Experimental Analysis of Heat Flux Variation in a Brick Using Eutectic Phase Change Materials

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Abstract

Pakistan being developing country is going through tough financial conditions at the same time badly affected by climate change which caused huge flooding and according to World Bank, the assessment estimates total damages to exceed USD 14.9 billion. These alarming figures are turning point, where climate resilience and adaptation towards new sustainable energy systems is required. Currently according to Pakistan finance division in energy chapter about 59.4% electricity is being generated by burning fuel (including RLNG, Coal and Gas) and according to study conducted by The University of Newcastle has established that 39 percent energy is consumed in just heating and cooling of buildings.

So in view of above the aim of study was to lessen the cooling load of buildings by incorporating Eutectic Phase Change Materials (PCMs) as thermal energy storage material (TES) in ordinary brick. Multiple fatty acids based organic PCMs were examined for eutectic point using Schrader equation. Keeping the melting range and latent heat in view Lauric Acid and Palmitic Acid were selected for eutectic mixtures for possessing melting point range of 33-38 0C. For other thermophysical properties including latent heat, melting point and specific heat capacity Differential Scanning Calorimetry (DSC) was performed for individual material and eutectic samples. Thermogravimetric analysis (TGA) was also done to check the thermal stability of selected materials. For examining reduction in temperatures and respective cooling load, two testing compartments, one with PCM incorporated brick and other with ordinary brick were made and investigated both in controlled condition and direct sun light. Both heating and cooling temperature profiles for individual brick and compartments were studied. Results showed the decrement of 4-5.5^{0}C in inside temperature and time lag of 3-5 hours for the compartment made with PCM brick. The overall reduction in heat flux was 25-30%.

Key Words: *Keywords— Application of Eutectic Phase Change Material, Application of PCMs in Brick, Passive energy storage in buildings, Eutectic Lauric-Palmitic acids, Heat storage with PCMs, Heat flux reduction with PCMs*

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CHAPTER 1: INTRODUCTION

1.1 Background

Energy crisis has proven a remarkable effect on the society from single person to entire economies. On one side energy supply is not enough to run the society on the other hand due to increased fuel prices energy prices are also getting higher thus directly and indirectly leading towards inflation and societal problems. Not only affecting economy, but the high energy demands are also pushing the conventional fuel powered power plants to burn more fuel thus another cause factor of global warming. Now considering all these factors it is crystal clear that new appropriate techniques are required which will not only lessen the heating/cooling load of buildings but also indirectly will help in less burning of fuel thus reducing carbon emissions, global warming and abrupt climate change. Thanks to the researchers which have taken lead worldwide and from energy saving to energy efficient buildings many techniques have been discussed and examined with remarkable results. One of them is using Phase Change Materials in building materials which have been proven to play a vital role in storing thermal energy in the form of latent heat. Various methods and techniques are used for utilizing PCMs for energy saving which are discussed in detail in literature review section.

1.2 Phase Change Materials

Phase change material (PCM) is a material which changes its state from solid or liquid to other one. During phase change state they take a lot of heat energy in form of latent heat. This latent heat associated with PCMs during their phase changing process made them capable of storing/releasing heat energy much more then that of sensible heat storage. Phase change materials are classified into organic, inorganic and eutectics categories. The classification of PCMs and their further subdivision is shown in Fig.1. However, the selection criteria of PCM depends on following factors:

A. Melting Point
B. Latent heat associated with phase change
C. Specific heat
D. Thermal conductivity
E. Chemical stability

F. Non degradation after large number of phase change cycles

G. Cost and availability

H. Toxicity

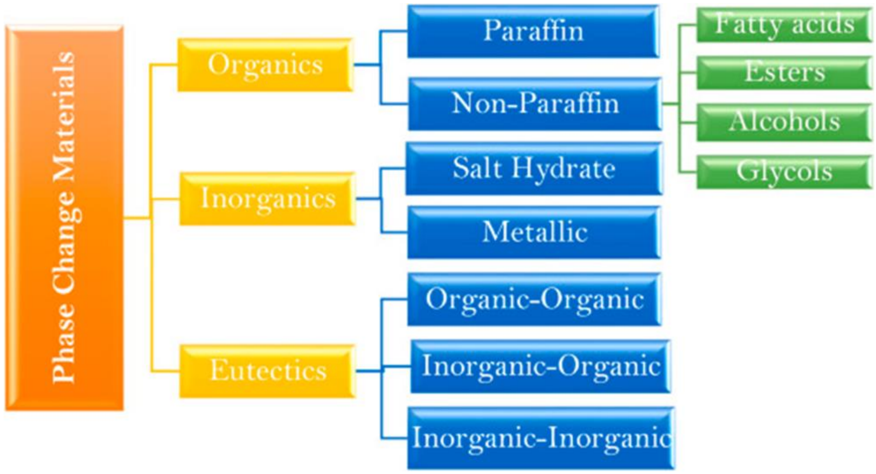


Fig.1 Classification of PCMs

Generally high latent heat is considered favorable. Other thermodynamic properties like melting point, thermal conductivity depend on application of PCM.

1.3 Eutectic Phase Change Materials

Eutectic is a mixture of compounds which have common melting point. Owing to the energy storage property of PCMs, investigation for eutectic PCM has opened a new window for thermal energy storage (TES) applications. Eutectic PCMs are preferred because of their capability to have more volume storage density due to an increase transition gap in their melting temperature. Some materials having high latent heat can't be used alone due to their high melting temperature but while in eutectic system with other low melting material their operating temperature can be molded as per requirement. Therefore, the preparation of eutectic mixtures as binary and ternary eutectic PMCs with moderate operating temperature zone has been getting substantial recognition. Schrader equation derived from the second law of thermodynamics and phase equilibrium is use for finding melting point of eutectic PCM by varying the composition of parent PCM. Equations are given below as Eq.(1) and (2).

$$Tm = \left[\frac{1}{T_{0,A}} - \frac{R \cdot \ln X_A}{\Delta Hm,A}\right]^{-1} \qquad (1)$$

$$Tm = \left[\frac{1}{T_{0,B}} - \frac{R \cdot \ln X_B}{\Delta Hm,B}\right]^{-1} \qquad (2)$$

where T_M represents the melting temperature of the eutectic mixture in K, $T_{o,A}$ and $T_{o,B}$ represents the onset melting temperature in K, X_A and X_B represent the mole fraction, while $\Delta H_{m,A}$ and $\Delta H_{m,B}$ represents the molar latent heat in kJ·kmol−1, of component A and B respectively. R is the general gas constant (8.314 kJ·kmol−1·K−1) used in Eqs. (1) and (2).

1.4 Problem Statement

At present developing countries including Pakistan has been badly affected by adverse impacts of climate change (1). The major source responsible for greenhouse effect is carbon dioxide emissions (2). Despite of many clean energy power plants coal and natural gas-fired plants are still dominant for electricity production and in 2022, 60% of total electricity is generated by these power plants (3). According to International Energy Agency overview report of World Energy Balances in last 47 years, world total energy supply (TES) increased 2.6 times (from 230 EJ to 606 EJ) mainly fossil fuels highlighting oil remained on top (4). Talking about production of electricity generation a high increase 41% is observed from just less than 12,000 terawatt-hours in 1990 to over 29,000 terawatt-hours in 2022 due to increased comforts associated with it. In Pakistan the primary source of energy production is also burning fuel (including Regassified Liquefied Natural Gas (RLNG), Coal and Gas) which is responsible for 59.4% of country's electricity being generated (5). Another study done indicated that energy use in buildings estimates 36% of global final energy demand and for 2020 the carbon emissions associated with this accounts for 37% (6). Furthermore, the use of energy by HVAC systems utilizes a huge 60 % of the total energy consumption of buildings (7). Talking about specifically Pakistan 49.1% energy is consumed in household (5). Also, during last year in 2022 temperature exceeded 50°C (8) in Pakistan due to severe heat wave. Now considering all these factors it is crystal clear that new appropriate techniques are required which will not only lessen the heating/cooling load of buildings but also indirectly will help in less burning of fuel thus reducing carbon emissions, global warming and abrupt climate change.

1.5 Aim of Study

To reduce heat flux inside building envelope using Eutectic Phase Change Materials (PCMs) by incorporating it in brick.

1.6 Objectives

1. To investigate and prepare Eutectic Phase Change Materials (PCMs) for thermal management of buildings.
2. To make an experimental setup capable of multiple PCM testing facility for comparative analysis
3. To analyze temperature variation and reduction in heat flux by using eutectic PCM

1.7 Motivation

This study is motivated by remarkable results achieved by application of PCMs in building materials for energy saving and also at present situation it is need of hour to move towards net zero energy buildings and sustainable systems due to climate change because a lot of fuel is burnt for energy production in developing countries where renewable energy usage is not in much practice. PCMs are widely being used in building application for thermal management and they can provide an effective solution in different climates and temperature conditions for sustainable buildings and reducing carbon emissions with help of their thermal energy storage capacity(9).Reduction in thermal load will be beneficial at both individual and national level as it will help in reducing financial burden for individual in form of energy cost saving and at national level decreasing energy demand.

Chapter 2: Literature Review

2.1 Energy Usage in Buildings

At present developing countries including Pakistan has been badly effected by adverse impacts of climate change. The major source responsible for green house effect is carbon dioxide emissions (1). According to International Energy Agency overview report of World Energy Balances in last 47 years world total energy supply (TES) increased 2.6 times (from 230 EJ to 606 EJ) mainly fossil fuels highlighting oil remained on top (2). Talking about production of electricity generation a high increase 41% is observed from just less than 12,000 terawatt-hours in 1990 to over 29,000 terawatt-hours in 2022 due to increased comforts associated with it. Despite of many clean energy production plants still the major source is 60 coal and natural gas-fired plants used for 60% of total electricity production in 2022 (3). In Pakistan the primary source of energy production is also burning fuel (including RLNG, Coal and Gas) which is responsible for 59.4% of country's electricity being generated (4). Another study done indicated that energy use in buildings estimates 36% of global final energy demand and for 2020 the carbon emissions associated with this accounts for 37% (5). Further more the use of energy by HVAC systems utilizes a huge 60 % of the total energy consumption of buildings (6). Talking about specifically Pakistan 49.1% energy is consumed in household (4). Now considering all these factors it is crystal clear that new appropriate techniques are required which will not only lessen the heating/cooling load of buildings but also indirectly will help in less burning of fuel thus reducing carbon emissions, global warming and abrupt climate change.

2.2 Using PCMs in Building

Literature review has shown PCMs are widely used in building application for thermal management and they can provide an affective solution in different climates and temperature conditions for sustainable buildings and reducing carbon emissions with help of their thermal energy storage capacity(7) PCMs can be expressed as materials that have an intrinsic capability of absorbing and releasing heat during their phase transition cycles (8).

Use of PCMs for thermal energy storage has given a lot of interest by researchers wordwide because of the various merits associated with PCM (9). The key is PCM posses high energy storage density as compared to sensible heat storage of buildings material including concrete, brick and for some occasion aluminum and steel fabrications (10). and many more by using composite of PCM and sodium acetate in insulation wall, the energy consumption for heating was reduced by 17.5% in a dry climate and 10.4% in the semiarid climate. Similarly analysis done by Mohammad S. Bagazi et al using commercial PCM RT 35 & PCM RT 35 HC results showed reduction in the heat flux by 61.1% for PCM RT 35 & 68.2% for PCM RT 35 HC than the reference chamber without PCM. The maximum energy saving for PCM RT35 was 1920 kJ, or 0.533 kWh, for one wall only and for PCM RT35HC was 2880 kJ, or 0.8 kWh, which can reduce the energy consumption of an HVAC system by 97 kWh/m2 and 146 kWh/m2 per year, respectively (11). Another study done by Qudama Al-Yasiri et al was to examine effect of encapsulation of PCMs and results found that highest with ambient temperature 63.23^{0}C corresponding PCM brick temperature drop with 1207 W/m2 intensity was 3.9^{0}C with reference to normal brick containing five PCMs rectangular capsules of dimension 4x2cm (12). MK Gupta et al also did analysis on PCM encapsulation techniques in hot environment of India and found that maximum reduction in peak temperature of 4.20 C, 9.87 % less in comparison to conventional brick, was observed in tubular shape PCM (13).With these remarkable results PCMs got attention and further research was carried out to enhance the thermal properties of PCMs which includes low thermal conductivity, shape stability and suppression of the supercooling (14,15). Solid-liquid organic PCMs and their eutectics in this regard possess all the required capabilities of having even melting, non-toxic and eco-friendly bio-based nature, compatibility with the material of construction, reliability and most importantly their abundance in nature, makes them suitable for low to moderate temperature TES applications (16). Moreover, another advantage of using organic PCMs is the ability to develop eutectic PCM for a particular TES application with desired thermophysical characteristics. A series of eutectic PCMs mainly comprising of Lauric acid, Palmitic acid, Stearic acid and Myristic has been developed by H Nazir et all (17). Schrader equation (18) used for finding melting point of eutectic PCM

For developing of LHTES system thermophysical properties including mainly optimum operataing temperature range, temperature range, melting enthalpies, chemical stability and cyclic reliability is required (19). The eutectic PCMs had showed remarkable results for TES applications in operating temperature from ∼27–75 °C, with the latent heat from ∼127 to 210 kJ·kg−1 which in this range can be used easily for thermal management in buildings, photovoltaic/thermal and space heating applications (17)

2.3. Summary of Literature Review

Ref	Title	Country/Climate	PCM Type	Application	Performance Parameters	Results
Mustapha Mahdaoui Construction and building materials (ELSEVIER 2020)	Building bricks with phase change material (PCM): Thermal performances	Moroccan regions. Outside ambient temperature 45C during day and 25C at night.	Composite material PCM constituted of 60% of microencapsulated paraffin within a copolymer.	Integration of PCM into hollow bricks. Physical modeling and numerical analysis of heat transfer through PCM containing bricks carried out.	The brick studied is of 12 air cavities. This analysis was done using Ansys Fluent software. Validation was done with physical model with a brick of size 30x20x15cm placed in conditioned chamber.	Average error of numerical analysis was 5.19%. At optimized mass fraction of 16% PCM inner temperature drops to 27.5C for a peak temperature swing of 45C.
Mohammad S. Bagazi,, Ammar A. Melaibari , Ahmed B. Khoshaim, Nidal H. Abu-Hamdeh, Abdulmohsen O. Alsaiari and Hani Abulkhair Sustainability (ELSEVIE 2021)	Article: Using Phase Change Materials (PCMs) in a Hot and Humid Climate to Reduce Heat Gain and Energy Consumption	King Abdul Aziz University, Jeddah City, Saudi Aribia	PCM RT 35 PCM RT 35 HC	Economic analysis of the walls containing PCM is discussed.	Four chambers were built using a hollow-clay-brick-type shield. Ordinary With Insulation Styrofoam PCM RT 35 PCM RT 35 HC	PCM RT35 showed reduction in the heat flux by 61.1% ,62.9% than the foam chamber, and 68.2% than the RT35HC chamber. The maximum energy saving for PCM RT35 was 1920 kJ, or 0.533 kWh, for one wall only and for PCM RT35HC was 2880 kJ, or 0.8 kWh, reducing energy consumption of an HVAC system by 97 kWh/m2 and 146 kWh/m2 per year

Qudama Al-Yasiria,b,c,*, Marta Szabob Case Studies in Construction Materials (ELSEVIER 2021)	Effect of encapsulation area on the thermal performance of PCM incorporated concrete bricks: A case study under Iraq summer conditions	Summer, September, Iraq	Paraffin with 44 ^{0}C melting temperature Latent heat 190(kJ/kg)	Applied PCM in bricks	Four bricks one ordinary and three with different number of capsules of PCM. In direct sunlight	Highest ambient temperature 63.23^{0}C Corresponding PCM brick temperature with 1207 W/m^2 intensity Brick A 1.6^{0}C Brick B 1.8^{0}C Brick C 2.2^{0}C Brick D 3.9^{0}C
Manglesh Kumar Gupta a, Pushpendra Kumar Singh Rathore a,*, Rajan Kumar b, Naveen Kumar Gupta c Journal of Energy Storage (ELSEVIER 2023)	Experimental analysis of clay bricks incorporated with phase change material for enhanced thermal energy storage in buildings	Summer October, India	n-octadecane (OD) melting temperature 30.42 and Capric Acid(CA) 37.42 G.I sheet encapsulation	Applied PCM in bricks	PCM integrated clay bricks for different shapes of macrocapsules was prepared on the roof top.	Maximum reduction in peak temperature of 4.20 C, 9.87 % less in comparison to conventional brick, was observed in Tubular PCM
Rajat Saxena, Dibakar Rakshit, S.C. Kaushik Renewable Energy (ELSEVIER 2019)	Experimental assessment of Phase Change Material (PCM) embedded bricks for passive conditioning in buildings	Summer May, June India	Eicosane melting temperature 36-38 OM35, melting temperature 35		Tested single and multilayer PCM incorporation in brick placed on roof	A temperature reduction up to 9.5 C for dual PCM layer within the brick and a temperature reduction of 6 C is achieved for single layered PCM brick.
Chao Jia, Xiaoying Geng, Fudan Liu, Yanna Gao	Thermal behavior improvement of hollow sintered bricks integrated with both thermal insulation	Weather condition of Aug. 1–6, 2020 Shanghai city, China	Paraffin 25 Phase change temperature 20◦C–30 ◦C		PCM in hollow sintered bricks was used to enhance the wall thermal behavior	PCM had the high contribution on reducing the maximum heat flow in inner surface and the peak heat flow was decreased from 38.7 W/m^2 ~35.2 W/m^{2}to 19.2 W/m^2 26.1 W/m^2, leading to the 50% reduction.

Case Studies in Thermal Engineering (ELSEVIER 2021)	material (TIM) and Phase-Change Material (PCM)					
Chelliah Arumugam , Saboor Shaik* Sustainable Energy Technologies and Assessments (ELSEVIER 2021)	Air conditioning cost saving and CO_2 emission reduction prospective of buildings designed with PCM integrated blocks and roofs	Jodhpur and New Delhi were selected for the hot-dry and composite climatic conditions. (May and December)	organic mixtures of fatty acids (OM21, OM30, OM35, and OM46) for thermo-economic analysis.		PCM integrated building configuration models were assessed through a validated analytical model to explore the thermo-economic performance, energy cost-saving potential, and payback periods in two distinct climatic conditions (hot-dry and composite).	OM30 PCM provides the highest total air-conditioning cost savings ($ 94.3/ annum in hot-dry and $ 96.9/annum in composite) OM30 PCM provides the highest carbon emission reduction of 4.3 tons of CO/ year and 4.2 tons of CO/year in hot-dry and composite climates of India, respectively.
Mustapha Mahdaoui a,Said Hamdaoui b, Abdelouahad Ait Msaad b, Tarik Kousksou, Abdelmajid Jamil b, Mohammed Ahachad a c, Tarik El Rhafiki d Construction and Building Materials (ELSEVIER 2020)	Building bricks with phase change material (PCM): Thermal performances	a sinusoidal thermal wave swings between 25 C and 45 C is adopted to simulate the outdoor temperature fluctuations of a typical summer day in Morocco	PCM (n – Nonadecane) Melting Temperature 32		Thermal response of a hollow brick (12 holes) incorporate PCM is numerically evaluated and analyzed	The molten fraction is higher for Tm = 32 C, about 65%, exceeds 45% for Tm = 28Cand less than 40% for Tm = 37 C.Indeed, the stored heat of the brick with PCM is important for Tm = 32 C.
Youssef Hamidi a,b, Zakaria Aketouane b,c, Mustapha Malha a, Denis Bruneau,	Integrating PCM into hollow brick walls: Toward energy conservation in	Tripoli (Libya) and Naples (Italy)	Six different PCMs investigated, differing mainly in terms of median melting temperature T		A standard building envelope consists of a wall of hollow bricks each with eight holes to be filled with PCM	The results proved that the PCMs with median melting temperatures of 28C, 30C and 32C were efficient in reducing the heat flux peak. he PCM with 26 C median melting

Rémy Goiffon c b,c, Abdellah Bah A Energy & Buildings (ELSEVIER 2021)	Mediterranean regions		from 22C to 32C)			temperature can save up to 56% of the energy needed to maintain the internal comfort temperature at a 26C

Chapter 3: Methodology

The research work in this dissertation has been presented in two parts. The first part is related to investigation and preparation of Binary Eutectic Phase Change Material (PCM) to be applied in brick for thermal management of buildings. The objective of this part is to prepare eutectic PCM whose melting temperature lies in such range that it can be used for thermal management in buildings. Also, the investigation of thermal properties of selected PCM is covered in first part. The second part is designing of experimental setup and application of prepared PCM in brick for examining temperature variation in brick and respective heat flux variation caused by modified brick.

3.1 Materials and Methods

3.1.2 Material Selection

Different PCMs are available in the market which are selected generally according to their thermal characteristics, composition, stability and more specifically according to application. The melting temperature should be close to the average temperature of the outdoor environment (20). Zhangetal (21)suggested that the performance of PCM outfitted walls is best when the mean phase change temperature of PCM is equal or close enough to the outside mean ambient temperature. For heat flux reduction it was found by Yang et al. (22) that the attenuation and delay of the heat flux were more significant when the fluctuation in average temperature and ambient temperature are close enough to the phase change temperature of PCM.

Considering the above data and looking for the average high temperature in Islamabad for the peak summer months which is as (23) :

May-35°C, June 37.2°C, July 35°C, and August 33.33°C , the PCMs selected for preparing eutectic are Lauric acid and Palimitic acid as their melting point lies in the range of 35-38°C (24).

The properties of selected PCMs along with melting temperature and latent heat are mentioned below in Table 1 while figure 1 and 2 show the melting point and latent heat of available organic PCMs respectively.

Table 1. Properties of Selected Materials

S.No	**Material**	**Molecular Weight g/mol**	**Melting Point ◦C**	**Latent Heat of Fusion $J.g^{-1}$**	**Specific heat capacity ($J. g^{-1}. K^{-1}$)**		**Make**
					At 60–70°C Cp_{liquid}	**At 20–30°C Cp_{solid}**	
1	Lauric acid (LA)	200.31	43–45	181.19	2.2	1.6	Sigma Aldrich

2	Palmitic acid (PA)	256.42	62–66	209.46	2.8	1.9	Sigma Aldrich

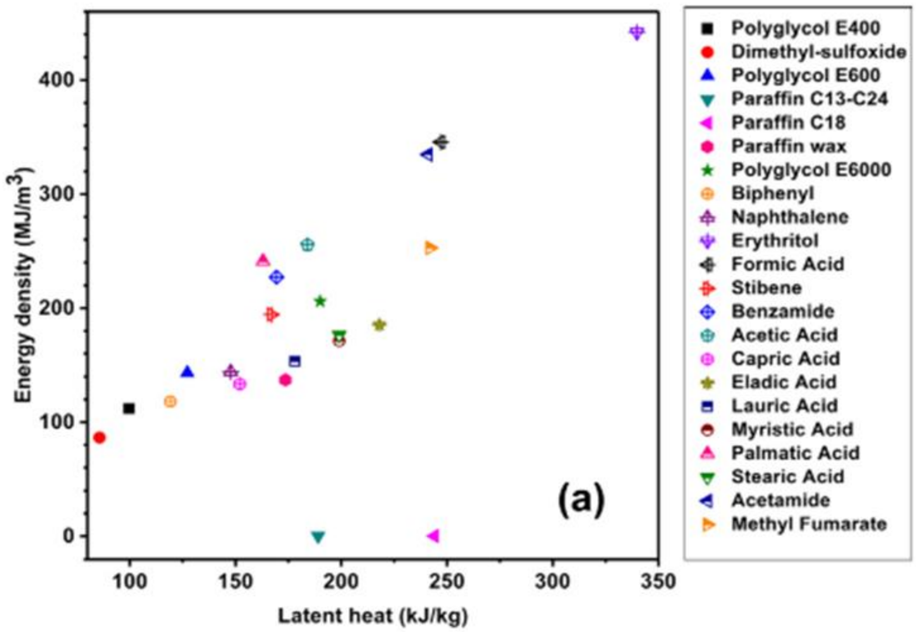


Figure 1. Latent Heat of Organic PCMs

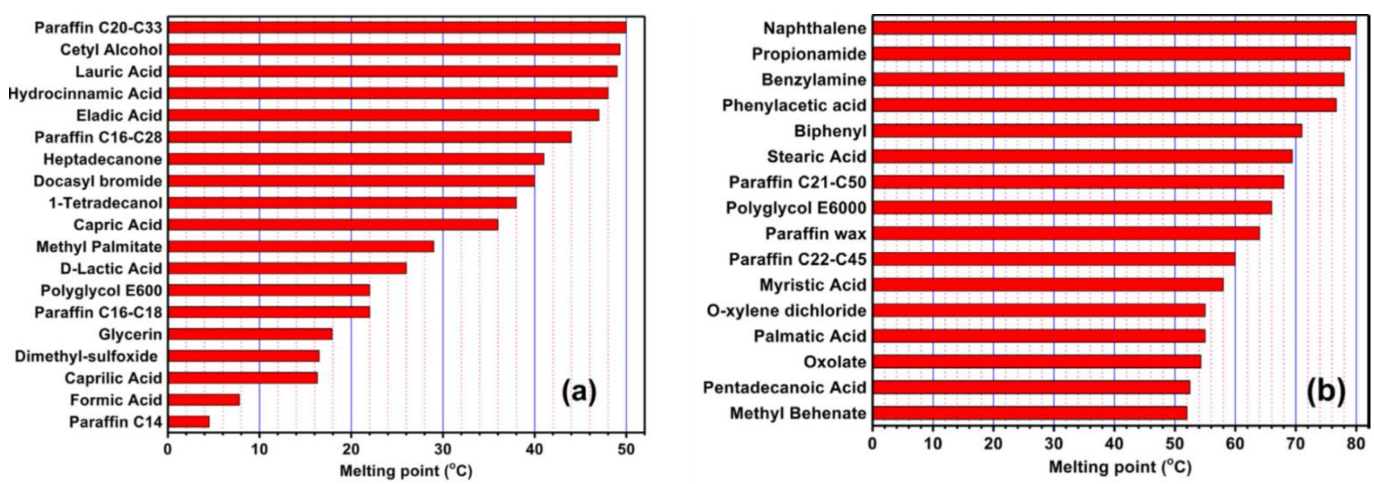


Figure 2. Melting Point (a) from 0-50 ^0C, (b) 50-80^0C

3.1.2 Determination of Eutectic Point for Selected PCMs.

For finding the eutectic point, the theoretical prediction method is used for the preparation of the multiple binary eutectic mixture PCMs prior to experiment for minimizing the number of test samples as well as the cost associated with the characterization. Theoretical eutectic mass ratios of multiple fatty acid eutectic mixtures are determined through the phase diagram. Schrader equation(25) derived from the second law of thermodynamics and phase equilibrium theory(26) relates the thermophysical properties of the eutectic PCMs with varying composition, is used for this purpose as mentioned below:

$$Tm = \left[\frac{1}{T_{0,A}} - \frac{R \cdot \ln X_A}{\Delta Hm,A}\right]^{-1} \quad (1)$$

$$Tm = \left[\frac{1}{T_{0,B}} - \frac{R \cdot \ln X_B}{\Delta Hm,B}\right]^{-1} \quad (2)$$

where T_M represents the melting temperature of the eutectic mixture in K, $T_{o,A}$ and $T_{o,B}$ represents the onset melting temperature in K, X_A and X_B represent the mole fraction, while $\Delta H_{m,A}$ and $\Delta H_{m,B}$ represents the molar latent heat in kJ·kmol−1, of component A and B respectively. R is the general gas constant (8.314 kJ·kmol−1·K−1) used in Eqs. (1) and (2). The results obtained from phase diagrams are shown in Table 2.

Table 2. Theoretical Composition of Eutectic PCM

S.No	**Eutectic PCMs**	**Mass Eutectic Point g.mol^{-1}**	**Eutectic Temp ^{0}C**	**Melting Enthalpy J.g^{-1}**
1.	Eutectic LA-PA	Mass eutectic composition LA 72---PA 28	Eutectic Temp 37.43	189.09

3.2. Experimental

3.2.1 Brick

The standard brick with dimension 9x4.5x3 (LxWxH) inches is used and then perforated with holes of diameter 0.5 inch along 3 inches height side. In total three bricks were used for testing with four holes made lengthwise and three holes made widthwise such that they are in triangular arrangement with respect to each other. The arrangements of holes in brick is shown in figure 3.

Figure 3. Drilling of Holes in Brick

3.2.2 Preparation of Eutectic PCM LA-PA

Eutectic PCM LA-PA is prepared based on eutectic mass ratios obtained from phase diagram. First the PCMs are weighed by using a precision balance of weighing precision±0.5 mg, then the mixture is heated in water bath maintained at ~70 °C for 60 min, then stirring at 900 rpm for 40 min followed by ultra-sonication at ~60 °C for 20 min. In this way, eutectic mixture of LA-PA is prepared using melt blending technique. The mixture is then left at room temperature for uniform solidification and flow diagram is represented as Figure 4.

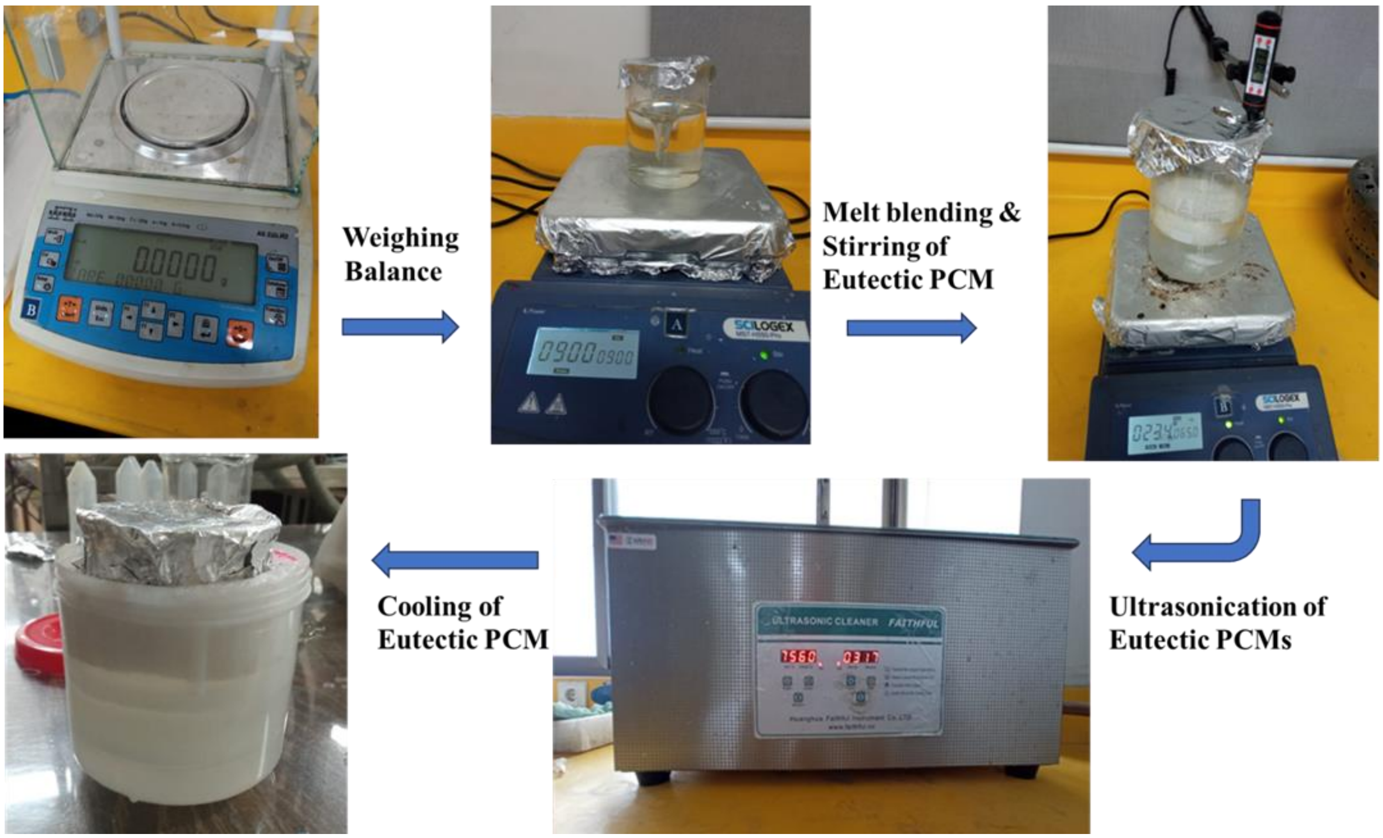


Figure 4. Preparation of Eutectic PCM

Table 3. Equipment Specification used for Characterization

S.No	Name of Equipment	Make & Model	Specification
1.	Hot plate and stirrer	Scilogex MS7-H550-Pro	Max Temp:550 ºC Max RPM: 1500 +/- 1ºC
2.	Weighing balance	RADWAG AS 220.R2 PLUS Analytical Balance	Maxium capacity: 220 g Readability: 0.1 mg
3.	Ultrasonic cleaner	FAITHFUL FSF-080S	Frequency: 40KHz Timer: 0-30min Heater: RT-80℃ Ultrasonic Power(W): 480W
4.	Differential Scanning Calorimeter	TA Instruments, TA 2920 MDSC V2.6A	Accuracy ±0.1 °C

5.	Thermogravimetric Analyzer	TA Instruments, TA 5500	Temperature Accuracy ±1 °C Weighing Precision ±0.01 % Resolution <0.1 µg
6.	Solar meter	Daystar DS-05A	Range: 0-1999 W/m2 Resolution: 1 W/m2 Accuracy: +/-3%
7.	Hydraulic Universal Testing Machine	SHIMADZU UH-X Series	Loading capacity: 1000kN

3.2.2 Chemical and thermal characterization

Eutectic PCM LA-PA is prepared based on eutectic mass ratios obtained from phase diagram. First, the PCMs are weighed by using a precision balance of weighing precision±0.5 mg, then the mixture is heated in water bath maintained at ~70 °C for 60 min, then stirring at 900 rpm for 40 min followed by ultra-sonication at ~60 °C for 20 min. In this way, eutectic mixture of LA-PA is prepared using melt blending technique. The mixture is then left at room temperature for uniform solidification. The details of instruments used is given in Table 3.

3.2.3 Encapsulation of PCMs

Macro encapsulation technique is used for incorporation of PCMs into brick. Copper tubes were selected for encapsulation of PCM owing to its high thermal conductivity so that maximum heat encountered by brick can be transferred to PCM. The outer diameter of copper tube is 0.5 inch whereas thickness of copper tube selected was 0.8mm to reduce the resistance barrier. The particular tubes were filled with melted PCMs with the help of syringe and around 20% of volume is left empty to incorporate for liquid expansion. Around 12ml liquid PCM is filled in each tube. The encapsulation process is shown in figure 5.

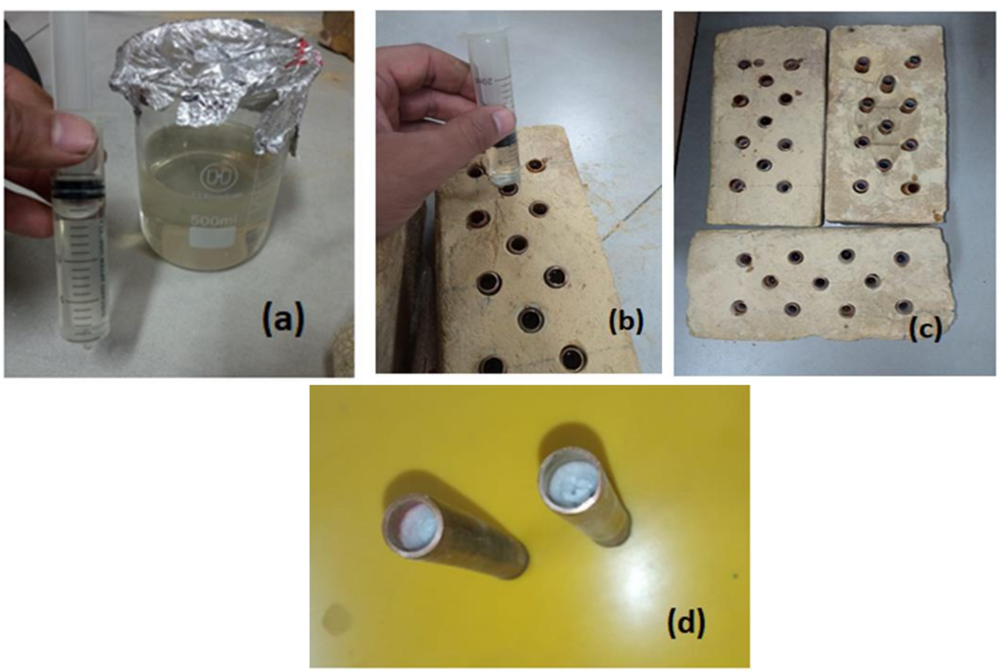


Figure 5 Incorporation of PCMs in Brick (Melting (a), Pouring (b), Cooling (c), Solidification (d))

3.2.4. Testing Chamber

A testing setup is designed with two separate compartments made inside for comparative analysis of temperature profile of wall with PCM brick and ordinary brick. The testing setup is made of wood originally and then three sides are insulated by thermopole insulation of two inches thickness to further minimize the heat transfer from thermopole . The front side is covered with the bricks wall being tested. Within the testing setup two separate compartments are made, one to be covered by PCM incorporated bricks and the other with ordinary bricks. The testing setup is placed so that the brick wall faces the sunlight. The testing setup 3D model is shown in figure 6 and actual model is shown in figure 7.

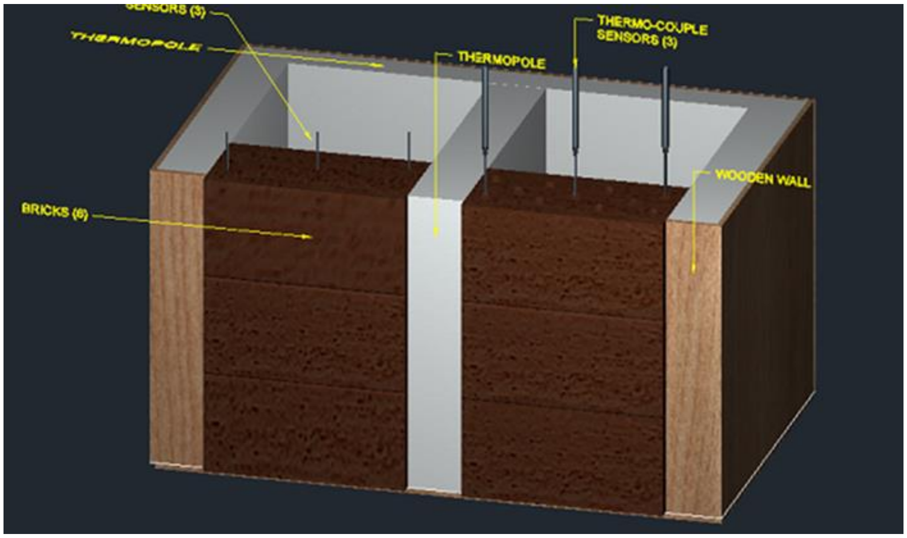


Figure 6. 3D Model of Testing Setup

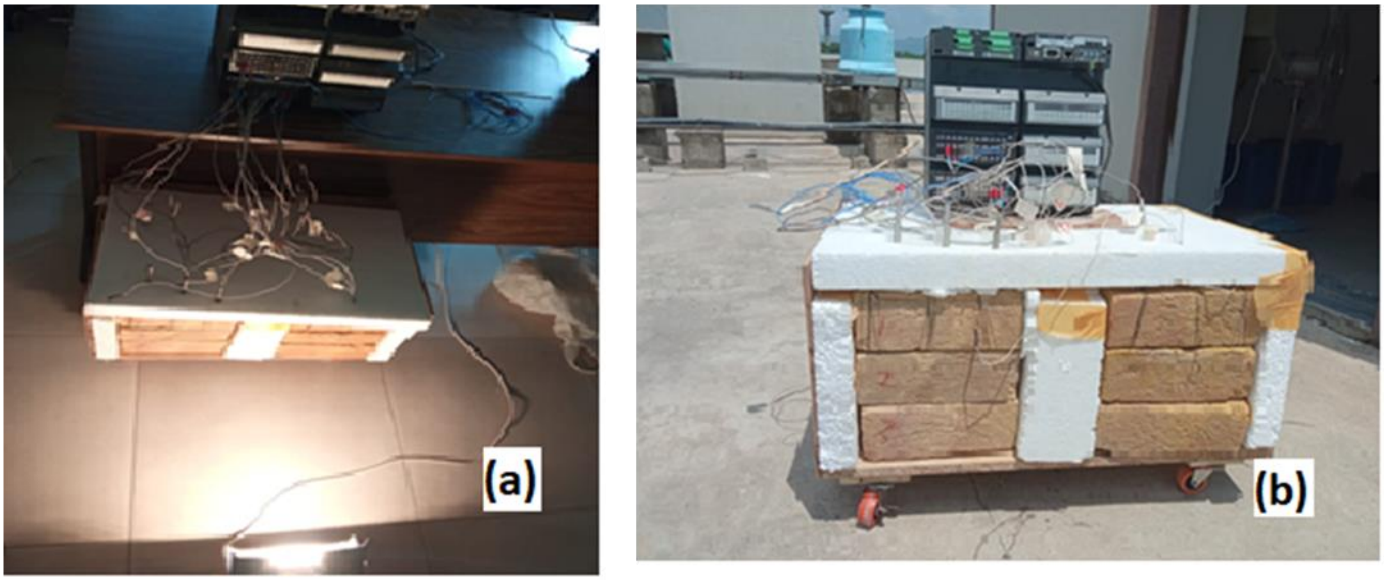


Figure 7. Testing of Brick Walls (a) With lamp Heat Source, (b) With Sunlight in Open Environment

3.2.5. Temperature Sensors

K-type thermocouple (measuring range:0-8000C, probe diameter and length 6 mm and 2 inches respectively) are used for recording temperature. Three probe type thermocouples are used for measuring PCM tube temperature at three different positions of brick and bead type thermocouple is used for measuring surface temperature of brick at three different places i.e front, mid and back end of brick with respect to sun face side. Two temperature sensors are inserted in two testing compartments covered with bricks with and without PCM respectively. One temperature sensor is used for measuring ambient temperature. The detail is shown in Fig 8. All these sensors are plugged into data logger with sampling rate of one second.

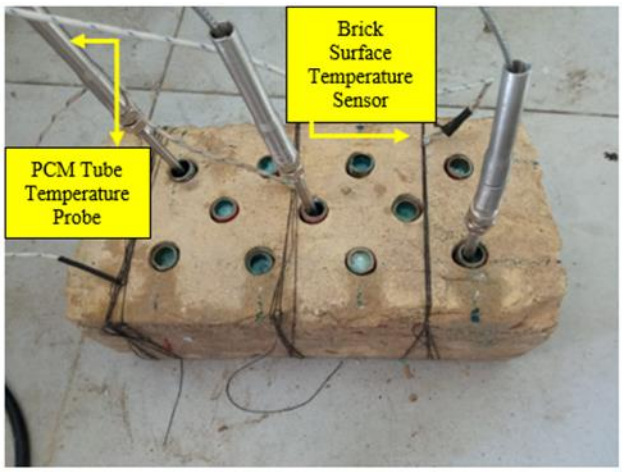


Figure 8. Temperature Sensors in Brick

3.2.6. Testing at Lamp

In this experiment a filament lamp of 500W power is also used to heat the brick wall so to observe the heat flux variation in controlled environment. The apparatus is placed at irradiance of 250~300 W/m^2 so that effect of temperature profile can be observed in detail. The lamp used was halogen lamp with power 500W and irradiance value of 1200~1400 maximum at source point.

3.2.7. Testing in Direct Sunlight

The testing setup is placed on roof of USP-CASE (US Funded Pakistan Center for Advanced Studies in Energy) Islamabad (Latitude: 33.738045, Longitude: 73.084488) (27) for 24 July 2023, 08-09 August 2023.

3.2.8. Compression testing

Bricks generally bear compressive load. To check for brick strength after PCM tube incorporation compressive strength analysis of brick was done using SHIMADZU Hydraulic Universal Testing Machines UH-X Series. Brick was first filled with sand mortar to give it smooth even shape and then was given compressive load of 0.28 MPa per second. Both bricks were of same composition and size and show in figure 9.

Figure 9. Compression strength Testing of Bricks

CHAPTER 4: RESULTS & DISCUSSION

4.1.Thermal Properties of PCMs Used

4.1.1. Theoretical Prediction of Eutectic Point

The results obtained from phase diagrams calculated by equation 1 and 2 are shown in figure 10. The theoretical values obtained are shown in table 4. Based on these values 8~10g samples were made for DSC and TGA analysis. The results obtained from DSC are shown in figure 8. It was observed that computational values of eutectic point and enthalpy of fusion was 37.34^0C and $189.09 J.g^{-1}$ respectively, whereas experimental values for heating are onset temperature 32.77^0C, peak melting 36.25^0C and endset temperature was 40.41^0C. The melting and freezing enthalpy observed are $182.73 J.g^{-1}$ and $184.26\ J.g^{-1}$. However, the DSC results showed a single peak for melting and solidification which shows mass eutectic point for LA-PA is M_{LA}=72% with eutectic point 36.25^0C. Thermal properties of eutectic PCM are presented in table 4.

For TGA the samples were analyzed from temperature 25 to 300^0C at scan rate of 10^0C per minute in constant nitrogen atmosphere. The mass loss with respect to temperature is shown in table 5.

Table 4. Thermal properties of Eutectic PCM

S.No	Eutectic PCMs	Mass Eutectic Point	Eutectic Temp ^{0}C	Melting Enthalpy $J.g^{-1}$
Computational Values				
1.	LA-PA	M_{LA}=72%	37.43	189.09
From DSC Results				
1.	LA-PA	M_{LA}=72%	36.25	182.73

Table 5. Thermal Stability of PCM

S.No	Temperature ^{0}C	Mass Loss %
1.	30.93	0
2.	233.24	25
3.	252.34	50
4.	265.25	75
5.	296.57	95

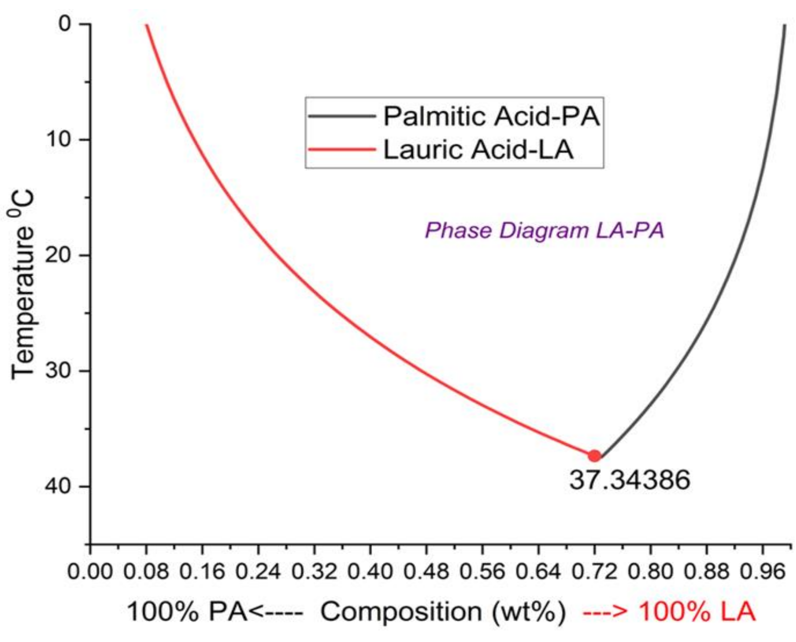


Figure 10. Phase Diagram Eutectic LA-PA

4.2. Heat Provided by lamp

As discussed above the experiment was performed for both controlled and real time environment. Fig. shows that the temperature variation in rooms under heat source of lamp. It can be seen clearly the temperature rise for room without PCM incorporated bricks is more then that for room with PCM incorporated bricks. To understand this rise temperature sensors within bricks were also placed with bricks at different placed as mentioned in temperature sensors portion. Fig. shows the temperature variation for bricks in which it can be seen that in initial thirty minutes the difference between PCM brick and normal brick is 1.4^0C which more or less remains around this deviation but after 2.5 hours this difference increase as brick temperature reaches to 35^0C the PCM starts melting, due to which the heat is now utilized by PCM in form of latent heat and so the difference between PCM brick and normal brick reaches to 3.1^0C. Similarly during start the temperature difference between both rooms is not much the slight difference of 1.4^0C is can be due to sensible heat gained by PCM but as temperature reaches near melting point of PCM the difference between rooms temperature also increases and goes up to 3.8^0C. Temperature rise graph for bricks and PCM is shown in Fig. where it can be seen that PCM gains a lot of heat because of which PCM brick temperature doesn't rises much as compared to normal brick.

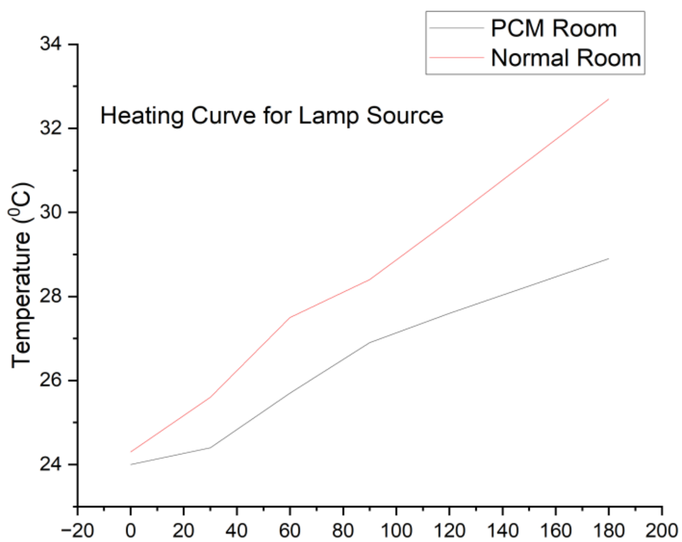


Figure 11. Heating Curve for Rooms At Lamp

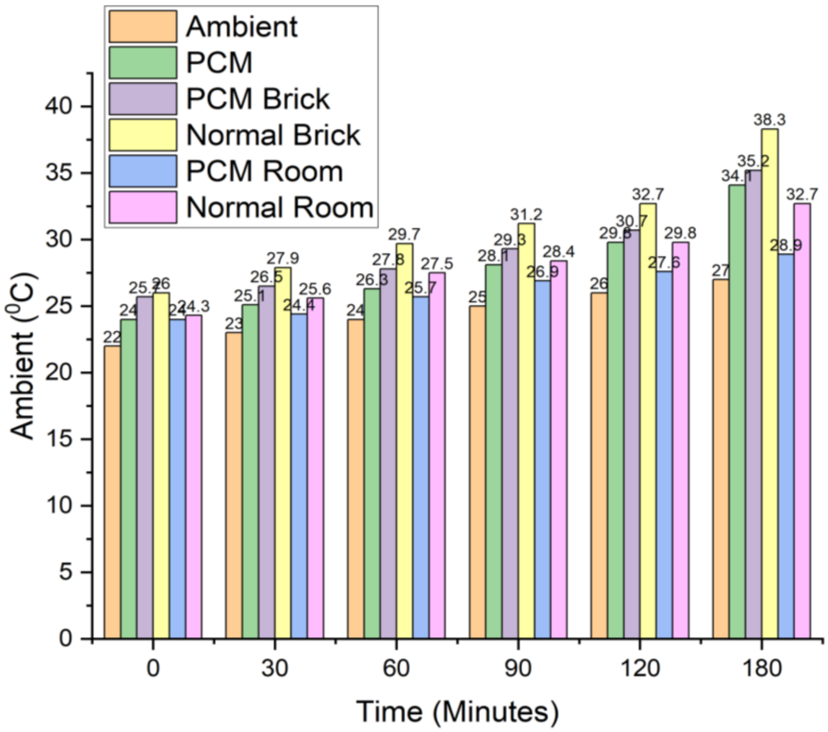


Figure 12. Temperature Comparison for Bricks & Rooms At Lamp

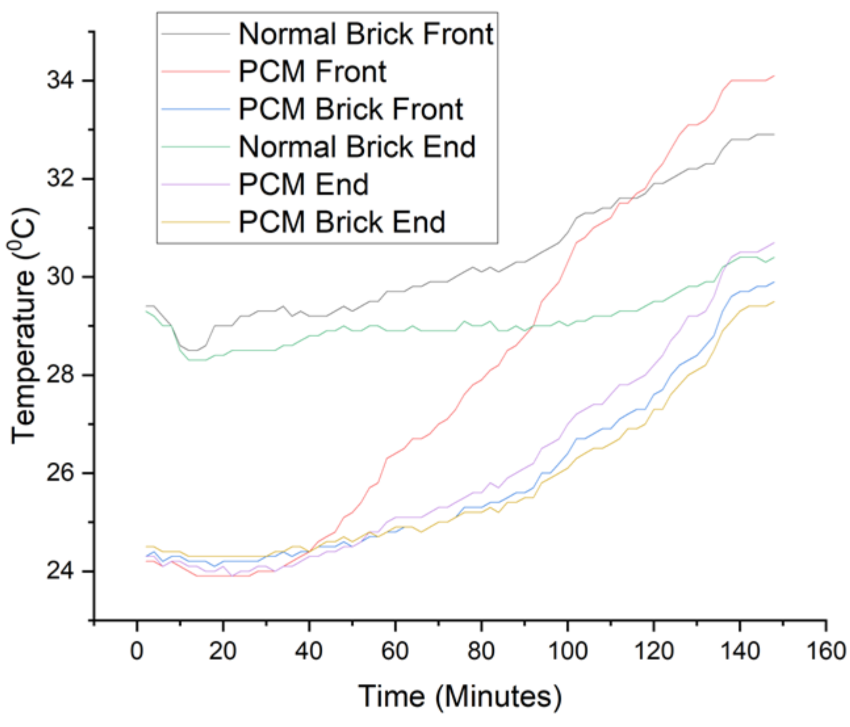


Figure 13. Temperature Comparison for PCM Brick and Normal Brick At Lamp Heating

4.3. Heat Provided by Sunlight

For open environment the results are shown in Fig 14. In first peak it is observed that the ambient temperature reaches to around 51^0C where respective temperature for normal room and PCM room is 45^0C and 41^0C which shows a decrement of 4^0C for PCM room. The ambient temperature reached to a maximum of 53^0C on same day. Corresponding maximum temperature for normal room and PCM room reached to 48^0C and 43^0C respectively showing a decrement of reasonable 5^0C. It can be explained with the help of temperature variation graph for both bricks and PCM shown in Fig. where it can be seen that PCM is gaining heat, more specifically in time 50 to 200 minutes its in range of PCM melting point so a lot heat is being utilized in PCM melting thus lowering the temperature of PCM brick and room.

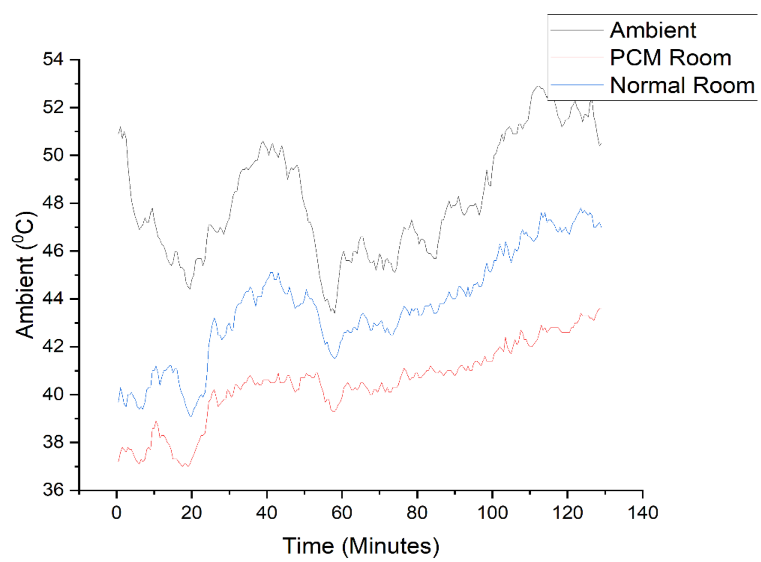


Figure 14 Temperature Variation for PCMs and Compartments

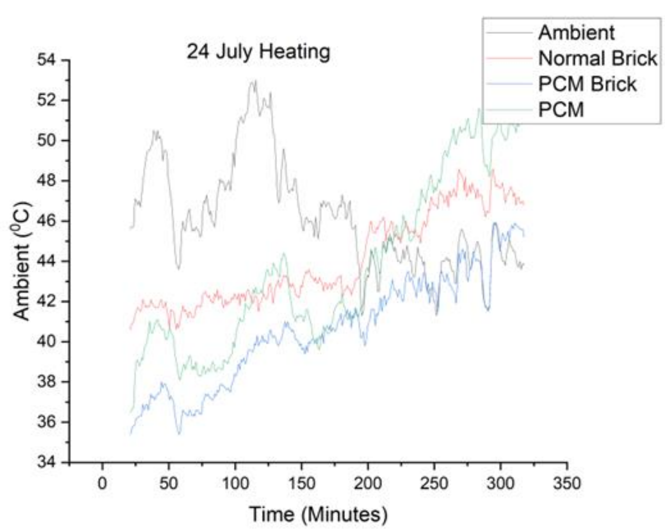


Figure 15. Temperature Variation for Bricks

4.4.Cooling Curves

It is crystal clear that PCM reduces heat flux during day time however heat stored in it is also a matter of concern for off load time. For this reason cooling curves are also examined. The results are shown in Fig. for lamp source heating and Fig. for open environment heating. For lamp source heating it can be seen that as no latent heat was involved the cooling curves for both rooms are almost similar and only a difference of 0.25^0C was observed However for open air environment results are different. Fig. shows the cooling curve for testing setup when placed in open air environment. Initial difference given was around $5\text{-}6^0$C for rooms and it can be seen that cooling curve slope is same for both rooms. Due to drop in ambient temperature the rooms temperature also dropped in same behavior and the initial gap of $5\text{-}6^0$C converged to 0.8^0C. At steady state it can be seen that ambient temperature was 28.5^0C whereas respective PCM room temperature is 29.5^0C and normal room temperature is 28.15^0C. This slight difference 1^0C from ambient and 1.5^0C within rooms is reasonable as compared to initial difference of $5\text{-}6^0$C. This is due to the heat stored in PCM in both latent and sensible form as it can be seen in graph Fig. which shows the temperature variation between bricks and PCM that sensors in bricks showed sudden fall in temperatures with respect to ambient temperature but PCM temperature fall is not so steep as compared to brick temperature fall due to stored heat.

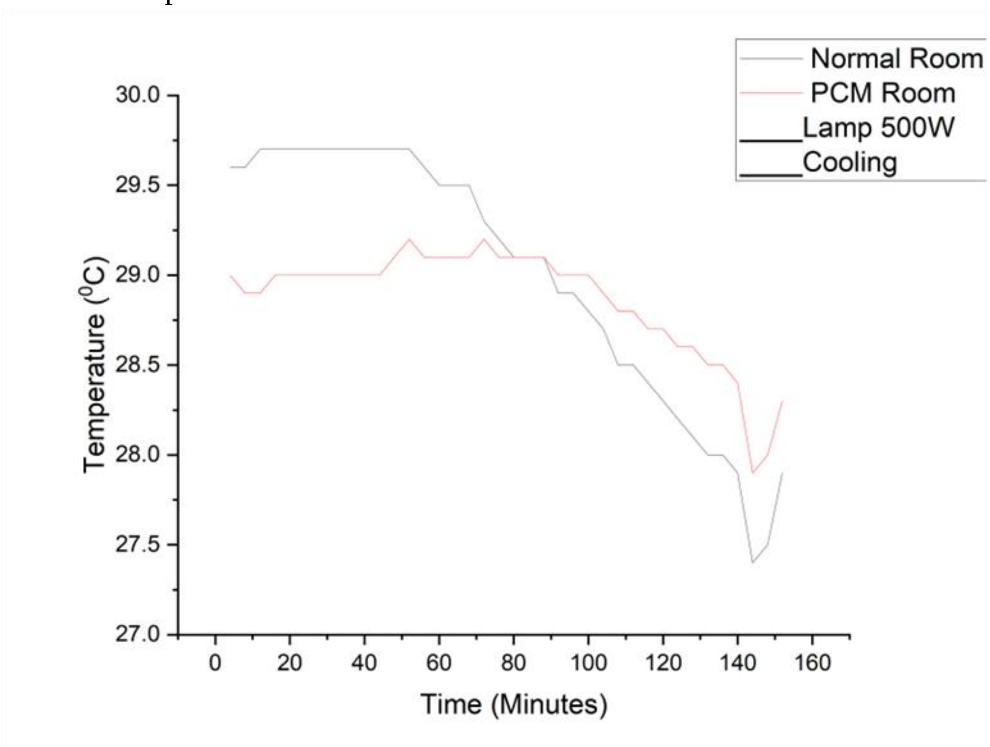


Figure 16 Cooling Curve for Lamp Heating

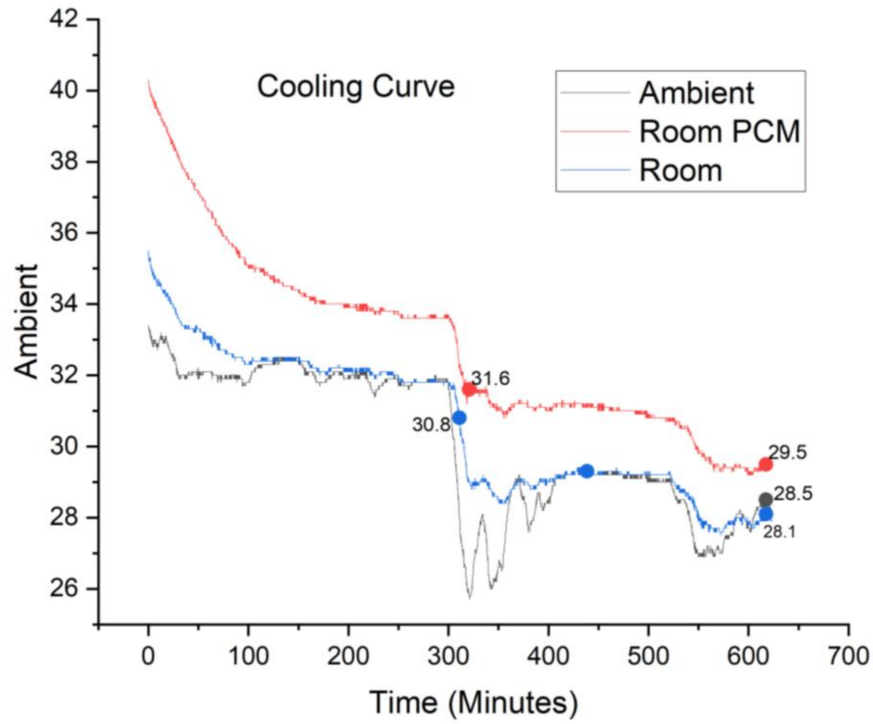


Figure 17 Cooling Curves for Rooms in Open Air Environment

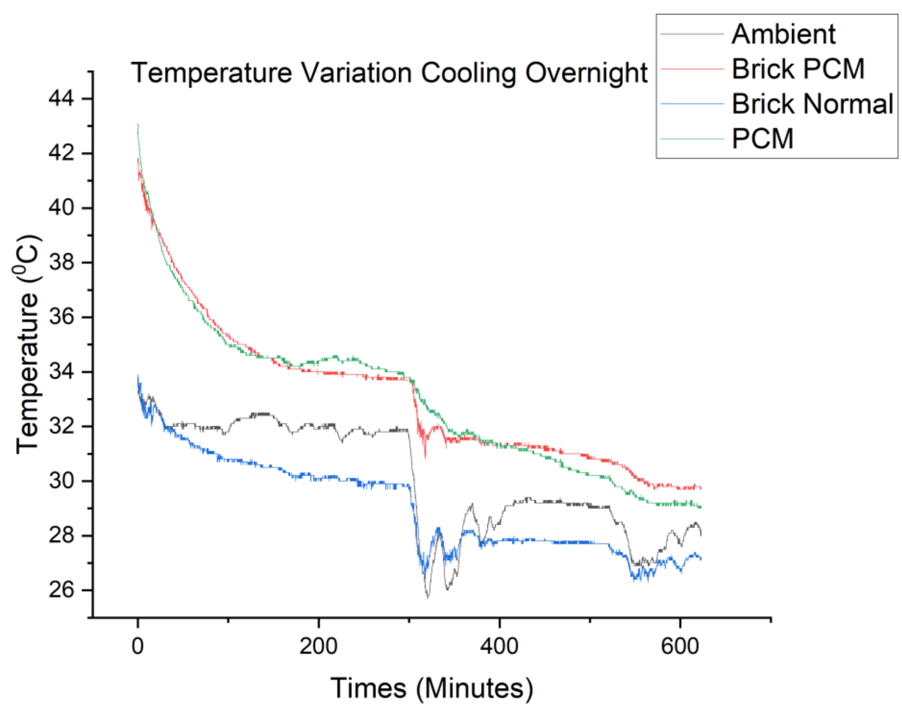


Figure 18. Cooling Curves for Bricks and PCM

4.5. Reduction in Heat Flux

For calculating heat flux conduction phenomena is considered as it's a case of heat conduction through solid brick wall. Fourier law is used for heat flow through conduction process. The heat moves per unit length in the solid dT⁄dx (28) (29) . For including material effect on heat transfer the thermal conductivity (k) is included and thus due to temperature gradient heat transfer through conduction in watts is given by: (30).

$$Q = -k.A.dT/dx \text{ (W)} \qquad (3)$$

Where Q is heat transfer, k is thermal conductivity, A is area and dT/dx is temperature difference per unit length.

Brick with PCM can be considered as porous material. Thermal conductivity for PCM capsule can be given as (31,32):

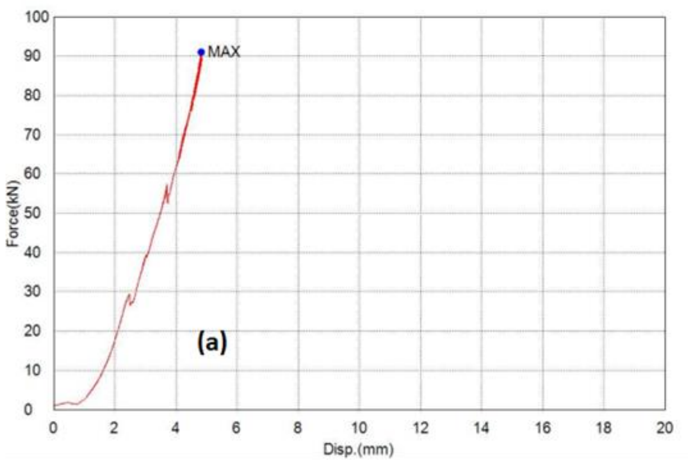
$$k_{PCM\ capsule} = (1 - \varphi)k_b + \varphi k_{PCM} \text{ (4)}$$

Where $k_{PCM\ capsule}$ is thermal conductivity of PCM capsule, φ is porosity percentage,k_b is thermal conductivity of brick. Anotrher term associated with heat transfer is heat flux also named as thermal flux, is referred to as heat flux density, heat-flow density is defined as flow of energy per unit of area per unit of time with units watts per square meter (W/m^2) (33). By using above equations it was found heat flux observed for ordinary brick which was 89.199 W/m^2 and for PCM incorporated brick it was 64.56 W/m^2 that is a difference of 24.7 W/m^2 was observed by incorporating PCMs in brick which is almost 28% less than heat flux observed by ordinary brick.

4.6. Compression Results

Two bricks of same composition were tested under compressive load of 0.28 MPa per second. One was icoporated with PCM tubes. During testing it was observed that the brick with PCM tube exhibited more strength under compressive testing. It can be becase of copper as copper strength is more than that of brick composition materials. The PCM tube brick showed strength of 120kN, while ordinary brick showed strenght of 90kN. Bricks are shown in figure 19 while results are shown in figure 20.

Figure 19. Bricks after Compression Test



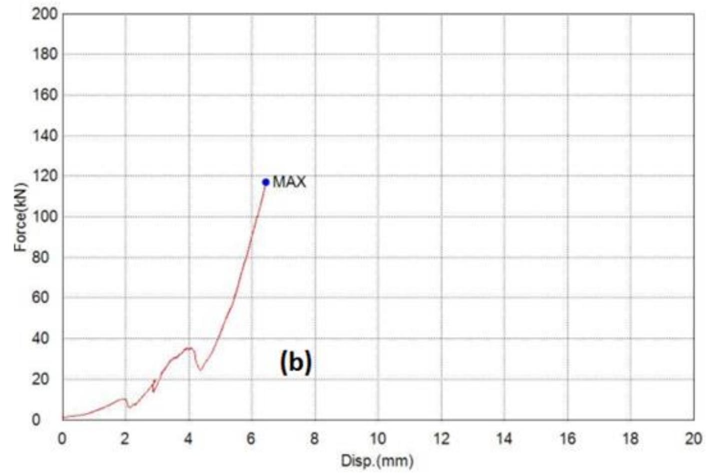


Figure 20 Compression Test Results (a) Normal Brick, (b) Brick with PCM Tubes

CHAPTER 5: CONCULSION & FUTURE WORK

The aim of above study was to reduce heat load of buildings by use of PCMs in buildings for thermal energy storage. Also it is observed that fatty acids based eutectic phase change materials provided better melting temperature window to be used for thermal management in buildings. Keeping this in view, a binary eutectic phase change material was made in labortary from lauric acid and palmitic acid having melting point 36.25^{0}C and latent heat 182.73 J/g and was incorporated in brick. Microencapsulation technique was used to incorporate PCM in brick using copper tubes for encapsulation owing to its good thermal conductivity. A down scale experimental setup was then made to check for temperature variation in brick due to incorporation of PCM in it. Two walls were made, one with normal brick and other with PCM incorporated brick and inside walls were made two compartments surrounded by thermopoleinsulation of 2-inch thickness. The brick walls were then examined both in controlled condition of room and in outdoor environments. In indoor testing walls were heated with lamp source of 500W and maximum irradiance of 1200-1500 W/m^2. For outdoor testing, experimental setup was placed on rooftop in direct sunlight in the month of July and August 2023. Along with heating, cooling profile was also studied to check for PCM heat rejection during off load hours. The key findings are listed below:

1. Maximum temperature decrement of 4.8^{0}C was observed in PCM compartment when placed in sunlight for corresponding maximum ambient temperature of 53^{0}C on 24 July and for 08 August the decrement was 5.5^{0}C for ambient temperature of 48.1^{0}C. With the help of PCM tube temperature sensor it was observed that PCM temperature was 33.8^{0}C at 09:48am and at 12:15pm it was 39.9^{0}C. This rise can be explained with the help of DSC result of eutectic LA-PA where it was found that the onset temperature for PCM melting was 32.77^{0}C and endset was 40.41^{0}C so it can be concluded that during this time of 4 hours the heat was retained in PCM tube for its melting thus lowering the temperature inside PCM compartment with remarkable value of 5.5^{0}C.
2. For heating done by lamp in controlled environment it was observed that temperature difference between both rooms was 1.4^{0}C for first 60 minutes but as temperature reached near melting point of PCM the difference between rooms temperature increased and went up to 3.8^{0}C due to latent heat involved.

3. Similarly from brick temperature profiles it was observed that the normal brick temperature was always higher than PCM brick this was due to the fact that PCM was gaining heat and it was observed that PCM temperature was high and respective brick temperature was low for instance at 14:22 it was observed normal brick temperature was 47.1^0C, PCM brick 41.4^0C and PCM temperature was 44.4^0C showing a decrement of 5.7^0C in PCM incorporated brick.
4. For data gathered overnight for examining the PCM heat rejection profile it was observed on 08 August night that the initial values for PCM compartment and normal compartment were 45.3^0C and 44.1^0C respectively whereas PCM temperature was 57.1^0C around 17:00 but heat rejection was very step and PCM comes to temperature of 39.9 and respective PCM compartment and normal compartment temperatures were 38.1^0C and 37.1^0C respectively. This difference of 1^0C becomes even more less after 20:00 and also very less as compared to 5.5^0C temperature saving during day peak load hours.
5. With the help of PCM thermal energy storage ability a time lag of more than 5 hours was observed on 08 August day.
6. With temperature data recorded a reduction of 28% was observed in heat flux by incorporating PCMs in brick as compared to ordinary brick.
7. It can be noticed that percentage of PCM in bricks is ~21.34% by volume and just ~3.5% by mass which is providing sufficient decrement in temperature. By increasing the amount of PCM further reduction can be caused in temperature and relevant heat flux.

5.1. Future Recommendations

In future other eutectic PCMs can be checked for comparative analysis with low melting point for less ambient temperature seasons. Also, a numerical analysis of such bricks can be done with the help of simulations to check for temperature profiles of these PCM incorporated bricks in other climate and zones. Temperature profile of brick with eutectic PCM can be studied for comparative analysis with the original PCM of same melting point.

REFERENCES

1. Gao, F., Wu, T., Zhang, J. et al. Shortened Duration of Global Warming Slowdowns with Elevated Greenhouse Gas Emissions. J Meteorol Res 35, 225–237 (2021). https://doi.org/10.1007/s13351-021-0134-y.

2. https://www.iea.org/reports/world-energy-balances-overview/world. (Last accessed on 19 August 2023)

3. https://www.statista.com/statistics/270281/electricity-generation-worldwide/. (Last accessed on 19 August 2023)

4. https://www.finance.gov.pk/survey/chapter_22/PES14-ENERGY.pdf. (Last accessed on 19 August 2023)

5. Salata, F.; Falasca, S.; Ciancio, V.; Curci, G.; Grignaffini, S.; de Wilde, P. Estimating building cooling energy demand through the Cooling Degree Hours in a changing climate: A modeling study. *Sustainable Cities and Society* **2022**, *76*, 103518. doi:10.1016/J.SCS.2021.103518.

6. Liu, F.; Yan, L.; Meng, X.; Zhang, C. A review on indoor green plants employed to improve indoor environment. *Journal of Building Engineering* **2022**, *53*, 104542. doi:10.1016/J.JOBE.2022.104542.

7. Ahangari, M.; Maerefat, M. An innovative PCM system for thermal comfort improvement and energy demand reduction in building under different climate conditions. *Sustainable Cities and Society* **2019**, *44*, 120–129. doi:10.1016/J.SCS.2018.09.008.

8. Giro-Paloma, J.; Martínez, M.; Cabeza, L. F.; Fernández, A. I. Types, methods, techniques, and applications for microencapsulated phase change materials (MPCM): A review. *Renewable and Sustainable Energy Reviews* **2016**, *53*, 1059–1075. doi:10.1016/J.RSER.2015.09.040.

9. Wang, G.; Feng, L.; Altanji, M.; Sharma, K.; Sooppy Nisar, K.; khorasani, S. Proposing novel "L" shaped fin to boost the melting performance of a vertical PCM enclosure. *Case Studies in Thermal Engineering* **2021**, *28*, 101465. doi:10.1016/J.CSITE.2021.101465.

10. Gupta, M. K.; Rathore, P. K. S.; Kumar, R.; Gupta, N. K. Experimental analysis of clay bricks incorporated with phase change material for enhanced thermal energy storage in buildings. *Journal of Energy Storage* **2023**, *64*, 107248. doi:10.1016/J.EST.2023.107248.

11. Bagazi MS, Melaibari AA, Khoshaim AB, Abu-Hamdeh NH, Alsaiari AO, Abulkhair H. Using Phase Change Materials (PCMs) in a Hot and Humid Climate to Reduce Heat Gain and Energy Consumption. Sustainability. 2021; 13(19):10965. https://doi.org/10.3390/su131910965.

12. Al-Yasiri, Q.; Szabó, M. Effect of encapsulation area on the thermal performance of PCM incorporated concrete bricks: A case study under Iraq summer conditions. *Case Studies in Construction Materials* **2021**, *15*, e00686. doi:10.1016/J.CSCM.2021.E00686.

13. Gupta, M. K.; Rathore, P. K. S.; Kumar, R.; Gupta, N. K. Experimental analysis of clay bricks incorporated with phase change material for enhanced thermal energy storage in buildings. *Journal of Energy Storage* **2023**, *64*, 107248. doi:10.1016/J.EST.2023.107248.

14. Ahmed, S. F.; Khalid, M.; Rashmi, W.; Chan, A.; Shahbaz, K. Recent progress in solar thermal energy storage using nanomaterials. *Renewable and Sustainable Energy Reviews* **2017**, *67*, 450–460. doi:10.1016/J.RSER.2016.09.034.

15. Sari, A.; Biçer, A. Thermal energy storage properties and thermal reliability of some fatty acid esters/building material composites as novel form-stable PCMs. *Solar Energy Materials and Solar Cells* **2012**, *101*, 114–122. doi:10.1016/J.SOLMAT.2012.02.026.

16. Zalba, B.; Marín, J. M.; Cabeza, L. F.; Mehling, H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering* **2003**, *23*(3), 251–283. doi:10.1016/S1359-4311(02)00192-8.

17. Nazir, H.; Batool, M.; Ali, M.; Kannan, A. M. Fatty acids based eutectic phase change system for thermal energy storage applications. *Applied Thermal Engineering* **2018**, *142*, 466–475. doi:10.1016/J.APPLTHERMALENG.2018.07.025.

18. Kahwaji, S.; Johnson, M. B.; Kheirabadi, A. C.; Groulx, D.; White, M. A. Stable, low-cost phase change material for building applications: The eutectic mixture of decanoic acid and tetradecanoic acid. *Applied Energy* **2016**, *168*, 457–464. doi:10.1016/J.APENERGY.2016.01.115.

19. Iten, M.; Liu, S. A work procedure of utilising PCMs as thermal storage systems based on air-TES systems. *Energy Conversion and Management* **2014**, *77*, 608–627. doi:10.1016/J.ENCONMAN.2013.10.012.

20. Mahdaoui, M.; Hamdaoui, S.; Ait Msaad, A.; Kousksou, T.; El Rhafiki, T.; Jamil, A.; et al. Building bricks with phase change material (PCM): Thermal performances. *Construction and Building Materials* **2021**, *269*, 121315. doi:10.1016/J.CONBUILDMAT.2020.121315.

21. Zhang, Y.; Deng, M. Taguchi optimization and a fast evaluation method on the transient thermal performance of phase change material outfitted walls. *Journal of Energy Storage* **2021**, *43*, 103120. doi:10.1016/J.EST.2021.103120.

22. Yang, J.; Lan, H.; Zhu, X. Course Reform of Metal Cutting Machine Tool Design under the Background of Engineering Education Accreditation. *Advances in Social Sciences Research Journal* **2020**, *7*(8), 128–131. doi:10.14738/assrj.78.8812.
23. *https://weatherspark.com/y/107761/Average-Weather-in-Islamabad-Pakistan-Year-Round*.
24. Fan, Z.; Zhao, Y.; Liu, X.; Shi, Y.; Jiang, D. Thermal Properties and Reliabilities of Lauric Acid-Based Binary Eutectic Fatty Acid as a Phase Change Material for Building Energy Conservation. *ACS Omega* **2022**, *7*(18), 16097–16108. doi:10.1021/acsomega.2c01420.
25. Wu, W.; Xia, M.; Huang, J.; Dou, Y.; He, Y.; Guo, C.; et al. Preparation and characterization of binary and ternary composite PCMs with two phase transition temperatures for solar water heating system. *Solar Energy* **2022**, *231*, 1015–1024. doi:10.1016/J.SOLENER.2021.12.045.
26. Huang, X.; Alva, G.; Liu, L.; Fang, G. Preparation, characterization and thermal properties of fatty acid eutectics/bentonite/expanded graphite composites as novel form–stable thermal energy storage materials. *Solar Energy Materials and Solar Cells* **2017**, *166*, 157–166. doi:10.1016/J.SOLMAT.2017.03.026.
27. *https://www.latlong.net/place/islamabad-pakistan-2245.html*. (Last accessed on 19 August 2023)
28. *https://www.engineeringtoolbox.com/conductive-heat-transfer-d_428.html*. (Last accessed on 19 August 2023)
29. *https://www.sfu.ca/~mbahrami/ENSC%20388/Notes/Staedy%20Conduction%20Heat%20Transfer.pdf*. (Last accessed on 19 August 2023)
30. Abdulhussein, M. A., & Hashem, A. L. (2022). An experimental study of the thermal behavior of bricks integrated with PCM-capsules in building walls. Al-Qadisiyah Journal for Engineering Sciences, 14(3).
31. *Bejan, A., & Kraus, A. D. (Eds.). (2003). Heat Transfer Handbook (Vol. 1). John Wiley & Sons.*
32. Smith, D. S.; Alzina, A.; Bourret, J.; Nait-Ali, B.; Pennec, F.; Tessier-Doyen, N.; et al. Thermal conductivity of porous materials. *Journal of Materials Research* **2013**, *28*(17), 2260–2272. doi:10.1557/jmr.2013.179.
33. *https://www.toppr.com/guides/physics-formulas/heat-flux-formula/*.