIX -34 Line Graph Showing Uninsulated Temperatures at 13:30 Between January 14–22, 2025



ÖZGEÇMİŞ

KİŞİSEL BİLGİLER

Adı Soyadı	**:**	Mehmet Fatih YILMAZ
Uyruğu	**:**	Türk

EĞİTİM

Derece		**Adı**	**Bitirme Yılı**
Üniversite	:	Hasan Kalyoncu Üniversitesi	2021
Yüksek Lisans	:	Hasan Kalyoncu Üniversitesi	2025
Doktora	:		

İŞ DENEYİMLERİ

Yıl	**Kurum**	**Görevi**

UZMANLIK ALANI

YABANCI DİLLER

İngilizce

BELİRTMEK İSTEĞİNİZ DİĞER ÖZELLİKLER

YAYINLAR