-A TECHNO ECONOMIC FEASIBILITY STUDY TO EVALUATE THE ENERGY REDUCTION OF PHASE CHANGE MATERIAL WITH MYCELIUM INTEGRATION IN RESIDENTIAL APARTMENTS, IN THE CASE OF AMMAN

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Abstract

This study investigated the feasibility of reducing energy demand in residential buildings using a new material called "Phase Change Material with Mycelium Integration (PCMMI)", considering the climatic conditions in Jordan, Amman. Feasibility study in this research was evaluating the materials cost (with and without PCMMI) versus the return on the energy savings. All costs calculations where in Jordanian Dinars (JD). Parametric analysis of a room in the simulated residential building was studied (using Autodesk-Dynamo program) to compare materials' cost and energy savings throughout the year (techno-economic feasibility study). The results of the techno-economic feasibility study showed that by adding a layer of PCMMI (costs JD 7/m^2), the room materials' cost increased by JD 469, but it would reduce JD 600 of the annual energy consumption cost as compared to building materials currently used.

Keywords: Energy reduction; energy savings; parametric analysis; high-lands climatic zone.

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1. Introduction

Jordan, a country facing limited natural resources such as natural gas and crude oil, heavily relies on imports for 97% of its national energy needs, which costs around 17% of its Gross Domestic Product (GDP). (1) The residential sector alone accounts for 21% of energy consumption and 43% of total electricity consumption. Due to this dependence on foreign energy resources, Jordan encounters numerous energy challenges, relying on neighboring countries for over 95% of its energy supply. Natural gas constitutes 88% of the country's electricity generation. (2)

Residential buildings rank second in energy consumption after the transportation sector, and the building sector as a whole contributes to around 40% of global energy consumption, responsible for a significant portion of greenhouse gas emissions. To address rising energy costs and enhance energy efficiency, there is a growing interest in improving heating and cooling systems in buildings. (1)

By adopting available technologies, new buildings have the potential to reduce their energy consumption by approximately 30% to 80%. Thermal insulation plays a crucial role in reducing the energy requirements for residential heating and cooling (3). However, despite adopting insulation codes since the early 1980s, the implementation and enforcement of these codes have been limited in Jordan. As a result, the implementation of thermal insulation in residential buildings varies based on factors such as income, ownership type, and education levels. Improving energy performance in buildings is a significant area of research, aiming to introduce new materials, systems, and technologies that reduce dependence on fossil fuels. (4)

Phase Change Materials with Mycelium Integration (PCMMIs) have emerged as a promising technology for Thermal Energy Storage (TES) applications, enabling passive and sustainable utilization of solar thermal energy. PCMMIs can be utilized in the building envelope as a thermal mass. The material stores heat during hot outdoor conditions, undergoing a phase change from solid to liquid. Encapsulated within a specific container, it provides daytime cooling by reducing heat transfer from the envelope to the interior. During nighttime, as the outdoor temperature drops, the PCMMI solidifies and releases stored heat, providing interior heating (5) . This leads to a reduction in heating and cooling loads, electricity consumption, and energy requirements during peak periods. Mycelium, a root system of fungi, holds great potential. While often unseen, it surrounds us and can be harnessed for various applications.(6)

In this study, the focus will be on comparing a residential building in Jordan with its current materials with a simulated residential building that has PCMMI (Enhanced material) to see the affection of the new material on the thermal performance of the building and if it reduces energy consumption.

The methodology conducted a techno-economic feasibility study (TEF) illustrate the prices of the current construction materials before adding the PCMMI layer, and after adding the PCMMI layer. Then comparing the energy consumption in both cases, by using a dynamo script, to calculate the amount of energy reduction after adding the PCMMI.

Energy security is one of the most significant challenges facing Jordan. Giving an address to it, will reduce the country's burdens and freights to ensure it sustainability. Jordan imports 96% of its energy resources (1), and its existing building stock is a high energy consumer with a performance that has a level below the standards of new construction.

Accordingly, the problems investigated in this research are directly connected with the evaluation of heat flows (the emergence of heat throughout the buildings envelope in different seasons of the year). In addition to the enhancement and reinforcement of the heat storage capacity of the systems (thermal insulation, and the usage of stored heat in the material of PCMMI), taking advantage of latent heat storage capacity that is involved with the PCMMI (phase change processes). This research focuses on the integration of both PCM and mycelium in architecture (PCMMI).

The energy efficiency ratings of Jordan's existing buildings are substantially lower than what the country's Energy Efficient Building Code mandates. Although the Local Thermal Insulation Code has been set since 2009, constructors have historically disregarded it to avoid the higher costs that associated with it, which led to a huge number of thermal inefficient buildings.

Hypothesis Assessment: The enhanced material will help reducing energy consumption in buildings, which will result in a significant drop in heating and cooling demands.

Research question: Can the PCMMI reduce the energy demand in residential buildings?

Research Objective: To determine the feasibility of implementing TES (Thermal Energy Storage) technology in the buildings envelope to improve the thermal system efficiency and reduce operating energy costs in peak climatic conditions.

A previous study of Life-Cycle Assessments of Sculptured Tiles for Building Envelops in Mediterranean Climate studies the life cycle assessment of conventional cement mortar enhanced with mycelium for thermal insulation of a typical residential building in a hot Mediterranean climate. The article studied the design of sculptured tiles (cement with mycelium) by understanding the materials characteristics and taking into consqideration the variables, which were local climate and construction technology. The findings of this study evaluated the environmental damage/benefits or replacing conventional flat tiles with sculptured tiles for a typical residential building. (7)

Another study Thermal Energy Storage with Phase Change Materials (PCMs) for the Improvement of the Energy Performance of Buildings where it studied the usage PCM in different typologies of buildings, the results shows that PCM integrated building materials lead to higher energy savings. Taking into consideration that the study was held in a Mediterranean climate area. (8)

PCMMI was studied by multiple researchers and its effectiveness in reducing energy demand. This thesis is the first study to investigate the feasibility of applying Phase Changing Materials into residential buildings in Jordan-Amman, contributing to its climatic conditions and locations. The study resulted in proving that PCMMI performs effectively in “high-land” climatic zone. Using the results of this research, architects and designers will be able to determine the impact of reducing energy demand in residential buildings, so they can apply the new enhanced material which acts as a thermal mass. They will also be provided by numerical and computerized methods suggested for simulating the residential buildings and evaluating the direct impact of using PCMMI in the buildings.

2. Literature Review

Phase Change Material (PCM)

Phase Change Materials (PCMs) are substances that undergo a transition from solid to liquid or vice versa based on the surrounding temperature. They have the ability to absorb and store heat as latent heat within the material itself, causing a phase change from solid to liquid when heat is absorbed, and from liquid to solid when the material releases the stored heat as the temperature drops. (9)

Phase Change Material with Mycelium Integration (PCMMI)

Phase Change Material with Mycelium Integration (PCMMI) refers to the combination of PCM and mycelium. PCMMI research focuses on using inorganic salt hydrate PCM with mycelium integration, which has a higher heat capacity compared to other PCMMI classifications (10). Inorganic salt hydrate PCM consists of salt, water (as a crystal matrix), and mycelium. These materials possess a significant latent heat and a melting temperature range of 15°C to 117°C (11). Salt hydrates are widely studied for their applications in thermal energy storage systems due to their availability and relatively low cost (12)

To ensure safety, the integration of mycelium with building materials has been recognized as safe, as indicated by the Generally Recognized as Safe Notice (GRASN) submitted by Sustainable Bioproducts. (13)

In the context of Jordan, PCMMI utilizes salt hydrates like $CaCl_2.6H_2O$ (Calcium Chloride Hexahydrate), which is abundantly available in the Dead Sea. The Dead Sea's declining water level causes salt accumulation on its lakebed. (14) The region's salt evaporation ponds are used to extract sodium chloride and potassium salts for various applications, including the production of PCMs for building envelopes (15). As the water level decreases, the lake becomes saltier, leading to the formation of salt layers at the bottom (16). Mycelium, on the other hand, can be sourced from industrial areas as it grows on industrial waste, making it easily accessible and inexpensive as a raw material for testing (17).

Climatic Zone
Precise Melting Temperature

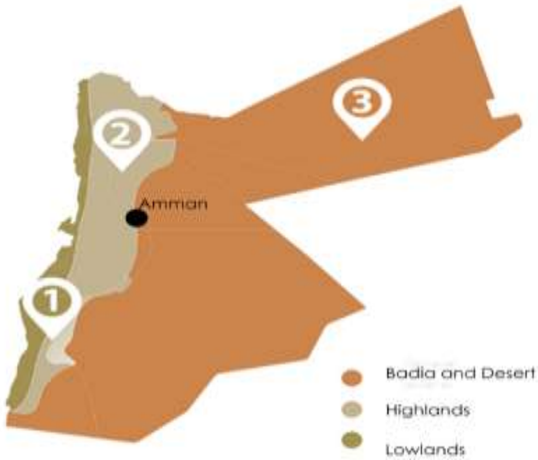

Figure 1 *Jordans Three Regions*

PCMMI is a phase change material that changes its phase by absorbing heat and transitioning to a liquid state, then solidifying by releasing heat. It has a specific melting point and solidification temperature (sharp melting
point), which raises two important considerations: (i) determining the appropriate melting point for Amman's weather, and (ii) ensuring that the PCMMI remains in a liquid state without leakage. To define the precise melting temperature for PCMMI, the climatic conditions in Amman are taken into account, as it serves as the case study in this thesis. Figure 1 (Jordans Three Regions) illustrates the regions of Jordan: the Jordan Valley (known as the Ghore Region) with a Mediterranean climate, the Highlands Region (where the case study is located) with cold winters and hot summers, and the Desert Region (Badia) covering the majority of the country's land as a semi-desert area. An analysis of Amman's average temperatures (in the Highlands) reveals that the peak average temperature reaches around 27°C. Therefore, the PCMMI material should have a melting temperature close to this range. In the case of CaCl2.6H2O (Calcium Chloride Hexahydrate) with Mycelium integration, its melting temperature is reported to be 25°C (18).

Microencapsulation in PCMMI

PCMMI is a phase change material, which turns into liquid if the exterior temperature exceeds its melting point. To avoid its leakage a coverup is needed. Microencapsulation is a container for the PCMMI, the container is a sheet 100mm in thickness, the sheet has empty bubbles. As seen in Figure 2 (Microencapsulation in PCMMI), the sheet has empty bubbles where the PCMMI's mixture should be poured prior to the construction. The sheets get filled with the mixture of PCMMI having the appropriate characteristics as studied and mentioned in the literature (12).

Figure 2 *Microencapsulation with PCMMI in site*

3. Methodology

Research Area and Climatic Zone

In the methodology the questions of this study will be answered in addition to proving the hypothesis or rejecting it. The methodology focuses on a comparative output, by comparing the residential building (with its current material's thermal performance and energy demand) with the same residential building after adding PCMMI to its layers. The way of comparison depended on simulating a residential building in Amman with its current materials then simulating it after adding a PCMMI layer.

Analyzing the residential building's envelope helps to understand the thermal performance of its different components. Prior to the calculation of the thermal performance, some information is needed, which are climatic conditions, the desired indoor temperature, quality conditions and the building characteristics. As mentioned, Jordan has three climatic zones, and this thesis will study a residential building located in Amman in zone number two (highlands) in Khalda.

- **More specifications on the location:**

Latitude: 31.59 Deg.N
Longitude: 35.5 Deg.E
Elevation: 980m

- **General Information about the residential apartment:**

Floor Area= 200 m^2
Ceiling Average Height = 3m
Set Point of Heating = 15
Set Point of Cooling = 24
Occupancy Density = 40 m^2/person (a family of 5)

Parametric Analysis

The parametric simulation of the residential building, where two adaptive points were simulated: Point A was an external heating point with adjustable temperature, and Point B was an internal sensor. Numerical Simulation to Calculate the Thermal Performance of The Materials. The main point of using parametric analysis was to see how the residential building is affected by the climatic conditions of Amman in addition to the surrounding variables. The test that was done by a SketchUp-Plugin to estimate the heat transfer throughout the building's current envelope.
How was the Parametric Analysis Performed?

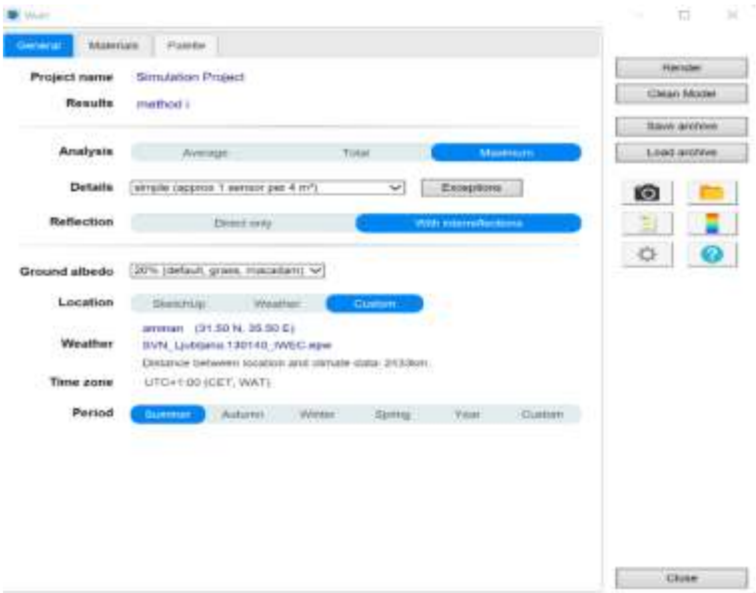

***Figure 3** Parameters*

The residential building had a climatic simulation using Autodesk software, where the climate of Amman was uploaded in addition to the location and time zone as illustrated in Figure 3 (Parameters). The parameters taken into consideration through the simulation were the climatic conditions on a year time zone and the location of the building. The parametric analysis was performed as per the following steps:

a) Identify the analysis: for a better output it is better to select maximum analysis, a sensor's maximum irradiance for the chosen period. W/m^2 is used to represent the value.
b) Details: at this bar, the number of sensors is identified, for this parametric analysis there was one sensor at each $4m^2$ of the surface area.
c) Reflection: in interreflections, energy from the sun and the sky is combined with reflections from nearby objects like the ground and building facades.
d) Ground albido - the ground Reflection factor.
e) Location: Global Positioning System (GPS) coordinates for the building. To create an accurate sky distribution, this information is combined with weather information.
f) Weather: annual weather file for the building.

After completing the simulation of the model with its current materials, the parametric analysis analyzed the hours by which the surface of the building is exposed to heat by color zones (Red as the highest heat exposure to blue which is the lowest). Figure 4 (Parametric Analysis Results) shows that the average heat exposure to the buildings envelope through the year is mainly yellow green, which is an average heat exposure.

Figure 4 *Parametric Analysis Results*

Techno-Economic Feasibilty Study
Feasibility study in is evaluating the materials cost (with and without PCMMI) versus the return on the energy savings. All costs calculations where in Jordanian Dinars (JD).
In the third stage, the feasibility study was applied to one room in the residential building as illustrated below in Figure 5 (Simulated Room). The room is in the same residential building, it is surrounded by two exterior walls. This room was chosen for feasibility testing as a result of the heat exposure shown in the parametric analysis. The calculations of the material costs were obtained from Jordan Wholesale Price Indexe (JWPI), 2021. (19)

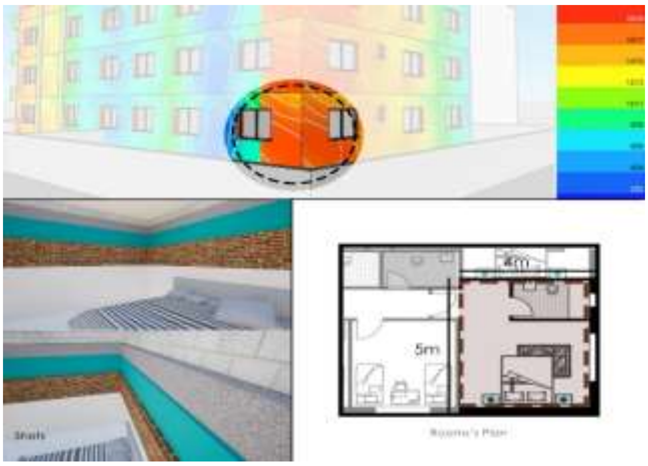

Figure 5 *Simulated Room*

Using the room area shown in Figure 5 (Residential building room) with dimension 5*4 in Area and 3 meter in height, Table 1 (Envelope of the current residential building materials costs) illustrates the prices of the layered materials. Taking into consideration that there is additional implementation cost 25% of the total material costs (20).
Using the information from Table 1 (Envelope of the current residential building materials costs), the material cost was calculated as followed:

a) Total cost of the materials in square meter = the area of the materials * the total price of the materials
b) Total cost of the materials in cubic volume = the volume of the materials * the total price of the materials
c) Total Envelopes construction price = Total cost of the materials in square meter + Total cost of the materials in cubic volume.

Table 1 *Envelope of the current residential building materials costs*

W01 Layers	Name	Thickness (mm)	Price in JD/m^2	Price in JD/m^3
1	Jordanian Stone	60	18	-
2	Castin-Site Concrete	80	-	40
3	Extruded Polysterne	30	3	-
4	Hollow Concrete Block	100	12	-
5	Cement Plastering	20	10	-

R01 Layers	Name	Thickness (mm)	Price in JD/m2	Price in JD/m3
1	Cement Mortar	20	9	-
2	Sand & Gravel	70	4	-
3	Water Proofing (bi-tumen roll)	4	12	-
4	Light Weight Concrete	100	-	40
5	Re-inforced Concrete Slab	300	-	62
6	Cement Plastering	20	10	-

S01 Layers	Name	Thickness (mm)	Price in JD/m2	Price in JD/m3
1	Cement Mortar	20	9	-
2	Sand & Gravel	70	4	-
3	Re-inforced Concrete Slab	300	-	40
4	Water Proofing (bi-tumen roll)	4	12	62
5	Light Weight Concrete	100	-	-

Building Material Costs with PCMMI

Figure 6 (Residential Building Room with PCMMI) shows the room that was chosen for feasibility testing as a result of the heat exposure shown in the parametric analysis. The calculations of the material costs were obtained from Jordan Wholesale Price Indexes (JWPI), 2021.The calculation will take the total cost that was calculated with the current materials and add the price of PCMMI with them to compare the additions. (19)

Figure 6 *Residential Building Room with PCMMI*

The area of the room is 4*5 m^2 with a height of 3m.

The cost of PCMMI per square meter is 7 JDs

- The total price of the wall with PCMMI = total price of the wall + the price with PCMMI
- The price of PCMMI in the Roof = the area of the roof * 7
- The price of PCMMI on the ground floor = the area of the ground floor * 7

After calculating the materials cost and comparing the cost of constructing the room with and without PCMMI, the next step in the feasibility was the calculation of energy consumption in the simulated building with its current materials and comparing the results after adding PCMMI. This was done by parametric analysis through Autodesk Dynamo.

Parametric Analysis to Evaluate Energy Performance

Determining the temperature distribution is important to calculate heat transfer. The energy equation is used to determine the temperature distribution.

Using the model shown previously in Figure 3, the parametric analysis was conducted by adding more parameters. An estimated energy consumption analysis was performed using: (i) the thermal performance of the materials with and without PCMMI (as calculated previously), (ii) time lag of each material and, (iii) material mathematical equations. The thermal performance and energy usage were evaluated. Multiple equations were used in the parametric analysis to add specificity to the outputs.

Energy Equations:

The energy equation contains certain terms that include velocity (V). Motion is a necessary condition for the existence of velocity. The momentum equation, which is derived from Newton's second law, must be solved to get the components of velocity.

The amount of radiation will change when the angle of each surface with respect to the horizon changes since the sun's radiation is angular. As a result, while the wall receives the same quantity of radiation, the roof does not. The following equation gives the amount of radiation that reaches a surface at an angle of (y).

Details of the parameters involved in equations (1-2) are reported in references (21, 22) that specifies each variable and its importance.

The energy equation must be solved to achieve heat transfer from the building.

The quantity of heat exchanged from the wall and roof can be calculated based on the ambient temperature and radiation intensity. It should be emphasized that the heat exchange between the room and the interior space, which is determined by the previous equations, is a crucial parameter in this study.

Taking into consideration the location and climatic conditions, where the case studied is in Khalda with the coordinates (31.95 ^{o}N, 35.5 ^{o}E).

Software's used: Autodesk Revit, Autodesk Dynamo. Figure 7 (Dynamo Heat Transfer Analysis) shows the parameters and adaptive points used in the algorithm of heat transfer analysis.

Software's used: Autodesk Revit, Autodesk Dynamo.

Some important inputs:

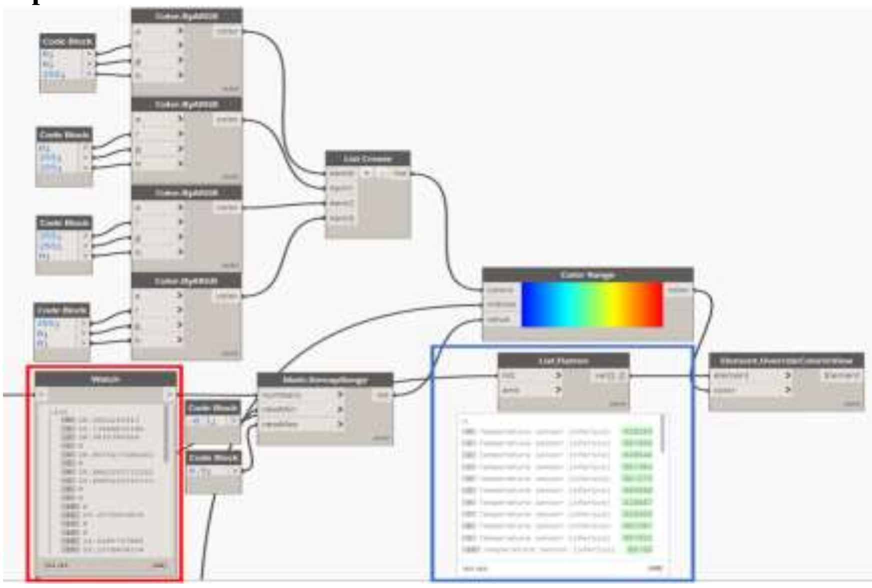

Figure 7 *Dynamo Heat Transfer Analysis*

Amman's comfortable temperatures in winter is (23.5-27 ^{0}C), in summer the comfortable temperature is (20-23.5 ^{0}C) (23).

- a feasibility assessment was performed to compare the effect of adding an extra layer in the envelope (with PCMMI) and monitor the amount of energy reduction. This method achieved the objective of this study "To determine the feasibility of implementing TES technology in the built environment to improve system efficiency and reduce operating costs, specifically about peak climatic conditions that is related with the heat storage and release".

4. Results and Discussion

Current Building Material Costs

A. External Walls material and labor costs Results

Estimating the cost of building two walls, given the first side is 5 meters in length and the other side is 4 meters, with a height of 3 meters.

- Total cost of materials per square meter = 43 JD/m^2 .
- Total cost of materials per cubic volume = 40 JD/m^3 (Additional costs implementations 25% of the total material costs [21]).

The total cost of installing two external walls in the room (Residential building room) with the current constructed materials is 1323 JDs.

B. Roof and Ground Floor Slab material and labor costs (22)

Using the room area of the (Residential building room) with dimension 5m*4m in Area and 3 meters in height. Taking into consideration that there's Additional costs implementations 25% of the total material costs (21).

Using the information from Table 1, The calculation will be as followed:

- Materials costs by area = the area of the roof*the total price per area
  Materials costs by area = (4m*5m) * 35JD
- Materials costs by cubic volume = the volume of the roof's materials (Concrete and reinforced concrete) *the total price per cubic volume

Materials costs by cubic volume in the roof = 452 JDs

Total roof material costs = 1152 JDs

C. Current **Ground Floor Slab material costs**

- Materials costs by area = the area of the ground floor slab* the total price per area

Total Materials costs by area = 500 JDs

- **Total ground floor material costs = 952 JDs**
- Materials costs by cubic volume = the volume of the ground floor's slab materials (Concrete and reinforced concrete) * the total price per cubic volume

Materials costs by cubic volume = 452 JDs

Building Material Costs with PCMMI

(For a room in the residential building with dimensions of (4m*5m) floor area and 3 meters of height)

A. PCMMI Price in the Walls

The price of PCMMI in the walls = the area of the walls * 7JD

- **The total price of the wall with PCMMI = 1512 JD**

B. Roof and Ground floor slab material costs with PCMMI

The price of PCMMI in the Roof = the area of the roof * 7

- **The total price of the roof with PCMMI = 1292 JD**
  The price of PCMMI in the roof = the area of the roof * 7 JD
- **The total price of the roof with PCMMI = 1092 JD**

Results of the parametric analysis, comparing energy consumption with and without using PCMMI in the layers of the residential building's ROOM shown in Figure 8 (Thermal Transfer Analysis in Walls) and Figure 9 (Thermal Transfer Analysis in the Roof)

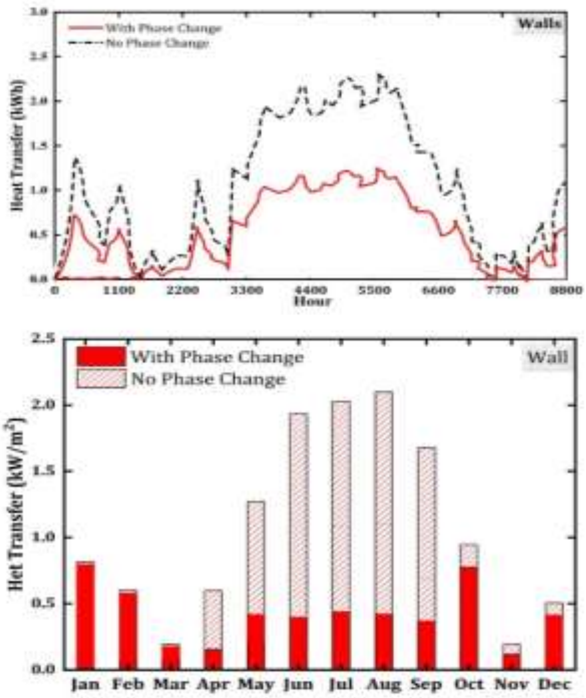

Figure 8 *Thermal Transfer Analysis in Walls*

Walls Thermal Transfer Analysis in Figure 8 (Thermal Transfer Analysis in Walls)

In a building with phase change, wall heat transmission is 6131 kWh, but it is 9242 kWh in a building without phase change. PCMMI reduces wall heat transfer by 35%, or 3293 kWh.

The Roof's Thermal Transfer Analysis in the room in Figure 9 (Thermal Transfer Analysis in the Roof), displays the monthly average heat exchange through the roof.

Phase change in the roof reduces heat transmission from 1982 kWh to 1291 kWh, a reduction of 34.9% or a 691 kWh energy savings.

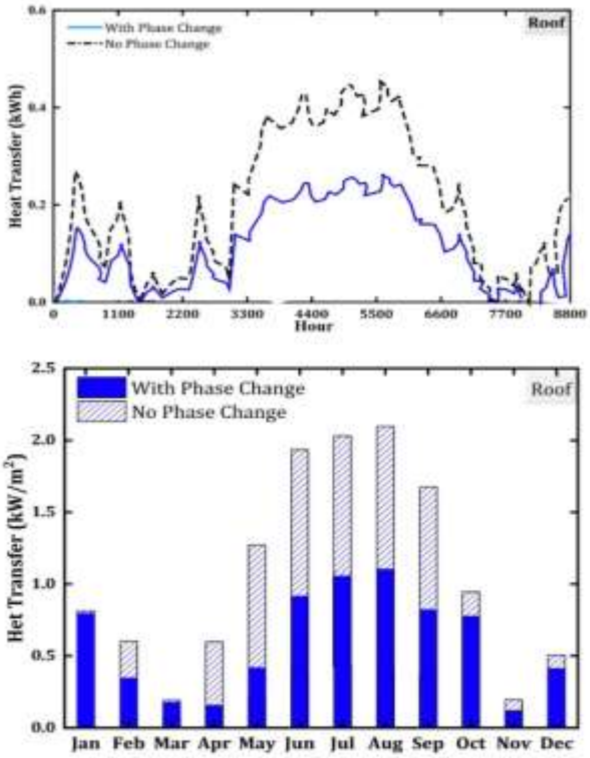

Figure 9 *Thermal Transfer Analysis in the Roof*

The price of kWh in Jordan is 0.15 dinars (National Electric Power Company, 2021), The amount of **energy reduction through a whole year is around 600 JDs in the residential room. (24)**

A feasibility study was conducted to illustrate the prices of the current construction materials before adding the PCMMI layer, and after adding the PCMMI layer. Then comparing the energy consumption in both cases, to calculate the amount of energy reduction after adding the PCMMI.

By using a room in the residential building, the cost of the walls materials, ground floor slab and the roof was calculated to compare it with adding PCMMI the results showed that:

i. The total cost of constructing the walls' current material was JD 1323, the roofs' material cost was JD 1152, and the ground floor material cost was JD 952 with a total cost of JD 3427. When adding PCMMI the cost of the component's materials was; walls JD 1512, the roof JD 1292, and the ground floor JD 1092 with a total cost of JD 3896. PCMMI added JD 469 to total room materials costs.
ii. The estimation of the energy reduction by using a parametric analysis (Autodesk Dynamo) illustrated that PCMMI performs best in Amman's climatic conditions during the months from April to October. The analysis showed that the wall heat transmission was 6131 kWh (compared to 9242 kWh in a building without phase change). PCMMI reduced wall heat transfer by 35%, or 3293 kWh energy savings. Phase change in the roof reduced heat transmission from 1982 kWh to 1291 kWh, a reduction of 34.9% or 691 kWh energy savings.

In conclusion, the parametric analysis on energy reduction in most months of the year with the climatic conditions of Amman, showed that **PCMMI added into the wall and the roof of a room can reduce heat exchange by up to 32%, which is equivalent to 3984 kWh energy saving.** The price of kWh in Jordan is JD 0.15/ kWh (24), **The amount of energy reduction through the year in the room is around JD 600, compared to PCMMI one-time added cost of JD 469, which means reduced energy cost through the lifetime of the building.**

A study called Heat Transfer Aspects of Using Phase Change Material in Thermal Energy Storage Applications, showed the ability of integrating mycelium with a type of PCM in the Mediterranean climates (25), conducted a feasibility study which showed that the PCMMI added 700 dollars to constructing a room but reduced energy demand by 28%. And this thesis study did comply with it. The way by which the reference studies the feasibility study is by estimating the reduction with 3 more energy equations in the parametric analysis that was done.

5. Conclusion

Jordan faces multiple energy challenges since it depends on the supply of foreign energy resources. This thesis investigated the feasibility of using a new material called Phase Change Material with Mycelium Integration (PCMMI) in the layers of residential buildings in Amman to reduce energy consumption. The study selected a residential building located in Amman, as residential buildings represent second sector in energy consumption in Jordan (1). The reason for choosing Amman is due to the development expansion, accounting for 46% of all constructed homes in 2019 (4). The study analyzed the energy consumption through the envelope of the residential buildings, considering its components, the exterior walls, the ground floor slab and the roof. The thermal quality of an envelope was studied by understanding the energy (heat) transfer aspects through the envelope.

Applying a techno economic feasibility study and comparing the added value of energy reduction with the added price of the PCMMI. The results showed that adding a layer of PCMMI added a one-time JD 469 to total room materials cost, will reduce its energy consumption per year by JD 600 in comparison with the current materials. The results of this stage were calculated by using a numerical simulation through Autodesk Dynamo.

In conclusion, the parametric analysis on energy reduction in most months of the year with the climatic conditions of Amman, showed that PCMMI added into the wall and the roof of a room can reduce heat exchange by up to 32%, which is equivalent to 3984 kWh energy saving. The price of kWh in Jordan is JD 0.15/ kWh (24), The amount of energy reduction through the year in the room is around JD 600, compared to PCMMI one-time added cost of JD 469, which means reduced energy cost through the lifetime of the building.

Using the results of this research, architects and designers will be able to determine the impact of reducing energy demand in residential buildings, so they can apply the new enhanced material which acts as a thermal mass. They will also be provided by numerical and computerized methods suggested for simulating the residential buildings and evaluating the direct impact of using PCMMI in the buildings**.**

Limitations and challenges of the study were due to Software Simulations, since Parametric analysis needed specific software's such as DYNAMO that was used in this thesis. The new software took a lot of time to figure out how to work with its plugins, so it was time consuming.

An open question for future studies: Would PCMMI perform as good in Jordan's Desert or Lowlands climatic zone?

6. Recommendations

Depending on the results and conclusions, this thesis recommends the following:

1. Using PCMMI type "salt-hydrates" as a layer in the envelope, reduces energy demand and exceeded the regulated code.
2. Future studies could evaluate the PCMMI with different material layering.
3. Evaluate other PCMMI type 'metallic alloys".

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