Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 4, Issue 4, 2026

ENHANCING BUILDING ENERGY EFFICIENCY: INNOVATIVE CONCRETE WITH PHASE CHANGE MATERIAL-COATED COARSE AGGREGATE

Shamotra Oad[*1], Sadam Hussain Jakhrani[*2], Muhammad Ibrahim Shaikh[3], Jabir Ali Keryio[4], Imran Ali Channa[5]

[*1, *2,4]*Department of Civil Engineering Technology, The Benazir Bhutto Shaheed University of Technology and Skill Development (BBS-UTECH), Khairpur Mirs, Sindh, Pakistan*
[*1]*Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia*
[3]*MS Scholar, USPCAS-W, Mehran University of Engineering and Technology (MUET), Jamshoro, Sindh, Pakistan*
[5]*Department of Civil Engineering, Quaid-e-Awam University of Engineering, Science & Technology, Nawabshah*

[*1]shamotra@bbsutsd.edu.pk, ORIC ID: https://orcid.org/0000-0002-0070-2980, [*2]dr.shj@bbsutsd.edu.pk

DOI: https://doi.org/10.5281/zenodo.19591963

Keywords
Building Energy; Concrete; Phase Change Materials; Coated Coarse Aggregates

Article History
Received: 16 February 2026
Accepted: 26 March 2026
Published: 15 April 2026

Corresponding Author: *
Shamotra Oad

Abstract
Global warming presents a pressing global challenge, with the construction sector emerging as a significant contributor to carbon emissions, accounting for 25% to 40% of global carbon emissions in Pakistan. To address this issue, the construction industry is seeking innovative methods to enhance thermal insulation in buildings. Recent attention has been drawn to phase change materials (PCM) for their thermal storage properties, owing to challenges in electrification, rising costs of digital equipment, electric transportation, and residential heating and cooling. PCM, substances that absorb and release energy at phase transition temperatures, offer promising solutions for heating and cooling applications in construction materials. This study focuses on developing PCM-coated coarse aggregates, employing lauric acid and paraffin liquid through vacuum impregnation. Different ratios of PCM-coated aggregates replaced natural coarse aggregates in concrete mixes (0%, 25%, 50%, 75%, 100%). The study aimed to assess the mechanical, thermal, and bonding characteristics of concrete by evaluating slump value, compressive strength, and thermal conductivity. The results indicated that 50% PCM-coated aggregates have exhibited a consistent physical strength and excellent heat conduction across various applications of concrete. However, PCM-100% and PCM-75% compositions demonstrate heightened thermal energy conduction sensitivity but lower compressive strengths that make PCMs inappropriate for high-stress atmospheres. This research underscores the potential of PCM-embedded concrete for sustainable construction practices in the construction industry.

1. INTRODUCTION

Concrete, recognized as the most widely used homogeneous construction material, though exhibits various characteristics due to its composition comprising various elements, like type and physio-chemical properties of cement, fine aggregate, coarse aggregate and water. Alongside these components, different types of chemical and mineral admixtures are often introduced to enhance its properties. Globally, concrete holds a prominent status in construction due to its remarkable resistance against weathering and its adaptability to diverse shapes during casting. The escalating demand for concrete, particularly fueled by rapid infrastructure development in countries like China and India, underscores its significance [1-3]. Constituted primarily of cement, sand, stone, and water, concrete showcases a spectrum of properties such as compressive strength, hardness, durability, and workability, which evolve over time. Evaluating these properties early on is pivotal for ensuring construction quality [4]. The strength characteristic of concrete denotes its capacity to withstand applied loads without failure, while insulation pertains to a structural element's ability to retain its functionality under elevated temperatures [5]. Traditional insulation materials such as mineral wools, expanded cork, and expanded perlite are widely utilized owing to their reliability, ease of installation, and cost-effectiveness. However, these materials exhibit limited capability in energy storage [6]. In contrast, the recently introduced phase change materials (PCMs) emerge as an innovative solution within thermal energy storage systems, significantly enhancing building energy performance. PCMs harness the latent heat of storage materials, enabling them to store substantial thermal energy during phase transitions between solid and liquid states [7].

Phase change materials (PCMs) represent the pinnacle of efficiency in latent heat thermal energy storage (TES) systems [8]. During melting, energy per unit mass is stored, subsequently released during freezing, typically within a constant or narrow temperature range. The remarkable capability of PCMs to enhance the performance and trustworthiness of thermal energy storage applications has been well documented [8]. This has sparked particular interest in various fields including thermal management and greenhouses. For a PCM to be suitable for integration into a thermal energy storage system, it must meet several criteria encompassing thermo-physical, kinetic, and chemical properties [9]. Firstly, phase transition should occur inside the anticipated working temperature range of the system, ensuring that the majority of the additional heat is deposited as latent heat within a narrow temperature band. Additionally, the PCM should exhibit high latent heat storage capacity, facilitating efficient energy storage [10]. High thermal conductivity is essential to aid in the absorption and release of energy within the storage system, while high specific heat capacity provides additional sensible heat storage. Moreover, minimal volume changes during phase transformation, high density, and a high nucleation rate to prevent super-cooling of the liquid phase are imperative. Super-cooling, where a material exhibits a substantially lower freezing point than its melting point, must be avoided. Chemical stability, resistance to degradation over numerous cycles, non-toxicity, non-flammability, absence of corrosion effects on structural materials, as well as relative affordability and widespread availability, are further prerequisites for an ideal PCM [10]. Addressing the imperative to augment energy storage capacity in buildings, the integration of phase change materials (PCMs) into concrete mixtures emerges as a viable approach within thermal energy management systems [11-13].

The significance of building thermal energy storage in the context of global sustainability is paramount, especially as building energy consumption continues to escalate. The study by Fan Z. et al. 2022 [14] introduced a novel approach wherein a ternary eutectic compound composed of lauric acid, palmitic acid, and paraffin, termed lauric-palmitic acid-paraffin ternary eutectic (LPP) was synthesized. The leakage tests revealed that EP could accommodate a maximum loading rate of LPP up to 75%. Based on the findings of the study, it was evident that

LPP/EP composite phase change materials hold tremendous promise for applications in building thermal energy storage systems, paving the way for significant advancements in sustainable building practices. In another study Kumar et al., 2021 [4] presented a comprehensive comparative analysis of building insulation materials, considering various properties including thermal conductivity, hygroscopicity, acoustic properties, and reaction to fire, environmental impact, and cost, while also evaluating their performance across different climate zones. The analysis highlighted that the cost-effectiveness of building walls varied depending on the climate zone, with walls featuring lower thermal resistance proving more cost-effective in cooling-dominated regions, while those with higher thermal resistance are more suitable for heating-dominated regions. Nevertheless, highly insulated and airtight structures may inadvertently lead to increased overheating risk and peak cooling demand during hot summers. The PCMs were integrated into cement for building construction purposes [15]. They possessed a distinctive characteristic of absorbing and storing energy, which holds significant potential for energy savings when incorporated into construction materials. The study focused on the passive integration of PCM into cement, aiming to assess the thermal properties resulting from this integration. By examining how PCMs impact cement within concrete mixtures, the research shed light on the role of PCM-based cements in enhancing the properties of concrete. Through this investigation, valuable insights were gained into the efficacy of PCM incorporation in cement and its implications for concrete mixtures [15]. This work [16] provided an overview of the characterization methods that were utilized to evaluate the properties of fresh concrete mixes containing PCM. By discussing the findings from obtained test results, the paper offered insights into the performance of concrete mixes with PCM additives, shedding light on their suitability and potential for use in sustainable building construction [16].

2. RESEARCH METHODOLOGY

2.1. Materials

The materials utilized in the production of concrete included Ordinary Portland Cement, fine aggregates, and coarse aggregates. However, in this particular context, an additional component is incorporated that is phase change material (PCM) based coated coarse aggregates. These coated coarse aggregates were prepared using organic PCMs such as lauric acid and paraffin oil, employing the vacuum impregnation technique. Paraffin liquid is a commercially available organic phase change material in the form of $CH_3(CH_2)nCH_3$, the details of that are given in Table-1. Lauric acid (LA, CH12H24O2) is a kind of organic PCM with outstanding thermal properties as given in Table-2.

Table 1 Characterization of paraffin liquid

Analysis	Typical data
Appearance	Transparent, colorless, bright and clear oily liquid.
Odor	Odorless
Density @ 29.5 °C	0.82-0.85 gms/cc
Kinematic Viscosity @ 40 °C	7.50-8.50°5 ct

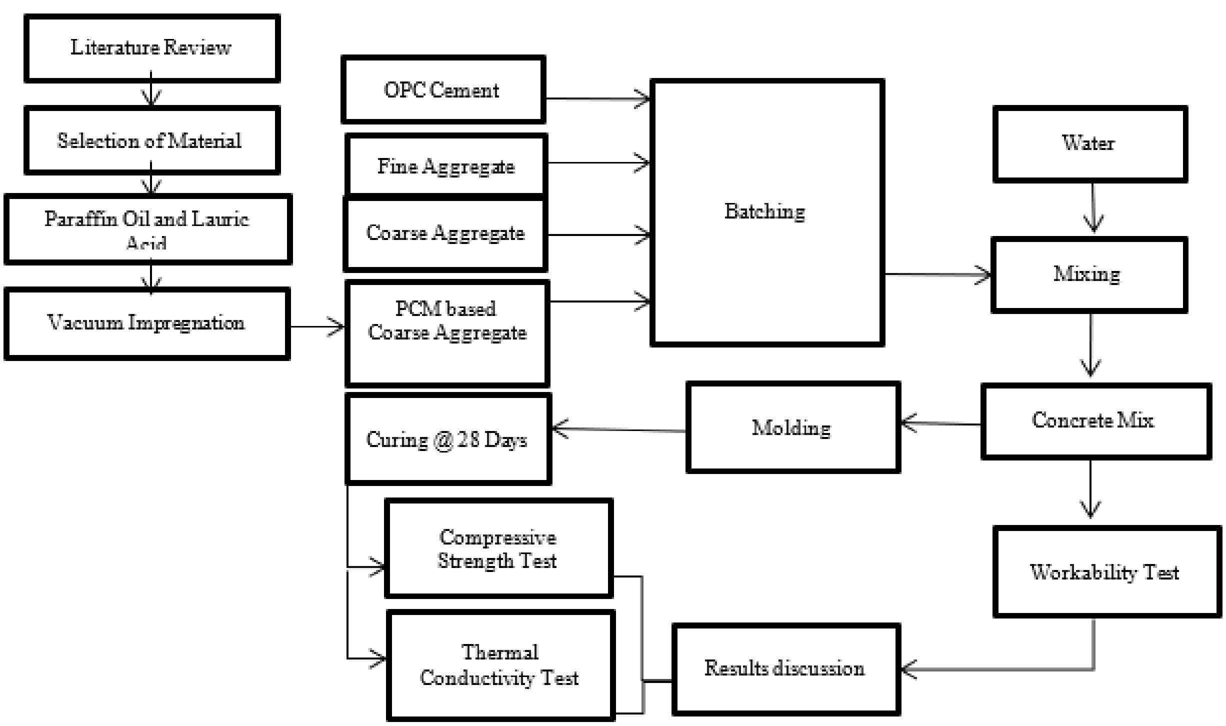
Table 2 Characterization of lauric acid

Analysis	Typical data
Melting temperature (℃)	43.5

Density (kg/m^3)	873 to 940
Specific heat (kJ/kg·K)	2.20 to 1.95
Thermal conductivity (W/m·K)	0.15 to 0.45
Viscosity (kg/m·s)	0.006
Melting latent heat (kJ/kg)	187.2

2.2. Development of phase change materials based coated coarse aggregate

The development of phase change materials (PCM) based coated coarse aggregate involved a meticulous process to ensure the effective absorption and enhanced performance. Initially, the coarse aggregates were washed and oven dried to remove any contaminants and moisture. Subsequently, they were placed inside a vacuum chamber for 30 minutes to eliminate air from their porous structure. Once the vacuum chamber was prepared, a composite of melted lauric acid and paraffin was introduced into the chamber. The vacuum chamber was maintained at a pressure of -0.1MPa, while the melted lauric acid and coarse aggregates undergone further vacuuming for 60 minutes. Throughout this process, the vacuum chamber was immersed in a water bath to sustain a temperature range of 50-60°C, ensuring that the lauric acid remained in a melted state. Finally, the coarse aggregates impregnated with lauric acid were removed from the vacuum chamber and stored in a refrigerator below 4°C. This step was crucial to facilitate the solidification of the composite of lauric acid and paraffin within the pores of the coarse aggregates, thus forming the phase change material based coated coarse aggregate. Further, to accomplish the aim and objectives of the research work, certain specific research working method was followed, as given in **flow-chart** below;



2.3. Mix Proportion for the concrete

To attain the expected characteristics of strength and durability, a variety of appropriate mix proportion was very necessary to adopt. Throughout the study, a nominal mix of 1:2:4 at a w/b of 0.55 was applied. The precise mix proportion was designated to make concrete workable enough.

Table (3): Mix proportions Details of 1:2:4 Concrete

Sr. No.	Mix ID	Binder	Coarse aggregate		F.A (% age)	W/B ratio
		Cement (% age)	PCM-CA (% age)	C.A (% age)		
1	CM	100	0	100	100	0.55
2	PCM –CA 25	100	25	75	100	0.55
3	PCM –CA 50	100	50	50	100	0.55
4	PCM –CA 75	100	75	25	100	0.55
5	PCM –CA 100	100	100	0	100	0.55

3. RESULTS AND DISCUSSIONS

3.1. Workability

In the investigation of workability within concrete mixes, the integration of phase-changing material (PCM) based coated coarse aggregate emerged as a significant variable, as delineated in the findings of Figure 1. Notably, the conventional mix (CM) exhibited a baseline slump value of 36 mm, served as a reference point for evaluation. As the proportion of PCM-coated coarse aggregate increased, there was a discernible enhancement in concrete workability. This trend was evident in the progressive reduction of slump values, from 32 mm at 25% PCM replacement to 24 mm at 100% PCM replacement. The culmination of this enhancement is observed at full substitution, where the maximum workability was achieved, indicated by a slump value of 24 mm. These findings underscored the positive correlation between PCM-coated coarse aggregate dosage and concrete workability, highlighting the potential of this innovative material in optimizing construction practices.

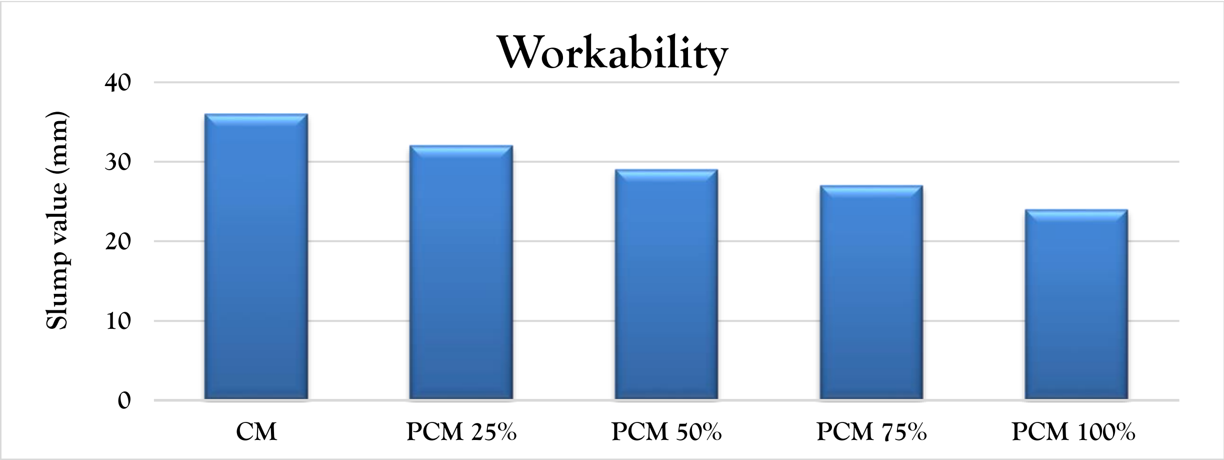


Figure 1: Workability of PCM based coated coarse aggregate.

3.2. Compressive Strength

Figure 2 presents a comprehensive view of compressive strength values for both standard concrete and concrete mixes incorporating phase-changing material (PCM) based coated coarse aggregate after a 28-day curing period. In examining the compressive strength of these formulations, a distinct trend emerged. Initially, as the dosage of PCM increased, there was a notable improvement in concrete strength, peaking at 50% replacement, where a maximum compressive strength of 31.5 MPa was achieved. This represented a significant enhancement over standard concrete. However, beyond this threshold, a diminishing return in strength was observed. At 100% PCM replacement, the compressive strength decreased to 25.2 MPa, signifying a reduction compared to the 50% replacement level. These findings highlighted the complex interplay between PCM dosage and concrete strength. While PCM incorporation initially enhanced compressive strength, there existed an optimal dosage beyond which the benefits diminish. This understanding was crucial for optimizing concrete formulations and ensuring structural integrity in various applications.

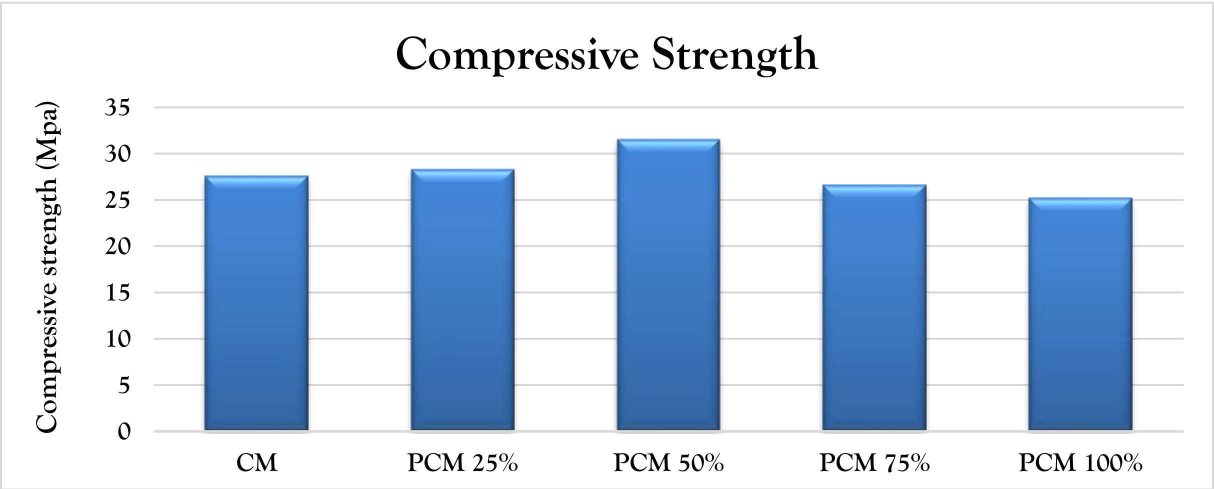


Figure 2: Compressive Strength of PCM based coated concrete at 28 days.

3.3. Thermal Conductivity

Figure 3 depicts the thermal conductivity values of different concrete compositions, including convention mix concrete and those incorporated with phase-change material (PCM) based coated coarse aggregate. For the standard concrete mix (CM), the thermal conductivity stood at 1.56 W/mK. As the proportion of PCM-coated coarse aggregate increased, there was a consistent decrease in thermal conductivity. At 25% PCM replacement, the thermal conductivity reduces to 0.68 W/mK. This reduction continued as the PCM dosage increased further, with values of 0.52 W/mK, 0.44 W/mK, and 0.39 W/mK at 50%, 75%, and 100% PCM replacements, respectively. Notably, the most significant reduction in thermal conductivity was observed at 100% PCM replacement, reaching its lowest value of 0.39 W/mK. These findings underscored the potential of PCM-coated coarse aggregate to significantly enhance the thermal insulation properties of concrete, offering promising implications for energy-efficient construction practices and improved temperature regulation in various structural applications.

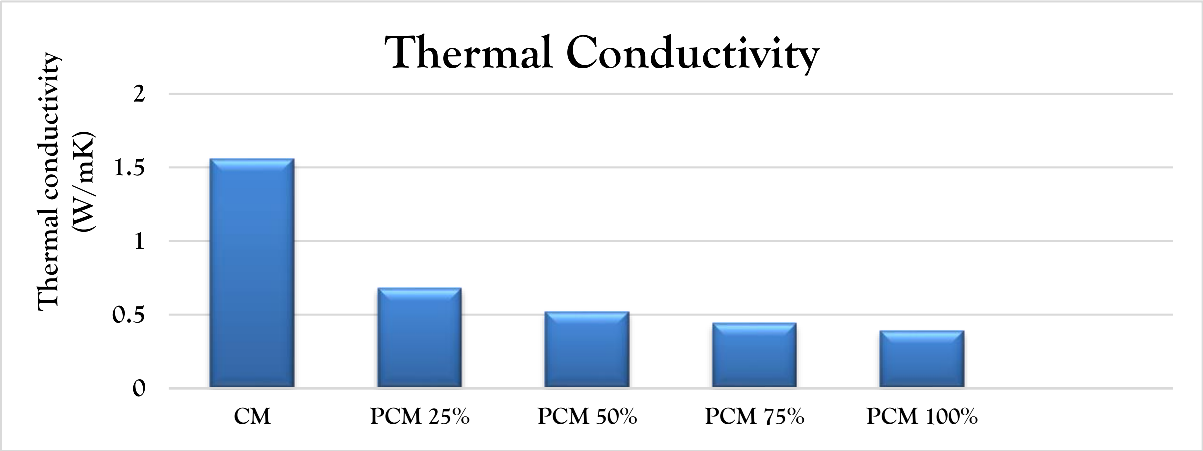


Figure 3: Thermal conductivity of PCM based coated coarse aggregate.

4. CONCLUSION

Utilizing phase change materials (PCMs) to store thermal energy emerges as an intelligent strategy for enhancing building insulation and contributing to renewable energy conservation efforts. This study highlights;

1. The significant benefits of incorporating 50% PCM into concrete, resulting in strengthened structural integrity and enhanced heat conductivity across diverse environmental conditions. However, when the PCM content reaches 100% or 75% in the coated coarse aggregates, they exhibit heightened sensitivity to heat but lack the necessary strength for demanding applications.
2. Moreover, higher PCM ratios compromise the concrete's overall durability while increasing its thermal conductivity. Notably, the research underscores the optimal balance achieved with 50% PCM content, fostering a pleasant indoor environment characterized by improved thermal comfort.

5. REFERENCES

[1] Khan, M. A., Channa, I. A., Hanif, S., Nawaz, M., & Wahab, A. (2026). Mechanical and Physical Performance of Lightweight Concrete Using Waste Pumice as Coarse Aggregate. *Spectrum of Engineering Sciences*, *4*(2), 12-26.

[2] Kim, Y., Hanif, A., Usman, M., Munir, M. J., Kazmi, S. M. S., & Kim, S. (2018). Slag waste incorporation in high early strength concrete as cement replacement: Environmental impact and influence on hydration & durability attributes. Journal of Cleaner Production, 172, 3056-3065.

[3] Lee, H., Hanif, A., Usman, M., Sim, J., & Oh, H. (2018). Performance evaluation of concrete incorporating glass powder and glass sludge wastes as supplementary cementing material. Journal of Cleaner Production, 170, 683-693.

[4] Kumar D, Alam M, Zou P, et al. Comparative analysis of building insulation material properties and performance. Renewable and Sustainable Energy Reviews, 2020, 131: 110038.

[5] Safna N, Igor K. Phase change materials for thermal energy storage applications in greenhouses: A review[J]. Sustainable Energy Technologies and Assessments.2022, 52c: 102241.

[6] G. Peng, G. Dou, Y. Hu, Y. Sun, Z. Chen, Phasechange material (PCM) microcapsules for thermal energy storage, Adv. Polym. Technol. 2020 (2020). https://doi.org/10.1155/2020/9490873

[7] Pielichowska, K. and K. Pielichowski, Phase change materials for thermal energy storage. Progress in Materials Science, 2014. 65: p. 67-123.

[8] Lazaro, A., et al., Intercomparative tests on phase change materials characterisation with differential scanning calorimeter. Applied Energy, 2013. 109: p. 415-420.

[9] Kenisarin, M.M., High-temperature phase change materials for thermal energy storage. Renewable and Sustainable Energy Reviews, 2010. 14(3): p. 955-970.

[10] Sharma, A., et al., Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 2007. 13(2): p. 318- 345.

[11] Z. Dakhli, K. Chaffar, Z. Lafhaj, The Effect of Phase Change Materials on the Physical, Thermal and Mechanical Properties of Cement, Sci. 1 (2019) 27. https://doi.org/10.3390/sci1010027.

[12] S. Drissi, T.C. Ling, K.H. Mo, A. Eddhahak, A review of microencapsulated and composite phase-change materials: Alteration of strength and thermal properties of cement-based materials, Renew. Sustain. Energy Rev. 110 (2019) 467–484.https://doi.org/10.1016/j.rser.2019.04.072.

[13] Li, J., et al., Micro-encapsulated paraffin/high-density polyethylene/wood flour composite as form-stable phase change material for thermal energy storage. Solar Energy Materials and Solar Cells, 2009. 93(10): p. 1761-1767.

[14] Fan, Z., Zhao, Y., Liu, X., Shi, Y., & Jiang, D. (2022). Development of a new composite material for building energy storage based on lauric acid-palmitic acid-paraffin ternary eutectic and expanded perlite. *Journal of Energy Storage*, *53*, 105136.

[15] Z. Dakhli, K. Chaffar, Z. Lafhaj, The Effect of Phase Change Materials on the Physical, Thermal and Mechanical Properties of Cement, Sci. 1 (2019) 27. https://doi.org/10.3390/sci1010027.

[16] H. Paksoy, G. Kardas, Y. Konuklu, K. Cellat, F. Tezcan, Characterization of Concrete Mixes Containing Phase Change Materials, IOP Conf. Ser.Mater. Sci. Eng. 251 (2017). https://doi.org/10.1088/1757-899X/251/1/012118.