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Investigating the Potential of Capric Acid as Phase Change Material by Simulating its Consequence on the Thermal Performance of Building with Diverse Wall Materials

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Abstract - *Energy demand in buildings has been observed to rise sharply in recent years. The consumption of energy is mostly for Heating and Air Conditioning of building envelope, for providing a comfortable thermal environment. Capric Acid (CA) is a Phase Change Material (PCM) competent at absorbing and discharging heat energy by altering its physical state. Such PCMs may be incorporated into construction materials to improve the energy performance of the building. This paper evaluates CA's potential as PCM by analyzing the thermal performance of building with different conventional wall materials and CA by employing DesignBuilder simulation software. Test results indicated that CA has the prospects of enhancing the thermal performance of the building. The inclusion of CA in building wall material has improved the thermal comfort hours by a minimum of 6.5%, and a minimum of 15% energy savings can be made in the building. On comparing CA with the existing thermal buffer, viz. Expanded Polystyrene (EPS), CA, was observed to provide longer thermal comfort hours. The performance of CA was more remarkable in wall materials where their natural thermal performance is low. This study emphasizes the importance of incorporating CA as PCM in building wall materials.*

Keywords - *Phase Change Material, Capric Acid, Energy savings, Thermal energy storage, Indoor air temperature, Thermal comfort, DesignBuilder.*

I. INTRODUCTION

Increased energy demand and simultaneous depletion of fossil fuels have created the need for using renewable energy sources for more sustainable development [1][2]. Post pandemic in light, the energy demand worldwide is expected to increase by 4.6% in 2021. Energy-related global CO_2 emission is projected for a 4.8% rise. In India, energy demand is said to increase by almost 7% [3]. Globally, one-third of the electrical energy consumption is used up by the building sector and accountable for 30% of the emission of overall greenhouse gas annually [3][4][5][6]. Most of the energy consumption is for warming and cooling the building envelope to maintain thermal comfort [7][8][9]. In India, the construction division consumes above 30% of the whole electricity consumption leading to the sumptuous discharge of greenhouse gases. India is dedicated to reducing the discharge intensity by 35% from 2005 amount in 2030 as per Nationally Determined Contribution, Paris agreement [10]. The government of India has recommended energy-efficient buildings as one of the metrics for smart cities [11]. Energy building codes focus on buildings that use climatic conditions and natural resources to their advantage [12]. Various researches were done to improve the efficiency of a building in the past decade [13][14].

Phase Change Materials (PCM) are an upcoming solution to improving a building's energy efficiency [15][16][17][18][19]. Thermal energy storage of the PCM provides an opportunity for absorption and dissipation of heat energy. If this process of absorption and dissipation can be modified according to an environmental condition, they may be integrated into building substances to alter the ambient air temperature conveniently [20][21][22][23][24]. PCM's are a grade of materials that absorbs and discharges heat energy by going through alteration in its physical nature from solid to liquid and, inversely, within a specified temperature range. On melting, it absorbs the heat energy, and while freezing, it releases the heat energy [25][26][27][28]. Based on their chemical nature, PCM's are grouped as organic and inorganic PCM [29]. Organic PCM's are more advantageous than inorganic PCM due to their high latent heat storage and less segregation at a time of phase altering[30][31].

The thermal and chemical stability of organic PCM's is proved to be excellent. They are also found to be more compatible with building construction materials [32][33]. Organic fatty acids were preferred for application in buildings than other PCMs because of their better thermal and physical properties [34]. Capric Acid (CA) is an organic fatty acid, sustainable material extracted from vegetable and animal oil [35]. CA has a transition temperature around the thermal comfort range and is non-toxic, making it suitable for enhancing the building's thermal performance [36]. Concrete incorporated with fatty acid PCMs including capric acid was studied by Cellat et al. [37] for thermal and mechanical performance. The results indicated enhanced thermal energy storage performance and compressive strength above the required limit for structural applications.

Studies were carried out on PCM integrated walls for enhancing the thermal properties of a building[38]. Vautherot et al. [39] simulated the energy savings and reduction in discomfort hours for a house in New Zealand to determine optimum PCM and found that the performance improved over 30%. A numerical evaluation directed by Sajjadian et al. [40] to evaluate the PCM influence on detached houses showed favorable results in reducing discomfort hours. Cabeza et al. [41] conducted investigational research on cubicles made of concrete enclosures incorporated with PCM. The result showed reduced inner temperature and enhanced thermal inertia. Shi et al. [42] experimentally examined the consequence of PCM concrete walls on indoor air temperature and humidity level. He discovered that the PCM wall reduced the inner air temperature by 4ºC and humidity by 16%. In all these studies, commercially available PCMs and paraffin were used. Some of the studies conducted using CA include Saikia et al., who optimized the orientation of PCM location in the walls. [43] He analyzed a Concrete-PCM wall, where capric acid was compared with zinc nitrate hexahydrate in terms of orientation and solar irradiance for hot and dry climate conditions. Despite the researches that have been carried out on PCM, its practical use with buildings is a long way down the road. The application of CA as PCM in real-time is significantly less because the full potential of CA on buildings' energy and thermal performance has not been well understood. Local conventional wall material's performance with CA needs to be studied to understand its performance for a particular climatic condition.

In this study, using DesignBuilder simulation software, the potential of CA as PCM in improving a building's performance in terms of thermal and energy efficiency has been studied. The incorporation of CA with different conventional building wall materials was considered and compared. The parameters such as air temperature, thermal comfort, heat gain, and energy savings were analyzed. A comparative analysis has also been carried out, where the CA wall was compared against an Expanded Polystyrene (EPS) incorporated wall. As EPS is the most common material that has been employed for thermal insulation and heat storage, this comparison would shed some light on the viability of CA incorporated walls and their efficiency in real-time applications.

II. METHODOLOGY

A. *Simulation*

DesignBuilder Version 6.1.6.011, which uses EnergyPlus version 8.9, has been employed in this study. It offers a better graphical interface for EnergyPlus [44]. The Bureau of energy efficiency has also approved this software for establishing concurrence with Energy Conservation Building Code (ECBC)[12]. DesignBuilder provides an opportunity to model the buildings with various materials, and it simulates the thermal and energy performance on multiple aspects with more accuracy [45]. Here, the performance of CA as PCM has been studied by using Conduction Finite Difference simulation solution algorithm employing Fully Implicit first-order scheme along with enthalpy(J/kg)-temperature(°C) function for simulating phase change energy [44][46]. For simulation, time steps per hour were set to 30 [47].

For a fully implicit scheme, the heat transfer model [7] is presented in the following equation:

$$\Delta x C\rho \frac{T_m^{n+1} - T_m^n}{\Delta t} = (k_{in} \frac{(T_{m+1}^{n+1} - T_m^{n+1})}{\Delta x}) + (k_{ex} \frac{(T_{m-1}^{n+1} - T_m^{n+1})}{\Delta x})$$

$$k_{in} = \frac{(k_{m+1}^{n+1} + k_m^{n+1})}{2}$$

$$k_{ex} = \frac{(k_{m-1}^{n+1} + k_m^{n+1})}{2}$$

Where, Δx = layer thickness (meter); C = Specific heat capacity (kJ/kg-K); ρ = Density (kg/m^3); Δt = calculation time step (seconds); T = Temperature at particular node (K); m = modeled node; $m+1$ and $m-1$ = adjoining nodes to interior and exterior of construction respectively; $n+1$ and n = new step of time and previous step of time respectively; k = thermal conductivity (kW/m-K).

In each step of time, the specific heat capacity of the CA is upgraded as per the equation below:

$$C_{CA} = \frac{h_m^n - h_m^{n+1}}{T_m^n - T_m^{n-1}}$$

$$h = h(T)$$

Where h = user-defined enthalpy (kJ/kg) of the CA varying according to the temperature.

This simulation study is carried out for Chennai city, Tamil Nadu, India. This city is characterized by its warm and humid climate [48]. The description of Chennai city is given in Table I. Indian Society for Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) temperature file for Chennai city available in Energy plus website was taken for analysis.

TABLE I. DESCRIPTION OF CHENNAI CITY

City	Chennai
Country	India
Latitude	13.00º
Longitude	80.18º
Elevation above sea level	16.0m
ASHRAE climate zone	1B
Weather file source	ISHRAE
Koppen-Geiger climateclassification	Aw

B. Building Model

In this study, a building model with a single room of size $4m * 4m$ and a height of 3.5 m complying with the National Building Code of India, was considered for simulation [49]. The Building model and skeleton are displayed in Fig. 1a and Fig. 1b, respectively. A doorway of size $2.1m * 1m * 0.025m$ was positioned, facing the south side. Two windows of height 1.5m were placed on the north and east sides at the sill height of 1 m. The window to wall ratio was taken as 20%.

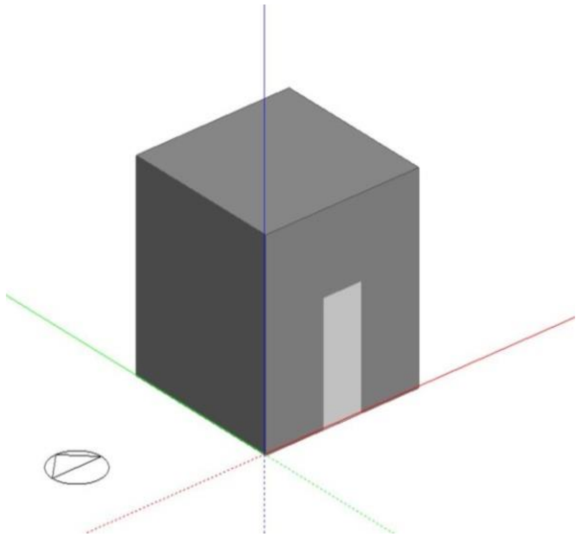

Fig. 1a Building model

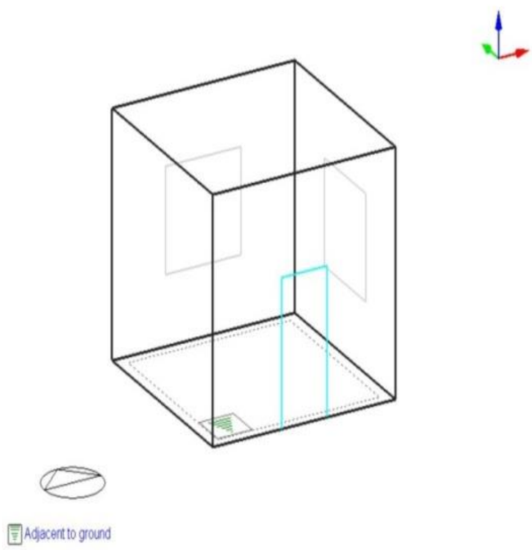

Fig. 1b Building Skeleton

The roof was made up of 150 mm thick Reinforced Cement Concrete (RCC) covered by 12.5 mm cement plastering on both sides, as shown in Fig. 2a [50]. The floor was comprised of 150mm dense concrete with 12.5mm cement plastering on the innermost layer, as shown in Fig. 2b [48]. Based on each layer's material property and thickness, the heat transfer coefficient for roof and floor is 3.708 W/m^{2}K and 2.535 W/m^{2}K, respectively, as calculated by the software.

Fig. 2a Cross-section of roof

Fig. 2b Cross-section of floor

Different cases of wall composition studied are explained below. Materials considered for ceiling and floor are identical for all the cases studied.

C. Cases studied

The foremost intent of this simulation is to evaluate the thermal performance of building with CA incorporated into building materials. To achieve this, CA was combined with common building wall materials in India, and their efficiencies were compared. Reinforced Cement Concrete wall (RCC Wall), Brick Masonry wall (BM Wall), and Limestone Masonry wall (LSM Wall) [43][51][52] were the building materials analyzed in this work. In each wall material, simulations were carried out with and without the CA layer. Hence, six cases were studied as follows RCC Wall, RCC-CA Wall, BM Wall, BM-CA Wall, LSM Wall, and LSM-CA Wall.

In each case, the inner and outermost layer was covered by cement plaster of 12.5 mm thickness. The Middle region was composed of different wall materials of 200 mm thickness, and a CA of 10 mm thickness was added on either side of the middle part, as displayed in Fig. 3.

Fig. 3 Cross sections of wall

The thermal and physical properties of wall particulars considered were defined in the software as per the standards [53] provided in Table II.

TABLE II. THERMAL AND PHYSICAL ATTRIBUTES OF WALL SUBSTANCES

Particulars	ρ (kg/m^3)	Thermal Transfer Ability (W/m-K)	Specific Thermal Capacity (J/kg-K)
RCC	2288	1.580	880
Burnt Brick	1820	0.811	880
Limestone	2420	1.800	840
Cement plaster	1760	0.720	840

The heat transfer coefficient (U) for each case, as computed by the DesignBuilder tool, is deliberated in Table III.

TABLE III. HEAT CONDUCT COEFFICIENT FOR CASES STUDIED

Case	Heat Transfer Coefficient (W/m^{2}K)
RCC Wall	3.018
RCC-CA Wall	2.443
BM Wall	2.216
BM-CA Wall	1.889
LSM Wall	3.166
LSM-CA Wall	2.539

D. Properties of the Capric Acid

Capric Acid (CA) is categorized as an organic fatty acid. Phase transition of CA occurs around the thermal comfort range of human beings. CA has a sublime latent thermal storage capacity, acceptable thermal transfer capacity, non-corrosive, non-toxicity, and economical. The heat and chemical firmness of CA is high [54][55]. Characteristics of CA employed in this simulation are enumerated in Table IV[56][57][43]. The user-defined enthalpy (J/kg) vs.

temperature (°C) curve [56] for simulating the phase change behavior of CA is indicated in Fig. 4. The following properties of CA were defined in design builder software, and simulations were carried out.

TABLE IV. PROPERTIES OF CAPRIC ACID

Onset melting temperature (°C)	29.19
Peak liquefying temperature (°C)	31.82
Latent thermal capability (J/g)	162.86
Thermal transferability (W/m-K)	0.2565
Specific thermal capacity (J/kg-K)	2279.50
ρ (kg/m^3)	870.10

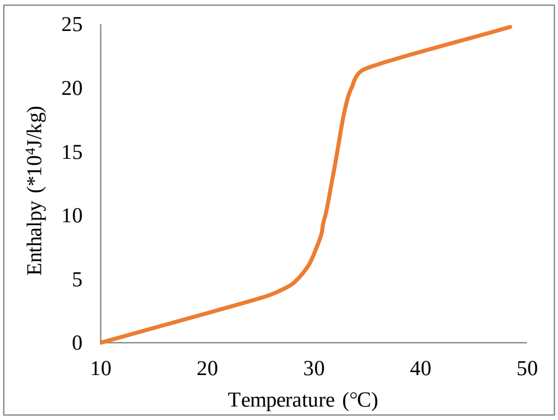

Fig. 4 Enthalpy – Temperature curve of Capric Acid

E. Thermal Performance

To assess the consequence of CA on the building's thermal behavior in each case, Heating and Air Conditioning (HAC) were kept off, and a natural infiltration rate of 4ac/h was set as per standard [53]. The indoor air temperature was studied for the selected day of peak summer months for all wall cases. Lowering in temperature peak and fluctuation in temperature was analyzed. A decrease in temperature variation due to CA is measured by Temperature Fluctuation Reduction Percentage (TFRP), as shown in Formula (1).

$$TFRP = \frac{DT - DT_{CA}}{DT} \times 100\ \% \qquad (1)$$

Where DT = Deviation between higher and lower temperature without CA;

DT_{CA} = Deviation between higher and lower temperature with CA.

In India, the thermal comfort range for humans is 25°C to 30°C, as suggested by the National Building Code of India [58]. ISHRAE [59] has proposed that an ambient temperature of 24°C - 30°C with a relative humidity of 40% to 70% would minimize virus transmission and provide thermal comfort. The increase or decrease in thermal comfort hours was analyzed throughout the year for each case. Annual gain of heat in the structure was simulated, and the percentage decrease in the gain of heat defines the effect of the addition of CA. Based on Fanger's model [60], the Predicted Mean Vote (PMV) scale of -0.5 - +0.5 and Predicted Percentage of Dissatisfied (PPD) not above 10% is recommended for thermal comfort by standards [61][62]. The deviation of PMV and PPD from the recommended range was analyzed for all the cases.

F. Energy Performance

The energy performance potential of CA was examined by switching HAC to ON condition. As suggested by ISHRAE COVID-19 guidelines, with the temperature buffer of 1ºC, the heating and cooling setpoints were defined as 25ºC and 29ºC, respectively, for energy analysis. Annual electricity consumed to sustain the internal temperature in the range of comfort was simulated for each case. The percentage of energy saved due to the inclusion of CA was determined and examined as indicated in Formula (2). Based on the data provided in reference [69], the amount of CO_2 emitted throughout a year due to energy consumption and the reduction of CO_2 emission due to saved energy was evaluated.

$$ES\ (\%) = \frac{AEC - AEC_{CA}}{AEC} \times 100\ \% \qquad (2)$$

Where ES = Percentage of Energy Saved;

AEC = Annual Electricity Consumed without CA;

AEC_{CA} = Annual Electricity Consumed with CA

G. Comparison with Expanded Polystyrene (EPS) incorporated wall

In India, EPS is the frequently utilized material for enhancing the thermal behavior of any structure[63]. EPS is sandwiched in the wall material due to its low thermal conductivity and improved thermal mass [64][65]. Hence the comparative study was made between EPS incorporated wall and CA incorporated wall for all the wall materials. The cases considered are RCC-EPS Wall, BM-EPS Wall, and LSM-EPS Wall, as shown in Fig. 5. The total amount of hours, a effective building temperature is in the range of 24°C to 30°C were compared and analyzed.

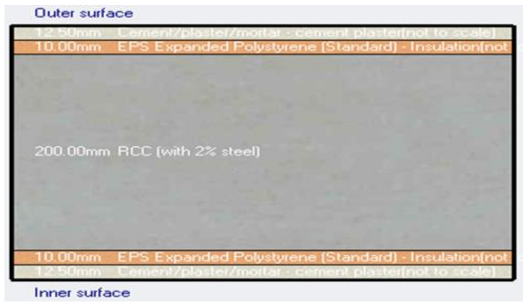

Fig. 5a RCC – EPS Wall

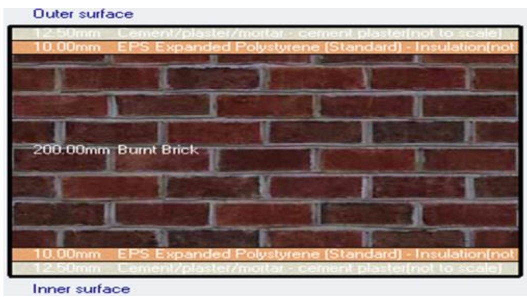

Fig. 5b BM – EPS Wall

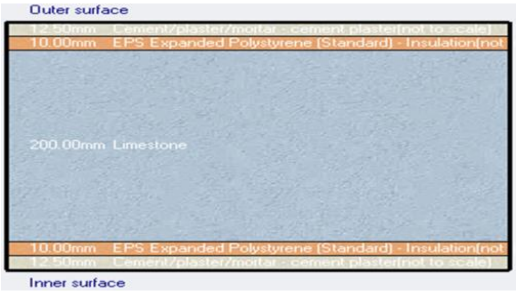

Fig. 5c LSM – EPS Walls

Fig. 5 Cross sections of EPS Walls

H. Validation

Tabares-velasco et al. 2012 [66] substantiated the EnergyPlus algorithm for PCM by analytical and empirical means. Hence, the directives given by reference [66] are followed for carrying out simulations in this study. Various researchers also validated the DesignBuilder - EnergyPlus model with experimental data [67][68][69]. In this study, the prototype was substantiated by relating the simulated outcome with the investigational results presented in the reference [50]. Hence, a similar building was modeled, and its thermo-physical properties were taken from reference [50]. As outlined in Fig. 6, the simulated and investigational outcomes had minor discrepancies. Results indicated that the average percentage deviation was less than 4%. Hence, the DesignBuilder – EnergyPlus model developed may be employed for simulating the thermal performances of the structure.

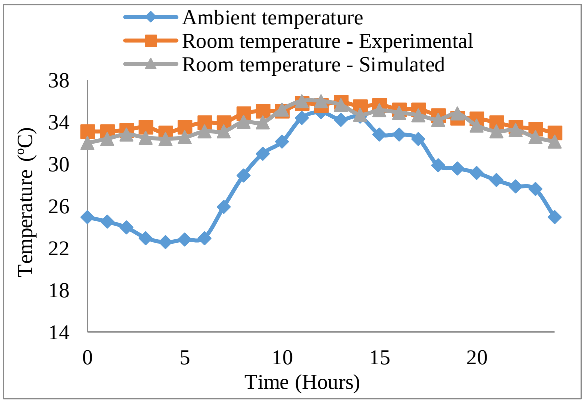

Fig. 6 Simulation result and Experimental data validation

III. RESULTS AND DISCUSSION

A. Thermal performance

a) Indoor air temperature

The indoor air temperature profile was outlined for a peak summer day, as shown in Fig. 7. For RCC, BM, and LSM, the temperature reached a maximum value of 35.38ºC, 35.01ºC, and 35.48ºC, respectively; in the meantime, the maximum temperature for RCC-CA, BM-CA, and LSM-CA are 34.74ºC, 34.50ºC, and 34.80ºC respectively. This decrease in the indoor air temperature clearly indicates that CA's high latent heat storage capacity [37] helps reduce the peak temperature. CA starts to store the heat energy when the outside atmospheric temperature rises beyond its liquefying point. Furthermore, the BM wall showed a lower peak due to its low heat transfer coefficient compared to the RCC wall and LSM wall.

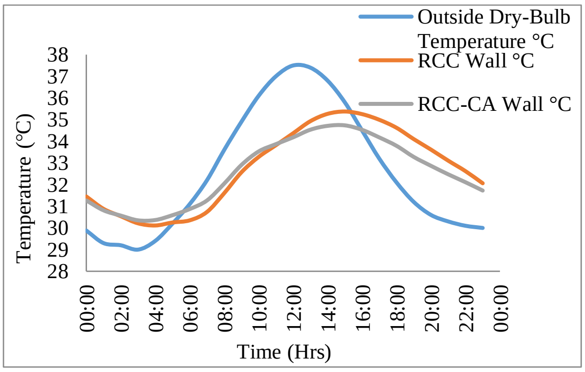

Fig. 7a Indoor air temperature for RCC wall case

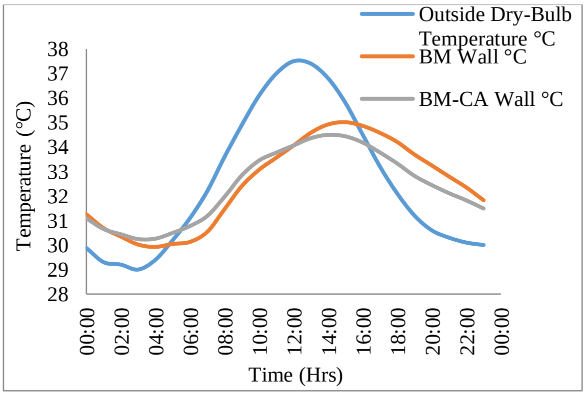

Fig. 7b Indoor air temperature for BM Wall case

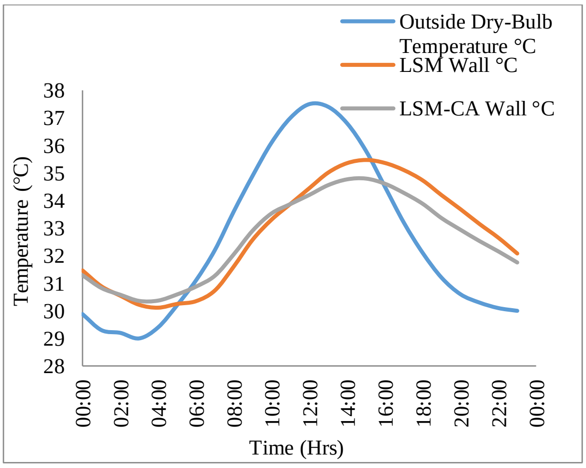

Fig. 7c Indoor air temperature for LSM Wall case

Even though the reduction in peak temperature was low, the efficiency of CA can be well understood by Temperature Fluctuation Reduction Percentage (TFRP) as provided in TableV. The TFRP in RCC, BM, and LSM cases due to the addition of CA is 16.70%, 16.30%, and 17.10%, respectively, for summer peak days. Here, the LSM wall showed more temperature fluctuation of 5.37ºC, but the addition of CA indicated higher TFRP for this case. These results vividly demonstrate that the efficiency of CA increases with the increase in temperature fluctuation. Heat storing and releasing the potential of CA [70][71] helps reduce the maximum and minimum peak variation by the charging and discharging process. To conclude, the addition of CA reduced the peak temperature and also improved the TFRP.

TABLE V. INDOOR AIR TEMPERATURE AND TFRP FOR ALL CASES

Cases	Peak Summer Day		
	Max Temp (°C)	Min Temp (°C)	TFRP (%)
RCC Wall	35.38	30.11	-
RCC-CA Wall	34.74	30.35	16.7
BM Wall	35.01	29.92	-
BM-CA Wall	34.50	30.24	16.3
LSM Wall	35.48	30.11	-
LSM-CA Wall	34.80	30.35	17.1

b) Thermal comfort

ISHRAE [59] recommended the temperature range of 24°C to 30°C for maintaining thermal comfort and restricting problems caused by pathogens. Fig. 8 shows the total amount of time when the effective temperature of the building was within the mentioned comfort range annually for all the cases. The obtained results show that the amount of time in the comfort range for RCC, BM, and LSM cases are 6278.5hrs, 6485.6 hrs, and 6220.3hrs, respectively. Simultaneously the addition of CA increased the number of hours by 485.2hrs, 426.2hrs, and 512.5hrs for RCC-CA, BM-CA, and LSM-CA cases, respectively. As the transition temperature of CA is around the thermal comfort range, it helps reduce the temperature fluctuation, thereby increasing the number of hours in the comfort range.

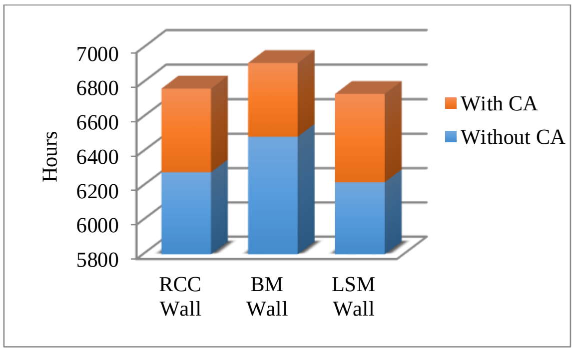

Fig. 8 Annual thermal comfort hours

The percentage increase in the number of comfort hours due to the addition of CA is provided in Table VI. The results show that BM wall building has more comfort hours mainly owing to its poor thermal transfer capability. The performance of CA was better in the other two cases, i.e., the RCC wall and LSM wall. Recently RCC walls were used to construct buildings [72] due to their improved structural performance but have poor thermal performance. This RCC-CA wall will meet structural requirements and provide better thermal performance similar to the BM wall.

TABLE VI. ANNUAL THERMAL COMFORT HOURS

Cases	Percentage of Hours in Comfort Range Annually (%)	Percentage Increase in Comfort Hours Due to Addition of CA (%)
RCC Wall	71.67	-
RCC-CA Wall	77.21	7.73
BM Wall	74.04	-
BM-CA Wall	78.90	6.57
LSM Wall	71.01	-
LSM-CA Wall	76.86	8.24

c) Heat gain

Yearly gain of heat across structure walls was considered and analyzed as shown in Fig. 9. Annual gain of heat in the structure through the RCC wall, BM wall, and LSM wall are 2839.28kWh, 2353.42kWh, and 2915.11kWh, respectively. Table VIIshows the effect of CA addition on the heat gain of the building. Results indicate that CA influences reducing the heat gain in the structure; this is mainly due to its high specific heat capacity that is nearly three times the conventional building materials. The capability of the CA to store latent heat energy aids in reducing the heat gain in the building. Heat gain reduction percentages for RCC-CA, BM-CA, and LSM-CA cases are 9.66%, 6.60%, and 10.10%, respectively. This result expresses that the thermal behavior of building wall material is in the descending order of BM, RCC, and LSM cases. However, the efficiency of CA was in the ascending order of BM, RCC, and LSM cases.

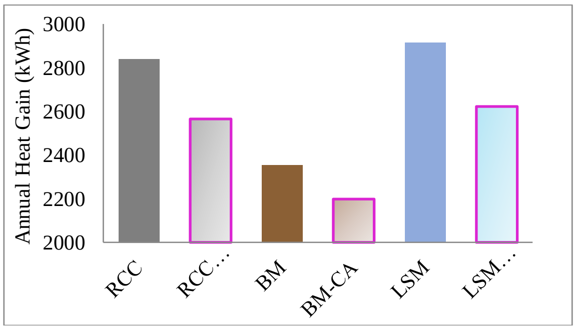

Fig. 9 Annual heat gain through building walls

TABLE VIIEFFECT OF CA ON HEAT GAIN OF THE BUILDING

Cases	Annual Heat Gain (kWh)	Percentage Reduction in Heat Gain(%)
RCC Wall	2839.28	-
RCC-CA Wall	2565.08	9.66
BM Wall	2353.42	-
BM-CA Wall	2198.16	6.60
LSM Wall	2915.11	-
LSM-CA Wall	2622.15	10.10

d) Fanger's thermal comfort

The thermal comfort of building suggested by standards [61][62] based on Fanger's model is in the range of -0.5 to +0.5 for PMV and not above 10% for PPD. This range is recommended for occupant's comfort and satisfaction in the building. As displayed in Table VIII, the deviation of PMV and PPD value from the recommended range for the RCC, BM and LSM cases are +0.361, +0.246, +0.379 and +24.02%, +21.17%, +24.60% respectively. PMV and PPD values indicate the huge amount of energy load is required to bring the values within the recommended range. After the addition of CA, the deviation is reduced to PMV of +0.284, +0.198, +0.297, and PPD of +20.06%, +17.80%, +20.46% for RCC-CA, BM-CA, and LSM-CA cases, respectively. One of the main factors influencing this fanger's model is air temperature [73]. As discussed in earlier topics, the addition of CA will diminish the interior crest air temperature and temperature variation; thereby, it will reduce the PMV and PPD deviation and move the value towards the recommended range and reduce the energy load.

TABLE VIII DEVIATIONSOF PMV AND PPD VALUES

Cases	PMV Range (-0.5 to +0.5)			PPD Range (<10%)		
	PMV Value	Deviation from the Recommended Range	Percentage Reduction in Deviation (%)	PPD Value (%)	Deviation from the Recommended Range (%)	Percentage Reduction in Deviation (%)
RCC Wall	+0.861	+0.361	-	34.02	+24.02	-
RCC-CA Wall	+0.784	+0.284	21.3	30.06	+20.06	16.5
BM Wall	+0.746	+0.246	-	31.17	+21.17	-
BM-CA Wall	+0.698	+0.198	19.5	27.80	+17.80	15.9
LSM Wall	+0.879	+0.379	-	34.60	+24.60	-
LSM-CA Wall	+0.797	+0.297	21.6	30.46	+20.46	16.8

B. Energy performance

As mentioned earlier, the HAC setpoints are 25ºC and 29ºC to maintain comfort in the building as per recommendations [59]. In this section, the potential of CA in saving energy was studied. Fig. 10 displays the annual electricity consumption of all the six cases studied. It indicates that the annual electricity consumption for RCC wall, BM wall, and LSM wall cases is 2171.28kWh, 1929.55kWh, and 2226.29kWh. This is due to more temperature fluctuation; the HAC system requires more fuel consumption to bring the indoor temperature within the required limit. In the cases of the RCC-CA wall, BM-CA wall, and LSM-CA wall, the annual electricity consumption reduced to 1807.12kWh, 1656.10kWh, and 1836.48kWh, respectively. This resulted in an energy-saving percentage of 16.77%, 14.17%, and 17.51% for RCC, BM, and LSM cases, respectively, due to the addition of CA as indicated in Table IX. Observed result conveys that addition of CA has a positively influential result in energy savings. This is primarily because of its potential to reduce the peak maximum and peak minimum temperature. This, in turn, flattens the temperature fluctuation, thereby increasing the number of comfort hours on its own. Hence, the energy load required to maintain the temperature range gets reduced.

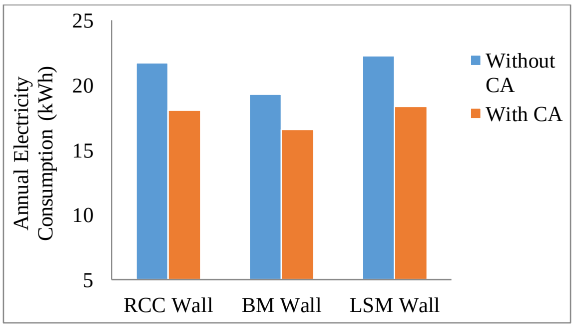

Fig. 10Yearly energy consumed for HAC

CO_2 emission intensity for the fuel consumed for producing electricity is around 700gCO_2/kWh as provided by [74]. Table X presents the CO_2 emission analysis for the cases studied. The annual CO_2 emission for RCC wall, BM wall, and LSM wall cases is 1519.10kg, 1350.69kg, and 1558.40kg. On inclusion of CA, the reduction in CO_2 emission of 254.92kg/yr, 191.42kg/yr, and 272.86kg/yr was observed for RCC, BM, and LSM wall cases, respectively. An increase in energy savings directly resulted in reduced CO_2 emissions in CA cases. This analysis is carried out for a small cubicle room model. The reduction in CO_2 emission will be much higher in large-scale structures. Overall, the incorporation of CA results in saving energy and reducing the emission of CO_2, thereby making the building eco-friendly and sustainable.

TABLE IX ANNUAL ELECTRICITY CONSUMPTION AND ENERGY-SAVING PERCENTAGE

Cases	Annual Electricity Consumption (kWh)			Energy Saving (%)
	Heating (kWh)	Cooling (kWh)	Total (kWh)	
RCC Wall	357.02	1814.26	2171.28	-
RCC-CA Wall	324.30	1482.82	1807.12	16.77
BM Wall	384.43	1545.12	1929.55	-
BM-CA Wall	346.75	1309.35	1656.10	14.17
LSM Wall	357.62	1868.67	2226.29	-
LSM-CA Wall	323.34	1513.14	1836.48	17.51

TABLE XCO_2EMISSION ANALYSIS

Cases	Yearly Electricity Utilization (kWh)	Yearly CO_2Disch arge (kg)	Reduction in CO_2 Emission (kg/yr)
RCC Wall	2171.28	1519.90	-
RCC-CA	1807.12	1264.98	254.92

Wall			
BM Wall	1929.55	1350.69	-
BM-CA Wall	1656.10	1159.27	191.42
LSM Wall	2226.29	1558.40	-
LSM-CA Wall	1836.48	1285.54	272.86

C. Comparison with Expanded Polystyrene (EPS) incorporated wall

EPS is utilized for improving the thermal behavior of the structure in most cases due to its enhanced thermal insulation property and higher specific heat capacity [53] than conventional building materials. In this section, EPS incorporated wall is compared with CA incorporated wall in terms of its ability to provide thermal comfort for all the wall materials. Fig. 11dictates the percentage of hours in the comfort range (24ºC to 30ºC) annually for all the cases. It indicates that the percentage of comfort hours is more in the cases of CA incorporated walls.

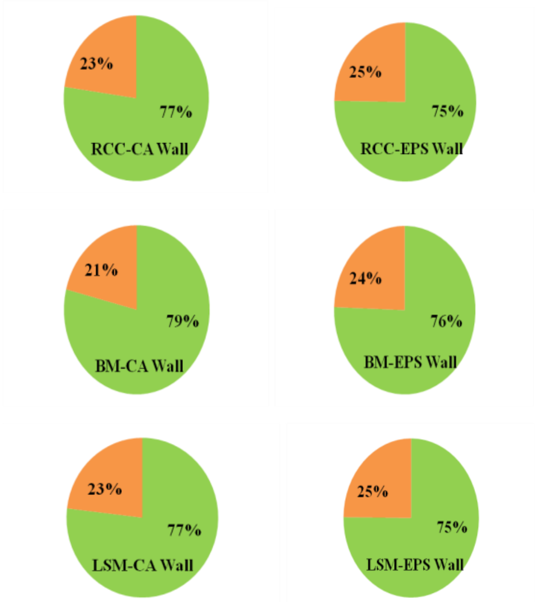

Fig. 11 Annual thermal comfort performances of CA and EPS cases (Percentage of Discomfort hours and Comfort hours)

The total numbers of hours in comfort range annually for RCC-EPS, BM-EPS, and LSM-EPS cases are 6590.8hrs, 6620.3hrs, and 6583.8hrs, respectively. But in RCC-CA, BM-CA, and LSM-CA, the number of comfort hours increased to 6763.7hrs, 6911.8hrs, and 6732.8hrs, respectively. As shown in Table XI, the percentage increase in comfort hours is higher in CA incorporated wall than EPS incorporated wall. Performance of CA in RCC, BM, and LSM wall cases are 1.6X, 3.2X, and 1.4X the EPS performances, respectively. The specific heat capacity of CA is twice that of EPS, which resulted in improved performance. CA has a peculiar property of storing and releasing heat energy by melting and freezing physically. Whereas in the case of EPS, heat storage capacity is low and it only insulates the heat flow. Hence the incorporation of CA improves the thermal behavior of the structure significantly and enhances the thermal comfort of the structure.

TABLE XIPERFORMANCESOF CA AND EPS IN TERMS OF THERMAL COMFORT

Cases	Annual Comfort Hours (Hrs)	Cases (CA and EPS)	Annual Comfort Hours (Hrs)	% Increase in Comfort Hours
RCC	6278.5	RCC-CA	6763.7	7.73
		RCC-EPS	6590.8	4.97
BM	6485.6	BM-CA	6911.8	6.57
		BM-EPS	6620.3	2.08
LSM	6220.3	LSM-CA	6732.8	8.24
		LSM-EPS	6583.8	5.84

III. CONCLUSIONS

Simulations were carried out for test model with six cases of building wall materials (RCC, RCC-CA, BM, BM-CA, LSM, and LSM-CA), and the following conclusions were made:

- The addition of CA has reduced the indoor peak temperature and temperature fluctuation for all building wall materials. It indicated high TFRP for the LSM wall and low TFRP for the BM wall. It is suggesting that the transition temperature of CA suits the LSM wall than the BM wall. However, CA showed good performances in all the cases.
- Thermal comfort hours increased considerably on the incorporation of CA, recording a percentage increase of 8.24%, 7.73%, and 6.57% for LSM, RCC, and BM cases. The influence of CA on reducing the heat gain and improving the building's comfort level was significant. The heat-storing capacity of CA played a vital role in enhancing its thermal performance.
- Solidification and melting temperature of CA close to heating and cooling setpoint led to a more significant reduction of fuel consumption. They observed an energy-saving increment of 17.51%, 16.77%, and 14.17% for LSM, RCC, and BM cases, respectively. Hence, CA incorporation has improved the energy efficiency of the building.
- Compared with EPS, CA showed better performance and was best suited for the warm and humid climate condition of Chennai.

Generally, the thermal and energy behavior of the BM-CA envelope is superior compared to other cases. But the effectiveness of CA is higher for low-performing materials like RCC and LSM compared to BM. To conclude, it is most certain that the addition of CA has resulted in enhanced thermal and energy behavior of the structure in all the cases. Future studies can be carried out to further maximize its efficiencies by optimizing the position and orientation of CA in the building wall panels.

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