Mechanical characterization of a concrete masonry block enhanced with micro-encapsulated phase changing materials

Talal Salem¹, Mohamad Kazma¹, Judy Bitar¹, Joseph Moussa¹, Dalia Falah¹

¹Department of Civil and Environmental Engineering, Notre Dame University – Louaize, Zouk Mosbeh, Lebanon

tsalem@ndu.edu.lb, mkazma@ndu.edu.lb

Abstract. Global energy demand has been increasing exponentially in the last three decades, which has been exacerbated by climate change. To alleviate the energy load, researchers have been exploring innovative passive techniques to enhance the thermal performance of building envelopes. This research evaluates a novel building envelope solution, which includes the development of a Concrete Masonry Unit that is integrated with bio-based micro-encapsulated Phase Changing Materials. The mechanical behaviour of the enhanced CMU is investigated to study the applicability of PCMs into the no-slab concrete mix. Compatibility with the applicable standards opens a broader prospect for thermal characterization and building performance simulations of PCM enhanced CMU building envelopes.

1. Introduction

Throughout the last decade, with energy related emissions hitting record highs, a reduction in greenhouse gas (GHG) emissions has become more vital than ever before. Energy demand is predicted to rise by 1.3% each year until 2040 raising a concern about the growth in the CO₂ emissions, which will exacerbate the issue of global warming [1]. The building sector and its operations account for 36% of the global final energy use, and 39% of the energy-related CO₂ emissions [2]. This sector, which represents the largest among the main emitting sectors, should be a primary target for greenhouse gas emissions mitigation efforts. Energy end-use for buildings is due to space conditioning and heating, water heating, and lighting. Specifically, space cooling demand has increased by over 33% throughout 2010 and 2018 [2].

Nevertheless, on a local level, a study conducted by the Lebanese Center for Energy Conservation, showed that the residential building sector has been the largest consumer of electricity, responsible for about 30% of Lebanon’s overall electricity demand, with indoor space cooling generating 19% of the total electricity demand. It is therefore of importance to develop new energy strategies that can help maintain indoor temperatures within comfort levels, while reducing the building’s energy consumption and GHGs emissions [3].

Improving a building’s efficiency can be achieved by either active energy strategies such as HVAC systems or passive energy strategies that include improvements to the building envelope elements [4]. It has been mentioned that building envelopes, materials and construction have a large influence on cooling loads. This suggests that there exists a large savings potential from improvement in the building envelope performance of buildings [2]. Furthermore, with concrete masonry units (CMUs) being the main construction material utilized for partitioning and on the external façade of most buildings in the...
Middle East region, it is of importance to improve the thermal properties of the CMUs and thus, to alleviate the demand for indoor space cooling [5].

One interesting topic in energy conservation strategies is thermal energy storage (TES), relating to renewable and heat recovery energy. TES utilizes existing or new materials to store heat energy in a thermal form [6]. Through TES the material can reserve heat in three main methods; sensible heat where heat is stored in the temperature increase of the material, latent heat storage where thermal energy is stored or released when the material changes in phase by either melting or solidifying, and thermo-chemical energy storage [7].

Phase Changing Materials (PCMs) are one of the heat storage systems that involve relatively high latent heat storage capacities; the energy is stored or released by physical state changes that can occur over ambient diurnal temperature variations. The incorporation of such materials in the building envelope will allow for enhanced thermal resilience of the building envelope [8]. PCMs can be incorporated within building construction materials using several methods that include direct incorporation, immersion, encapsulation – either micro or macro – and form stabilized composite PCMs. Reference [9] mentioned that the most prominent use of PCMs in building materials is through microencapsulation, allowing thermal storage to be part of a light construction building. Nevertheless, the incorporation of micro-encapsulated PCMs in concrete affects its mechanical characteristics, such as compressive strength. The influence of PCMs on compressive strength tends to be inconsistent in literature [10].

The aim of this paper is to illustrate the compatibility of the mechanical properties of concrete masonry units that are enhanced with bio-based micro-encapsulated phase changing materials (ME-PCMs) with applicable standards. The compressive strength, density and absorptivity of the blocks are evaluated and compared to a conventional no-slump concrete mix used to cast CMUs. A compromise between thermal and mechanical properties should be maintained. The prospect of this research is to characterize the thermal diffusivity of the enhanced blocks and to study the impact of the PCM-CMU envelope wall on the thermal comfort levels and building energy consumption both experimentally and numerically.

2. Building envelope application of Phase Changing Materials

The aim of an energy storage system in a building envelope is to reduce the indoor temperature fluctuation while enhancing the thermal comfort and lowering the energy consumption of the building [11]. PCMs are products that can be considered excellent for the thermal management solutions [12]. The incorporation of PCMs in building materials leads to improved thermal inertia of the façade, and as such allow for passive heat storage and consequently, increase energy savings in buildings.

One study evaluated the addition of a 1 cm layer of PCM integrated within the thermal insulative layer and applied to the outside face of the building envelope that is subjected to a Mediterranean climate. The results showed an improved thermal inertia of the envelope along with a 2 hours’ time lag shift and up to 13.4% energy saving [13].

For this research, a preliminary building performance simulation was developed using a transient simulation software TRNSYS-18 to assess the impact of the integration of PCMs into a CMU wall. Figure 1 shows the preliminary simulation results of a single wythe CMU wall test room of size 2.4m (L) × 2 m (W) × 2.7 m (H) under a 2-day Mediterranean summer climate for Beirut, Lebanon.

CMUs were the point of interest in our tests because of their heavy usage in Lebanon and in the Middle East area. These concrete masonry units are mainly used for partition-walls and building envelopes, rather than structural building elements. Two rooms were simulated with a single wythe CMU wall 15 cm thick with a U-value = 1.517 W/m²°C, density ρ = 2500 kg/m³, and specific heat capacity \( c_p = 1 \)
kJ/kg°C. For the second room a 1 cm PCM layer – which represents around 2% by mass of the CMU – was simulated using an experimentally validated Type 399 which uses the enthalpy method to model PCMs on TRNSYS-18 [14]. The PCM retained in the simulation is analogous to the ME-PCMs used for the mechanical characterization. The bio-based ME-PCMs used herein are INERTEK-26 in powder form and are made from vegetable wax. The ME-PCMs have a phase change range from 24 to 28 °C and a latent energy storage of 185 kJ/kg. The ME-PCMs are characterized by a small thermal conductivity coefficient $k = 0.15$ W/m°C, $\rho = 700$ kg/m$^3$ and $c_p = 2$ kJ/kg°C. The ME-PCM was chosen based on its phase change temperature that is in the range of desired indoor air temperature for thermal comfort.

The simulation showed that for a typical summer 2-day cycle of outdoor dry bulb temperatures fluctuating from 24.5°C to 29.6°C, the root mean square (rms) indoor air temperature for the conventional CMU room was $T_{rms} = 26.6$°C, and that for PCM integrated CMU room $T_{rms} = 25.9$°C. This 0.7°C decrease in the rms indoor air temperature shows promising prospects for the integration of ME-PCMs in CMUs. With such prospect in mind, the mechanical properties are assayed in this research and are discussed in the following sections.

3. Design and Methodology

3.1. Materials and Mix Design

No-slump concrete mixes were developed to understand the influence of adding ME-PCMs on the physical and mechanical properties of the concrete blocks. The mix was developed using locally sourced aggregates with proportions conforming to the guide for proportioning no-slump concrete – ACI 211.3. A mixture of coarse aggregates that represent crushed aggregates of 9.5 mm maximum nominal size and fine aggregates that represented powered gravel of 4.75 mm maximum nominal size. The blended gradation of 50% coarse and 50% fine aggregates has a fineness modulus FM = 4.0 is illustrated in figure 2. This gradation conforms with the suggested gradation for casting no-slump concrete for normal weight CMUs with a medium texture having a FM = 3.7. The gradation utilized leans towards a mix that would result in a coarser texture of the CMU.

Table 1. Mix composition for 1 m$^3$ proportion.

| Mix    | Cement | Coarse Agg. | Fine Agg. | Water$^a$ | PCM$^b$ |
|--------|--------|-------------|-----------|-----------|---------|
| 0%PCM  | 0.15   | 0.375       | 0.375     | 0.1       | 0       |
| 1%PCM  | 0.15   | 0.375       | 0.375     | 0.1       | 1       |
| 2%PCM  | 0.15   | 0.375       | 0.375     | 0.1       | 2       |
| 3%PCM  | 0.15   | 0.375       | 0.375     | 0.1       | 3       |
| 4%PCM  | 0.15   | 0.375       | 0.375     | 0.1       | 4       |

$^a$ Water is added to the mixes integrated with the micro-encapsulated PCMs to compensate for PCM absorptivity.

$^b$ Percentage of PCM added by concrete mix weight.

![Grading FM=4.0](image)

**Figure 2.** Mixed aggregate gradation curve.

Table 1. shows the 5 compositions that were developed to produce a 1m$^3$ volume of concrete. Keeping the same proportions, bio-based ME-PCMs with thermo-physicals properties mentioned in section 2 and having particle sizes ranging between 25 and 50 µm were added to the control mix with percentages of 1%, 2%, 3%, and 4% by weight of concrete. Water is added to achieve a zero-slump mix. The 5 compositions were used to cast non-loadbearing CMUs of size 40 (L)×10 (W)×20 (H) cm.
For casting the CMUs, all the dry aggregates were added into the mix for 1 min and then water was added for an additional mixing time of 2 mins. PCMs were then added in the final stage to avoid increased mixing durations that would lead to the breakage of the micro-encapsules. Additional water was added proportionally to the PCMs to account for their water absorptivity that is equal to approximately 70%. A total of 20 CMUs were cast, 4 for each of the 5 concrete compositions.

3.2. Test Methodologies

Compressive strength, density, and water absorption tests were performed on the PCM enhanced concrete masonry blocks. The sampling and testing of the CMUs were conducted according to ASTM C140 standard.

The compressive strength of the masonry blocks for the 5 compositions was tested at days 7, 14, and 28. A compressive strength setup was devised using rectangular plates situated over the steel bearing blocks of the testing machine. The blocks were then tested for compressive strength at a rate of 0.14 MPa/s such that failure would occur within 1 to 2 minutes, while ensuring that the CMUs were centered in between the steel plates of the testing machine. The average compressive strength results were then compared to the minimum strength requirements for non-load bearing CMUs which is specified as 4.14 MPa for the average of the 3 blocks that were retained (ASTM C129).

Density and absorptivity of the CMUs were also evaluated to study the weight range of the blocks and their durability in wet conditions that is vital for the function of building envelopes. The tests were conducted for the 3 testing periods. The received, immersed, saturated, and oven-dry weights of the CMUs were measured in order to calculate the density and absorption of the CMUs according to ASTM C140. The measured results were then evaluated with respect to the standards. For density, the threshold between medium-weight and normal-weight blocks is 2000 kg/m$^3$ (ASTM C129). For absorptivity, the maximum absorption for normal-weight blocks is 208 kg/m$^3$ (ASTM C90).

4. Results

A compressive strength test was performed to test the condition of the masonry blocks. During testing days 7, 14 and 28, all the examined specimens were compatible for use as non-load bearing CMUs. The results of the compressive strength tests in terms of average value at the three curing periods are presented in Figure 3 below.

Figure 3. 7, 14, and 28-days compressive strength for the 5 mixes – ASTM C129.

Figure 4. Relative change in compressive strength with increase in PCM content.

Based on Figures 3 and 4, a clear trend in the compressive strength results can be observed for the three curing periods of concrete. The average compressive strength decreases with the increase in PCM content due to the weakness of the ME-PCM materials themselves for each of the testing periods. However, for the 7-day curing period, the average compressive strength of the blocks with 1%-PCM was 16.88 MPa which was 23 percent higher than the control block. This outcome can be explained by
the fact that the amount of PCM that was added to Mix 1 did not affect cohesion between the aggregates and the PCMs thermal properties allowed for a slow cement hydration process which ameliorated the development of the concrete’s early strength.

For the mix with 2% PCM, the average compressive strengths were 12.61, 15.11, and 15.81 MPa for 7, 14 and 28 days of curing, respectively. The decline represents 7.9, 28.8, and 29.1 % reduction in compressive strength with respect to the control respectively, showing slight difference between 14 and 28 days of curing. It can also be noticed that at the 14 days curing period, the concrete has reached about 95% of its 28-day strength. The 3%-PCM and 4%-PCM showed a more increased drop in compressive strength reaching 11.33 and 6.88 MPa respectively, at day 28. This represented a decrease of 49% and 69% for each of the aforementioned compositions which is due to the weak strength of the inclusions. All the compositions met the minimum required of 4.14 MPa for the average compressive strength of 3 blocks.

Furthermore, density and absorptivity tests of the CMUs were conducted. Referring to figure 5 the net density for the control 0%-PCM composition is around 2527 kg/m$^3$ which is in the range of normal-weight blocks. The density values obtained at each testing day for each mix were averaged. The amount of ME-PCMs added to the compositions did not make a shift from normal-weight to medium-weight blocks, however, it can be observed that there is a decrease in density for all the PCM compositions. The density decreased by 10.14 %, from 2527.02 kg/m$^3$ reaching 2270.72 kg/m$^3$ with the 4% addition of PCM by mass with respect to the control mix – decreasing at an average of 50 kg/m$^3$ with every 1% of PCMs added. Regardless of the fact that the blocks with the PCMs added to their mixes are still normal weight blocks, the addition of PCMs reduced the densities and resulted in lighter masonry blocks.

![Figure 5. Average density results for the test specimens – ASTM C90.](image)

![Figure 6. Absorptivity results for 7, 14, and 28-day specimens – ASTM C90.](image)

Water absorption testing is intended to determine the susceptibility of an unsaturated concrete to the penetration of water. This can affect the optimum performance of the concrete block that is under wet conditions. As mentioned earlier, the tested blocks were ascertained to be of normal weight. The absorption of the enhanced blocks for this weight category is illustrated in Figure 6.

The incorporation of PCM into CMUs lead to an increase in the absorbent property of the block, which is associated with the characteristics of PCM. It can also be observed that the absorption is affected by the curing period where there is an increase in absorptivity with an increase in curing time. The average water absorption for the 28-day testing period was 133.60, 146.08, 154.66, and 180.06 kg/m$^3$ for 1, 2, 3, and 4% PCM addition, respectively – this represents a 61.5, 76.6, 86.9, and 117.7% increase in water absorption with respect to the control. All the PCM compositions comply with the maximum absorptivity value of 208 kg/m$^3$. 


5. Conclusions and Future Work
In this research, the mechanical properties of enhanced masonry blocks, prepared using bio-based micro-encapsulated PCMs were investigated. The ME-PCM utilized has a melting point of 26°C, which was chosen based on its phase change temperature of 24 to 28°C. Compressive strength, density, and water absorption tests of the PCM enhanced concrete masonry blocks were performed according to ASTM C140 standard and recorded for 3 curing periods: 7, 14, and 28 days.

The average compression strength results were satisfactory and complied with the minimum compression strength for non-load bearing CMUs (ASTM C129). The average compressive strength declined with amount of ME-PCMs incorporated. Similarly, the water absorption and the oven-dry density test results were satisfactory according to the ASTM C 90 and C 129 standards. Moreover, the presented preliminary simulation showed that for a 2% ME-PCM envelope, a 0.7°C decrease in the rms indoor air temperature was estimated. This thermal enhancement is traded off with a decline in mechanical properties as presented experimental results illustrated in this paper.

Compatibility of the mechanical properties of PCM-CMUs with the applicable standards opens a broader prospect for thermal characterization and building performance simulations. As such, the prospect of this research is to obtain the thermal diffusivity of the blocks and to develop and experimentally validate a numerical transient simulation model on TRNSYS-18 to study the impact of the PCM-CMU block on the building energy consumption and of thermal comfort levels.

Acknowledgments
This research is co-funded by Notre Dame University-Louaize (NDU) and the Center for Innovation and Technology (CIT) of the Industrial Research Institute (IRI).

References
[1] IEA 2019 World Energy Outlook 2019
[2] IEA and UN Environment Programme 2019 Global Status Report for Buildings and Construction
[3] Kheradmand M, Azenha M, Aguiar L B de and Castro-Gomes J 2016 Energy 94 250–61
[4] Sadineni S B, Madala S and Boehm R F 2011 Renew. Sustain. Energy Rev. 15 3617–31
[5] Awwad E, Choueiter D and Khatib H 2013 Journal of the European Ceramic Society vol 28 pp 183–92
[6] Zhang H, Baeyens J, Cáceres G, Degrève J and Lü Y 2016 Prog. Energy Combust. Sci. 53 1–40
[7] Akeiber H, Nejat P, Majid M Z A, Wahid M A, Jomehzadeh F, Zeynali Famileh I, Calautit J K, Hughes B R and Zaki S A 2016 Renew. Sustain. Energy Rev. 60 1470–97
[8] Sharifi N P and Sakulich A 2015 Energy Build. 103 83–95
[9] Tyagi V V., Kaushik S C, Tyagi S K and Akiyama T 2011 Renew. Sustain. Energy Rev. 15 1373–91
[10] Drissi S, Ling T C, Mo K H and Eddahahk A 2019 Renew. Sustain. Energy Rev. 110 467–84
[11] Frigione M, Lettieri M and Sarcinella A 2019 Materials (Basel). 12 1–34
[12] Cabeza L F and Perez G 2014 Eco-efficient Construction and Building Materials (Woodhead Publishing) pp 287–310
[13] Saafi K and Daouas N 2019 Energy 187
[14] Claros-marfil L J, Dentel A, Padial J F and Lauret B 2014 1st Int. Congr. Res. Constr. Archit. Technol.