Climate-Adaptable Building Envelope Materials

Reham Eldessuky Hamed
Assoc.Prof. Beni-Suef University, Architecture Dep., Faculty of Engineering, Beni Suef, Egypt, Reham011299@eng.bsu.edu.eg

Abstract

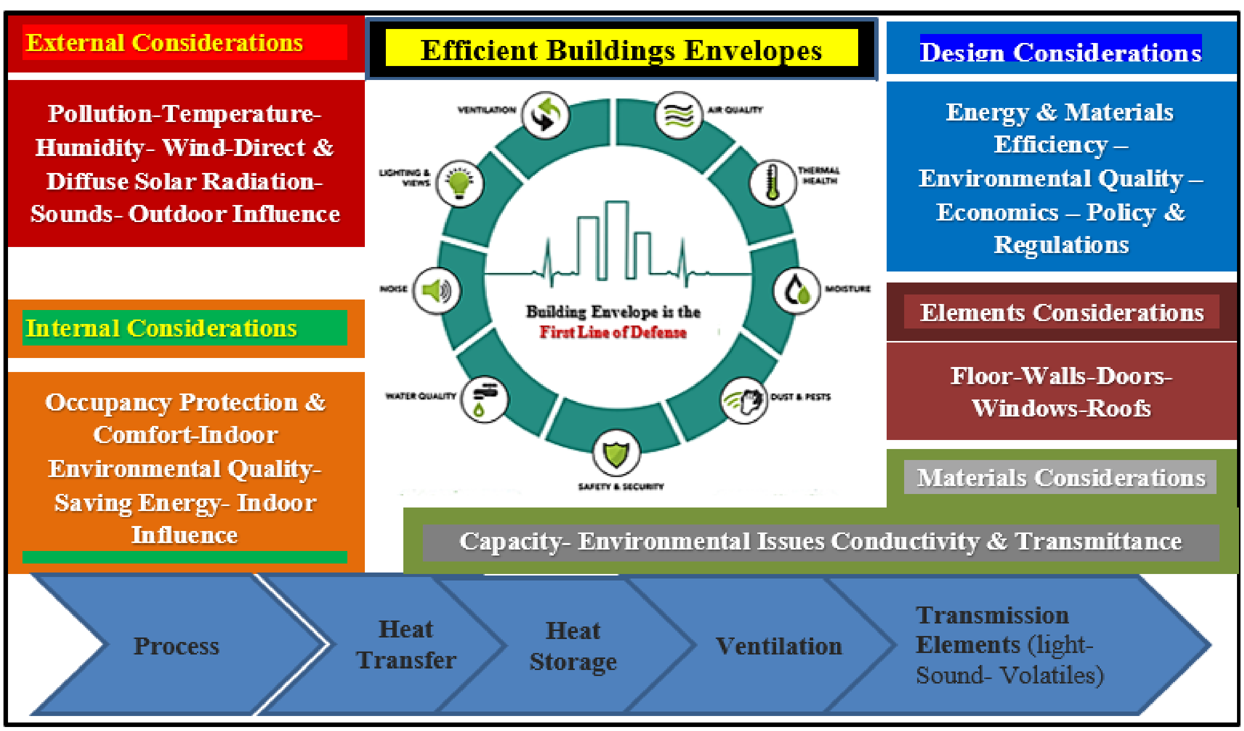
The appearance of a pandemic in contemporary years has created a fundamental shift in the architectural community. Building effectiveness, environmental considerations, passenger comfort, and the interior environment must all be upgraded, based on new solutions for energy-efficient building skins that should be developed in the construction community. The first protection mechanism for safeguarding users and seeking to manipulate the indoor environment is the construction of the outer surface. Building skin layers that are developed to be energy efficient provides performance improvement and occupant satisfaction. In terms of heating, cooling, venting, and lighting requirements, as well as safety and sustainability, this issue can be fixed by minimizing energy consumption as much as possible with thermal energy storage. On the other hand, the envelope layers of the construction necessitate environmentally friendly components that are limited in number and quality. Notwithstanding the hazardous nature of the material produced, it has environmental influences throughout its expected lifetime. Covering phase transformation materials for providing thermal approaches in the skin cross-section and developing and testing thermal solutions to provide a better environment and boost the quality of the environment, can all lead to practical solutions. Phase Change Material is a natural recyclable material that increases the comfort, safety, and efficiency of buildings, which leads to less energy consumption, minimizes greenhouse gas emissions, and causes a reduction in the redistributing energy usage to shift load time from peak to off-peak hours, reducing total energy consumption. The research on student accommodation at Beni Suef University (BSU) in New Beni Suef City is to determine how integrating different materials into the building envelope could result in a better inside environment. Then, by applying phase change materials with specific physical properties and reorienting the existing model to assess their impact on indoor environmental quality, particularly thermal comfort, and to calculate energy consumption and cost. Depending on the findings research findings, the most effective mechanism for building energy-efficient envelopes is integrating hanging materials with construction components in built-in envelope systems, internal walls, floor levels, ceiling layers, opening glazing, and rooftop modifications.

Keyword: *Buildings Envelopes Efficient, Global Climate Change, Thermochemical Energy Capacity, BSU student housing, Phase Change Materials, BioPCM.*

1. INTRODUCTION

Dormitories are a form of acceptance and effective rewards that help students have a very positive impact on their living conditions. Universities focus on making effective use of available budgets to meet growing student accommodation requirements and boost their performance characteristics. As a result, on-campus accommodation is crucial for individuals to create conducive living and studying conditions as well as to boost social and intellectual engagement. That should improve the effectiveness of housing, promote a deeper feeling of community, and meet college growth targets. However, in Egypt, student housing has not attracted the significant attention that it deserves for assessment activities' cleanliness and the potential benefits of a sense of accomplishment, cost savings, and productivity improvements. The Green Concept encourages pupils to become comfortable dealing with principles by imposing a set of architectural guidelines. Following a set of architectural standards, green concepts also inspire students to learn about green and sustainable conservation principles. In contrast to certain other building design guidelines, university students' accommodation should create functional and efficient privacy, and neighborhood, which could help create a sense of living, foster a stronger shared identity and capture the university's meaningful and professional goals. In practice, university undergraduates' indoor environment would be used for learning and studying, and it has a significant impact on the community. Architects and academics have lately expressed concern about the consequences of bad IEQ on student achievement. The outside skin seems to be the primary frontline for controlling the inside environment, protecting inhabitants, and helping to reduce emissions. Modifications in the framing of thermal energy including skin walls, floor types, ceiling layering, glass apertures, and rooftop changes convert discrepancies between interior and ambient circumstances. Indoor comfort (temperature, humidity, air movement), visual quality (vision, light intensity), and indoor air clearing (internal air, impurity, and indoor airflow breathing), all outline the key characteristics that influence the confined surroundings and acoustics (noise solutions and sound shadow). A well-designed indoors improves occupant comfort while satisfying heating, ventilation, air conditioning, and soft lighting needs [Figure 1]. In hot regions, meanwhile, daily temperature and solar radiation variations detrimentally affect thermal comfort for building occupants, which needs an additional update on building exterior modifications to cut total heat load and boost interior comfort while reducing the impact on HVAC systems. Accordingly, skin facades layer, reducing electricity demand, conditioning systems, and developing energy-efficient buildings.

Fig. 1. Techniques for Energy-Efficient Envelope Modeling

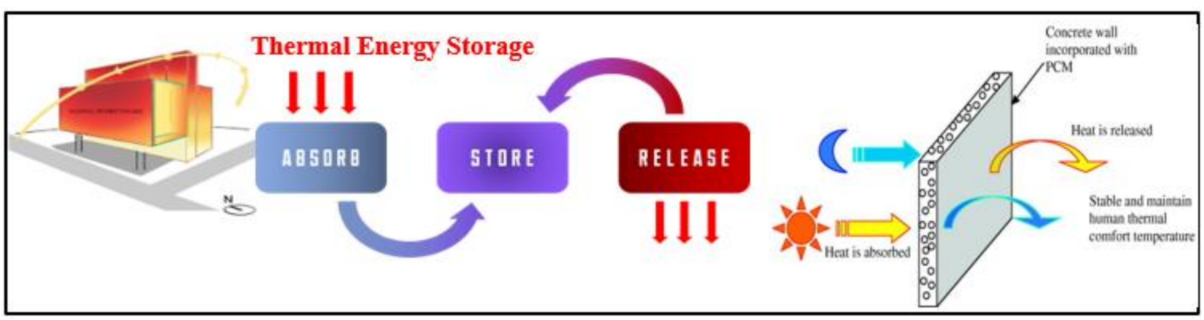


Many strategies are currently being researched to preserve the energy efficiency and thermochemical conversion of building skins. This helps to choose responsible construction methodologies that use eco-resources throughout its entire life - cycle. As well as the use of thermal mass in the exterior walls as a low-cost passive design strategy for decreasing energy waste. As a possible consequence, determining building materials with perfectly adequate energy storage can assist in eliminating the energy barrier between customers and manufacturers, resulting in better energy management and occupant satisfaction. New construction materials and procedures may lead to PCM, a natural product that is fully recyclable. This promotes the comfort, stability, and productivity of the buildings, due to lower heating and cooling electricity demand and reduced CO2 emissions, causing a reduction in redistributing electricity consumption to shift load step back from peak time demand, minimizing overall energy consumption.

2. Thermal Energy Storage

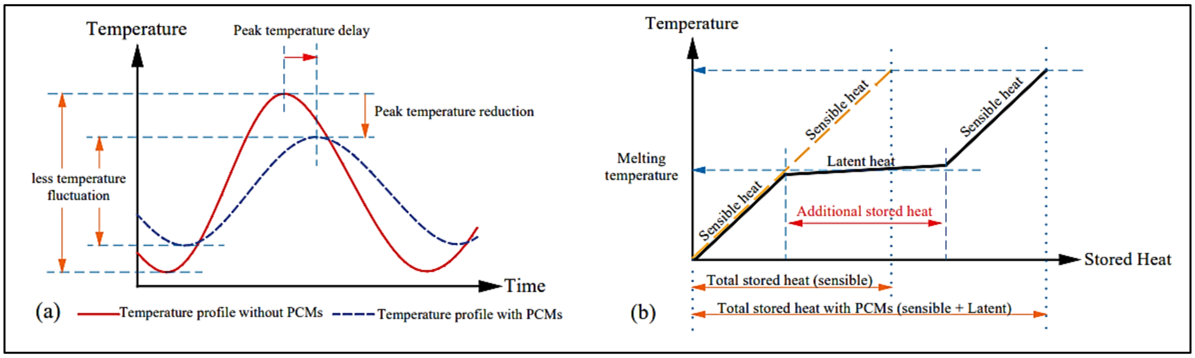
Even though people are spending more than 80% of their own time indoors, thermal comfort appears to affect both optimum performance and productivity. In addition, the need for total adjustments is expected to increase by 150% by 2050, increasing in the range of 300 to 600% in developing countries. Numerous strategies are recommended for energy conservation in hot countries, Low-cost self-reflective materials such as construction characteristics, Internal and exterior shading, as well as low penetration opening coatings, are the greatest strengths. The outermost covering should be from sustainable materials that have a low carbon footprint over their whole life cycle and promote conservation. Through similar improvement of the rind process, clever answers consisting of section alternate substances may be evolved to generate thermodynamic schemes on the rind of buildings as well as proposing and assessing thermal approaches to create a better indoor environmental quality. Energy ThermalStoragee (ETS) is described as the temporary storing of thermal energy at high or low temperatures, which assists in saving energy via reducing the time duration or unbalance level between supply and demand, as seen in [Fig. 2], [1].

Fig. 2. Thermodynamic energy storage Mechanism.



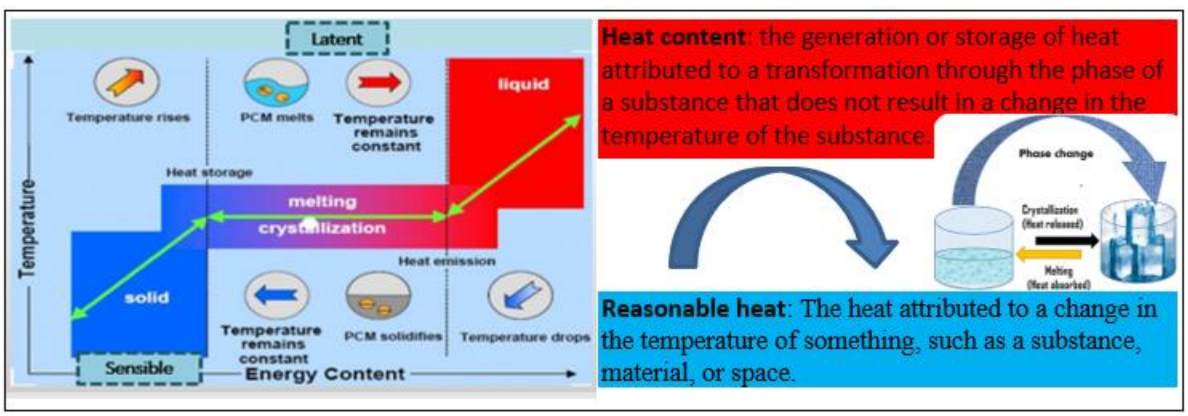
There are crucial concerns in comparing the ability of materials storage technology. Various claims for storing energy with the lowest total losses due to conduction, convection, and radiation loss. The thermal energy process has the following drawbacks: Volumetric energy amplitude, or the amount of energy stored per unit volume, with a limited lifetime, affects the efficiency of storage techniques, which is reliant on a compact size fulfilling a similar function. Consequently, the proper method of energy storage should be compact in form per component capacity of stored energy and have an extended storage period. Sophisticated heat energy-storing techniques, as well as other materials with good processing temperatures at various temperatures, such as phase transformation materials, are becoming more widely used in construction [2].

Fig. 3. Heat storage systems



PCMs can improve a building's internal climate by lowering temperature peaks and fluctuations, as shown in [Fig 3(a)]. The cap potential of a tiny layer of PCM to store a large amount of heat is likewise an advantage of making use of PCMs. The point at which a material changes phase, as shown in [Fig 3 (b)], has a great impact on absorption capacity. This allows you to maintain an additional thermal energy frequency with fewer temperature fluctuations. There are two basic strategies for storing and controlling thermal energy[3]; The first is sensible heat, wherein thermal energy is gained or lost as the body temperature changes. The second classification is "latent hidden energy," which happens when the skin generates energy due to temperature versions withinside the material`s components [Fig.4]. Note that the second strategy is the most commonly used strategy for energy-efficient building envelope design [4].

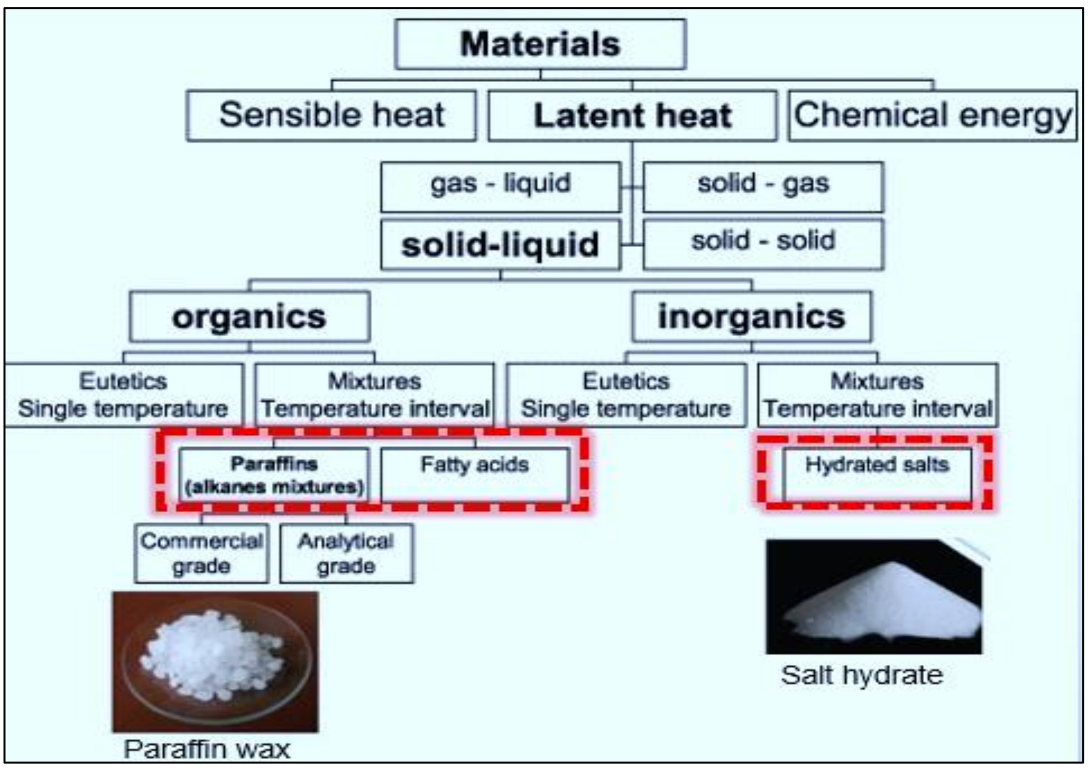
Fig. 4. An Overview of Thermal Energy Storage Methods



3. phase-change material

Material that undergoes section transition has a good-sized burning height which for this reason surely can switch and get a better and big overall quantity of energy, its phase shifts from a harder to a more flexible state when heat energy is absorbed or discharged. Temperature differences are assumed to be collected with thermodynamics. When phase-alternate components gain strength through chemical bonds and move from a rough to a fluid phase, this is known as a phase transition., heat energy is released PCMs to bridge the energy demand-supply gap. Indoors, phase transformation materials vary from 19 to 24 °C, This however refers to being within the scope of human thermal comfort. PCM's responsiveness is characterized by its potential to adapt to climatic variations while maintaining indoor comfort [5]. However, there are other challenges such as the chemical instability of salt hydrates due to Non-uniform melting, the ability to cool below freezing, and damaging material properties. Accordingly, phase change materials have been isolated or preserved in enclosed shells to address these difficulties. Encapsulation is the process of putting an active material inside a thin cover. Phase change materials have been isolated or maintained in enclosures. Polymers, on the other hand, because of their strength and flexibility, are ideal for enhancing material energy performance. There is motivation to actively try to control limited natural resource utilization and to improve safety, efficiency, comfort, and health. This can result from designing a proper internal environment by reducing indoor temperature and controlling greenhouse gas emissions, as well as using recyclable materials such as Phase Change material that can be reused in other buildings, as it is a sustainable product that saves energy [6]. Unfortunately, there are numerous types of PCM, and not all compounds are acceptable for use in the construction market. Inorganic and organic salt hydrates are the constructions of PCM used throughout construction such materials have advantages and disadvantages that must be considered [Fig 5].

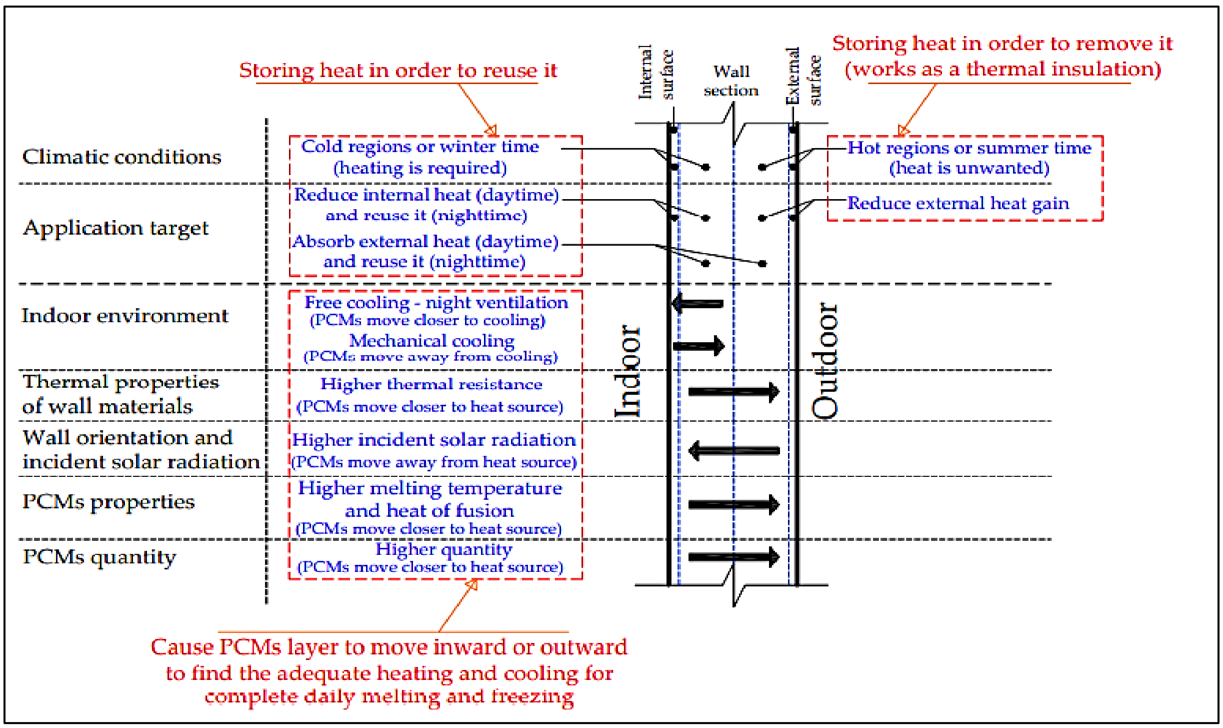
Fig. 5. physicochemical properties of PCM.



Many methodologies have been proposed to examine the effectiveness of integrating PCMs into building envelopes to enhance enclosed environmental energy and health performance. PCM was carried out in the manufacture of blocks, boards, panels, and gypsum [7]. Heat conservation (J/kg. K) evaluation for concrete work 1000, masonry 1008, woodwork 2300, gypsum work 850, PU 1400, PSE 1400, PCM 86 000 J / kg. Which identifies the classification of the thermophysical sensitivity of construction materials [14]. PCM was used to make blocks, boards, slabs, and plaster with heat storage (J / kg.K), It may also be needed in places with a much stronger connection to the outside. Many studies have been done on non-conditioned rooms in various orientations, locations, and building characteristics. The PCM layer should be implemented on the inner surfaces in all conditions and climates to maintain the indoor conditions, cooling and heating reductions, and annual energy efficiency, as demonstrated in [Fig.6]. Furthermore, the PCM should melt between 21 and 25 degrees Celsius in hot climates [8].

A composite PCM layer made up of two PCMs with different melting temperatures was tried on the inner surface to improve the wall's performance in summer and winter. The data revealed an improvement in thermal efficiency in both periods. It has also been tested in conjunction with night ventilation for cooling purposes on PCM-impregnated gypsum boards on the internal surface of the walls, resulting in a total electricity savings of 73%. When a 20 mm thick PCMs coating was applied in de the building's external wall, it was found to reduce summer cooling by 1.7 % and winter heating by 1.6 %, respectively.

Fig. 6. The best location in the cross-section of the building envelope



Buildings have used active and passive systems as storage solutions to reduce energy waste, shift on-peak demand, and reduce sustained power needs. Using thermal storage systems in building design includes advanced strength efficiency, decreased working costs, and reduced pollution and CO2 emissions. The practical method to control wathe warmth switches between outside and indoor environments is to insulate the constructing envelope. This can be a workable solution for adjusting the inside temperature to some extent, but there are better options available than insulation, such as integrating Phase Change materials to control building envelope heat transfer in response to changes in the ambient temperature to produce the optimum indoor environment, which significantly reduced indoor heat stress gain while also increasing occupant comfort and satisfaction.

Reducing overall energy consumption helps improve financial and environmental conditions.

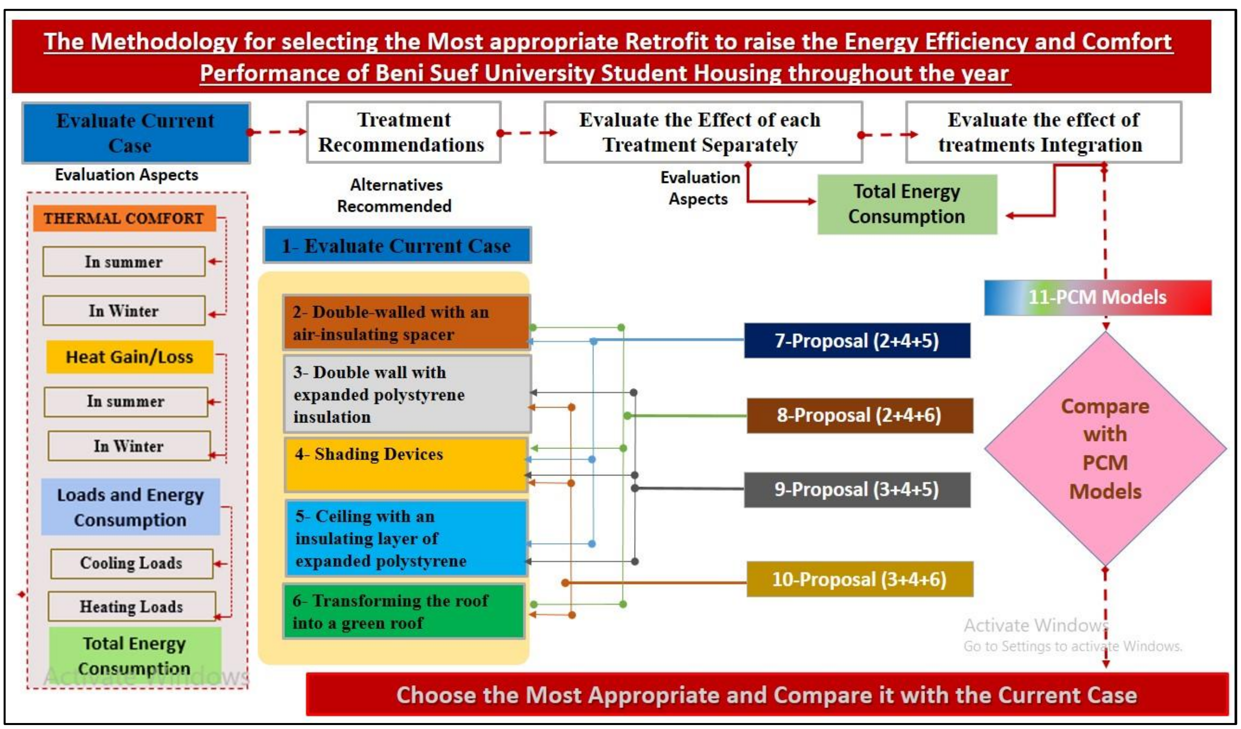
4. Research Methodology

According to the most recent global climate assessment, increasing heatwave intensity and frequency are responsible for the current level of global warming. As a result, phase-change materials assist in climate adaptation, and developing more effective and sustainable solutions for building thermal management can dramatically reduce energy consumption and greenhouse emissions. In this context, PCMs have demonstrated remarkable promise as a passive technique for achieving thermal comfort in both new and existing buildings envelopes. The research was carried out at the BSU student dormitory campus [Fig. 7], which used Design Builder software to improve the current model and investigate altering envelope exterior materials to produce a healthy inside environment while saving energy. Then, using phase change materials with specific physical properties and reorienting the existing model, researchers can look at their impact on indoor environmental quality, particularly thermal comfort, as well as estimate energy consumption and cost. The study aims to increase indoor thermal comfort while lowering energy demand, which will significantly reduce carbon dioxide emissions. This can be accomplished by concentrating on the building envelope, particularly its materials, as well as the thermal mass and orientation that could change the building's thermal behavior and energy consumption. The simulation is based on the existing BSU student accommodation dormitory buildings, then test retrofitted envelopes with available construction materials to compare the base case with traditional passive techniques double-wall with an air-insulating filler; double-wall with expanded polystyrene insulation; shading appliances; roof with an expanded polystyrene insulating layer; and creating a green roof. Then, apply phase change materials with specific physical properties to envelop cross-sections to reach the comparative analysis before and after using PCMs. Also, reorienting the base model should be analyzed for energy consumption and cost to achieve the effects of the envelope cross-section layers and modifications in building materials To upgrade construction performance, gain thermal comfort, and decrease electricity consumption. The analysis methodology consists of selecting the most appropriate solutions to improve the efficiency of the university housing buildings' performance to save energy for Beni Suef University students throughout the year. Student accommodation is regarded as a significant component of higher education services, it is divided into 3 separate four-story buildings including dormitory units, a dining hall, a kitchen, restrooms, and open spaces such as lounges and lobbies define student accommodation configurations. Residence buildings present unique challenges to thermal comfort levels because of their compartmentalization into large numbers of bedrooms accessed from the corridors. Despite their varying locations, shapes, and sizes, the architecture of the dormitories is a common feature in all public university housing units, where vertical entrances, kitchens, and health facilities are integrated at the core of the service.

Fig. 7. BSU Student Accommodation Dormitory Buildings

The study's goal is to adapt internal temperatures to comfort rates and reduce energy consumption, which directly impacts indoor environmental quality. As a result, the analysis methodology focuses on the building envelope, particularly its materials, as well as its thermal mass and orientation using. The simulation is applied to an existing model of student housing buildings, followed by retrofitting the building envelope with phase change materials with certain physical properties and reorientation to determine their effect on indoor environmental quality, notably thermal comfort and thermal loads. [Fig. 8.] presents the analysis methodology consisting of selecting the most appropriate solutions to improve the efficiency of the housing buildings' performance to save energy for BSU students throughout the year.

Fig. 8. Research Analysis Methodology



5. Results and Discussion

1- Current Buildings

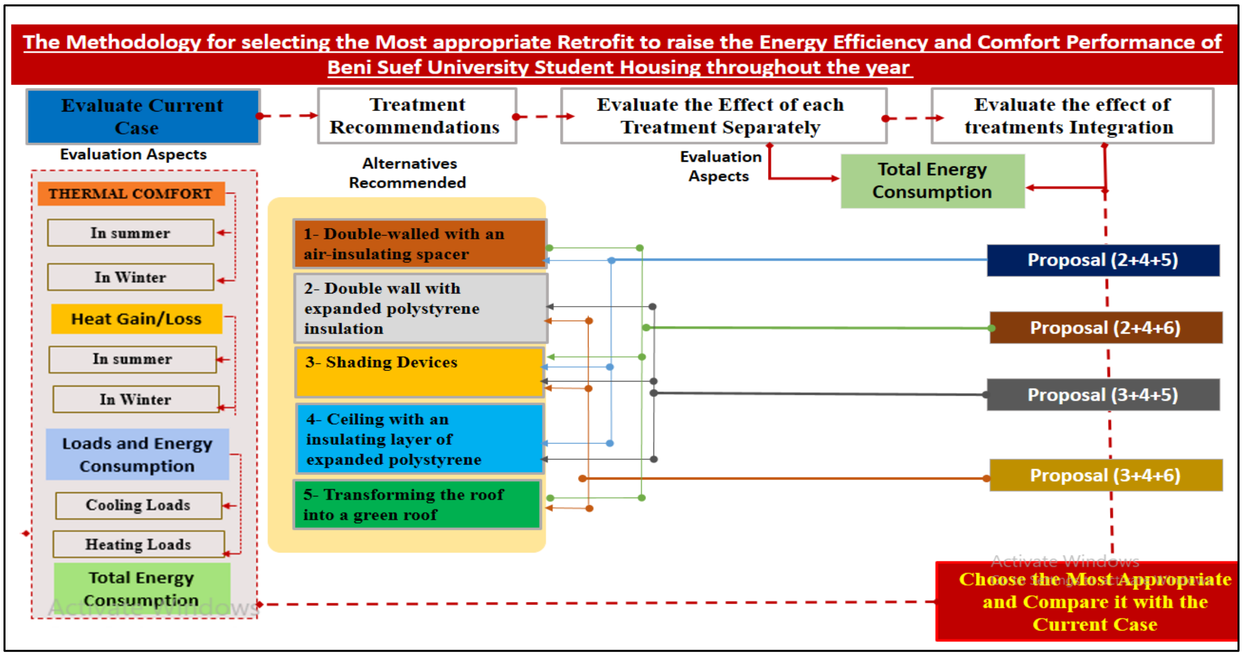
Northern-Southern Building: Simulations indicate that the temperature inside the building is higher in winter than the outside temperature, as it reaches a temperature of 12.4 degrees Celsius and the relative humidity is 42%. It is not achieved despite the high temperature outside, but rather the relatively low humidity as well as the incidence of thermal infiltration due to temperature differences and limited heat intake from solar radiation. And by evaluating one of the winter days, we find that the temperature reaches 18 Celsius inside the building, although it decreases outside the building to reach 13 Celsius, while the relative humidity maintains its rate at 55%. Notwithstanding the solar exposure at noon, the PMV is not comfortable. As a result, heat loss must be kept as low as possible. In the winter, limited ventilation is permitted. Also, using materials capable of heat storage, water, or glass to trap the solar radiation to achieve thermal comfort and designing sun breakers in the summer and making them an outlet for the winter sun. Throughout the summertime, the total inner temperature climbs above the average outside temperature, reaching 28.9 degrees Celsius, the ventilation increases and reaches 32.7 Celsius in the afternoon, which is better than outside the building, where solar radiation rises and ventilation decreases. Thermal comfort reaches acceptable levels from PMV in the dawn hours and the transitional seasons. It is recommended to increase. The ventilation in the summer, especially by using night ventilation. According to the heat gain evaluation, solar radiation is one of the most significant contributors to heat absorption across envelope layers, which could be reduced by adding sun defenders in the summer and making them accessible in the winter. As walls are one of the most important causes of heat loss in summer and winter, as the ventilation feels the internal climate in summer with heat loss, glass is one of the most important causes of heat loss after walls.

East and West Buildings: Temperatures in the northern buildings are lower in the winter, while temperatures in the south range from 15–18 degrees Celsius and seem to be higher than average in summer, reaching 39 degrees. The equinox months indicate that the main issue is in both buildings. On a hot summer day, a study of thermal comfort reveals that when the relative humidity declines, ventilation reduces, and solar radiation increases. PMV is not in the comfortable range except in the last hours of the night, which shows the need for the building of shading devices, sources of moisture in the summer, such as fountains or green elements, and night ventilation to improve conditions at night. Whereas materials are capable of thermal storage and insulation, heat loss appears in the summer as a result of external ventilation, but it is still impossible to achieve thermal comfort because it is obvious that the walls are one of the most significant causes of loss in the winter, harming the built environment in terms of Summer heat gain is offset by winter heat loss.

2- Passive Modifications

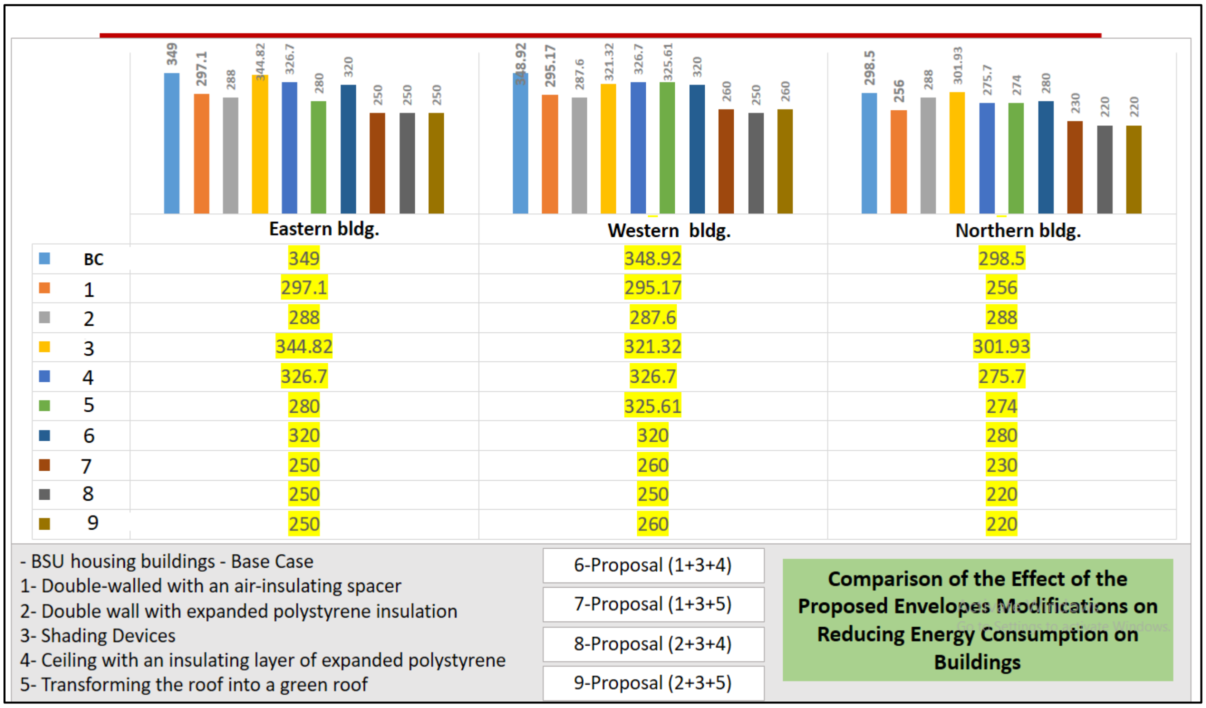
The thermal gains and losses levels of a building are determined largely by its envelope, energy consumption quantities, and users' convenience, which makes it necessary to modify the building envelope, Accordingly, the suggested modifications include reducing heat loss, Reducing ventilation in winter Increasing the u-factor for the building envelope by increasing the insulating layers Considering the requirements of natural lighting rates, increasing the ventilation in the summer by making stairs like chimneys tilted in the direction of the sun increases the ventilation rates. Increase the humidity by vegetation green covers beside buildings to let the fresh air indoors. The methodology of selecting the most retrofitted to raise the energy efficiency and comfort performance of BSU housing buildings throughout the year is shown in [Fig. 9].

Fig. 9. Passive Modifications to maximize energy efficiency and comfort.



The envisaged on the base case assessment is the envelope cross-section layers of the primary causes of gain and loss, which strongly implies a negative influence on thermal comfort in terms of summer heat gain is out by winter heat loss. Therefore, building cross sections play the main role in thermal gain and loss, which is reflected in energy consumption rates and user comfort. Therefore, it has to grow to be essential to increase envelope substances to evolve to the climate and maximize performance for BSU housing buildings throughout the year. [Fig. 10] depicts the effectiveness of passive improvements Reducing energy consumption of the outer skin of the building compared to the existing situation. The comparison of the following components: base-case; double-wall with an air-insulating filler; double-wall with expanded polystyrene insulation; shading appliances; roof with an expanded polystyrene insulating layer; and creating a green roof. To achieve the effects of the envelope cross-section layers and modifications in building materials To improve building performance, obtain thermal comfort, and reduce electricity consumption.

Fig. 10. Impact of exterior layers modification on power consumption reduction.



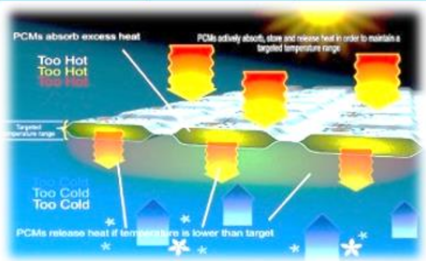
With an analysis of common passive solutions to improve the energy efficiency of buildings, the best passive techniques for reducing energy consumption and achieving indoor occupant comfort are Proposal 7 (double-walled with an air-insulating spacer shading devices ceiling with an insulating layer of expanded polystyrene), Proposal 8 (double wall with expanded polystyrene insulation + shading devices + ceiling with an insulating layer of expanded polystyrene), and Proposal 9 (double wall with expanded polystyrene insulation Shading Devices transforming the roof into a green roof). Because of the importance of improvement to reach the highest levels of energy efficiency and improve the internal environment, it was found that it is necessary to test PCMs applications in the building envelopes.

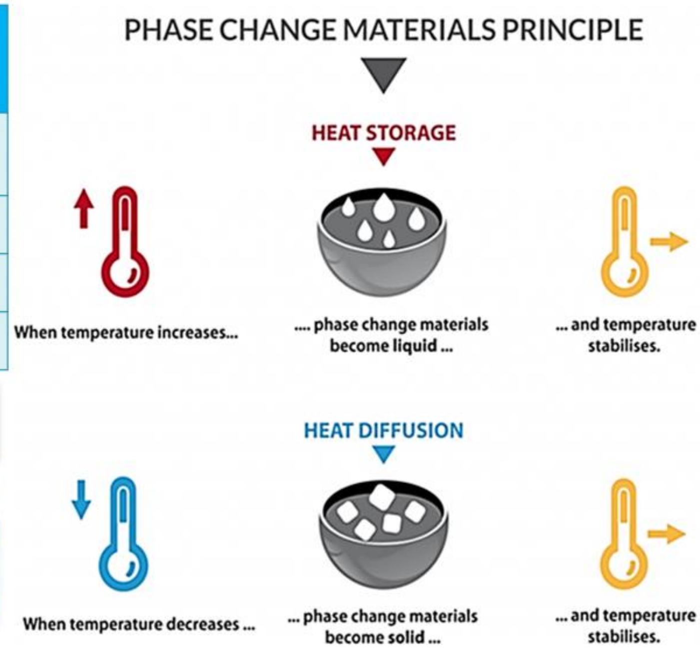
3- Phase Change Materials

According to Egyptian norms to increase the strength and efficiency of buildings, BSU dormitory buildings require outer skin modifications where the required heat transfer behavior of facades (m2 k/w) is: R = 0.59 North, R = 0.75 South, R = 1.08 East & West. The Roof: R = 2.7 m2/k/w. The analysis methodology consists of selecting the most appropriate solutions to improve the efficiency of the housing buildings' performance to save energy for BSU students throughout the year. In some tests with different PCM materials, the best results were obtained with the PCM type M182 / Q27 with a thermal mass capacity of 574 Wh/m2 and a phase-changing temperature of 28 degrees Celsius, this made a significant impact on internal comfort. The temperature fluctuated by 1.3 degrees Celsiwith us, with deviation at the peak. During winter, the effect of PCMs on indoor consolation is decreased and the pleasant one changed into loca be the PCM kind M182/Q27, where temperature changes of 0.5 °C and 0.8 °C improved the indoor environment and increased energy efficiency. Bio / PCM absorbs heat from the sun and internal gains during the day and dissipates that heat at night to increase comfort while reducing the mass of heating and cooling associated with power consumption[9] Bio/PCM materials are marketed in the categories indicated in [Fig .11]

Fig. 11. Bio/PCM Specification

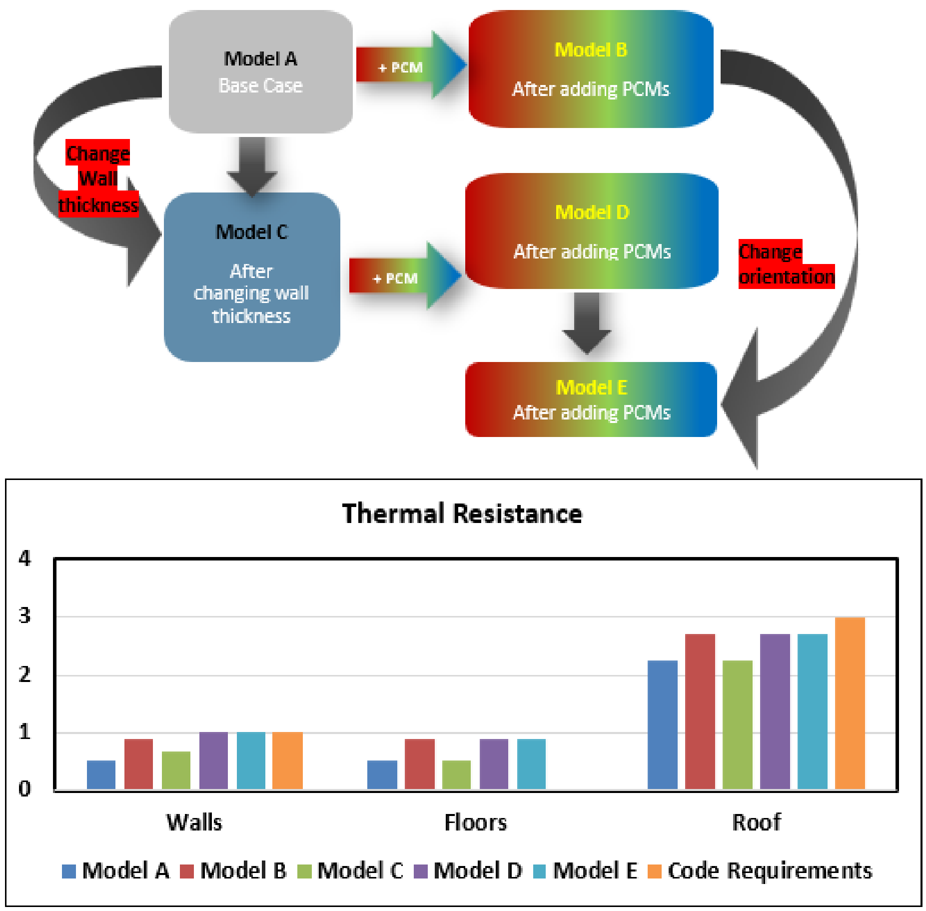
Material type	Phase change temperature [°C]	Latent heat storage [Wh/m2]
BioPCM M27/Q23	23	85
BioPCM M27/Q25	25	85
BioPCM M182/Q23	23	574
BioPCM M182/Q25	25	574





The analysis shown in [Fig.12]concluded that comparing (Model A) and (Model C) is to demonstrate the effect of modifying the layer thickness to improve internal thermal comfort and complete reliance on natural ventilation, which resulted in sensible heating savings of approximately 6% and sensible cooling savings of approximately 10%. The comparison of (Models A and B) explains the impact of including phase change material, as well as modifying the wall thickness to achieve internal thermal comfort solely by natural ventilation, resulting in reductions in sensible heating of approximately 39% and sensitive cooling of approximately 54%. While the comparison between (Model C) and (Model D) shows savings in sensible heating of about 57% and sensible cooling of about 52%, when studying Climate Consultant analysis to provide specific design guidelines for each location, the building reorientation has been done. As a result, the major apertures and the long side have been oriented to the northern facade, lowering heating and cooling loads on envelopes while preserving thermal comfort with the fewest requirements. A comparison between (Model A) and (Model D) shows the consequence of applying a change of materials on the skin when the building's orientation is changed. Savings in sensible heating are about 55% and in sensible cooling are about 59%, so PCMS can lead to sensible heating and cooling savings, and that solution can be applied to new construction or even retrofitting existing buildings, but it has been proven that taking into consideration the right building orientation could make savings of over 58% for cooling only, which is worth value, especially with rising costs.

Fig. 12. The effects of envelope modifications on reducing energy consumption.



R (kWh)	*Model A*	*Model B*	*Model C*	*Model D*	*Model E*	*Code requirements*
Wall	0.52	0.9	0.66	1	1	0.75-1.08
Floor	0.52	0.89	0.52	0.89	0.89	-
Roof	2.26	2.7	2.26	2.7	2.7	2.7

The comparative analysis before and after the use of PCMs revealed heat balance reductions in walls of more than 30%, floors of more than 15%, and roofs of more than 15%. This results in a 55% reduction in total heating and a 52% reduction in cooling.

6. Conclusion

The following are the main conclusions:

- Passive substances, including phase-converting substances utilized in constructing envelopes, can Manage thermal long-term equilibrium and eliminate the need for active heating and cooling.

- The use of PCM has evolved to require less power. This is an important consideration when remodeling a building envelope and increasing its performance at a decreased cost, just like the Application of warmth switch compounds withinside the building context.

- The thermoelectric impact of buildings, together with phase-converting materials, is characterized with the aid of using the subsequent advocated styles of residences: B. Ratio of thermal residences to conventional materials, and constructing design, orientation, and weather restrictions.

- The phase-changing material influence is particularly significant in improving life-cycle performance when the build is well-ventilate dilated, either mechanically or naturally. Thermal degradation will be smaller in a place with PCM on the side than in a same without PCM.

- According to other experiments with different PCMs, the best results were from the type with high heat storage and phase change temperature of about 25 ° C. This is a distinction in temperature fluctuations from 1.2 ° C to 2.4, which has a giant effect on indoor comfort at its peak.

- PCMs are being implemented into building envelopes to offer the necessary the shortest possible size of thermal mass, suitable for both new and existing structures.

- Temporary heat-enhanced PCM decisions when using different PCM types and quantities can vary significantly depending on variables such as occupants, ventilation systems, internal gains, and temperature settings.

- PCM can be produced in natural conditions such as western Egypt's deserts. The consolidated salt sands of Bahariya Oasis, in particular, are widely recognized.

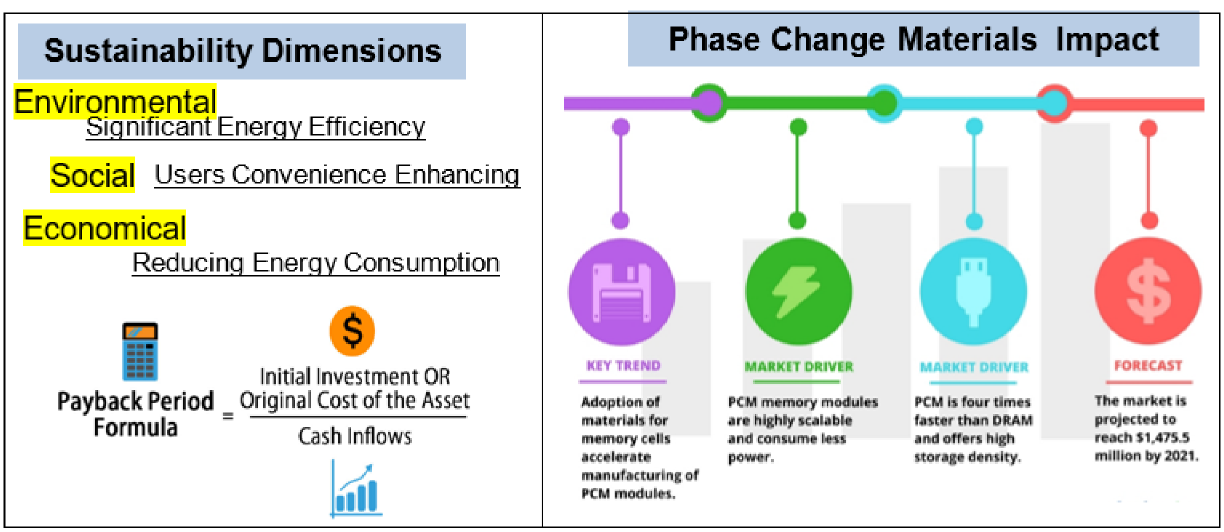
- The application of PCM products, such as concrete, has a detrimental effect, weakening strength characteristics by approximately 10tely10% to 15%.

- PCM is an effective means of attempting to reduce heat loss in hot, dry weather.

- Depending on the ventilation approach, PCMs can be applied for both heating and cooling. The return on investment for PCMs fluctuates on region and energy costs.

- Some demanding situations for PCMs production and availability consist of continuing to increase thermal potential, lowering manufacturing costs, improving polymeric, improving implementation methodologies, and boosting the supply and variety of PCM answers withinside the production industry, as shown in [Fig.13].

Fig.13. Challenges and advantages of PCMs applications in the construction field



Reference

[1] Abuelnuor, A.A., Omara, A.A., Saqr, K.M. and Elhag, I.H., 2018. Improving indoor thermal comfort by using phase change materials: A review. International Journal of Energy Research, 42(6), pp.2084-2103

[2] Al-Absi, Z.A., Mohd Isa, M.H. and Ismail, M., 2020. Phase change materials (PCMs) and their optimum position in building walls. Sustainability, 12(4), p.1294.

[3] Valiyev, Famil. (2017). Synthesis of Novel Nucleoside Analogs of Purines.

[4] Singh, S., Gaikwad, K.K. and Lee, Y.S., 2018. Phase change materials for advanced cooling packaging. Environmental Chemistry Letters, 16(3), pp.845-859.

[5] Al-Yasiri, Q., & Szabó, M. (2022). Energetic and thermal comfort assessment of phase change material passively incorporated building envelope in severe hot Climate: An experimental study. Applied Energy, 314, 118957.

[6] Faraj, K., Khaled, M., Faraj, J., Hachem, F., & Castelain, C. (2021). A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. Journal of Energy Storage, 33, 101913.

[7] Barbi, S., Barbieri, F., Marinelli, S., Rimini, B., Merchiori, S., Bottarelli, M., & Montorsi, M. (2022). Phase change material evolution in thermal energy storage systems for the building sector, with a focus on ground-coupled heat pumps. Polymers, 14(3), 620.

[8] Ahmed, A., Mateo-Garcia, M., McGough, D., Caratella, K., & Ure, Z. (2018). Experimental evaluation of passive cooling using phase change materials (PCM) for reducing overheating in a public building. In E3S Web of Conferences (Vol. 32, p. 01001). EDP Sciences.

[9] Andrei - Stelian, Bejan & Catalina, Tiberiu & Virgone, Joseph. (2016). Comparison of different PCMs' impact on indoor comfort in an energy-positive house.

[10] Phase Change Memory Market - Trends and Forecasts by Technavio. (2017, April 26). Phase Change Memory Market - Trends and Forecasts by Technavio | Business Wire. https://www.businesswire.com/news/home/20170426006249/en/Phase-Change-Memory-Market-Trends-and-Forecasts-by-Technavio