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Effect of phase change materials on the thermal behavior of biomass-based composites

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Abstract
This research explores the thermal performance of biomass-based composite panels enhanced with Phase Change Materials (PCM) for energy-efficient building applications. The experimental method under lab-controlled conditions was used to investigate thermal performances. Four samples of PCM-biomass-based composite were fabricated using encapsulated PCM, straw, and mortar as a binding material, and four sample without PCM as a reference. The effective thermal conductivity of each sample was determined using the guarded hot plate method under steady-state conditions. Results indicate that the incorporation of PCM does not significantly alter the thermal conductivity of the composite, but it enhances the material's ability to store thermal energy. Compared to conventional construction materials, both the reference and PCM-enhanced samples exhibit superior thermal insulation properties, making them promising candidates for sustainable building applications. The findings suggest that optimizing PCM concentration and distribution could further enhance thermal performance, contributing to the development of passive energy-saving solutions.

Keywords: PCM, Straw composite, Biomass-based composite, Thermal conductivity, Energy-efficient buildings, Sustainable construction

1. Introduction

To reduce environmental impact and enhance energy efficiency, the construction industry is increasingly seeking sustainable materials and solution [1]. Therefore, pursuing sustainable development practices caused a growing demand for eco-friendly and energy-efficient building materials [2]. Conventional nonrenewable construction materials (concrete, steel, etc.) [3] are resource-intensive and have a significant environmental footprint [4]. On the other hand, adaptive facades [5] and natural and renewable materials like straw, may offer a sustainable alternative due to low embodied energy and very good thermal insulation properties [6]. Straw as an agricultural byproduct is a renewable and eco-friendly, that may be used as building material. It poses a low thermal conductivity [7] and carbon footprint, making it a promising option in sustainable construction [8]. Due to high thermal resistance, straw bales have been used in construction for centuries. However, straw-based materials alone may not fully address the need for thermal energy storage, especially in regions with significant temperature fluctuations.

To improve energy storage properties of straw bales, Phase Change Materials (PCMs) may play an important role in reducing this limitation by integrating PCMs into straw-based composites. PCMs are substances that have the ability to store and release thermal energy during its melting and solidifying. Due to this property, PCMs can enhance the thermal mass and energy storage capacity of PCM-straw-based composite if combined with straw [9]. This way, thermal performance of straw-based buildings can be improved by stabilizing indoor temperature fluctuation and consequently reducing energy consumption [10]. The integration of PCMs into straw-based composites indicates that adding PCMs to straw composites can enhance thermal storage without significantly increasing thermal conductivity [11].

Even though the integration of PCMs into straw-based materials is still in its early stages, several challenges are identified to overcome including manufacturing process optimization, long-term performance evaluation, PCM-straw composites durability and cost-effectiveness.

1.1. Straw as a building material

Straw bales for walls have been used in construction for centuries. The walls formed in this way are plastered with clay or lime, which offers good thermal insulation, sustainability, and cost-effectiveness [12]. Straw is a renewable resource and can be locally obtained. This reduces transportation emissions, and associated costs. Such walls have high thermal resistance helping to maintain indoor thermal comfort and reduce heating / cooling energy consumption [13]. Additionally, straw can capture CO_2 during its growth and contributes to greenhouse gas emissions reduction. The comparison of straw properties with conventional building materials is presented in Table 1.

Table 1. Comparison of straw and conventional building materials

Property	Straw Bales	Concrete	Fiberglass Insulation
Thermal conductivity	Low (approximately 0.055 - 0.076 W/mK) [7], [14]	High (approximately 1.4 W/mK) [15]	Low (approximately 0.045 W/mK) [15]
Cost	Low [16]	High [16]	Medium [16]
Sustainability	High [17]	Low [4]	Medium [17]
Carbon capture	Yes [17]	No [18]	No [19]
Fire resistance	Moderate (depends on treatment) [16]	High [16], [20]	High [21]

Table 1 highlights the advantages of straw bales as an environmentally sustainable and cost-effective material with low thermal conductivity and carbon capture potential. It is observed that conventional materials like concrete and fiberglass offer higher fire resistance but lack sustainability benefits. As drawbacks of straw can be considered vulnerability to moisture, moderate fire resistance, and structural stability. However, these issues can be mitigated through proper design, treatment, and the use of protective coatings [22].

1.2. Integration of PCMs in building materials

Substances that absorb and release thermal energy during phase transitions, like melting and solidification, are known as Phase Change Materials. By storing extra heat during the day and releasing it at night, PCMs can be incorporated into building materials to control indoor temperature fluctuation and save energy. PCMs help maintain thermal comfort without largely relying on mechanical heating and cooling systems, they are especially effective in climates with significant temperature variations [23]. Better temperature regulation, increased energy efficiency, and peak load shifting are just a few advantages of incorporating PCMs into building materials. PCMs can minimize energy expenses and carbon footprint by reducing the requirement for HVAC systems [24]. Nevertheless, issues including PCM high price, incompatibility with construction materials and potential leakage can hinder the widespread adoption of PCMs in building applications. These challenges are essential for widespread applications of PCMs in practice [25]. Comparison of PCM properties with common storage materials is presented in Table 2.

Table 2. Comparison of PCM with common storage material

Property	PCMs	Water	Stone
Storage mechanism	Latent heat (phase change) [26]	Sensible heat (temperature change) [27], [28]	Sensible heat (temperature change) [27], [28]

Property	PCMs	Water	Stone
Energy density	High (e.g., 200 kJ/kg for paraffin) [29]	Moderate (4.2 kJ/kg·K) [30]	Low (0.8–1.47 kJ/kg·K) [31]
Temperature range	Tailored (e.g., 0°C to 100°C+) [29]	0°C to 100°C (before boiling) [30]	High (up to several hundred °C) [32]
Thermal inertia	High (maintains temperature during phase change) [33]	Moderate (stores heat as temperature rises) [30]	Low (requires large mass for significant storage) [33]
Volume required	Low (high energy density) [33]	Moderate (higher than PCMs) [33]	High (low energy density) [32], [33]
Cost	High (expensive materials and encapsulation) [33]	Low (cheap and widely available) [30]	Very Low (abundant and inexpensive) [5]
Advantages	High energy density, compact, precise temperature control [33]	Low cost, non-toxic, high specific heat [30]	High temperature tolerance, durable, low cost [32]
Disadvantages	Higher cost, phase separation, subcooling [33]	Lower energy density, requires large volumes [30], [33]	Very low energy density, requires large volumes [32], [33]
Typical applications	Energy storage in buildings, electronic cooling, solar energy storage [29]	Domestic hot water, solar thermal systems [30]	High-temperature thermal storage (e.g., solar power plants) [34]

Table 2 shows that PCMs offer significant advantages over conventional storage materials like water and stone utilizing its latent heat energy storage across different temperature ranges. The higher cost and potential issues such as phase separation and subcooling are considered as challenges. Despite these limitations, PCMs are still well-suited for energy-efficient applications in buildings.

1.3. Position of PCM within a building wall

The effective position of PCM layer in building wall depends on building orientation, climate, and the thermal performance objectives. A layer of PCM within the structure can increase energy savings by 1% to 7% [35], [36]. Optimal placement depends on wall material, insulation properties, and the specific thermal characteristics of the PCM used. Achieving a full daily melting and solidification cycle is essential for PCM placement to guarantee preparedness for the next day. By absorbing extra heat during the day and releasing it at night, PCMs can reduce the need for mechanical heating and cooling systems [37]. Table 3 shows a short analysis of PCM layer position within a building wall as well as its recommended thickness.

Table 3. Position of PCM layer within a building wall and its thickness

PCM placement	Optimal climate/conditions	Benefits	Source
External layer	Hot climates	Absorbs excess heat during the day and releases it to the outdoor environment at night, reducing indoor heat gain.	[38]
Internal layer	Cold climates	Stores heat from indoor sources during the day and releases it back at night, enhancing thermal comfort.	[38]
Middle of the wall	Regions with significant diurnal temperature variations	Balances heat absorption and release over a 24-hour cycle, optimizing thermal performance.	[37], [39]
Optimum thickness	Optimal PCM thickness of 3 cm	Balanced trade-off between energy savings and material costs.	[37]

External layer may be beneficial to place the PCM closer to the outside in areas with hotter climates. This configuration lowers interior heat gain by allowing the PCM to collect surplus heat during the day and release it back to the outside environment at night [38]. *Internal layer* may be beneficial to place the PCM closer to the interior in areas with colder climates. This configuration improves thermal comfort and lowers heating needs by allowing the PCM to store heat from interior sources during the day and release it back into the indoor environment at night [38]. *Middle of the wall* may balance heat absorption and release throughout a 24-hour cycle, some research indicates that placing the PCM in the center of the wall can maximize thermal performance. In areas with notable daily temperature fluctuations, this location may work well [37], [39].

An optimal PCM thickness of 3 cm offers a balanced trade-off between energy savings and material costs. For example, in research on educational buildings, a PCM layer of 3 cm can reduce heat transfer by 13.4%, with an estimated payback period of around 50 months [37]. It is important to note that the optimal placement can also be influenced by factors such as wall material, insulation properties, and the specific thermal characteristics of the PCM used. Therefore, a detailed analysis considering these variables is recommended to determine the most effective placement for PCMs in building walls.

1.4. PCM-straw-based composites

A new method for improving thermal performances of a building is the combination of PCMs and straw-based materials. Straw has a good insulation capacity while PCM has a capacity to store heat. Combining the two advantages in PCM-straw composites may be promising in creating an effective construction material. These composites can be applied to floors, walls, and roofs to increase occupant comfort and energy efficiency [11]. These composites can save energy, improve indoor comfort, improved thermal performance, reduce the demand for mechanical heating and cooling [40].

Establishing compatibility between PCMs and straw, streamlining the production process, and assessing long-term performance are some of the obstacles facing composite development. In addition, a lot of research in these areas is required to reach a large-scale application [11], [41] as well as to solve issues associated with financing green technologies [42]. Some of the advantages and challenges of PCM-straw-based composites are highlighted in Table 4.

Table 4. Advantages and challenges of PCM-straw composites

Aspect	Advantages	Challenges
Thermal performance	Enhanced thermal storage due to the high latent heat of PCMs [40].	Compatibility with straw, as the addition of PCM to straw-based composites can affect thermal conductivity [11].
Energy efficiency	Reduced HVAC energy consumption by utilizing the thermal storage properties of PCMs [40].	High cost of PCMs, which can impact the overall cost-effectiveness of the composite materials [40].
Sustainability	Eco-friendly and renewable, utilizing agricultural residues like straw [43], [44].	Long-term durability concerns, as the integration of PCMs may affect the lifespan and stability of the composite [11].
Comfort	Stable indoor temperatures due to the thermal buffering capacity of PCMs [6], [43], [44].	Manufacturing complexity, as incorporating PCMs into straw composites may require specialized processing techniques [11].

Reffering to Table 4, it is observed that PCM-straw composites may offer improved thermal storage of a building structure. However, challenges such as high costs of PCMs, potential impacts on material durability, and the complexity of manufacturing processes has to be addressed to improve feasibility and long-term performance.

This research focuses on combining the distinct advantages of straw and PCM in creating a PCM-straw-based composite by considering the position and thickness of the layer within a composite structure. The main goal is to assess how PCM affects PCM-straw-based composite thermal performance. The project is to investigate how this arrangement improves heat control and energy efficiency by carefully positioning the PCM layer on the inside side of the wall. The results will advance our knowledge of how to best utilize sustainable building materials for better thermal control.

2. Research method

The research method relies on a series of experiments conducted in the laboratory environment, which includes sample preparation, testing and data analysis.

2.1. Sample preparation

Four PCM-straw-composite samples were made using the following materials: straw, encapsulated PCM and mortar as binding material. To provide a baseline for assessing the thermal performance of the PCM-enhanced composites, another group of four samples was produced without PCM as a reference. The dimension of each sample was approximately A x B x H = 15 cm x 17 cm x 22 cm. The binding material was applied to both sides of the test sample, as it is shown in Figure 1.

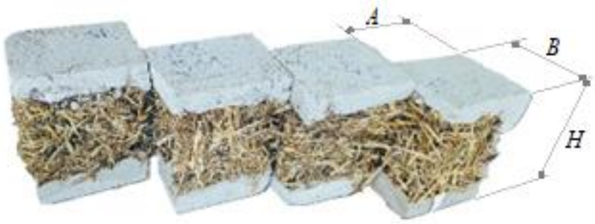

Figure 1. Test samples (four samples based on PCM-straw and four without PCM)

Each sample utilized approximately the same amount of straw and maintained a consistent volumetric ratio of binder. The PCM used was RT22HC, encapsulated in approximately 10 mm capsules and incorporated as a layer within the mortar, with the aim of enhancing the thermal storage capacity of the interior sample layer. The PCM properties re shown in Table 5.

Table 5. Properties obtained from Rubitherm data sheets [45]for RT22 HC

Property	Value
Melting and congealing area	20–23°C
Heat storage capacity	190 kJ/kg
Specific heat capacity	2 kJ/kg·K
Density (solid at 15°C)	0.77 kg/l
Density (liquid at 40°C)	0.88 kg/l
Volume expansion	12.5%
Heat conductivity	0.2 W/(mK)
Max operating temperature	50°C

For both types of samples, a homogeneous mixture of straw and mortar was created. The mixture was molded into panels with the specified dimensions, ensuring uniform distribution of straw and binder. For the PCM-enhanced samples, the encapsulated PCM capsules were evenly distributed and layered within the mortar during the sample fabrication process.

Figure 2. Cured test samples

All samples were cured in a controlled environment for a minimum of 28 days to allow the mortar to set properly and achieve optimal bonding (Figure 2).

2.2. Testing procedure

The guarded hot plate method is employed to determine the thermal conductivity of straw-based samples. The experimental setup is depicted in Figure 3, illustrating the cross section of the guarded hot plate configuration.

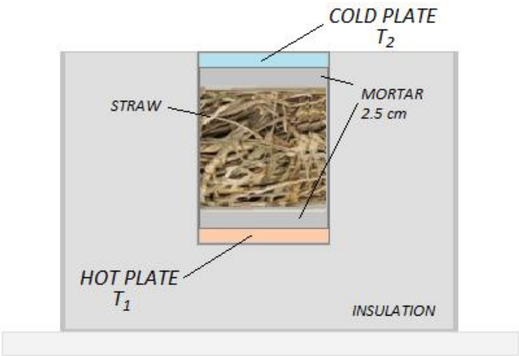

Figure 3. Experimental setup

Each sample was positioned between the hot and cold plates, ensuring good thermal contact and proper alignment with the guard ring. During the test period, T_1 and T_2 temperatures are recorder on both sides of the test sample under known constant heat flow conditions. Data collection continued for each sample until the steady-state conditions were achieved. A Vernier LabQuest 2 data logger is used for temperature measurements. The accuracy of the surface temperature sensors is ±0.2°C at 0°C and ±0.5°C at 100°C, which is sufficiently precise for this study.

The *effective thermal conductivity* is determined based on the recorded data. It describes the entire heat conduction behavior of a system composed of several layers or materials, accounting for their thicknesses, thermal characteristics, and layout [46]. While the term *thermal conductivity* describes an inherent capacity of a single homogeneous material to transmit heat. Overall, *thermal conductivity* of the material remains constant regardless of its size or shape, while the *effective thermal conductivity* represents overall thermal behavior of a system. The effective thermal conductivity of each sample was calculated using Fourier's Law and following the principles outlined in ASTM C177 and ISO 8302 [47], [48].

$$\lambda_{eff} = \frac{Q \cdot H}{A \cdot (T_1 - T_2)} \qquad (1)$$

where Q represents heat flow rate (W), H is thickness of the sample (m), A is cross-sectional area of the sample (m²), T_1 is temperature of the hot plate (°C), T_2 is temperature of the cold plate (°C).

3. Results and discussion

Based on the recorded data for the steady state heat transfer, and the Equation (1), effective thermal conductivities of each sample were calculated, and the results are shown in Table 6. The reference samples without PCMs and the samples with PCMs are the two groups into which the table is separated.

Table 6. Measured temperatures and calculated effective thermal conductivities for each sample

Type	Sample	Hot plate T_1 (ºC)	Cold plate T_2 (ºC)	λ_{eff} (W/mK)
Reference sample (NO PCM)	S1	95.3	18.5	0.13
	S2	93	27	0.15
	S3	86.3	23.8	0.16
	S4	98	26.5	0.14
PCM samples	S5	93.3	27	0.15
	S6	89.1	26.3	0.16
	S7	91.9	26.2	0.15
	S8	93.7	25.68	0.15

Referring to Table 6, samples S1 to S4 exhibit effective thermal conductivities ranging from 0.13 to 0.16 W/mK. These values are typical for materials without PCMs, indicating standard thermal performance. Samples S5 to S8, which incorporate PCMs, show effective thermal conductivities between 0.15 and 0.16 W/mK. This suggests that the inclusion of PCMs does not significantly alter the thermal conductivity compared to the reference samples. A comparison of the effective thermal conductivities is shown in Figure 4.

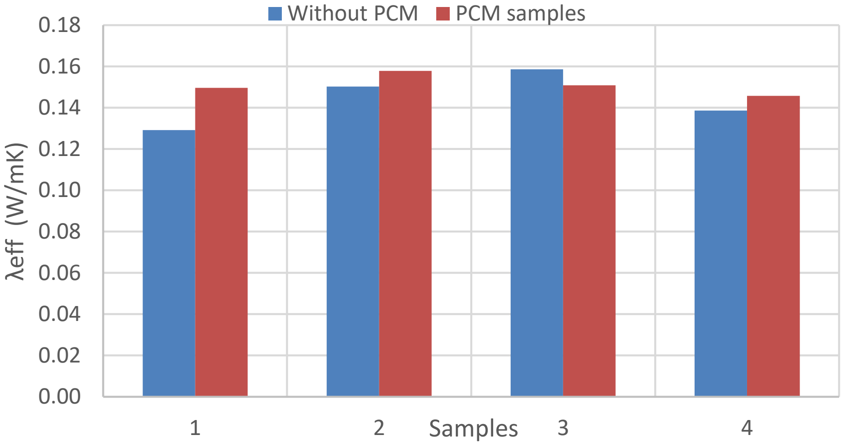

Figure 4. The influence of PCM on the effective thermal conductivity of composites

The fact that there was little difference in the reference and PCM samples' effective thermal conductivity suggests that the PCMs used may not substantially increase the thermal conductivity of the composite. This outcome could be due to the thermal conductivity of PCMs used (0.2 W/mK) is lower than those of the mortar. In addition, the amount of PCM in the composite might not be enough to have a major impact on the total thermal conductivity. To get a more noticeable impact, higher PCM concentrations could be required.

Designing energy-efficient structures requires comparing the findings of this study with those found in the literature for different building materials. Table 7 that follows provides an overview of common wall building materials, together with information on their compositions, usual uses and estimated ranges of thermal conductivity.

Table 7. Common construction materials [49]

Material		Composition	Thermal Conductivity (W/m·K)
Load-bearing	Concrete Blocks	Cement, sand, and aggregates	1.13 – 1.63
	Clay Bricks	Fired clay	0.62 – 0.84
	Natural Stone	Various types of stone (e.g., granite, limestone)	1.21 – 1.63
	Masonry	Brick, stone, or concrete blocks	0.62 – 0.84
Non-load-bearing	Insulated Concrete Forms (ICFs)	Interlocking foam blocks filled with concrete	0.19 – 0.38
	Plasterboard (Drywall)	Gypsum plaster sandwiched between paper layers	0.17 – 0.25
	Autoclaved Aerated Concrete (AAC)	Cement, lime, sand, and water, cured under pressure in an autoclave	0.18 – 0.19
	Straw Bales	Compressed straw from cereal crops	0.038 – 0.08
	Mortar	Lime, cement, water, and aggregate (e.g., sand)	0.82 – 1.13

Referring to Figure 4, Table 6 and Table 7, it is observed that thermal conductivities of the reference and PCM samples, ranging from 0.13 to 0.16 W/mK, are notably lower than those of common construction materials. For instance, concrete blocks have thermal conductivities between 1.13 and 1.63 W/mK, clay bricks range from 0.62 to 0.84 W/mK, and natural stone varies from 1.21 to 1.63 W/mK. The significantly lower thermal conductivities of the reference and PCM samples suggest they are more effective insulators compared to traditional construction materials. This property is advantageous for applications requiring enhanced thermal insulation, such as energy-efficient building designs. In contrast, materials like plasterboard (0.17–0.25 W/mK), autoclaved aerated concrete (0.18–0.19 W/mK), and straw bales (0.038–0.08 W/mK) exhibit thermal conductivities closer to those of the reference and PCM samples.

The thermal behavior of a sample containing PCM during its melting and solidification processes is depicted in Figure 5. The figure clearly illustrates the capacity of the PCM to control temperature variations. The temperature transition range, melting and solidification times, and the important role that PCM integration plays in preserving a steady temperature environment are all explained in the diagram.

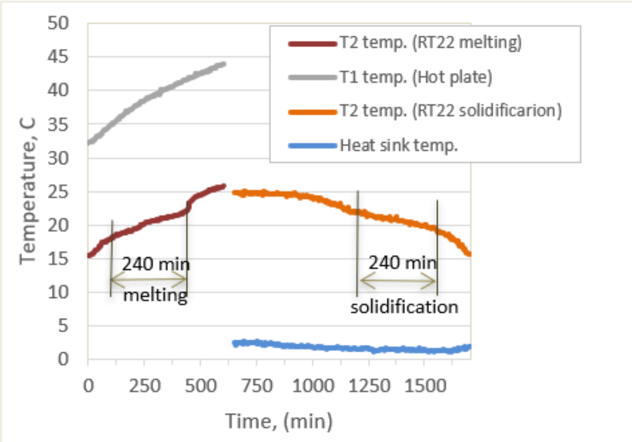

Figure 5. The impact of RT 22HC on the thermal behavior of composites

The diagram illustrates the melting and solidification times are approximately 240 minutes, demonstrating the ability of PCM to store and release thermal energy over a period of time. Rapid temperature changes are slowed down by the flattening effect of PCM during its melting and solidification processes, which was from 16°C to 22°C. Without PCM, the temperature rises more quickly, leading to quicker oscillations that could result in thermal instability. Therefore, the addition of PCM to composite improves the composite capacity to mitigate temperature variations. This characteristic is useful in building and energy-efficient systems since it reduces the need for external heating or cooling while conserving energy. The integration of PCM in building materials promotes sustainable building practices and enhances building energy management.

4. Conclusion

The samples studied showed competitive thermal insulation qualities when compared to traditional building materials. Their potential use in energy-efficient building applications was indicated by the results, which were more equivalent to non-load-bearing materials. The results imply that the main advantage of PCM integration is its potential to store thermal energy. The encapsulation and dispersion of the PCM (RT22HC) within the composite, along with its comparatively low thermal conductivity (0.2 W/mK), does not significantly influence the thermal conductivity of the sample. To further improve thermal performance, future studies could investigate different PCM formulations or greater PCM concentrations as well as energy storage performances. Optimizing PCM integration and assessing long-term thermal performance in dynamic environments should be the main goals of future research. With a transition temperature range of 16°C to 22°C, PCM integration successfully reduces temperature fluctuations during both the melting and solidification phases, demonstrating its potential to increase thermal stability and energy efficiency in straw-based composites

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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References

[1] G. Tlaiji, P. Biwole, S. Ouldboukhitine, and F. Pennec, “A Mini-Review on Straw Bale Construction,” *Energies 2022, Vol. 15, Page 7859*, vol. 15, no. 21, p. 7859, Oct. 2022, doi: 10.3390/EN15217859.

[2] H. S. Abbas, S. S. Ali, and A. Hassoon, “Using recycled bricks to improve the compressive strength of concrete and produce lightweight concrete,” *Heritage and Sustainable Development*, vol. 5, no. 2, pp. 175–182, Aug. 2023, doi: 10.37868/HSD.V5I2.238.

[3] A. A. Adday and A. S. Ali, “Flexural behavior of steel fiber reinforced concrete beams comprising coarse and fine rubber and strengthened by CFRP sheets,” *Heritage and Sustainable Development*, vol. 5, no. 2, pp. 280–308, Oct. 2023, doi: 10.37868/HSD.V5I2.257.

[4] J. Bujnak, “Environmental impact of steel and concrete as building materials”.

[5] B. M. Kadhim, A. S. Al_maamory, and A. M. Al_ghaban, “Quantum potential energy: Adaptive facades in architecture,” *Sustainable Engineering and Innovation*, vol. 6, no. 2, pp. 249–260, Nov. 2024, doi: 10.37868/SEI.V6I2.ID367.

[6] B. Rudalija and B. Duraković, “Thermal Characterization of Straw-Based Panels Made Out of Straw and Natural Binders,” in *Advanced Technologies, Systems, and Applications VI. IAT 2021. Lecture Notes in Networks and Systems*, Springer, Cham, Jun. 2022, pp. 297–304. doi: 10.1007/978-3-030-90055-7_22.

[7] F. Collet, S. Prétot, and C. Lanos, “Hemp-Straw Composites: Thermal and Hygric Performances,” in *Energy Procedia*, Elsevier Ltd, Dec. 2017, pp. 294–300. doi: 10.1016/j.egypro.2017.11.211.

[8] J. P. Costes *et al.*, “Thermal Conductivity of Straw Bales: Full Size Measurements Considering the Direction of the Heat Flow,” *Buildings 2017, Vol. 7, Page 11*, vol. 7, no. 1, p. 11, Feb. 2017, doi: 10.3390/BUILDINGS7010011.

[9] S. K. Jha, A. Sankar, Y. Zhou, and A. Ghosh, “Incorporation of Phase Change Materials in Buildings,” *Construction Materials 2024, Vol. 4, Pages 676-703*, vol. 4, no. 4, pp. 676–703, Oct. 2024, doi: 10.3390/CONSTRMATER4040037.

[10] Z. Ben Zaid, A. Tilioua, I. Lamaamar, O. Ansari, and M. A. Hamdi Alaoui, “Thermal performance of clay-straw wall incorporating phase change materials in Errachidia city (South Eastern Morocco): A simulation approach,” *Case Studies in Construction Materials*, vol. 15, Dec. 2021, doi: 10.1016/J.CSCM.2021.E00786.

[11] B. Duraković, N. Peštalić, and A. Habibović, “Incorporation of Phase Change Materials in Straw-Based Composites: Thermal Characterization,” in *Advanced Technologies, Systems, and Applications IX*, Springer, Cham, 2024, pp. 164–171. doi: 10.1007/978-3-031-71694-2_13.

[12] “Straw Bale Construction – theconstructor.org.” Accessed: Feb. 13, 2025. [Online]. Available: https://theconstructor.org/building/straw-bale-construction/34685/?utm_source=chatgpt.com

[13] C. Sun, J. Gu, Q. Dong, D. Qu, W. Chang, and X. Yin, “Are straw bales better insulation materials for constructions? A review,” *Developments in the Built Environment*, vol. 15, p. 100209, Oct. 2023, doi: 10.1016/J.DIBE.2023.100209.

[14] N. Oudhof, M. Labat, C. Magniont, and P. Nicot, “Measurement of the hygrothermal properties of straw-clay mixtures,” 2015, pp. 474–479.

[15] T. R. Commins, “Tested R-value for Straw Bale Walls and Performance Modeling for Straw Bale Homes”.

[16] V. Marković and M. Milić, “6 th INTERNATIONAL CONFERENCE Contemporary achievements in civil engineering 20,” *CONFERENCE PROCEEDINGS INTERNATIONAL CONFERENCE*, 2018, doi: 10.14415/konferencijaGFS2018.029.

[17] “STRAW-BALE – Carbon Smart Materials Palette.” Accessed: Feb. 13, 2025. [Online]. Available: https://www.materialspalette.org/straw-bale/?utm_source=chatgpt.com

[18] S. von Greve-Dierfeld *et al.*, “Understanding the carbonation of concrete with supplementary cementitious materials: a critical review by RILEM TC 281-CCC,” *Mater Struct*, vol. 53, no. 6, p. 136, Dec. 2020, doi: 10.1617/S11527-020-01558-W.

[19] U. Epa, “U.S. Fiberglass Insulation Industry Carbn Intensitites (2019),” 2019, Accessed: Feb. 13, 2025. [Online]. Available: https://www.epa.gov/ghgreporting/subpart-n-technical-support-

[20] B. Yumkham, C. Shijagurumayum, and T. Suresh, “Fire Resistance of Concrete Structure- A Review,” *SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology*, vol. 14, no. 01 SPL, pp. 63–67, Jun. 2022, doi: 10.18090/SAMRIDDHI.V14SPLI01.12.

[21] “Will Fiberglass Insulation Burn? Here are Things You Should Know About.” Accessed: Feb. 13, 2025. [Online]. Available: https://insulationline.com/will-fiberglass-insulation-burn-here-are-things-you-should-know-about/?utm_source=chatgpt.com

[22] Y. Chen, X. Alice Wang, D. Li, D. Rodrigue, and L. Gosselin, “Hygrothermal performance of straw bales split-insulation wall assembly in cold and humid climates,” *Energy Build*, vol. 307, p. 113974, Mar. 2024, doi: 10.1016/J.ENBUILD.2024.113974.

[23] S. J. Osibodu, A. M. Adeyinka, and O. V. Mbelu, “Phase change material integration in concrete for thermal energy storage: techniques and applications in sustainable building,” *Sustainable Energy Research 2024 11:1*, vol. 11, no. 1, pp. 1–17, Dec. 2024, doi: 10.1186/S40807-024-00138-8.

[24] A. A. A. Shohan *et al.*, “Developments on energy-efficient buildings using phase change materials: a sustainable building solution,” *Clean Technol Environ Policy*, vol. 26, no. 2, pp. 263–289, Feb. 2024, doi: 10.1007/S10098-023-02626-9/METRICS.

[25] R. Sharma, J. G. Jang, and J. W. Hu, “Phase-Change Materials in Concrete: Opportunities and Challenges for Sustainable Construction and Building Materials,” *Materials 2022, Vol. 15, Page 335*, vol. 15, no. 1, p. 335, Jan. 2022, doi: 10.3390/MA15010335.

[26] F. Chebli and F. Mechighel, “Phase change materials: classification, use, phase transitions, and heat transfer enhancement techniques: a comprehensive review,” *Journal of Thermal Analysis and Calorimetry 2025*, pp. 1–59, Jan. 2025, doi: 10.1007/S10973-024-13877-Z.

[27] F. S. Barnes and J. G. Levine, “Large energy storage systems handbook,” *Large Energy Storage Systems Handbook*, pp. 1–237, Jan. 2011, doi: 10.1201/B10778.

[28] “2009 ASHRAE Handbook - Fundamentals (SI Edition),” *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.*, Feb. 2009.

[29] B. Duraković, “Phase Change Materials for Building Envelope,” in *PCM-Based Building Envelope Systems: Innovative Energy Solutions for Passive Design*, Springer Nature, 2020, pp. 17–37. doi: 10.1007/978-3-030-38335-0_2.

[30] S. Furbo, “Using water for heat storage in thermal energy storage (TES) systems,” *Advances in Thermal Energy Storage Systems: Methods and Applications*, pp. 31–47, Jan. 2015, doi: 10.1533/9781782420965.1.31.

[31] S. Zhang, Y. Li, and Y. Yan, "Hybrid sensible-latent heat thermal energy storage using natural stones to enhance heat transfer: Energy, exergy, and economic analysis," *Energy*, vol. 286, p. 129530, Jan. 2024, doi: 10.1016/J.ENERGY.2023.129530.

[32] W. Zhang and C. Lv, "Effects of mineral content on limestone properties with exposure to different temperatures," *J Pet Sci Eng*, vol. 188, p. 106941, May 2020, doi: 10.1016/J.PETROL.2020.106941.

[33] B. Duraković, "Introduction," in *PCM-Based Building Envelope Systems - Innovative Energy Solutions for Passive Design*, Springer, 2020, pp. 1–15. doi: 10.1007/978-3-030-38335-0_1.

[34] H. Yang, W. Zhang, Y. Zhu, Y. Shao, Y. Shao, and X. Zhang, "Preparation and characterisation of sodium nitrate/stone-sawing mud shape-stabilized phase change materials for medium-high temperature thermal energy storage," *J Energy Storage*, vol. 56, p. 106047, Dec. 2022, doi: 10.1016/J.EST.2022.106047.

[35] X. Shi, S. A. Memon, W. Tang, H. Cui, and F. Xing, "Experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels," *Energy Build*, vol. 71, pp. 80–87, Mar. 2014, doi: 10.1016/j.enbuild.2013.12.001.

[36] A. A. Elhamy and M. Mokhtar, "Phase Change Materials Integrated Into the Building Envelope to Improve Energy Efficiency and Thermal Comfort," *Future Cities and Environment*, vol. 10, no. 1, 2024, doi: 10.5334/FCE.258.

[37] R. F. Jam, M. Gholizadeh, M. Deymi-Dashtebayaz, and E. Tayyeban, "Determining the optimal location and thickness of phase change materials in the building walls: an energy-economic analysis," *Journal of the Brazilian Society of Mechanical Sciences and Engineering 2023 45:10*, vol. 45, no. 10, pp. 1–13, Sep. 2023, doi: 10.1007/S40430-023-04472-8.

[38] Z. A. Al-Absi, M. H. M. Isa, and M. Ismail, "Phase change materials (PCMs) and their optimum position in building walls," *Sustainability (Switzerland)*, vol. 12, no. 4, Feb. 2020, doi: 10.3390/SU12041294.

[39] ; Jan Kośny and David W. Yarbrough, "Use of PCM-Enhanced Insulations in the Building Envelope," *Journal of Building Enclosure Design*, pp. 55–59, 2009.

[40] A. Bashir, M. Imran, A. Arshad, J. Darkwa, and N. Radouane, "A Comprehensive Review of Composite Phase Change Materials (cPCMs) for Thermal Management Applications, Including Manufacturing Processes, Performance, and Applications," *Energies 2022, Vol. 15, Page 8271*, vol. 15, no. 21, p. 8271, Nov. 2022, doi: 10.3390/EN15218271.

[41] G. E. Rodríguez, C. B. Ávila, and A. Cloutier, "Use of Phase Change Materials in Wood and Wood-Based Composites for Thermal Energy Storage: A Review," *Bioresources*, vol. 18, no. 4, pp. 8781–8805, Nov. 2023, doi: 10.15376/BIORES.18.4.RODRIGUEZ.

[42] I. Petrunenko, O. Zhuk, O. Litvak, S. Litvak, and V. Yemets, "The impact of renewable energy sources on economic recovery in Ukraine," *Sustainable Engineering and Innovation*, vol. 6, no. 2, pp. 297–308, Nov. 2024, doi: 10.37868/SEI.V6I2.ID399.

[43] Y. Zhou, A. Trabelsi, and M. El Mankibi, "Hygrothermal properties of insulation materials from rice straw and natural binders for buildings," *Constr Build Mater*, vol. 372, p. 130770, Apr. 2023, doi: 10.1016/J.CONBUILDMAT.2023.130770.

[44] J. Cui, J. Li, Y. Du, and G. Habert, "Cement-MgO synergetic stabilized earth-straw mix: From material performance to building simulation," *Energy Build*, vol. 327, p. 115099, Jan. 2025, doi: 10.1016/J.ENBUILD.2024.115099.

[45] "Data sheet for RT22HC." Accessed: Feb. 14, 2025. [Online]. Available: https://www.rubitherm.eu/media/products/datasheets/Techdata_-RT22HC_EN_09102020.PDF

[46] F. Gori and S. Corasaniti, "Effective thermal conductivity of composites," *Int J Heat Mass Transf*, vol. 77, pp. 653–661, Oct. 2014, doi: 10.1016/J.IJHEATMASSTRANSFER.2014.05.047.

[47] L. L. Baranowski, G. Jeffrey Snyder, and E. S. Toberer, "Effective thermal conductivity in thermoelectric materials," *J Appl Phys*, vol. 113, no. 20, May 2013, doi: 10.1063/1.4807314.

[48] Y. Gowayed and J. C. Hwang, “Thermal conductivity of composite materials made from plain weaves and 3-D weaves,” *Composites Engineering*, vol. 5, no. 9, pp. 1177–1186, Jan. 1995, doi: 10.1016/0961-9526(94)00106-J.

[49] “Thermal Conductivity : chart of 300+ common materials.” Accessed: Feb. 19, 2025. [Online]. Available: https://www.myengineeringtools.com/Data_Diagrams/Chemical_Compound_Thermal_Conductivity.html?utm_source=chatgpt.com