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Hosam AMR, Androw Khairy

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Improving the Thermal Comfort of Industrial Building Using Insulation Materials

Hosam .A Aziz.Amr[1], A.khairy[2]

[1]Hosam Abd el-Aziz Amr – email: Hosam.moftah@bue.edu.eg
[2]Andro Khairy – email: andro186441@bue.edu.eg

***Abstract*-Construction industry is very important worldwide, and every day it grows noticeably in many forms producing residential, commercial, and industrial buildings along with roads and bridges. With that fast growth, the introduction of insulation materials was very essential, and their development was a requirement to enhance a variety of parameters and one of these parameters is the thermal comfort inside the building. Thermal comfort became one of the important aspects in construction industry and this is reflected mainly in residential buildings along with commercial buildings. However, when it comes to industrial buildings it might not be considered or prioritized in planning and designing phases. Architects tend to design any industrial building to the lowest cost and to serve the functions required only but never thinks of how important thermal comfort can be and its contribution in the productivity improvement of the workers as well as the administrative employees as well as reducing the high costs of electricity bills that is consumed by the air-conditioning systems. And for these reasons, building materials were improved to enhance thermal comfort inside the buildings and many insulation materials were introduced to contribute with that as well. One of these insulation materials is hemp and in fact, many associates consider it the best insulation building material ever made for its properties. Hemp comes from the hemp plant and hemp wool can be produced from the strong fibers of this plant. Hemp can be shaped in the form of blankets or boards, and both are used as environmentally friendly insulation materials. The importance of this plant is that it can grow fast and on any type of soil worldwide. In 3 months of time, a hemp plant can reach 4 meters, taking in a huge amount of CO_2 that helps as well in purifying the air.**

***Keywords*- Thermal comfort, Hemp Insulation, Industrial buildings, Insulation materials.**

I. Introduction

Thermal comfort became one of the biggest objectives required to be achieved inside any construction project. It refers to the person's state of mind whether they feel too hot or too cold (Health and Safety Executive). However, residential buildings and commercial buildings are always the type of buildings that look forward to achieving internal thermal comfort through façade and roof designs, usage of more sustainable building materials as well as paints, etc. But when it comes to industrial buildings, it feels more like to neglect the importance of internal thermal comfort while designing the industrial building. This can be because of several reasons such as completing the project much faster and reducing construction cost. Nevertheless, if the client prioritizes these two aspects, then it would be so much better for him to consider sustainability that results from the designing phase of the facades to enhance the internal thermal comfort. To do that, the architect needs to understand the factors that affect thermal comfort which include controlling air temperature, air velocity, and humidity. Air temperature refers to the temperature of the air that surrounds the human being, where air velocity describes how fast the air moves across a person and this speed can result in cooling the person who's directed to the air. However, humidity is the result of water being heated and evaporated in the surrounding environment.

The research main pillars are:

- *Insulation materials:*

The variety of insulation materials includes thick fibers like fiberglass, rock and slag wool, cellulose, and natural fibers as well as stiff foam boards and sleek foils. In a building cavity, bulky materials impede the movement of convective and, to a lesser extent, conductive heat. To block the flow of heat, solid foam panels capture air or another gas. Highly reflective foils are particularly helpful in cooling climes because they reflect thermal radiation away from interior spaces using thermal barriers and reflective insulating materials.

- *Insulation material types:*

  1. Organic materials: Organic raw materials (such as different types of resins, corks, wood – wools, and wood chips, etc.) are used to make organic insulating materials.
  2. Inorganic materials: During the industrial revolution, a number of artificial materials were produced as well in addition to organic materials. By the first third of the 1900s, they had mostly replaced natural materials due to their durability, fire resistance, and water resistance, among other benefits.

Figure 1. Insulation Materials.

- *Benefits of insulation materials:*

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- Causes a reduction of 40% in the expenses of heating and cooling.
- Reserves the unsustainable sources of energy due to the reduction in the usage of HVAC systems as well as reducing greenhouse gas emissions.
- Can also reduce noise pollution in spaces because most insulation materials have acoustic insulation properties by the fact that they increase wall thickness.

- *Thermal Comfort:*

Meanwhile during all seasons of the year, the air inside spaces with thermal insulation materials tend to be cooler on hot days and hotter on cold days.

- *Energy Efficiency:*

According to [3], thermal insulating material is one ecologically friendly method that effectively uses energy to deliver the necessary level of thermal comfort. The basic idea behind thermal insulation is to properly implement insulation boards or bats using energy - efficient materials to lower heat gain or loss, thus, lowering energy costs.

- *Industrial Buildings:*

Industrial buildings usually neglect the sustainability aspects to reduce construction costs and forget about many other aspects such as running costs, energy efficiency, thermal comfort and workers ‘productivity due to thermal comfort.

- *Research Methodology:*

The research methodology embraces a mixed strategy that is needed to investigate different components of the study.

1. It comprises qualitative analysis which is done through the data collection of the various types of insulation materials and comparing them through the main pillars of the research (thermal comfort and energy efficiency).
2. Applying a practical study through a simulation done on Design Builder software where a base model will be placed in Cairo with conventional walls as per the Egyptian codes and then compared with 6 specimens using the 3 insulation materials used in this research to come out with the best specimen to be used in the construction of industrial buildings from now onwards.

II. LITERATURE REVIEW

A. *Chapter Introduction:*

In this chapter, thermal comfort and sustainable design aspects of industrial buildings will be defined and tested to identify the enhancement in productivity and workability of the workers after the implementation of façade design techniques. The chapter will be divided into 3 sections: Section 1 shall define thermal comfort and the 6 main aspects that affect it which include air temperature, radiant temperature, relative humidity, air motion, metabolic rate, and clothing insulation. However, in section 2, industrial buildings shall be analyzed according to their design, building materials’ properties and the reason behind using these building materials, different spaces and properties. Section 3 shall start with the definition of insulation materials and gets focused on 3 main materials which are hemp, rockwool and fiberglass. The section will contain a history background of each material, the thermal properties and aging and installation of each of those materials.

B. *Thermal comfort:*

Definitions:

Understanding thermal comfort is crucial to architecture since it influences not just how buildings are designed but also how sustainable design is accomplished [9]. A state of mind known as thermal comfort indicates contentment with the surrounding atmosphere.

Figure 2. Thermal Comfort Factors.

Thermal comfort is subjective; hence it differs for each person. Thermal comfort in the body is preserved by allowing the heat produced by human metabolism to escape at a rate that maintains thermal equilibrium. Any further thermal gain or loss causes significant discomfort. In order to ensure thermal comfort, heat production and heat loss must be equal. It has long been understood that factors other than merely air temperature affect how hot or cold you feel. In actuality, there are six main factors that affect thermal comfort:
• Ambient temperature (air temperature).
• Radiant temperature (the surrounding temperature).
• Relative humidity (the water vapor content in the air).
• Air motion (the speed at which air travels around and touches skin).
• Metabolic rate (amount of energy resulted from the metabolic reaction in the body).
• Clothing insulation (materials used to retain or remove body heat).

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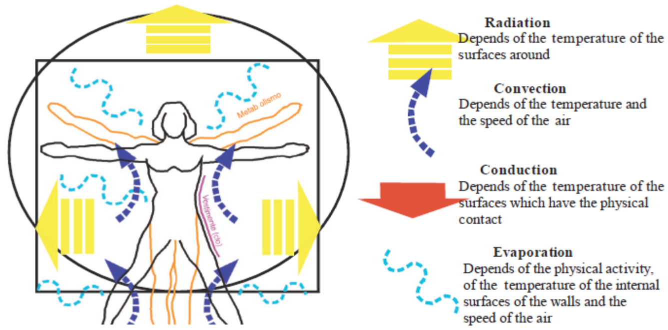

Figure 3. Schematic representation of the human physiology and thermal EXCHANGES; SOURCE: Albee UFSC (2011).

Making smart judgments when planning and designing an industrial building air conditioning system requires proper understanding of these six aspects. Understanding how these systems affect a building's energy load is crucial, though.

Heat exposure in the workplace and industrial environments:

Numerous elements of the working environment, including high and low temperatures, colors, ventilation, and different techniques of lighting, can either be harmful or beneficial to human health depending on their intensity and length of exposure. It should be a suitable site to balance a good standard of life quality since it is where humans use their hands to carry out duties to ensure their own survival. The components that affect the thermal equilibrium of the human body in each thermal environment include air temperature, relative humidity, air speed, average radiant temperature, clothing, and levels of human activity. There are several concepts that link these elements to how people feel comfortable in this literature [8]. According to [8], if the temperature in your workplace is higher than the highest level advised, those there may eventually feel the impacts of such temperatures. Heat stress, as the name suggests, is a condition that can be widespread in situations like industries, manufacturing facilities, power plants and other areas where heat is an essential aspect or byproduct of the work. In order to reduce the risk of the aforementioned problems, it's critical that internal room temperatures are well maintained to have ideal temperature. Heat stress can cause concentration problems, extreme thirst, heat rash, exhaustion, or heat stroke as shown in Fig. 4.

Figure 4. Heat Stress Diagram.

Thermal and Environmental Comfort:

When the Estimate Men Vote (PMV) values fluctuate within the range of - 0.5 to + 0.5 and the Percentage of Unsatisfied Persons (PPD) is 10 %, it is determined that the environment is thermally comfortable. In this regard, sections 6 and 7 of the standards make clear that the heat gain and loss of buildings or workplaces must change over time and that changes in those conditions are permitted as long as they stay within advised limitations. Clause 9 of the aforementioned standard focuses on a method to be employed over the long term for an environment thermal evaluation as stated by [8].

Thermal balancing: Heat exchange between the environment and the human body:

It is stated by [8] that evaporative cooling is the only resource available for the body systems to avoid overheating and maintain a good thermal balance with close – to - skin breezes in hotter conditions above 35 ℃ at a temperature of about 24 ℃, air movement is thought to be pleasing between 0.1 and 0.2 m / s.

The ideal air increases to 0.2 to 0.5 m / s for hard work operations above 24 ℃ in saturated air. For soft industrial activities, the maximum air speed is 0.75 m / s according to the (Norm NR – 17). Along the winter, this rate needs to be lowered to 0.15 m/s. In order to keep the body's internal temperature from rising to as high as 37℃, heat must be released from the surrounding area in order to sustain thermal equilibrium. Fig. 3 illustrates the thermal change mechanisms that cause the heat to escape.

Energy Use and Thermal Comfort Conditions:

The planning, development, functioning, and destruction of our urban environment accounts for more than half of the energy required in our economy. Building cooling and / or heating uses a large portion of that energy. A building uses 44% of its energy usage for air conditioning as shown in Fig. 5.

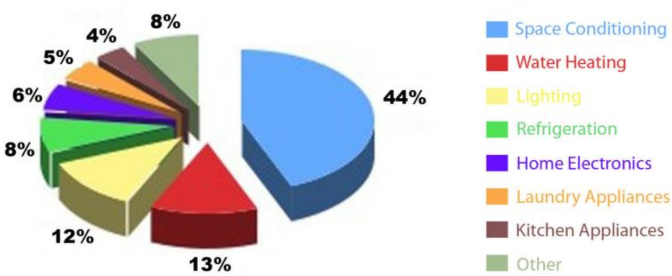

Figure 5. Building energy consumption by TYPE.

By enhancing air conditioning systems, designers can significantly improve a building's energy usage rates. However, this would not result in the best of results hence energy would be used in passive ventilation techniques and the main aim is to minimize it even further. The combination of internal thermal comfort conditions and personal conditions that are acceptable to the majority of occupants is defined by the " American Society of Heating, Refrigerating, and Air Conditioning Engineers (AHSRAE) Standard 55, Thermal Environmental Comfort for Human Occupancy ".

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There are two methods for determining what this confluence of variables needs to be:

- Analytical: Individuals are placed in temperature - controlled settings, and their reactions are observed. This approach prefers tightly regulated thermal conditions, and the outcomes are utilized to create a model that can forecast the ideal level of comfort.
- Behavioral: Individuals are observed in their everyday conditions, and their reactions are determined by the surroundings that they deal within. To better understand how people and buildings interact, the results are statistically examined.

Results from these two methods vary, especially under different circumstances. The analytic method employs computer software applications that regulate environmental factors to maximize satisfaction. An application of a psychrometric chart is made in the behavioral approach. It's vital to think about the history of heating and cooling systems and what we can learn from it before delving more into this latter application [9].

Psychrometric Chart:

Willis Carrier, the creator of modern air conditioning, defined psychrometric as " the management of the humidity of the air by either raising or lowering its moisture content “. It is the study of the physical and thermodynamic aspects of air - water vapor mixtures. In addition to controlling humidity, you can also regulate temperature by heating or cooling the air, cleanse the air by washing it or filtering it, and regulate airflow and ventilation. We must look at all the factors that affect thermal comfort, including humidity, temperature, air purification, air motion, and ventilation, in order to optimize our air conditioning systems. In order to choose the best air conditioning system and identify the ambient factors that influence people's thermal comfort, psychrometric is applied. Additionally, it is helpful to comprehend the regional climatic context of a facility and better handle issues related to human occupancy, use, and structural factors. In situations where moisture and heat transmission in the air are essential, the examination and evaluation of psychrometric qualities is particularly crucial.

The psychrometric chart contains the majority of psychrometric. The psychrometric chart can be used to diagnose issues with air temperature and humidity by being aware of how to use it. The diagram serves as a tool for analyzing the cooling process and assists in informing designs for particular climates. It bases the design of effective and appropriately sized HVAC systems on three key factors temperature, moisture, and relative humidity [9].

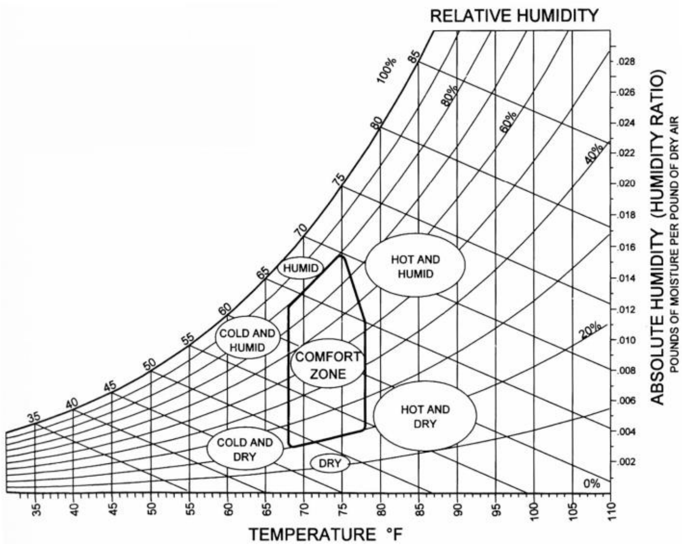

Figure 6. The psychrometric chart.

The dry - bulb temperature scale on the horizontal axis, the humidity ratio (moisture content) scale on the vertical axis, and an upper curved boundary that symbolizes saturated air, or 100 percent relative humidity, make up the three main boundaries of the psychrometric chart. The graph also displays additional crucial characteristics like specific volume (the space occupied by a given mass of air) and enthalpy (the energy content of an air - water mixture, expressed in BTUs per pound of dry air). Knowing either of these attributes establishes a spot on the chart from which all other properties may be derived, which gives the chart its versatility. The chart's use is straightforward, and the sections that follow break down the graph's individual elements to describe its applications in more detail according to [9].

Temperature:

Building heat comes from both internal and external sources. External sources include solar radiation, conduction, ventilation, and infiltration; where internal sources include people, lighting, appliances, and machinery. On the psychrometric chart, temperature rises from low to high temperatures along the x-axis. The temperature in this instance was established using a standard thermometer to measure the " dry - bulb " temperature, which is the temperature of an air sample. Since the thermometer's reading tip is dry and therefore does not compensate for the air's moisture content, it is known as a " dry – bulb " [9].

Moisture:

The psychrometric chart (Fig. 6) includes moisture in the air since it is a key factor in the design of air conditioning systems. Moisture comes from both interior and exterior sources, just like temperature. External factors include ventilation, infiltration, and permeation; where internal factors include evaporation, desorption, and humans (breath, clothing). Since each individual emits 0.25 pounds of moisture per hour, 100 people with moderate levels of activity produce three gallons of water each hour, making internal moisture sources just as

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vital to take into consideration as external ones. On the y – axis, a measurement of the humidity ratio is used to calculate how much moisture is present. Horizontal lines with the same humidity ratio are used to measure moisture. The amount of water per unit of dry air is known as the humidity ratio. This is commonly defined as grains of moisture per pound of dry air, with 7,000 grains of moisture per pound of water [9].

Humidity:

How close air is to its saturation state is determined by its relative humidity. It compares the volume of water in the atmosphere with the maximum volume of water the air could possibly hold at a certain temperature. This has an impact on how hot an area feels, the formation of mold, and the durability of construction materials. On the psychrometric chart (Fig. 6), the arcs that are sweeping up from the bottom left and top right of the chart show lines of constant relative humidity.

The circulation of air past a moist sensor tip, which is impacted by air saturation, is how wet - bulb temperature is measured. This is the measurement of a thermometer whose detecting bulb is shielded by a wet sock that is rapidly evaporating into the sample air. (Note: When the air specimen is completely saturated with water, WBT and DBT are the same since there is no water loss.) The upper, left corner of the graph (in Fig. 6) represents the line for saturation, or 100 % relative humidity. The temperature of dew point is also at this level. The temperature at which water shall start to condense out of humid air is known as the dew point. Generally, the dew point temperature for a particular region is equal to that region's annual nighttime temperature. Desiccants that adsorb or absorb water, cooling below the air's dewpoint, and compression to condensate water out of the air are some of the methods for removing moisture from the air in a structure. Whichever approach is chosen, it's critical to evaluate both its effectiveness and annual energy use across the board [9].

Conclusion:

Looking back in time helps us gain a better understanding of how different building cultures adapted their designs to their local climates by taking into account the right orientation for air circulation along with other thermal comfort factors. One of the key objectives of architecture engineers today is to preserve the thermal comfort of building users. When the option to remove a jacket or move away from a heat source is not available and people are unable to adapt, problems can occur. These adaptive strategies involve taking off clothing, unintentionally changing position, and relocating to more comfortable areas away from heat sources. As a result, when developing and constructing a building, the following elements must be taken into account:

- The importance of cooling or heating to reach the peak of thermal comfort and energy efficiency.
- Develop plans that help reduce the usage of HVAC systems and thus reduce energy usage.
- Encouraging the use of passive techniques to control the temperature indoors.
- Develop standards for comfort and energy consumption to be followed.
- Using building simulations after designing to decide the optimal design.
- Consider climatic changes over the age while designing a building.

C. *Industrial Buildings:*

Introduction:

The term " building " is frequently used to describe an enclosed space where people can carry out activities. According to the Building Regulations, a " building " can be either permanent or temporary, but not another type of construction or erection.

Buildings utilized for industrial purposes are known as industrial buildings. During the industrialization of the 1700s and 1800s, when new activities, the supply of new materials, and new techniques led to the production of some of the most avant-garde structures of the era, industrial buildings as a definable architectural form rose to prominence.

Facades:

The dominant architectural trends of the time, available building technologies, and the principal's preferences all influence the building's exterior design. Due to financial constraints, the façade typically goes unflustered, resulting in the distinctive style that defines industrial structures. For more complex industrial structures, bricks are combined with stone and plastered surfaces. Raw concrete and metal corrugated sheets started to appear on facades around the turn of the nineteenth and twentieth century; with time, these materials acquired popularity [5].

The building's facade design and its ability to insulate against heat and moisture influence how a façade should be refurbished. It is simple to add more heat insulation to a plain plastered structure, but it is much more difficult to add heat insulation to an existing brick façade because it is impossible to arrange the insulation in the appropriate location on the exterior of the wall for most of the insulation materials because of the probability of forming thermal bridges during the installation process. Water, chemicals, or grit blasting can be used to clean the surface if the façade is not significantly harmed (dry or wet). Depending on the amount of damage or deformations in the façade, repairs shall be done before the installation of any insulation materials as shown in the (Table 1) below [5].

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Table 1. Industrial buildings façade materials and wall fillings

Structure	Materials	Test	Refurbishment
Filling walls	Brick Artificial tuff (gas concrete), Cork derivatives Sand-lime brick Gypsum board	Cavity building test Heat tests Moisture damage test Crack pattern test	Repairing the cracks (cement mortar injection, elastic sealing kit, rebuilding the walls) Partial or full replacement
Façade materials	Brick Plastering Stone, artificial stone Concrete, reinf. concrete Corrugated sheet (Wood)	Corrosion test Strength test Deformation test	Additional heat insulation Replacement of elements Cleaning the surfaces (water, chemical or grit blasting technology) Material conservation (with chemicals) Building new covering

Façade building materials:

According to reports, the thermal behavior of the materials that are used in the construction of a building's walls and roofs can significantly affect the internal thermal comfort of a building. One of the biggest parts of the building envelope that shelters the industrial building from changes in the environment outside is the material used for the walls and façades. Heavyweight (HW) materials, like brick and concrete, have enormous thermal energy storage capabilities and behave differently from light - weight (LW) walls, such a sandwich wall in terms of thermal behavior. Hence, heavyweight blockwork slows down the movement of heat through the indoor environment while also increasing air temperature by allowing the heat during the afternoon to escape. The thermal comfort inside a building with HW material (high thermal inertia) walls was investigated by researchers in a study, and they found that the HW improves thermal comfort. However, (Hoffman et al.) have conducted research on how different façade colors affect the external temperature environment. They said that the dark colors increase the façade's surface absorption, which raises the temperature of the outside air. It is clear from the review that different façade materials affect the thermal environment both inside and outside in different ways. Hence, by changing the wall material or adding further elements on its surfaces, the thermal behavior of the building can be improved. Many environmentally friendly methods related to the urban heat island phenomenon have been put to the test in this context, but they have not adequately addressed the issue. For instance, the green building idea is typically exclusively used for new construction; it is challenging to apply to buildings that are already in place [5].

Table 2. The U – Value for Each building façade element

The U-value for each building façade element.

Façade System	U-Value (W/m^{2}K)
Brickwall	2.49
Concrete	2.40
ACP + Brickwall	2.46
Low-E glass	5.76
Clear glass	5.71

Table 3. The Thermo – PHYSICAL PROPERTIES of the building components

The thermophysical properties of the building components.

Building Components	Density		Specific Heat		Thermal Conductivity	
	ρ (kg/m^3)	Ref.	c (J/(kgK))	Ref.	k (W/(mK))	Ref.
Brick	1600–1800	[63]	879–974	[63]	~0.60–0.73	[64]
Concrete/ cement plaster	2000	[63]	880	[63]	0.61	[64]
Aluminium Composite Panel (ACP)	2700	[65]	-		0.4	[66]
Low-E glass	2180	[67]	750	[67]	1.38	[67]
Clear glass	2200	[68]	800	[69]	1.0	[69]

D. Insulation Materials:

Introduction:

The variety of insulation materials includes thick fibers like fiberglass, rock and slag wool, cellulose, and natural fibers as well as stiff foam boards and sleek foils. In a building cavity, bulky materials impede the movement of convective and, to a lesser extent, conductive heat.

Figure 7. (Variety of insulation materials).

To block the flow of heat, solid foam panels capture air or another gas. Highly reflective foils are particularly helpful in cooling climes because they reflect thermal radiation away from interior spaces using thermal barriers and reflective insulating materials. The third decade of the twenty-first century has seen a rise in the importance of worldwide energy consumption in industrial building. The main contributors to greenhouse gas emissions are the production of products, raw material processing, and building construction. Since constructions are one of the top energy consumers, they also contribute significantly to climate change and global warming, which is accelerating up global warming and endangering the life of millions around the world, plants, and animals. Carbon dioxide products are the principal results of the use of fossil fuels. The construction industry has been identified as the largest energy consumer, contributing up to 40% of global energy and emitting up to 1/3 of the world's annual greenhouse gas emissions (GHG), as per Directive 2010/31/EU of the European Parliament and of the Council of May 19, 2010, on the energy performance of buildings. New construction will need to consume almost no energy and that energy will primarily come from renewable resources.

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According to the Energy Information Association in 2018, the significant increase in residential, commercial, industrial, and urban construction as a result of the development of industrial sector and population growth which will result in a 64% increase in global energy consumption by the year 2040. Environmental catastrophes and climatic changes are consequently becoming increasingly evident. For instance, it is anticipated that the average surface temperature of the Earth will increase from 1.1 to 6.4 C by the end of 2100 due to the greenhouse effect, which is caused by 45% of the world's carbon dioxide emissions coming from buildings and the construction industry. Commercial buildings utilize a significant amount of energy because of the increasing natural resource use for various mechanical and electrical systems within the buildings.

History Background:

There are five distinct eras in which thermal insulation material development can be classified. Each era began with a crucial advancement in the history of humanity, science, or industry. These were the primary factors that caused change in the market for thermal insulation materials, which led to the emergence of a new product or the oblivion of an older one. It is obvious from the market of the thermal insulation materials industry that synthetic materials are the most widely used goods according to analysis done by [1]. About 50 – 55% of the production is made up of products containing mineral wool, while 40 – 45 % of it is made up of plastic foam. The present century has exposed the fact that fossil fuels are limited and will run out rather soon. Additionally, the use of fossil fuels contributes significantly to the greenhouse gas emissions (in particular CO2) that cause the major issue of the twenty-first century, climate change and global warming. Around 70 – 80 % of the energy used in a building is used for mechanical ventilation. Thermal insulation can help to prevent heat exchange, which lowers ventilation expenses and CO2 emissions simultaneously. The need for organic thermal insulation materials is growing as a result of the significant energy requirements for the manufacturing of artificial thermal insulation materials and the continued usage of fossil fuels. For instance, over the past 20 years, the production of these products has increased from 1% to 6% in Germany. Their expansion should be significant because their production uses substantially less energy. However, this isn't the case because people are cautious of them. In comparison to artificial materials, they have a few drawbacks (flammability, low durability, frequently poor dimensional stability, threats from rodents, insects, etc.), while their benefits (environmentally friendly, economical, and affordable) are frequently neglected.

Table 4. (The history of insulation materials: Modifications and Causes).

Time period	causes for modification	Modifications	Insulation materials
7000 BC	Nomadic lifestyle	Using fabrics	Animal skin, fur, wool
7000 BC – 1870 AD	Settled lifestyle	Durable materials Vegetable fibres	earth, wood, bricks straw, eelgrass, reed
1870-1950	industrial revolution calculations about heat loss	first natural insulating products	reed, cork, wood wool and flax plates, cellulose insulation
		development of bricklaying elements	ash-filled bricks, hollow bricks, AAC
		first products of artificial insulation materials	asbestos, rock wool, fiber- glass, foam glass, dross, expanded clay and perlite
1950 - 2000	spread of plastics	spread of artificial materials appearance of plastics foams nearly disappearance of natural materials	polystyrene, polyurethane, polyester, polyethylene, phenolic, formaldehyde and melamine foam
2000 - present	CO2 emission exhausting fossil fuels climate change global warming	revival of the natural materials	cellulose insulation, cork, straw bale, wood wool, sheep wool
		experiments with new materials	transparent thermal insulation, switchable thermal insulation, nano cellular insulation, vacuum insulation panels

The usage of thermal insulation materials:

Buildings are required to utilize thermal insulation materials as energy becomes increasingly valuable. When used effectively, thermal insulation is a material or a combination of materials that slows the rate at which heat moves by conduction, convection, and radiation. To manage buildings comfortably, using thermal insulation solutions lessens the need for (HVAC) systems. As a result, it saves energy and uses fewer natural resources. Profits, environmentally friendly materials, extending indoor thermal comfort times, lowering noise levels, fire prevention, and other benefits are also some of the insulation materials' benefits. Systems will

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be able to become more energy efficient thanks to these materials. Additionally, they are widely used in pipelines for liquefied natural gas, petroleum, and food cold storage. Numerous cutting-edge insulation materials are continually being introduced to the market, and sustainable insulation technologies with lower embodied energy and lower carbon emissions are also growing in popularity.

Aditya et al. and D'Alessandro et al. are a few studies that have gone into detail in the past about thermal insulation materials and how they are used in the building industry. The walls, roofs, ceilings, windows, and floors are some of the categories where insulation materials are applied.

Their varieties, attributes, advantages, and disadvantages were also covered.

The many types, manufacturing processes, and properties of both conventional and cutting-edge thermal insulation materials during the past few decades have been evaluated in the work of (Abu-Jdayil et al). A solid matrix material called a thermal insulating material typically has a gaseous material included into the cells, pores, or interstices either randomly or systematically.

Most thermal insulation materials in the market can be divided into four main categories: inorganic, organic, combined, and advanced materials. They can be made in a variety of shapes, such as a reflecting structure, a hard, natural form, or a porous blanket or batt. 60% of the market is made up of inorganic materials (like rock wool), while 27% is made up of organic insulation products (like fiber glass and hemp).

Wall configuration with insulation materials:

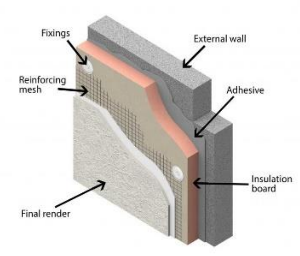

Figure 8. (Existing wall cross – section).

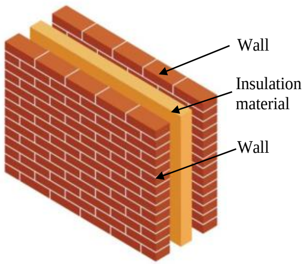

FIGURE 9. (NEW WALL CROSS – SECTION).

Classifications of insulation materials:

Organic Insulation:

Organic raw materials (such as different types of resins, corks, wood-wools, and wood chips, etc.) are used to make organic insulating materials. Fibers made from plants have long been widely accessible. Native people who lived in tropical regions for centuries constructed their lodges out of reed or dried eelgrass. Reed and long-stemmed wheat straw were especially employed for thatching roofs in chilly climes. Northern Europeans constructed thatched dwellings with 60-80 cm thick straw roof construction throughout the 12th and 13th centuries. Clay and straw were frequently used in the construction of the walls. Thatched buildings quickly became popular, especially in the northern regions of Europe and America, since the dry, hollow fiber of straw and reed offered a great level of thermal resistance.

The first insulated panels (made of reed, cork, and flax) were created in the late 19th century by processing these organic materials. They were affordable, but their primary disadvantage was that they were highly hygroscopic, necessitating the development of additional damp-courses. Reed panels were first utilized as thermal insulation in accessory buildings in the 19th century. They were well-liked despite having poor hygroscopic properties since they were resistant to deterioration. Reed panels with bituminous coatings first debuted at the beginning of the 20th century, but they did not take off due to their flammability and unstable nature. Hemp and fiber-glass however are considered as two of the biggest examples of organic insulation materials.

Inorganic Insulation:

During the industrial revolution, a number of artificial materials were produced as well in addition to organic materials. By the first third of the 1900s, they had mostly replaced natural materials due to their durability, fire resistance, and water resistance, among other benefits.

Starting with mineral wool products, since natural asbestos is a fibrous mineral, its advantages (fire resistance and high tensile strength) have been known since the dawn of humanity. In Finland, 3000-year-old log dwellings with asbestos chinking have been discovered by archaeologists. Only the ancient Greeks made substantial use of asbestos, which was also employed by the ancient Egyptians to reinforce their clothing. The flame-resistance of asbestos allowed for its usage in areas that were subject to high heat. During the industrial revolution, asbestos was well known as a material used as insulating material. It was utilized in the manufacturing sector to insulate chimneys, steam engines, boilers, and pipes. Later, it was utilized in the production of domestic appliances like refrigerators, irons, and hair dryers as well as in the automotive industry (brakes, clutches).

Even in antiquity, asbestos was recognized to have negative effects, but until the early 20th century, no one paid any attention to them. The first condition specifically linked to asbestos was described by an Austrian physician in 1897. In 1906, there was the first confirmed asbestos-related death. Asbestos use was outlawed in several nations throughout the world as the risks became clearer. However, natural mineral wool is created from effusive rocks when molten lava is transformed into fluffy fibers by escaping steam. Hawaiian Island natives who lived close to volcanoes utilized this material to cover their houses.

The ability to create threads from heated glass was first found by the ancient Egyptians and Venetian glass-makers, who used them to decorate their vessels. However, the mass production of fiberglass was not made practical until the development of fine set machines.

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Hemp:

Introduction:

CO^2 amount sent into the atmosphere can be reduced by employing hemp insulation.

Figure 10. (Hemp: plant and Fiber).

Hemp has high insulating characteristics and is totally natural insulation material. The hemp plant is the source of hemp. Hemp fibers are strong and woody, making them ideal for making hemp wool. Hemp wool can be used as an eco-friendly insulating material because it is a great insulator. The hemp plant can thrive in virtually any soil and is simple to cultivate. The plant also grows quite quickly, reaching a height of 4 meters in just 100 days. Hemp has the ability to filter the air as well since it absorbs a huge amount of CO_2. Hemp wool can be found as insulation boards or insulation blankets (batts). These are simple to install and can be sectioned into different sizes. The hemp insulation boards are connected to one another tightly and have a strong structure and therefore thermal bridges can be prevented as a result. In order to enhance the heat gain rate, cornmeal or polyester may occasionally be added when making hemp insulation. The thickness of the boards ranges from 3 to 19 cm whereas the batts range in thickness from 3 to 8 cm. Hemp is an ecological insulating material, making it incredibly eco-friendly. In addition, hemp material has many additional benefits, such as being totally recyclable, not irritating to the lungs or skin, contains no dangerous elements, resistant to bacteria and mold, has no smell, good thermal and acoustic insulation, low energy consumption, and moisture-regulating material.

History background:

One of the first crops that humans tamed, hemp is thought to have come from Asia according to researchers [2].
Bits of hemp fabric and other hemp-based goods have been found in tombs going all the way back to 8000 B.C. according to [2]. Hemp was also grown in China 4500 years ago to produce fiber, seeds, and oil for a variety of uses. For example, cords imprinted on ancient ceramic shards with hemp residues and pieces of hemp paper have been found. Hemp extracts were reportedly utilized to treat a variety of illnesses, according to ancient Chinese literature. The pharaohs of ancient Egypt also utilized hemp, as evidenced by the discovery of hemp-based fabric in the tomb of Pharaoh Alchanaten, which dates back to 1200 B.C.
For centuries, hemp fibers were used to make clothing, shoes, cordages, carpets, tarps, maritime ropes, sails, and nets, as well as paper. Hemp straw was also used for agricultural purposes, and as waste to be burned and, more recently, as fuel to power farm equipment. Hemp seeds were consumed for nutrition, and hemp oils were used for a variety of purposes, including cooking and personal care. According to several authors [2], the leaves were also used as mulch, compost, and animal bedding.
However, hemp production declined in the mid-19th century as a result of the decline of the sailing fleet, competition from cotton and jute for cloth products, and later due to the rapid development of synthetic fibers [2]. The growing of hemp was outlawed as well in most of the Western nations as well as North America in the 1930s. This led to a great deal of uncertainty as well as social, political, and moral controversies.
Not for too long, Schultes expressed the importance of the growth and utilization of hemp as he wrote: “Hemp is a green, very abundant and ubiquitous plant, economically valuable, a versatile and multi-purpose product, possibly dangerous and certainly in many ways mysterious” [6]. And therefore, from an agricultural, industrial, and scientific perspective, hemp cultivation was revived in the 1990s worldwide [6]. Indeed, since the 1990s, there has been an increase in interest in the commercial production of hemp and other "forgotten fibers" in Europe and North America. This is primarily because of the growing awareness of the importance of conserving natural resources, preserving energy, and converting biomass into bioproducts and biofuels [2].
As a result, hemp is considered to be an important crop with unique agronomic properties that produce raw materials, such as fibers and oil, ideal for a variety of possible applications. It swiftly discovered concrete industry uses, for example, hempcrete was developing into a practical substitute for conventional building materials, especially for insulation, panels, and roofs [2]. In order to reduce carbon dioxide emissions, it was important to use sustainable and environmentally friendly hemp-based materials for building insulation and construction.

Hemp as an insulation material:

Figure 11. Hemp panel wallboards made from 100% fibers.

Because of their hygrothermal qualities, natural fibers like hemp fibers offer a sustainable alternative to the conventional synthetic fiber materials for usage in a variety of applications

Doi: 10.21608/ERJENG.2023.218976.1190

in building construction. Several commercial items with different densities that mimic concrete, wood, and even plastic can be produced with hemp-based materials. These materials gain from the mechanical properties of the hemp fibers plus the natural benefits of employing plant matter. Hemp-based biomaterials have a variety of additional benefits over more well-established mineral and oil-based substitutes. These construction materials are strong, light, inexpensive to create, fireproof, waterproof, self-insulating, mold and moisture resistant, highly breathable, insect resistant, and have good heat resistance in the winter and coolness in the summer. Also, the materials are perfect for mitigating the effects of earthquakes, floods, and other natural calamities [6]. Additionally, it is asserted that the usage of hemp-based building materials is advantageous from an environmental standpoint because they capture carbon dioxide. The lack of durability assurances, however, is the fundamental drawback [6]. Hemp fibers are mostly utilized in building insulation, such as insulation wool and other insulating materials. According to the European Industrial Hemp Association, insulation is hemp fibers' second most significant current use. Furthermore, useful for acoustics and soundproofing purposes, these fibers can be used.

Insulating properties [3]:

- Heat storage capacity: 1600-2350 J/kgK
- Volume mass: 30-42 kg/m³
- Diffusion resistance: 1-10
- Fire class B2
- Lambda value: 0.038 W/mK

Rockwool:

Introduction:

Rockwool insulation is made of volcanic rocks that are melted at a temperature of 1600°C and then spun into a bundle of wool.

Figure 12. (Rockwool Board).

Rockwool insulation is held together by resins and oils, which also give the substance waterproof properties. Rock wool can be used to insulate practically every part of a building, including the walls, roof, and floors. Not only does rock wool provide thermal insulation, but it also provides excellent features in terms of noise and fire. As a result, it can also be used to block sound and protect against fire. Rock wool is another mineral-based substance. This suggests that it lacks an organic breeding habitat, making rock wool totally resistant to molds and rot. Some of the advantages that rockwool insulations hold include their unchanged insulation value, vapor permeable material, which means that moisture can easily be released without causing and problems, and finally the properties rockwool got in terms of sound insulation and fireproofing.

History background:

According to [3], construction worker Henrik Johan Henriksen and brickyard owner Valdemar Kähler established Rockwool as Korsr Stenforretning in 1909 as a gravel mining business. In 1935, Citation Hanna 2010 stated that based on a license Finn Henriksen obtained while travelling to the United States, a production of mineral wool (stone wool) was started there. The production of insulation had been the company's only focus by 1939.

Rockwool as an insulation material:

In a smelting furnace heated by gas, where steam or air is forced through it, the raw material for rock wool (limestone or basalt) is melted. Then, with the aid of high-speed spinning machines, fine, entwined fibers with a diameter of 6 to 10μm are produced. The addition of a binder substance (oil emulsion, phenol-formaldehyde resin) occurs during this process.

Insulating properties [3]:

- Heat storage capacity: 1030 J/kgK
- Volume mass: 30–180 kg/m³
- Diffusion resistance: 1
- Fire class A1
- Lambda value: 0.039 W/mK

Fiberglass:

Introduction:

According to [3], Fiberglass is a type of material that is mostly made of glass and is utilized in a wide range of industrial, commercial, and residential applications.

Figure 13. (Fiberglass).

In addition, fiberglass is employed in the manufacture of items as diverse as car bodies, boat hulls, arrows, roofing, shower curtains, and tent poles. As an insulator, it prevents the rapid transfer of heat, cold, and sound through buildings, vehicles, and airplanes. It provides a handy way to boost energy efficiency by keeping rooms cool in the summer and warm in the winter by trapping pockets of air. Because it doesn't provide a fire threat, fiberglass is a desirable option for home insulation. Thermal insulation (made of fiberglass and its substitutes) is thought to conserve up to 40% more energy

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than is lost during production, saving 12 times as much energy overall.

History Background:

According to [3], both the Phoenicians and the Egyptians of antiquity produced glass, and they both turned it into fiberglass or glass fibers. Glass fibers were available to many other civilizations. The glass fiber produced by the majority of these was quite coarse and was only produced in tiny quantities at a time. They only employed this fiber for adornment, not realizing its potential.
John Player invented a method in 1870 for mass-producing glass strands using a steam jet procedure to create mineral wool. This substance served as a reliable insulator.
A form of fiberglass cloth was given a patent in 1880 to Herman Hammesfahr. This fiberglass fabric was woven with silk. This fiberglass fabric was woven with silk. It was flame resistant and robust.
As with many scientific breakthroughs, the first glass fibers of the kind that we now know as fiberglass were created accidentally. In order to create an airtight seal, Dale Kleist, a young researcher with Corning Glass, had been attempting to fuse two glass blocks together. Unexpectedly, a stream of molten glass was struck by a jet of compressed air, which caused a shower of glass fibers and demonstrated to Dale how simple it is to make fiberglass.
To further improve the product, Corning Glass teamed up with Owens-Illinois, another business that had been experimenting with fiberglass, in 1935. They only had one "s" when they patented Fiberglas in 1936, after which the two businesses joined to form Owens-Corning in 1938, which is still operational today. They looked into the possibility of spinning the fibers into a fabric-like substance in the late 1930s and early 1940s. The use of heat for treating and cleaning Fiberglas fabric advanced in 1941. The heat treatment increased the fabric's elasticity and was crucial in preparing Fiberglas fibers for use as reinforcement in plastic laminates.
A polyester resin patent was granted in 1936 to Carlton Ellis of DuPont. To create a composite, polyester resin and Fiberglas can be mixed together. By improving the curing process, the Germans advanced the manufacture of polyester resin. Owens-Corning began manufacturing fiberglass and polyester aero plane parts for the war effort in 1942. These low-pressure plastic laminates were created from the patented fiberglass cloth that had been resin-impregnated.
Ray Greene made the earliest mention of a composite boat in his 1937 statement. Regarding fiberglass composites, Ray had been collaborating with Owens Corning. He did create a composite sailboat, but he refrained from commercializing the invention because he was seeking the ideal plastic for the composite's resin. He created a day Sailer in 1942 using a fiberglass and polyester resin composite. And practically every American family owns some kind of fiberglass item today. It might be a washbasin tap, a shower or a bathtub. It might be an automobile or a boat. Or possibly the walls have fiberglass insulation. Fiberglass composites have so many applications that the list might never end.

Fiberglass as an insulation material:

Quartz sand, limestone, dolomite, and 50–60% recycled glass are all ingredients in the production of fiberglass, which is first melted at a temperature of 1420–1550 °C. Tiny heated holes are used to inject the molten glass into rapid air streams. Very long and thin fibers are produced as a result of this process. To create insulating blankets, binder ingredients (phenol-formaldehyde resin) are filmed onto their surface.

Insulating properties [3]:

- Heat storage capacity: 800 J/kgK
- Volume mass: 25 kg / m³
- Diffusion resistance: 1
- Fire class A2, S1, d0
- Lambda value: 0.040 W / mK

Conclusion:

Table 5. Summary for literature review

Criteria	Hemp insulation	Rockwool insulation	Fiberglass insulation
Image			
Production	Strong fibers of hemp tree	Volcanic rocks that melt at a temperature of 1600 degree C	Made of recycled glass fragments and pure sand
Forms	Blankets Boards	Boards	Blankets Sheets
Thickness	3 - 8 cm (blankets) 3 - 19 cm (boards)	3 – 10 cm	2.5 – 6.5 cm
Heat storage capacity	1600 – 2350 J / kgK	1030 J / kgK	800 J / kgK
Density	30 – 42 kg / m3	30 – 180 kg / m3	25 kg / m3
Thermal conductivity	0.038 W / mK	0.039 W / mK	0.040 W / mK

The aim of this literature review was to consider the variety of types of insulation materials (hemp insulation, rockwool insulation, fiberglass insulation). Several aspects were discussed in the study such as:

1. The history of each insulation material.
2. The production of each material.
3. The forms and thickness.

The thermal properties for each insulation materials.
The effectiveness of insulation materials in hot area are best resulting when:

- Installation is done as per the instructions from the factory.

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- Choosing the optimal thickness for the insulation materials installed based on the thermal charts in the environment of the industrial building.
- Preventing any thermal bridges when installing the insulation materials.
- Well maintenance for the insulation materials as instructed by the manufacturer.
- Which provides better results in terms of thermal comfort, sustainability and energy efficiency.

Applied Studies:

Introduction:

In this chapter, a sample model shall be done using environmental simulation tools (EST).
Performative Design (PD) is the implementation of sustainability aspects in simulation tools and this helped change design methods to fit with sustainability. Some of the EST used to analyze building energy are Design Builder, Sefaira Architecture, Revit and Cypetherm suite.
In this research, DesignBuilder will be used to simulate energy performance of a sample model composed of 1 internal zone and will be created in the zone of Cairo, Egypt with a conventional wall composed of 3 layers (2cm cement mortar, 25 cm brick, 2 cm cement mortar). This will be the base model to be compared with six different specimens of modified walls with 3 different insulation materials having the same thickness to perform a comparative analysis between all 7 cases in terms of thermal comfort and energy efficiency.

Model specifications:

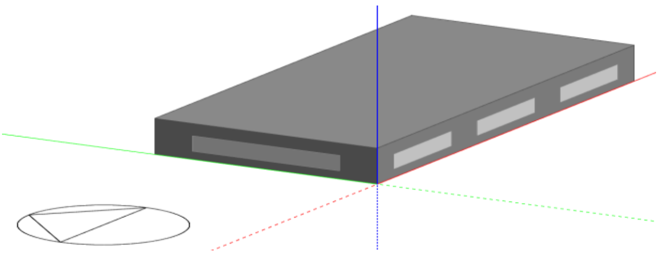

Figure 14. (Design Builder model).

A sample model is created that acts as an industrial building with 1 internal zone, 4 windows and 1 main door in the location of Cairo, Egypt. It will be composed of a single double-height floor with a total footprint of 100 m2. The total height of the model is 6 meters. The simulation will be performed on the whole model on an annual basis, knowing that the thermal conductivity of the brick is 0.65 W/mK. The simulation will be performed using Design Builder software of Energy Plus simulation engine.

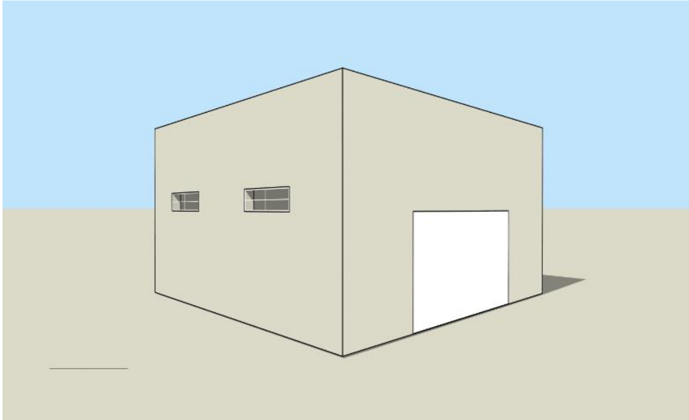

Figure 15. Design builder base model.

Table 6. Design Builder model general data

General industrial building design data:

Building type	Industrial building
Floor number	One floor
Building height	6 meters
Building area	100 m2

Weather data file:

The weather data file used for this study is EGY _ AL QAHIRAH _ CAIRO INTL AIRPORT _ ETMY.stat.

Table 7. Design Builder model Weather data

Weather data file	EGY _ AL QAHIRAH _ CAIRO INTL AIRPORT _ ETMY. epw
Type	Hourly weather data
Location	Cairo, Egypt, Africa WMO Region 1
Source	Egyptian Typical Meteorological Year (ETMY)

Simulation steps:

- Install Cairo, Egypt weather file data (Fig. 16).
- Model construction (Fig. 14).
- Application of different types of insulation materials on each model's facades.
- Simulation of each type in the same climatic region.
- Measuring energy consumption of each case.
- Using Optimization and selecting all cases to get optimal design.

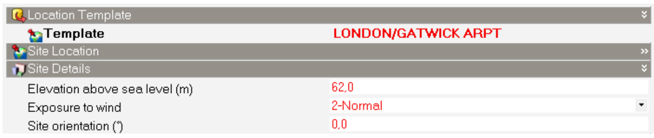

Figure 16. Location and site details.

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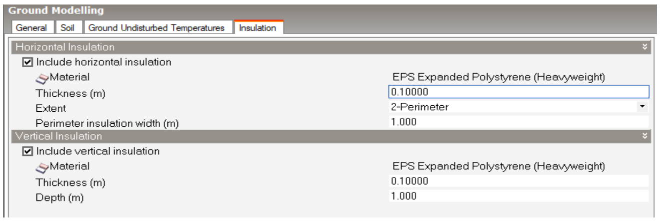

Figure 17. (General Modelling).

Model settings:

- Wall of base model has 3 layers:
  - 2 cm mortar
  - 25 cm Brick
  - 2 cm mortar
- Windows are 30% glazed.
- 5 working days from 8 am till 6 pm
- Roof is inaccessible.
- Ground floor and roof layers kept to Egyptian standards.

Specimen details:

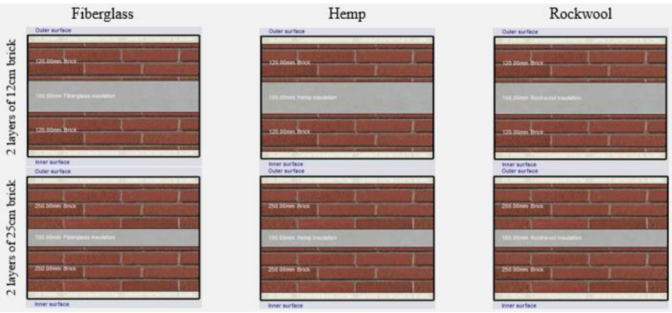

Figure 18. (MODEL SPECIMENS).

The Design Builder software simulation was done on 7 specimens on an annual basis. The specimens were configured as follows:

1. Base Specimen with 2 cm mortar layer on the 2 sides of a 25cm thick brick.
2. 2 cm mortar + 12 cm brick + 10cm fiberglass insulation + 12 cm brick + 2 cm mortar.
3. 2 cm mortar + 12 cm brick + 10cm hemp insulation + 12 cm brick + 2 cm mortar.
4. 2 cm mortar + 12 cm brick + 10cm rockwool insulation + 12 cm brick + 2 cm mortar.
5. 2 cm mortar + 25 cm brick + 10cm fiberglass insulation + 25 cm brick + 2 cm mortar.
6. 2 cm mortar + 25 cm brick + 10cm hemp insulation + 25 cm brick + 2 cm mortar.
7. 2 cm mortar + 25 cm brick + 10cm rockwool insulation + 25 cm brick + 2 cm mortar.

Simulation settings:

- Simulation is set on annual basis.
- HVAC system was set to OFF.
- Simulated data were total site energy and ASHRAE discomfort hours.
- EnergyPlus server was used to simulate the data.

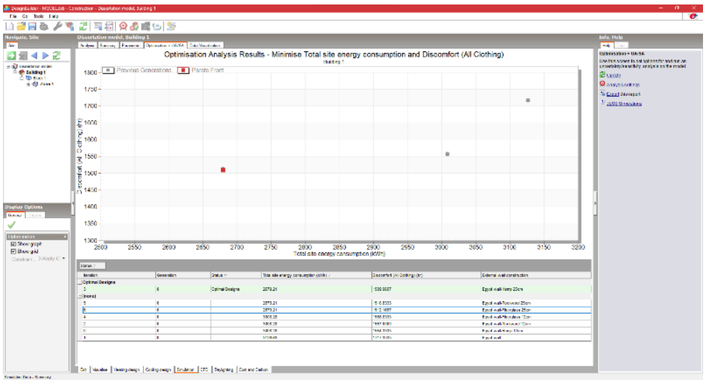

Figure 19. (Optimization results).

Results and Findings:

Introduction:

The main aim of this study is to recommend the best insulation material to be installed within the walls that has the ability to enhance indoor thermal comfort and achieve better energy efficiency. This aim will be achieved by minimizing the energy consumption and enhancing thermal performance. The research method is an industrial building placed in Cairo, Egypt. Simulation has led to analyze whether these different types have the capability to achieve their objectives or not. These obtained data were done by using design builder software; the results of the simulation investigate the total site energy consumption per year and the total discomfort hours per day.

Results and findings:

The simulation shows that using hemp was the optimal design for thermal comfort in both 12cm specimen and 25 cm specimen.
The 25cm hemp specimen showed 12.1% improvement in thermal comfort and 14.1% in energy efficiency compared to standard 25cm brick wall.

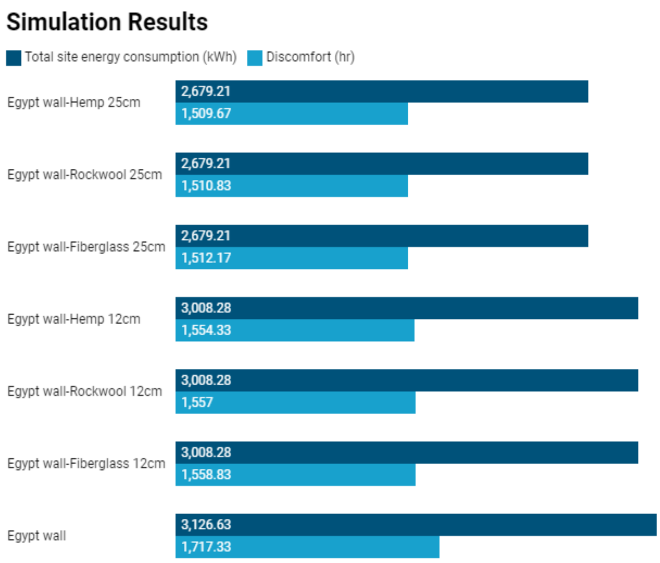

FIGURE 20. (RESULTS).

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Table 8. Simulation Results Comparison

Criteria	Total site energy	% Improve	Discomfort hrs.	% Improve
Building without insulation	3126.63	0	1717.33	0
12 cm wall + fiberglass	3008.28	3.8	1558.83	9.2
12 cm wall + Rockwool	3008.28	3.8	1557	9.33
12 cm wall + Hemp	3008.28	3.8	1554.33	9.49
25 cm wall + fiberglass	2679.21	14.3	1512.17	11.95
25 cm wall + Rockwool	2679.21	14.3	1510.83	12.02
25 cm wall + Hemp	2679.21	14.3	1509.67	12.1

Conclusion:

By applying the simulation by "Design Builder" software of "Energy Plus" simulation engine on a base model of an industrial building with a conventional 25 cm thick wall, along with 6 other specimens, the conclusion obtained was:

- Hemp insulation was the best over the 3 insulation materials used in this research.
- The proper installation for the insulation material in the walls matters with the results and can affect them significantly.
- For best results for energy efficiency, using 25 cm wall + insulation material + 25 cm wall is recommended.
- As the % difference in discomfort hrs. is not significant between 12 cm wall specimen and 25 cm wall specimen, it is not recommended to use the 25 cm wall specimens.

III. Conclusion and Recommendations

Conclusion:

This research and the analysis of the data extracted brought up to conclusion that there many approaches and varieties of the usage of insulation materials and the appropriate insulation material can be decided based on the targeted objective for the occupants. Insulation materials proved that they can significantly improve energy efficiency and thermal comfort in spaces, and this can prevent extra electricity bills for the owners of the industrial buildings and increase the productivity of workers by reducing the chances of heat stresses in industrial buildings.

The usage of insulation materials proved to be having another good advantage: that a building design does not need to follow a particular façade design or style because after the installing of the insulation material, it would not be visible neither outside nor the inside of the building.

In current construction advancements, using insulation materials in wall construction have proved to be significant. However, the main let down is that it is a more costly technique as compared to using conventional walls because in requires double the amount of bricks in the construction of external walls along with the cost of the insulation itself. However, many experts believe that the long-term cost-effectiveness of using insulation materials in building facades was much higher.

The data collected helps to conclude that insulation materials benefited the indoor environment as follows:

- Improvement in air quality indoors
- Enhance thermal comfort throughout the year.
- Improved productivity of workers

Recommendations:

- Never neglect sustainability aspects for the sake of reducing the construction costs.
- During the designing phase, it is recommended to use a simulation software to make sure that the design is optimized to run efficiently.
- Buildings need to be built with proper orientations to take full advantage of passive techniques of ventilation to make sure the electricity expenses are kept under control and assure reasonable thermal comfort.

Prospects of future research:

- Further improvements for designing industrial buildings to match thermal comfort standards.
- The availability of insulation materials worldwide.
- Design guidelines for industrial buildings.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

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