Journal of Namibian Studies, 33 (2023): 6237-6249 ISSN: 2197-5523 (online)

Parametric Analysis To Calculate Time-Lag 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. A parametric analysis was conducted to calculate the time-lag of the materials in the components of the residential envelope. The parametric analysis was applied to estimate the duration which the residential building is exposed to solar heat. The results showed that the average of the delay is about 8 hours. Which means that if the temperature outdoor is 30 °C it will take the envelope 8 hours to radiate it to the interior's peak temperature after adding the PCMMI layer to the layers of the envelope.

Keywords: *thermal performance; parametric analysis; time lag; ground albido; The Decrement Factor*

1. Introduction

Jordan faces a shortage of natural resources, including natural gas and crude oil, which leads to the need to import 97% of its total national energy requirements from neighboring Arab countries. This dependence on imports incurs a cost of 17% of Jordan's Gross Domestic Product (GDP). Within Jordan, the residential sector is responsible for consuming 21% of the energy and 43% of the total electricity usage (1).

The building industry plays a significant role in both national and global energy consumption. According to Zarie and Zare (2), population growth and improving living standards contribute to the rise in residential energy consumption and associated needs. Unfortunately, architectural practices have not been adequately responsive or accountable in this regard.

Efficient thermal insulation of buildings emerges as a crucial factor in decreasing the energy demand for heating and cooling in residential spaces. Despite the adoption of insulation codes in Jordan since the early 1980s, these codes have seen limited improvements and

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enforcement. As a consequence, the application of thermal insulation in residential buildings has been sporadic and inconsistent, varying based on factors such as income, property ownership, and education levels.

Enhancing the energy efficiency of buildings is a vital area of research focused on introducing novel materials, systems, and technologies to lessen the reliance of buildings on fossil fuels. Presently, there is a promising avenue known as Phase Change Materials with Mycelium Integration (PCMMIs) for Thermal Energy Storage (TES) applications. This innovative approach harnesses solar thermal energy in a passive and sustainable manner.

Phase Change Material with Mycelium Integration (PCMMI) serves as a thermal mass and can be utilized in the building's exterior envelope. Acting as a heat reservoir, the PCMMI undergoes a phase change from solid to liquid during periods of high outdoor temperatures, utilizing a specific encapsulation container within the exterior wall layers. This heat storage process facilitates daytime cooling by reducing heat transfer from the envelope to the interior of the residential structure. (3)

During cooler nighttime conditions, when outdoor temperatures drop, the PCMMI solidifies by transitioning from liquid to solid state. This transition releases stored heat to the interior, providing effective interior heating. As a consequence, this approach leads to reduced heating and cooling loads, decreased electricity consumption, and lowered energy demands during peak periods.

Mycelium, a naturally occurring fungi root system, plays a pivotal role in this process. Much like an iceberg, there is more beneath the surface when it comes to mycelium's capabilities and contributions. 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. (3)

The methodology used a parametric analysis was applied to estimate the duration which the residential building is exposed to solar heat. An analysis on energy audit was conducted to estimate the exposure (in W/hr./day) in each section of the residential building.

Energy security stands out as a paramount obstacle confronting Jordan. Addressing this challenge would alleviate the nation's burdens and strains, promoting its long-term sustainability. With a staggering 96% dependency on energy imports (1), Jordan's current building stock serves as a substantial energy consumer, displaying performance levels that fall short of contemporary construction standards.

Regrettably, a majority of Jordanian structures receive scant attention to climate and energy-efficient design principles. A prevalent tendency among designers is to adhere to conventional designs, often overlooking or neglecting passive strategies, despite their potential to serve as pivotal objectives in the building's design (4, 5). Consequently, a significant portion of these buildings fail to deliver on these fronts

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

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.

Previous studies calculated different materials time lag in different thicknesses, such as a study called Passive Techniques for Achieving Thermal Comfort by Mohammad Arif 2017, where it studied the time lag of concrete in the Mediterranean climate with different thicknesses (7). A study called An Assessment of Climatic Design Strategy for Low Energy Residential Buildings in Hot and Arid Climate by Kamal in 2013, where it studied the thermal affection of time lagging materials (8). Also. In study in Jordan named the impact of thermal mass on building energy consumption: A case study in Al Mafraq city in Jordan. Done in 2020, studied the time lag of materials in Jordans climate (9).

2. Literature Review

- **Phase Change Material (PCM)**

Phase Change Materials (PCMs) are substances capable of transitioning between solid and liquid states based on temperature changes. They possess the unique ability to absorb and store heat as latent energy, resulting in a phase shift from solid to liquid when heat is absorbed, and from liquid to solid when heat is released upon cooling (10).

- **Phase Change Material with Mycelium Integration (PCMMI)**

Phase Change Material with Mycelium Integration (PCMMI) denotes the combination of PCM and mycelium. Research on PCMMI centers on utilizing inorganic salt hydrate PCM integrated with mycelium, known for its elevated heat capacity compared to other PCMMI variations. Inorganic salt hydrate PCM comprises salt, water forming a crystal matrix, and mycelium. These elements exhibit substantial latent heat and a melting temperature range spanning from 15°C to 117°C. The versatility and relatively low cost of salt hydrates make them a widely studied option for thermal energy storage systems (3). The safety of integrating mycelium with building materials has been acknowledged, supported by the Generally Recognized as Safe Notice (GRASN) presented by Sustainable Bioproducts (11).

- **PCMMI in Jordan**

In the context of Jordan, PCMMI employs salt hydrates like $CaCl_2.6H_2O$ (Calcium Chloride Hexahydrate), readily available from the Dead Sea. The diminishing water level of the Dead Sea results in the accumulation of salt on its bed (12). The region's salt evaporation ponds are used to extract sodium chloride and potassium salts for diverse applications, including PCM production for building envelopes (13). As the water level decreases, the lake's salinity intensifies, leading to the formation of salt layers at the bottom (14). Conversely, mycelium can be sourced from industrial areas due to its growth on industrial waste, ensuring easy accessibility and affordability as a raw material for experimentation (15).

- **Climate Region and Precise Melting Temperature**

PCMMI represents a phase change material that transforms its state by absorbing heat, converting to a liquid form, and then solidifying through heat release. This material possesses specific points of melting and solidification (a distinct melting point), prompting two crucial considerations: (i) determining the suitable melting point for the weather conditions in Amman, and (ii) ensuring the PCMMI remains as a liquid without any leakage concerns. In order to pinpoint the precise melting temperature for PCMMI, the climatic circumstances in Amman are taken into consideration, given its role as the focal point in this research. The country's three climatic zones area: the Mediterranean climate of the Jordan Valley (referred to as the Ghore Region), the Highlands Region (the location of the study) characterized by chilly winters and scorching summers, and the Desert Region (Badia), encompassing a significant portion of the nation as a semi-desert expanse. Analyzing average temperatures in Amman's Highlands reveals a peak average of roughly 27°C. Consequently, the optimal melting temperature for the PCMMI material should closely align with this range. In the case of $CaCl_2.6H_2O$ (Calcium Chloride Hexahydrate) with integration involving Mycelium, its reported melting point stands at 25°C (16).

- **Microencapsulation within PCMMI**

PCMMI functions as a phase change material, transitioning into a liquid state when exposed to temperatures beyond its melting point. To prevent any potential leaks, a protective covering becomes essential. Microencapsulation serves as a containment method for PCMMI, employing a 100mm-thick sheet as the container, equipped with empty pockets. The pockets within the sheet are designed to accommodate the PCMMI mixture before the construction phase. The sheets are then filled with the PCMMI mixture possessing the specific traits studied and outlined in the literature (17).

3. Methodology

A parametric analysis was applied to estimate the duration which the residential building is exposed to solar heat. An analysis on energy audit was conducted to estimate the exposure (in W/hr./day) in each section of the residential building.

Time-Lag (Φ): It is the time needed for the heat wave to pass through the layers of the envelope materials (18). The more the time lag the better in the climatic zone of Amman. (19). The time lag improves by having a thicker material which will increase the resistance of the heat wave movement from the exterior to the interior. It also improves by having a material in the envelope absorbing the heat (in this case is PCMMI). PCMMI is a material which absorbs the heat at a certain temperature then release
it at night, and accordingly increases the time lag. Figure 1 (Time-lag in materials) illustrates how time lag works and shows the heat wave representation in time.

The Decrement Factor (μ): The thermal mass affection of the time-lag, where the envelopes material reduces the ease of the heat wave entrance. It will decrease the ability of the outside temperature to affect the inside temperature of a building. The decrement factor is defined as the ratio between the interior side of the wall's temperature divided by the exterior side of the wall's temperature. In a more scientific way, the decrement factor is Tsi (the maximum swing [heat wave] from the temperature on the inside) / Tso (the swing [heat wave] in external temperature).

The required time for the heat to transfer from the external side of the envelope to the internal side depends on the materials characteristics, conductivity (K), U-Value and thickness.
The methodology calculated the time lag depending on 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.

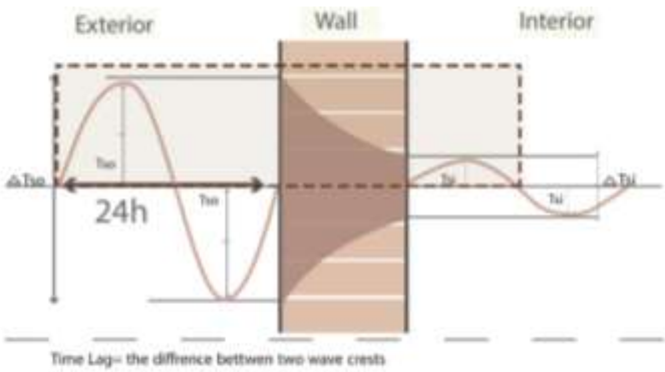

Figure 1 *Time-Lag in Materials*

- **How was the Parametric Analysis Performed?**

Figure 2 *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 2 (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 3 (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.

The parametric analysis has also analyzed the energy audit (energy consumption per square meter in area). The scaler shown in Figure 3 (Parametric Analysis Results) shows the number of hours the envelope is exposed to heat, in addition to the energy consumption per hour per day.

Figure 3 *Parametric Analysis Results*

Here comes the importance of time lag in the envelope's materials. Time lagging materials will delay the time by which the heat will transfer from the exterior to the interior and vice versa.

- Time lag calculations in this thesis was obtained from time lag values from previous studies. This section of the methodology compared the time lag of the envelope's current materials with the time lag using PCMMI.
- Time-lag with PCMMI is defined as the following:

PCMMI is a material that works as a thermal mass since it changes its phase from solid to liquid when absorbing heat. When the exterior temperature drops it releases the heat to the interior as mentioned in chapter 3. Figure 4 (PCMMI time-lagging) illustrates how the absorption of the heat by PCMMI increases the time lag. The more the time lag the better thermal mass and better thermal performance of the material. (21). By using PCMMI in the layers of the building's envelope, the building will act as a thermal mass and increase time to release the heat to the interior. (22). PCMMI, as discussed before, will absorb the exteriors heat in the material itself. When the outside temperature is 25^0C or above, the PCMMI will absorb the heat, and the material will keep on melting until the outside temperature drops below 25^0C.

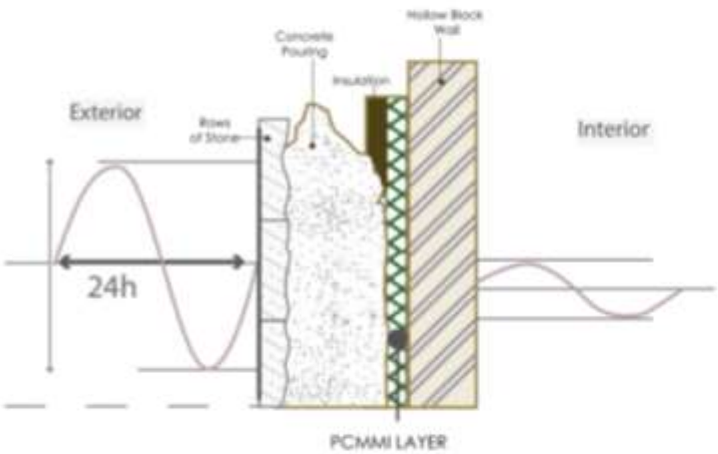

Figure 4 *PCMMI Time-Lagging*

4. Results and Discussion

- **Time-Lag in the Current Envelope Materials Results**

Each material in the envelopes layers has its own time-lag if placed in the same climatic conditions and has the same thickness (3). Table 1 (Time-lag of the current envelopes materials) calculates the time lag of the materials. The table will illustrate the time lag of material per mm (22).

Table 1 *Time-Lag of the envelope's current materials*

Envelop Component		Material Name	Thickness (mm)	Time Lag (hr/mm)	Time Lag (hr)
1	W01	Jordanian Stone	60	0.016667	1
2		Castin-Site Concrete	70	0.037143	2.6
3		Extruded Polysterne	30	0.05	1.5
4		Hollow Concrete Block	100	0.01	1
5		Cement Plastering	20	0.0065	0.13
		Total	280		6.23
1	R01	Ceramic Tile	8	0.0175	0.14
2		Cement Mortar	20	0.013	0.26
3		Sand & Gravel	70	0.002429	0.17
4		Water Proofing (bi-tumen roll)	4	0.0075	0.03
5		Light Weight Concrete	100	0.027	2.7
6		Re-inforced Concrete Slab	300	0.01	3
7		Cement Plastering	20	0.0065	0.13
		Total	522		6.43
1	S01	Ceramic Tile	8	0.0175	0.14
2		Cement Mortar	20	0.013	0.26
3		Sand & Gravel	70	0.002429	0.17
4		Re-inforced Concrete Slab	300	0.01	3
5		Water Proofing (bi-tumen roll)	4	0.0075	0.03
6		Light Weight Concrete	100	0.027	2.7
		Total	502		6.3

As discussed previously, the time lag of the materials describes the delay by which the envelope transfers the external heat to the interior. As shown in Table 1 (Time-lag of the current envelopes materials) the average of the delay is about 6 hours. Which means if the outside temperature is 30ºC, it will take the envelope 6 hours to radiate it to the inside.

- **Time-Lag in the Envelope with using PCMMI Results**

Table 2 (Time Lag with PCMMI in the envelopes layers) shows the performance of PCMMI as a thin layer but with high thermal performance. The time lag of each material was obtained from the literature (17). Each layer has a material, and each material has its own time lag per mm as mentioned before. The time lag is affected by the thickness and characteristics of each material.

Table 2 *Time Lag with PCMMI in the envelope's layers*

Envelop Component		Material Name	Thickness (mm)	Time Lag (hr/mm)	Time Lag (hr)
1	W02	Jordanian Stone	60	0.016667	1
2		Castin-Site Concrete	70	0.037143	2.6
3		Extruded Polysterne	30	0.05	1.5
4		Phase Change Material with Mycellium Integration	10	0.17	1.7
5		Hollow Concrete Block	100	0.01	1
6		Cement Plastering	20	0.0065	0.13
		Total	290		7.93
1	R02	Ceramic Tile	8	0.0175	0.14
2		Cement Mortar	20	0.013	0.26
3		Sand & Gravel	70	0.002429	0.17
4		Water Proofing (bi-tumen roll)	4	0.0075	0.03
5		Light Weight Concrete	100	0.027	2.7
6		Re-inforced Concrete Slab	300	0.01	3
7		Phase Change Material with Mycellium Integration	10	0.17	1.7
8		Cement Plastering	20	0.0065	0.13
		Total	532		8.13
1	S02	Ceramic Tile	8	0.0175	0.14
2		Cement Mortar	20	0.013	0.26
3		Sand & Gravel	70	0.002429	0.17
4		Re-inforced Concrete Slab	300	0.01	3
5		Phase Change Material with Mycellium Integration	10	0.17	1.7
6		Water Proofing (bi-tumen roll)	4	0.0075	0.03
7		Light Weight Concrete	100	0.027	2.7
		Total	512		8.00

The methodology calculated the time lag of the materials depending on the parametric simulation of the residential building, where two adaptive points were simulated, point A is an external heating point with adjustable temperatures, and Point B is an internal sensor. The parametric analysis was illustrated in tables by calculating the effects of the materials envelope before and after adding the PCMMI layer.

5. Conclusion

i. **Time-Lag of the envelope's materials without PCMMI:** the time lag of the materials describes the delay by which the envelope transfers the external heat towards the interior. The results showed that the average of the delay is about 6 hours. Which means that if the temperature outdoor is 30 ºC it will take the envelope 6 hours to radiate it to the interior's peak temperature.

ii. **Time-Lag of the envelope's materials with PCMMI:** the results showed that a small thickness of PCMMI of 10mm enhanced the time-lag on all the envelopes components. W.01 had a time lag of 6.23 hours while W.02 (with PCMMI) had a time lag of 7.93 hours, that is 1.7 hours delay improvement. The same applies for the roof and ground floor slab. If 1 mm of PCMMI has a time lag of 0.17 hours, 10 mm of the same material increased the total time lag by 1.7 hours per component.

The contribution of the study; 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.

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. Software Simulations, 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.

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