A NUMERICAL SIMULATION TO EVALUATE THE THERMAL PERFORMANCE OF PHASE CHANGE MATERIAL WITH MYCELIUM INTEGRATION IN RESIDENTIAL APARTMENTS, IN THE CASE OF AMMAN

Dalia Salah Swiety[1*], Tawfiq Mahmoud Abu-Ghazzeh[2]

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. A numerical simulation was conducted (through Autodesk-Revit program) to compare the thermal performance of a simulated residential building with currently used construction materials, and the thermal performance of the same building using PCMMI. The results of the numerical simulation showed that the main three components of the residential building: the external walls W.01, the roof R.01, and the ground floor slab S.01 all did not meet the regulated codes without the new material. The codes specified the value of the thermal transmittance (U-Value). The thermal performance of the building's envelope was enhanced by adding the PCMMI layer. The results of the calculations illustrated that the PCMMI helped the residential building envelope thermal performance by reducing the U-Value and meeting the limit of the codes of Jordanian regulations of thermal insulation.

Keywords: thermal performance; thermal transmittance; thermal comfort; high-lands climatic zone.

[1*]Architectural Department, School of Engineering, Amman 11185, Jordan. daliaswiety@hotmail.com
[2]Architectural Department, School of Engineering, Amman 11941, Jordan.

***Corresponding Author:-** Dalia Salah Swiety
[*]Architectural Department, School of Engineering, Amman 11185, Jordan. daliaswiety@hotmail.com

DOI: - 10.48047/ecb/2023.12.Si12.148

1. Introduction

Jordan is a county which suffers from short supplies of natural resources, including natural gas and crude oil. Consequently, 97% of total national energy needs are imported from neighboring Arab countries, which costs 17% of Jordan's Gross Domestic Product (GDP). The residential sector accounts for 21% of energy consumption and 43% of total electricity consumptions. (1)

The building sector is a major consumer of the national and global energy consumption. Zarie and Zare (2), stated that the increase of population and the improvement of living standards all contribute to increasing the residential energy consumption and living requirements. The architectural practices are not responsive or responsible enough.

Thermal insulation of buildings is a pivotal factor in reducing residential heating and cooling energy needs. Although the insulation codes in Jordan were adopted from the early eighties, enhancements and enforcements of these codes are limited. This resulted in infrequent and patchy implementation of thermal insulation in residential buildings that varies according to income, ownership type and the level of education.

The improvement of energy performance in buildings is an important field of research for the introduction of new materials, systems and technologies that could be used to reduce buildings dependency on fossil fuels. Today, Phase Change Materials with Mycelium Integration (PCMMIs) can be used in Thermal Energy Storage (TES) applications, which is a promising technology, to take advantage of solar thermal energy in a passive sustainable way.

Phase Change Material with Mycelium Integration (PCMMI) is a material that could be used at the envelope of the building, it acts like a thermal mass. The PCMMI stores heat when the outdoor climate is hot, in the process of storing the heat the material changes its phase from solid to liquid (taking into consideration that the [PCMMI] will be contained in a specific container which is called encapsulation [*]through the exterior wall layers). The heat gain process will provide day cooling by reducing the heat transfer from the envelop to the interior of the residential building. Through nighttime when outdoor temperature drops, the PCMMI) will solidify (changes its state from liquid to solid) and releases the heat to the interior providing interior heating. As a result, the heating and cooling loads, the electricity consumption and energy requirements during the peak periods are reduced. Mycelium**,** it surrounds us! Mycelium can be thought of as a root system of fungi, and much like an iceberg, there is much more below than what can be seen on the surface.

In this thesis, the main study will focus 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 used a numerical simulation by Autodesk-Revit software, that simulated a residential building once with its current material layering and another simulation with the new PCMMI layer, The methodology measured the thermal performance of the building’s materials. First section measured the thermal performance of the current materials in the envelope of the residential building by calculating its thermal transmittance (U-Value), then calculating the thermal performance of the residential building with PCMMI layer. The calculations used equations from the Jordan’s Thermal Insulation Code of 2009 (3).

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. Most Jordanian buildings give limited attention and are inconsiderate of climate and energy efficiency design. As most of the designers adopt a typical design without indemnifying and ensuring passive strategies or putting them into consideration as being one of the major objectives in the building’s design (4, 5). Accordingly, many of these buildings do not offer their residents a comfortable or a well thought of indoor environment, which would require increased cooling and heating demands, generating greater pressure on the Jordanian economy (6, 7).

Accordingly, the proposed study problem can be defined by: The increased demand on heating and cooling systems, is putting pressure on the usage of energy, which assures that the current building insulation system is not efficient in Jordan.

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: Using Phase Change Material with Mycelium Integration (PCMMI) will enhance the thermal performance of the residential buildings.

Research question: Would using Phase Change Material with Mycelium integration (PCMMI) in the residential building material enhance the thermal performance of the envelope?

Research Objective: Making a simulation of a residential building in Amman and evaluating its thermal performance with and without PCMMI.

A previous study analyzed innovative methods for providing sustainable heating and cooling systems through using thermal energy storage (TES). Where this article studied the successful implementation of TES in the built environment and analyzed phase change material in terms of material proportion characterization, numerical modeling, and validation of thermal storage. (8)

Another study studied the thermal energy storage in buildings through phase change materials (pcm) incorporation for heating and cooling purposes. This thesis applied passive systems in building envelops to reduce energy demand and shows how the thermal energy system (TES) could be used as an active storage unit in buildings. (9)

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

---

[*] Encapsulation: Microcapsules enhance thermal and mechanical performance of PCMMIs used in thermal energy storage by increasing the heat transfer area and preventing the leakage of melting 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 Materials (PCMs)

Definition of Phase Change Materials

PCM is a substance that changes its phase from solid to liquid or vice versa according to the temperature that the material is exposed to as seen in Figure 1 (Thermal Performance of the buildings Envelope with PCM). The way it works is by absorbing the heat and storing it as latent heat in the material itself, in the process of storing the heat in the material, the material itself starts to change its phase from solid to liquid. When the temperature drops, the material starts to solidify and change back its phase from liquid to solid by releasing the gained heat that it was absorbed. (11)

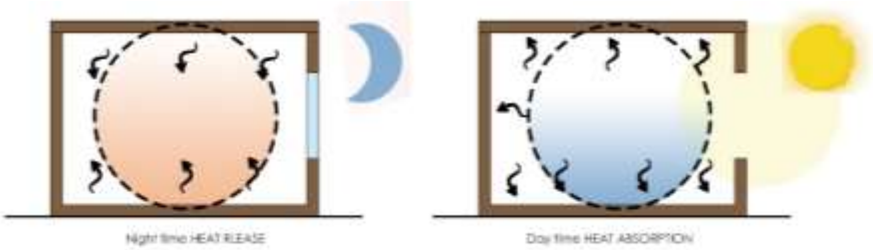


Figure 1Thermal Performance of the buildings Envelope with PCM

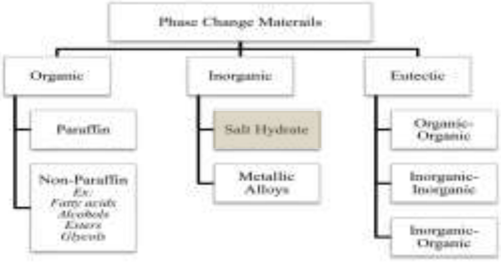


Figure 2 *Classification of solid-liquid PCMs*

Phase Change Material with Mycelium Integration (PCMMI)

This research investigated the ability of PCMMI to reduce energy demand and energy consumption in residential buildings. Phase Change material has three categories as illustrated in Figure 2 (Classification of solid-liquid PCMs), Organic, Inorganic and Eutectic. In this research the material that was studied is the inorganic salt hydrate phase change material with mycelium integration. This material is known for having a higher heat capacity than other classifications of PCMMI (12). Inorganic salt hydrate phase change material with mycelium integration consists of salt, water (as a crystal matrix), and mycelium (13). They have a high latent heat and a melting temperature range from 15°C to 117°C. Salt hydrates are considered one of the most important PCM groups, and their applications in TES systems were widely studied by researchers. The availability and relatively low cost of salt hydrates make them very attractive for the commercial applications in TES (13). PCM integrated with mycelium, were tested to obtain an ideal mixture at the required melting temperature with a desirable “sharp” melting behavior (14).

In addition to specific safety conditions and on behalf of Sustainable Bioproducts, they submitted the enclosed Generally Recognized as Safe Notice (GRASN) for the use of Fermented Microbial.

Which means that it is safe to integrate mycelium with the building materials. (15)

Figure 3 *CaCl2.6H2O in Jordan*

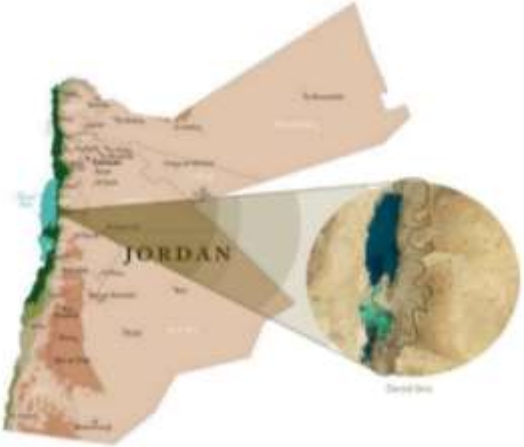


Figure 4 *Salts in the Dead Sea*

Phase Change Material with Mycelium Integration (PCMMI) in Jordan

As mentioned previously, PCMMI is a mixture between PCM and Mycelium. **PCM** consists of $CaCl_2.6H_2O$ (Calcium Chloride Hexahydrate) which is an example of a salt hydrate that is widely available at a low cost in Jordan. The availability of salt hydrates could be found in the Dead Sea as illustrated in Figure 3 ($CaCl_2.6H_2O$ in Jordan). The dead sea level is decreasing and as water level drops, salt is piling up on the lakebed (16). The dead sea is second saltiest sea in the world, with 34% of salt concentrated (17). The green rectangles on the south end of the dead sea are salt evaporation ponds, which are used to extract sodium chloride and potassium salts for the manufacturing of polyvinyl chloride (PVC) and other materials such as Phase Change Materials (PCMs) that could be used in building envelopes (18). As the water level drops, the lake becomes saltier, and as seen in Figure 3 (CaCl2.6H2O in Jordan) near the surface (where the lake was before shrinkage) salt is now consecrated. Scientists from the Dead Sea Observatory have concluded that salt was brought out of the water and coating the bottom of the lake. Figure 4 (Salts in the Dead Sea) shows the salt layers that were growing 10 centimeters every year for the past four decades, showing seasonal alternations of the lake's properties. (19)

Mycelium, on the other hand, could be found as a raw material near industrial areas. Since it is a type of fungus, it grows on the waste of the industrial areas. Therefore, it is considered to be one of the easiest materials to be found. It is cheap as a raw and testing material (20).

Climatic Zone

Precise Melting Temperature

PCMMI is a phase change material that changes its phase by the absorption of heat to liquid, then to solid by releasing heat. PCMMI has a precise melting point and temperature, and precise solidifying temperature (sharp melting point) (21). Which means there are two main critical points that should be taken into consideration, (i) what is the precise melting point that should be used in Amman's weather? (ii) how will the PCMMI turn into liquid without leakage?

The process of defining PCMMI's precise melting temperature, is by understanding the climatic conditions in Amman (as the case study in this thesis). Figure 5 (Jordans Three Regions) shows: The Jordan Valley (known as 'the Ghore Region'), the lowland, The Highlands Region. (It has a Mediterranean climate with cold winters and hot summers and includes about 87% of the population settlements) and the case study in this thesis is located in this region. The Desert Region (Badia), a semi-desert plot of that covers 81% of the country's land. (22).

Figure 5 *Jordans Three Regions*

The climatic analysis of Amman's average temperatures (highlands) shows that the peak average temperature is around 27°C. Which means that the PCMMI specific material, should have a melting temperature near to it. The melting temperature of $CaCl_2.6H_2O$ (Calcium Chloride Hexahydrate) with Mycelium integration is 25 °C (23)

Microe ncapsulation 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 6 (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 (14).

Figure 6 *Microencapsulation with PCMMI*

Figure 7 (Microencapsulation in PCMMI in Site) shows the thickness and supplication of the PCMMI rolls in the construction site.(24).

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

Figure 7 *Microencapsulation with PCMMI in site*

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 as seen in Figure 8 (Case Location).

- 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
The building is air conditioned; it needs cooling in summer and heating in winter.
Cooling and Heating Hours (based on the survey mentioned earlier) = 10 hr/day
Set Point of Heating = 15
Set Point of Cooling = 24
Lighting Power Density = 10 W/m^2
Occupancy Density = 40 m^2/person (a family of 5)

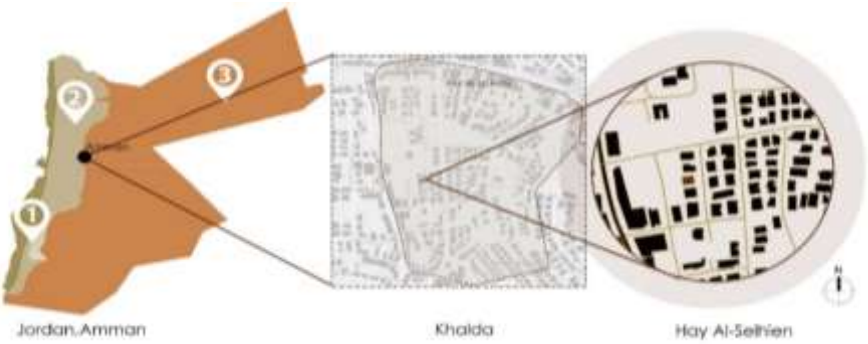


Figure 8 *Case Location*

Thermal Performance of Existing Buildings Envelope in Amman, Khalda.

The residential plan contains apartments that are 200m^2 in area with three bedrooms. The apartment is for a family of 5. Located in Khalda, Amman. The case study was chosen to identify the status and situation of the residential building's envelope in regards with thermal performance in Amman. The simulation focuses on the envelope's main components which act as a separation between the exterior and the interior. The simulation shown in Figure 9 (Residential Simulation) is done by using Autodesk Revit. Each layer in the envelope was simulated in a way that mimics real life situation, for more precise outcomes, the simulation used adaptive algorithms using DYNAMO plug-in, that preserves the U-Value of each layer and simulates the climatic conditions of Amman as well. The main advantage of using Revit simulation is to understand how the new material will perform according to the climatic conditions of Amman, and if it could reduce the energy demand.

Figure 9 *Residential Simulation*

Numerical Simulation to Calculate the Thermal Performance of The Materials.

The methodology used the simulated apartment by Autodesk-Revit software. To illustrate the layers of the envelope with and without PCMMI. The methodology measured the thermal performance of the building's materials. First section measured the thermal performance of the current materials in the envelope of the residential building by calculating its thermal transmittance (U-Value), then calculating the thermal performance of the residential building with PCMMI layer. The calculations used equations from the Jordan's Thermal Insulation Code of 2009 (10).

How was the thermal performance in the current building material measured?

It was important to Calculate the U-Value for each layer of the envelope then compare it to the maximum limit from the Local Codes.

Thermal Transmittance or Thermal Heat Factor U-Value: it is a measurable factor by which it calculates the heat that is transferred per unit area and its unit is W/m²K.

Main factors that affect calculations of the U-Value are the thickness of the layer (m) and the conductivity (K-Value) of the material. Figure 10 (U-Value Calculation) shows how the U-Value will be calculated where,

- R: is the thermal resistance (m^2K/W)
- U: is the thermal transmittance (W/ m^2K)
- K: is the thermal conductivity (W/mK)
- d: is the layers thickness (m)

The method for calculating the thermal performance is by taking each component of the residential envelope (Exterior walls, Roof, Ground Floor Slab) and analyzing its layers. The U-Value was calculated for each material then compared with the current local codes to evaluate the current building materials thermal performance in comparison with using PCMMI. Each building component has its own reference, (W.01) will be used for the external walls of the current residential building, (W.02) will be used for the external walls with the enhanced material. (R.01) refers to the current building roof, (R.02) refers to the roof of the enhanced envelope. (S.01) refers to the current slab of the building while, (S.02) refers to the enhanced slab material.

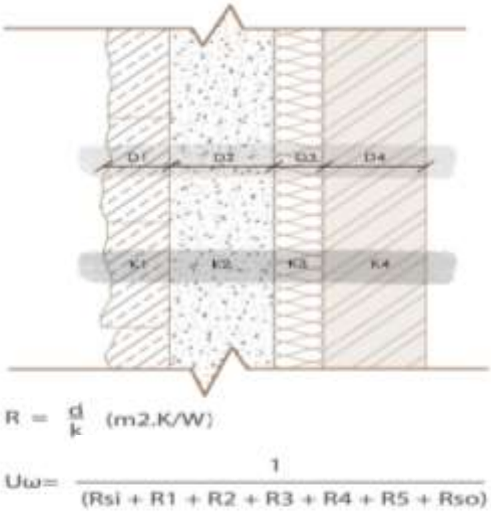
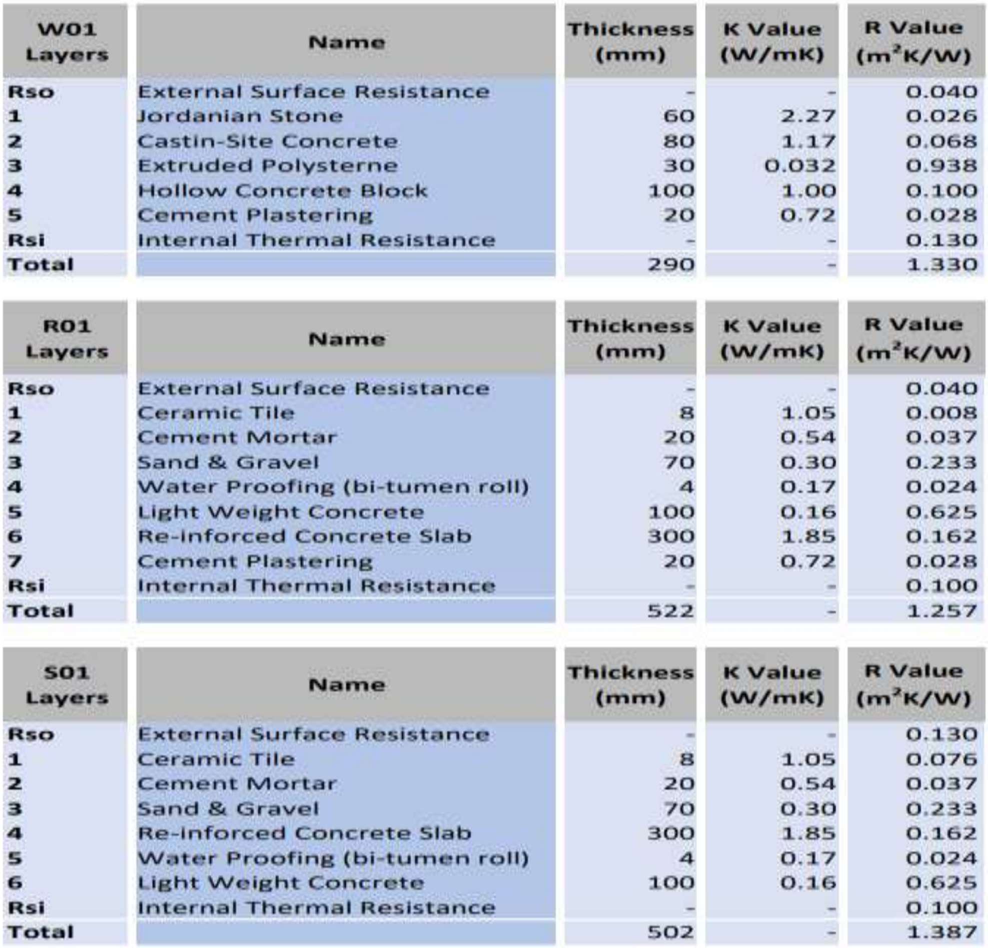


***Figure 10 U**-Value Calculation*

For calculating the thermal performance is by taking each component of the residential envelope (Exterior walls, Roof, Ground Floor Slab) and analyzing its layers as illustrated in table 1 (The Current Residential Building envelopes materials). Table 1 shows each material in the envelope with its thickness and conductivity that helps with calculating the U-Value (Thermal transmittance).

***Table 1** The Current Residential building envelopes materials*

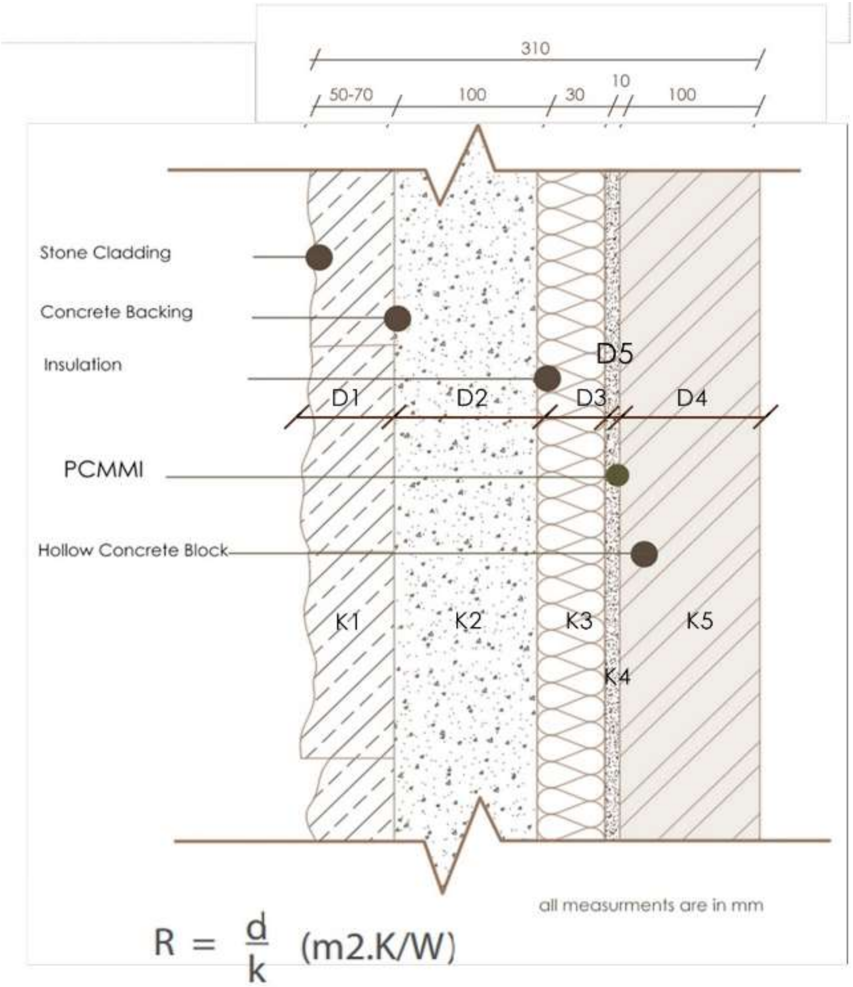


W01 Layers	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Jordanian Stone	60	2.27	0.026
2	Castin-Site Concrete	80	1.17	0.068
3	Extruded Polysterne	30	0.032	0.938
4	Hollow Concrete Block	100	1.00	0.100
5	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.130
Total		290	-	1.330

R01 Layers	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Ceramic Tile	8	1.05	0.008
2	Cement Mortar	20	0.54	0.037
3	Sand & Gravel	70	0.30	0.233
4	Water Proofing (bi-tumen roll)	4	0.17	0.024
5	Light Weight Concrete	100	0.16	0.625
6	Re-inforced Concrete Slab	300	1.85	0.162
7	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.100
Total		522	-	1.257

S01 Layers	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.130
1	Ceramic Tile	8	1.05	0.076
2	Cement Mortar	20	0.54	0.037
3	Sand & Gravel	70	0.30	0.233
4	Re-inforced Concrete Slab	300	1.85	0.162
5	Water Proofing (bi-tumen roll)	4	0.17	0.024
6	Light Weight Concrete	100	0.16	0.625
Rsi	Internal Thermal Resistance	-	-	0.100
Total		502	-	1.387

The method for calculating the thermal performance is by taking each component of the residential envelope (Exterior walls, Roof, Ground Floor Slab) and analyzing its layers. The U-Value was calculated for each material then compared with the current local codes to evaluate the current building materials thermal performance in comparison with using PCMMI. The process for calculating the thermal performance of the residential building with the new material does not differ. The calculations will depend on the same equations to calculate the U-Value as in the previous sections as illustrated in Figure 11 (U-Value Calculation with PCMMI). What is different in this section is the total thickness of each component and consequently the conductivity due to the addition of the extra PCMMI layer.



$$R = \frac{d}{k} \ (m2.K/W)$$

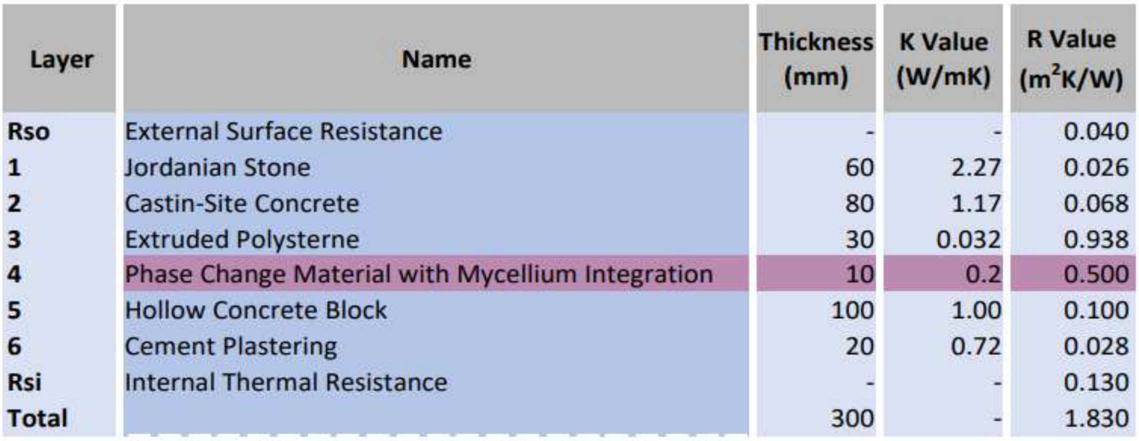
$$U\omega = \frac{1}{(Rsi + R1 + R2 + R3 + R4 + R5 + Rso)}$$

***Figure 11** U-Value Calculations with PCMMI*

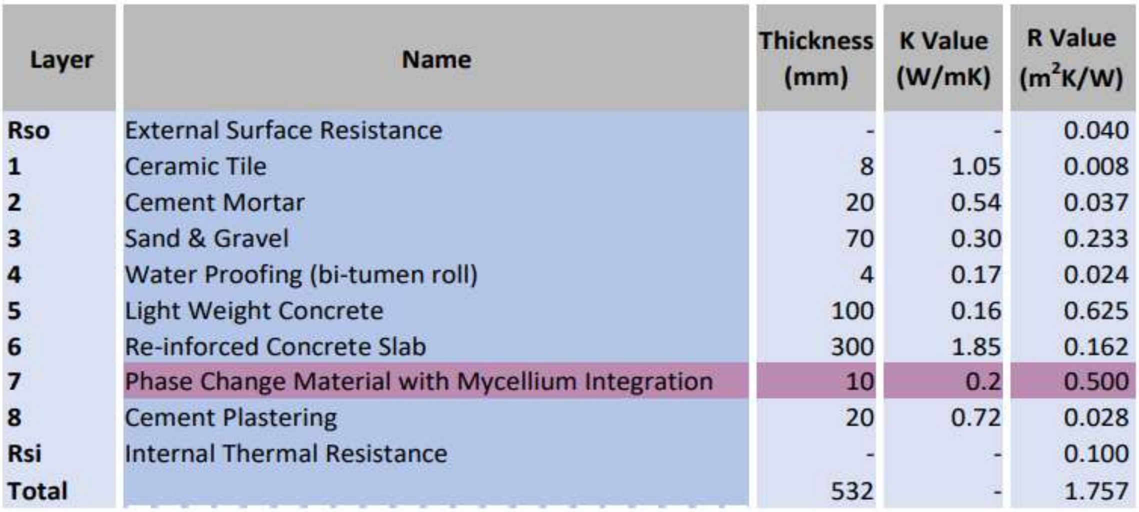
This concludes that the PCMMI with its container adds up about 10mm to the thickness of the layers, as illustrated in Figure 50 (U-Value Calculation with PCMMI) which shows the layers of the exterior wall with PCMMI and how the calculation was done. All the specific values and calculations are taken from Jordan's Thermal Insulation Code of 2009 (10). The calculations will be shown in chapter 5, each component has its own calculations in relation with U-Value to evaluate the thermal quality.

Table 2 (The envelopes materials with PCMMI) illustrated the position of the new material "PCMMI" in relation with other layers of the envelope, where PCMMI layer has a thickness of 10mm and a conductivity value of 0.2 W/mK.

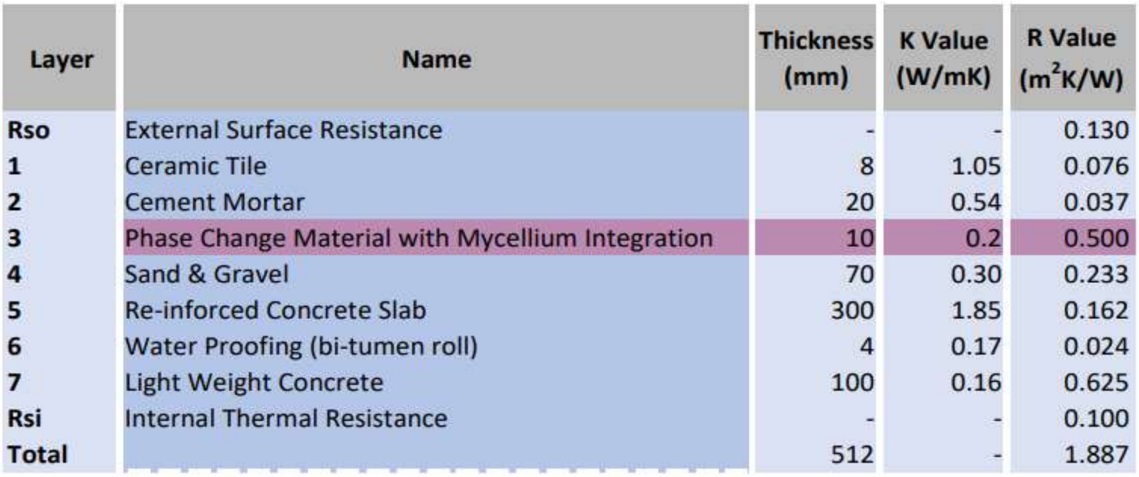
Table 2 The envelopes materials with PCMMI



Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Jordanian Stone	60	2.27	0.026
2	Castin-Site Concrete	80	1.17	0.068
3	Extruded Polysterne	30	0.032	0.938
4	Phase Change Material with Mycellium Integration	10	0.2	0.500
5	Hollow Concrete Block	100	1.00	0.100
6	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.130
Total		300	-	1.830



Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Ceramic Tile	8	1.05	0.008
2	Cement Mortar	20	0.54	0.037
3	Sand & Gravel	70	0.30	0.233
4	Water Proofing (bi-tumen roll)	4	0.17	0.024
5	Light Weight Concrete	100	0.16	0.625
6	Re-inforced Concrete Slab	300	1.85	0.162
7	Phase Change Material with Mycellium Integration	10	0.2	0.500
8	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.100
Total		532	-	1.757



Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.130
1	Ceramic Tile	8	1.05	0.076
2	Cement Mortar	20	0.54	0.037
3	Phase Change Material with Mycellium Integration	10	0.2	0.500
4	Sand & Gravel	70	0.30	0.233
5	Re-inforced Concrete Slab	300	1.85	0.162
6	Water Proofing (bi-tumen roll)	4	0.17	0.024
7	Light Weight Concrete	100	0.16	0.625
Rsi	Internal Thermal Resistance	-	-	0.100
Total		512	-	1.887

numerical simulation to calculate the thermal performance method was completed after calculating the thermal performance (U-Value) on both cases of the residential building materials (with and without PCMMI). Then comparing both results with the regulated Codes. Which proved the objective "Making a simulation of a residential building that is already built in Amman and evaluating the difference between the materials that is originally built with it, and the enhanced materials by using the PCMMI."

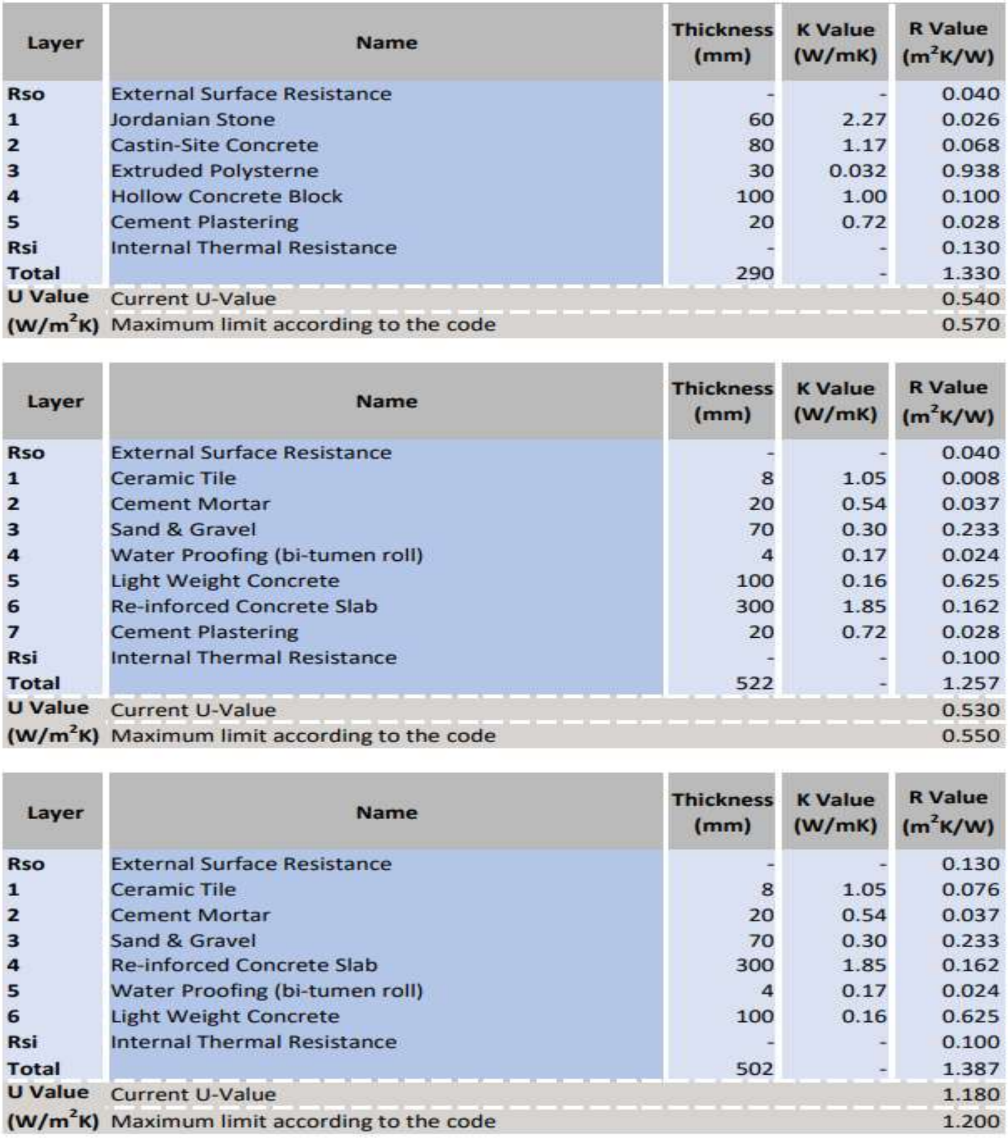
4. Results and Discussion

The result of this stage for calculating the thermal performance is by taking each component of the residential envelope (Exterior walls, Roof, Ground Floor Slab) and analyzing its layers. The U-Value was calculated for each material then compared with the current local codes to evaluate the current building materials thermal performance in comparison with using PCMMI. Each building component has its own reference, (W.01) will be used for the external walls of the current residential building, (W.02) will be used for the external walls with the enhanced material. (R.01) refers to the current building roof, (R.02) refers to the roof of the enhanced envelope. (S.01) refers to the current slab of the building while, (S.02) refers to the enhanced slab material. Table 3 (U-Value results of the current residential building materials) illustrated the results of calculating the thermal transmittance (U-Value) of the current residential building component materials.

Results of the current ground floor slab thermal performance S.01, current roof thermal performance “uninsulated flat reinforced concrete roof with ceramic tiles R.01” and the calculations of the current external wall thermal performance “insulated external walls (Stone Clad) W.01 is shown in Table 3.

The ground floor slab is only having support from the already-existing ground (the foundation). Typically, residential buildings with reinforced elements (as per design) consider slab thickness of 150mm. But the ground floor slab that was illustrated in this case has a total thickness of 554mm, the main function of the external walls is to provide shelter in a boundary, that protects the interior side from the exterior environment from wind and rain (25, 26). Jordanian residential buildings external walls differ in thickness, layers and materials. This case in Khalda, is a typical residential building with a typical exterior layer in the wall. Finally, The Reinforced concrete flat roof is the most constructed roof in residential buildings in Amman (25).

***Table 3** U-Value results of the current residential building materials*

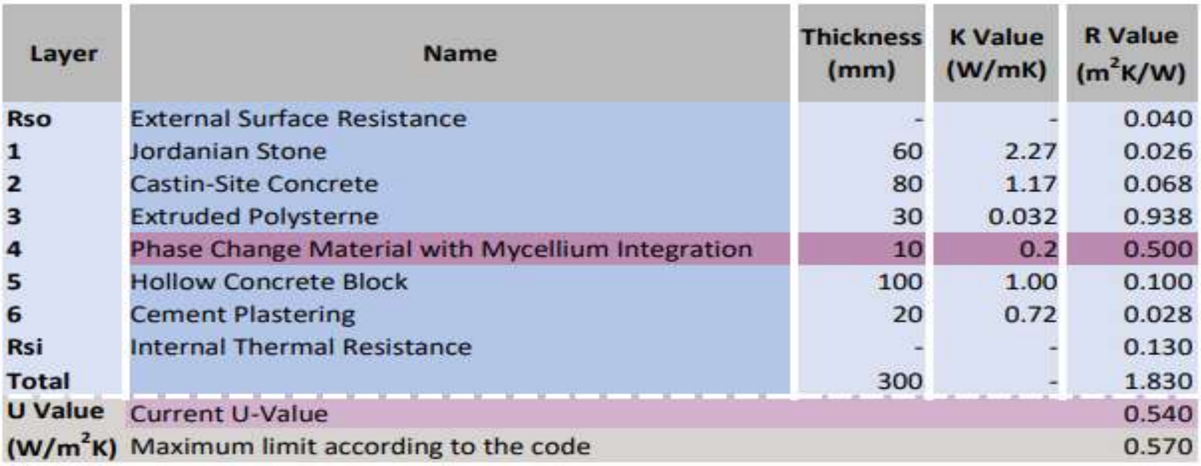


Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Jordanian Stone	60	2.27	0.026
2	Castin-Site Concrete	80	1.17	0.068
3	Extruded Polysterne	30	0.032	0.938
4	Hollow Concrete Block	100	1.00	0.100
5	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.130
Total		290	-	1.330
U Value	Current U-Value			0.540
(W/m^2K)	Maximum limit according to the code			0.570

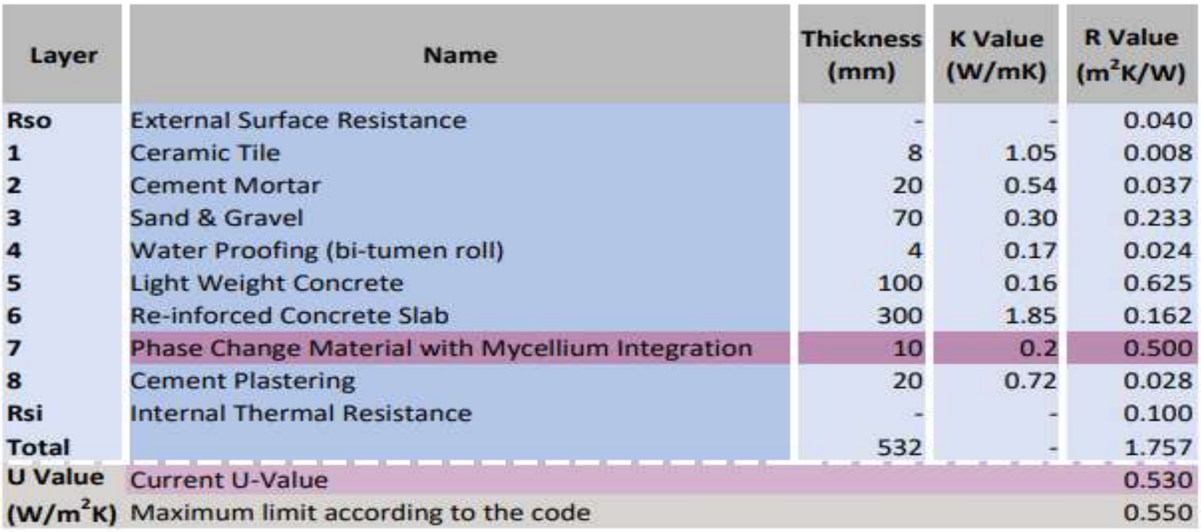
Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Ceramic Tile	8	1.05	0.008
2	Cement Mortar	20	0.54	0.037
3	Sand & Gravel	70	0.30	0.233
4	Water Proofing (bi-tumen roll)	4	0.17	0.024
5	Light Weight Concrete	100	0.16	0.625
6	Re-inforced Concrete Slab	300	1.85	0.162
7	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.100
Total		522	-	1.257
U Value	Current U-Value			0.530
(W/m^2K)	Maximum limit according to the code			0.550

Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.130
1	Ceramic Tile	8	1.05	0.076
2	Cement Mortar	20	0.54	0.037
3	Sand & Gravel	70	0.30	0.233
4	Re-inforced Concrete Slab	300	1.85	0.162
5	Water Proofing (bi-tumen roll)	4	0.17	0.024
6	Light Weight Concrete	100	0.16	0.625
Rsi	Internal Thermal Resistance	-	-	0.100
Total		502	-	1.387
U Value	Current U-Value			1.180
(W/m^2K)	Maximum limit according to the code			1.200

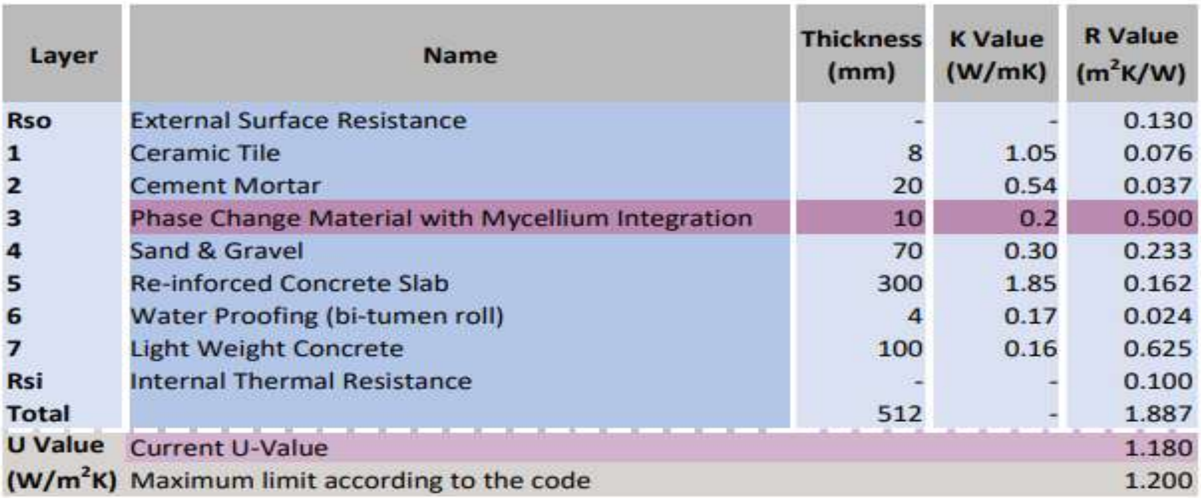
***Table 4** U-Value results of the residential building materials with PCMMI*



Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Jordanian Stone	60	2.27	0.026
2	Castin-Site Concrete	80	1.17	0.068
3	Extruded Polysterne	30	0.032	0.938
4	Phase Change Material with Mycellium Integration	10	0.2	0.500
5	Hollow Concrete Block	100	1.00	0.100
6	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.130
Total		300	-	1.830
U Value	Current U-Value			0.540
(W/m^2K)	Maximum limit according to the code			0.570



Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.040
1	Ceramic Tile	8	1.05	0.008
2	Cement Mortar	20	0.54	0.037
3	Sand & Gravel	70	0.30	0.233
4	Water Proofing (bi-tumen roll)	4	0.17	0.024
5	Light Weight Concrete	100	0.16	0.625
6	Re-inforced Concrete Slab	300	1.85	0.162
7	Phase Change Material with Mycellium Integration	10	0.2	0.500
8	Cement Plastering	20	0.72	0.028
Rsi	Internal Thermal Resistance	-	-	0.100
Total		532	-	1.757
U Value	Current U-Value			0.530
(W/m^2K)	Maximum limit according to the code			0.550



Layer	Name	Thickness (mm)	K Value (W/mK)	R Value (m^2K/W)
Rso	External Surface Resistance	-	-	0.130
1	Ceramic Tile	8	1.05	0.076
2	Cement Mortar	20	0.54	0.037
3	Phase Change Material with Mycellium Integration	10	0.2	0.500
4	Sand & Gravel	70	0.30	0.233
5	Re-inforced Concrete Slab	300	1.85	0.162
6	Water Proofing (bi-tumen roll)	4	0.17	0.024
7	Light Weight Concrete	100	0.16	0.625
Rsi	Internal Thermal Resistance	-	-	0.100
Total		512	-	1.887
U Value	Current U-Value			1.180
(W/m^2K)	Maximum limit according to the code			1.200

Table 4 (U-Value results of the residential building materials with PCMMI) illustrated the results of calculating the thermal transmittance (U-Value) of the residential building component materials with adding a layer of PCMMI.

A. Thermal Performance of the Wall:

i. **U-Value of the walls without PCMMI was 0.75 W/m^{2}K:** the U-Value regulated by the codes should not exceed 0.57 W/m^{2}K. As mentioned in Chapter 3, the lower the U-Value (thermal transmittance factor) the higher thermal efficient the material is.
ii. **U-Value of the wall with PCMM**I **was decreased to 0.54 W/m^{2}K**: which is even

lower than the regulated codes value of 0.57 W/m^{2}K. Comparing the results of the external wall's current thermal performance (without PCMMI) with the proposed enhancement (using PCMMI), the results showed that the current thermal performance is 0.75 W/m^{2}K and the proposed external wall, with PCMMI, is 0.54 W/m^{2}K, indicating a better thermal performance by 28%. As mentioned before the U-Value is an indicator to see how well the materials are performing in relation with the heat flow.

B. Thermal Performance of the Roof:

i. **U-Value of the Roof without PCMMI:** the codes regulated that the needed U-value should not exceed 0.550 W/m^{2}K for an efficient thermal performance with minimal heat transfer, but the calculations showed that the U-Value of the roof is 0.8 W/m^{2}K which is far away from the needed code.
ii. **U-Value of the Roof with PCMMI:** adding PCMMI layer enhanced the thermal performance of the residential buildings roof. PCMMI is a material with a K-Value of 0.2 W/mK and a thickness of 10 mm. To calculate its resistance (R-Value), the thickness was divided by the K-value, resulting in 0.5 m^{2}K/W (better than the regulated code). That resulted in a U-Value of 0.53 W/m^{2}K. The U-Value got reduced with the PCMMI to 33%.

C. Thermal Performance of the Ground Floor Slab:

i. **U-Value of the Ground Floor Slab without PCMMI:** the result calculated the thermal transmittance and showed that the U-Value was 1.6 W/m^{2}K which is higher than the regulated code (1.2 W/m^{2}K).
ii. **U-Value of the Ground Floor Slab with PCMMI:** the thermal performance of the ground floor slab with PCMMI resulted in an enhanced U-Value with a value of 1.18 W/m^{2}K which is better than the regulated code. The thermal performance got enhanced by 26%.

As a result, the main three components of the residential building: the external walls W.01, the roof R.01, and the ground floor slab S.01 all did not meet the regulated codes without the enhanced material. The codes specified the value of the thermal transmittance (U-Value). Having a lower U-Value is better for the thermal performance, since higher U-Value means easier transmittance of heat between the interior and the exterior of the residential building. This thesis proposed an additive material which is Phase Change Material with Mycelium Integration (PCMMI) to enhance the thermal performance of the building (27).

The thermal performance of the building's envelope was enhanced by adding the PCMMI layer. The results of the calculations illustrated that the PCMMI helped the residential building envelope thermal performance by reducing the U-Value and meeting the limit of the codes of Jordanian regulations of thermal insulation (JNBC, 2009).

5. Conclusion

This paper used a numerical simulation method, to conduct a comparison between the current materials of the envelope with and without using PCMMI, the simulated building was in Amman (31.59 ^{0}N, 35.5 ^{0}E) which concluded that using PCMMI in the residential building enhanced its thermal performance of the envelopes components, by calculating the U-Value with and without the PCMMI, the results showed that using PCMMI the U-Value was reduced (which is better) and met the thermal regulated code. While without the PCMMI, none of the components exceeded the U-value regulated by the code. The results of this stage were calculated by using a numerical simulation through Autodesk Revit.

The Contribution the Study and as mentioned in the previous studies, 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.

In addition to the limitations and challenges of the study There were no studies found online that studied PCMMI in Jordan as an envelope material. But through the adapted methodologies and the related references, this limitation was converted into an advantage as the first study in Jordan.

Depending on the results and conclusions, this thesis recommends reviewing and modifying the local codes related to building's insulation, educating people about the importance energy reduction, in both environmental and economic aspects and using SPCMMI type "salt-hydrates" as a layer in the envelope, reduces energy demand and exceeded the regulated code.

References

1. Ministry of Energy and Mineral Resources. (2017). The Second *National Energy Efficiency Action Plan* (NEEAP) for the Hashemite Kingdom of Jordan. Amman: Jordan.
2. Zarei, M., Zare, K.H. (2013). *Energy Consumption Modeling in Residential Buildings* (3rd ed.). International Journal of Architecture and Urban Developme. Retrieved from: …..https://ijaud.srbiau.ac.ir/ article_5 86.html.
3. Jordan Green Building Council, (2020). *Global Directory of Green Building Councils. Retrieved from*: https://worldgbc.org/global-directory-of-green-building-councils/.
4. Jaber, J., et al., (2008). Evaluation of conventional and renewable energy sources for space heating in the household sector. *Renew Sustain Energy* Rev, *12*, 278–289 doi: 10.1016/ j.rser.2006.05.004
5. Johansson, E., et al., (2009). Climate conscious architecture and urban design in Jordan towards energy efficient buildings and improved urban microclimate. (Unpublished …..maters thesis). LUND University, Lund, Sweden
6. Al-Hinti, I., Al-Sallami, H., (2017, July). *Potentials and barriers of energy saving in Jordan's residential sector through thermal insulation*. Retrieved from http://jjmie. hu.edu.jo/vol-11-3/JJMIE-112-16-01.pdf .
7. Bataineh, K., Al-Rabee, A., (2021) Design optimization of energy efficient residential buildings in Mediterranean region. *J Sustain Dev Energy Water Environ Syst*. doi: doi.org/10.13044/j.sdewes.d9.0385
8. Gunasekara, S., Ruijun, P., Chiu, ., Martin, V. (2016). Polyols as phase change materials for surplus thermal energy storage. *Applied Energy, 162*, 1439-1452, 0306-2619. Retrieved from: https://doi.org/10.1016/ j.apenergy. 2015.03.064
9. Lambie, E., Saelens, D., (2020). Identifcation of the building envelope perfor- mance of a residential building: a case study. *Energies, 13*(10), 1–2. doi: 10.3390/en13102469
10. Jordan national building council, (2009). *Thermal insulation code* (2nd edition). Retrieved from: https://www.buildings-mena. com/files/JordanNationalBuildingCodes.pdf.
11. Alkan, C., Sari, (2008). *Fatty acid/poly (methyl methacrylate) (PMMA)* blends as formstable phase change materials for latent heat thermal energy storage. Solar Energy. *82*(2): p. 118-124. doi: 10.1016/J.SOLENER.2007.07.001.
12. .M.A. Lacasse, M.A., (1999, December). *Durability of Building Materials and Components Canada*, pp. 2089-2098. Retrieved from https://www.irbnet.de/daten/iconda/CIB2285.pdf.
13. Thakkar, J., Bowen, N., Chang, A., Horwath, P., (2022, December 17) *Optimization of Preparation Method, Nucleating Agent, and Stabilizers for Synthesizing Calcium Chloride Hexahydrate* (CaCl2.6H2O) Phase Change Material. Retrieved from https://doi.org/ 10.3390/buildings12101762.
14. Tyagi, V.V, (2011). *Development of phase change materials based microencapsulated* technology *for buildings*: a review, Renewable and Sustainable Energy Reviews. *15* (2). Doi:1373–1391.
15. Baughan , J. S. (2020, January 14). GRAS Notice (GRN) No. 904. Mycelium. Retrieved May 20, 2023, from https://www.fda.gov/ media/142277/download?fbclid= IwAR2M8xNqnyaq ZCxFlgRHT….. Dp DC i1f5r1Y4C-Kz_-BlzN-Uqw4tkGYE9ESYuM
16. Slhab, S., (2007). *A Minireview on Mushroom: Emphasis on the Wild Mushroom of Jordan.* Retrieved from https://journals.ju.edu. jo/JMJ/ article/viewFile/1097/5396.
17. Feldman, D., Kahwaji, S., White, M.A., (1986). Organic Phase Change Materials for Thermal Energy Storage. *Solar Energy Materials*. *13*, 1-10.
18. Sharma, A., Tyagy, V.V., Chen, C.R., (2007). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews*. *13*(2) p. 318-345. Retrieved from https://ideas. repec.org/ a/eee/rensus/v13y2009i2p318345.html.
19. Warren, J., (2017). *Performance and Stability of CaCl2·6H2O-Based Phase Change Material S.* DOI:10. 13140/RG.2.2. 26572. 87685.
20. Regalado, C., (2022, June). *Mycelium: The Building Blocks of Nature and the Nature of Architecture* (unpublished doctoral dissertation). University of Massachusetts, Amherst, Massachusetts.
21. Zhou, C.Y., (2012). Review on thermal energy storage with phase change materials PCMMIs) in building applications, Applied Energy. *92* doi:593–605.

22. United Nations Environment Programme. (2009). Buildings and Climate Change: *a Summary for Decision-Makers.* Paris: UNEP.
23. Chiu, J. N., (2011). Heat Transfer Aspects of Using Phase Change Material in Thermal Energy Storage Applications.*Licentiate dissertation, KTH Royal Institute of Technology*. Retrieved from http:// kth. divaportal.org/smash/record.jsf?pid=diva2%3 A419998&dswid=9617Sharma.
24. Albert, P.C., (2019). *Nanoencapsulation of Organic Phase Change Material in Water via Coacervation Using Amphoteric Copolymer*. doi: 10.1021/acs.iecr.9b02507.
25. Kamal, A., (2013). An Assessment of Climatic Design Strategy for Low Energy Residential Buildings in Hot and Arid Climate. *Asian Journal of Civil Engineering*. *14*. 747-754.Retrievedfrom: https:// en.bhrc.ac.ir/ Portals/25/PropertyAgent/2905/Files/5915/747 .pdf.
26. Sharaf, F., (2020). The impact of thermal mass on building energy consumption: A case study in Al Mafraq city in Jordan. *Cogent Engineering. 7*. Doi:10.1080/23311916.20.
27. Zhou, C.Y., (2012). Review on thermal energy storage with phase change materials PCMMIs) in building applications, Applied Energy. *92* doi:593–6