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It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

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I, *"PUSHPENDRA KUMAR SINGH RATHORE"*, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of *"Prof. Shailendra Kumar Shukla" and "Dr. Jeevan Vachan Tirkey"* from *"January 2019"* to "March 2021", at the *"Department of Mechanical Engineering"*, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, theses, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

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It is certified that the above statement made by the student is correct to the best of my/our knowledge.

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Nomenclature

APD	Ambient pressure drying
CA	Capric acid
CNF	Carbon nano fibre
CNT	Carbon nanotube
CPCM	Composite phase change material
DMF	dimethylformamide
DSC	Differential scanning calorimetry
EG	Expanded graphite
EP	Expanded perlite
EV	Expanded vermiculite
FAEM	fatty acid eutectic mixture
GO	Graphene oxide
H	Latent heat (kJ/kg)
HCE-SSPCM	heat conduction-enhanced shape-stabilized PCM
HDPE	High density polyethylene
HVAC	Heating, Ventilation and Air-Conditioning
LA	Lauric acid
LJ	Diatomite from Linjiang, China
MCM-41	Mesoporous silica
MDI	Methylene diphenyl diisocyanate
mPCM	Microencapsulated PCM
MPCM	Macroencapsulated PCM
MWCNT	Multi walled carbon nanotube
PA	Palmitic acid

PCM	Phase Change Material
PEG	Polyethylene glycol
PU	Polyurethane
PUF	Polyurethane foam
RC	Red clay
SA	Stearic acid
SEM	Scanning electron microscopy
SEP	Sepiolite
ss-CPCM	Shape stabilized composite phase change material
SWCNT	Single walled carbon nanotube
TES	Thermal Energy Storage
TGA	Thermogravimetric analysis
T_m	Melting temperature (°C)
$T_{max,e}$	Maximum temperature of experimental cubicle
$T_{max,r}$	Maximum temperature of reference cubicle
$T_{min,e}$	Minimum temperature of experimental cubicle
$T_{min,r}$	Minimum temperature of reference cubicle
WP	Wood powder
wt%	Weight percentage
xGNP	Exfoliated graphite nanoplatelets
α	Percentage reduction in thermal amplitude
λ	Thermal conductivity (W/mK)
ρ	Density (kg/m^3)
Φ	Time lag

<u>PREFACE</u>

Economic development, improvement in living standards and globalization lead to raise the demand for energy. Consequently, to meet the increasing demand, fossil based energy reserves are over exploited causing global warming. Buildings (commercial and residential) have played a major role in further deepening the crisis of global warming. More than one third of the final energy consumption comes from building sector. The shift in global fuel use in buildings is partially due to changing end-use consumption, with space cooling and electrical appliance energy growth leading electricity demand growth in buildings. Space cooling and appliances and other plug loads are the fastest-growing building end uses; however, only space cooling has grown in energy intensity per unit floor area. The demand for space cooling become more intensive in countries having hot and humid climate or/and the countries lying in equatorial/tropical environment like India. Enhancing building energy efficiency through latent heat storage of the Phase Change Material will play a vital role in improving indoor thermal behavior of the building envelope. Consequently, it will improve the indoor thermal comfort, reduces the energy use for space cooling, and promotes the use of renewable sources of energy. PCM can be incorporated in the building envelope in many ways. One of the simplest and effective method of integrating PCM directly in building material is Macroencapsulation. This method not only improves the indoor thermal behaviour of the buildings, but also reduces the cooling load without or little compromising with the mechanical strength of the building structure.

Following research gaps were identified in studies conducted so far, for improving the indoor thermal behaviour of the building by integrating the PCM in the building element (a) the effects of integrating Macroencapsulated PCM in the building envelope of the tropical environment like India have not been reported yet (b) **Yearly/monthly or seasonal** effect of embedding PCM in the building envelope on the indoor thermal behavior need to be addressed (c) It is required to identify the impact on cooling load in **heavyweight constructed buildings** due to incorporation of Macroencapsulated PCM in building envelope (d) It is needed to evaluate the thermal energy storage performance of a **low cost commercially available PCM** to be embedded in the building envelope.

Based on these research gaps, the aim of this study was framed. The main aim of this study is to evaluate the indoor thermal behavior of the building envelope outfitted with Phase Change Material in the real outdoor tropical environment of India. Also, this study examines various thermal energy storage parameters of the PCM to assure the best possible performance when embedded in the building envelope.

To achieve the above mentioned aim, an experimental setup of two similar building structures (called as cubicles), one is with macroencapsulated PCM and the other is without macroencapsulated PCM, was developed. Based on the short duration and long duration field testing a comparative study was prepared, to evaluate the effect of embedding PCM in the building envelope on the indoor thermal behavior of the building in the tropical climate of India. Additionally, the commercially available low cost PCM used in the experiment was thermally characterized to analyze the thermal energy storage parameters like thermal conductivity, latent heat storage parameters, thermal stability, thermal reliability, heating and cooling behavior, and leak proof performance.

The thesis comprises of five chapters: Chapter 1- Introduction and background, Chapter-2 Literature review, Chapter 3- Method and materials, Chapter 4- Result and discussion, and Chapter 5- Conclusion and recommendation for future work. Chapter 1 focuses on the need and concepts of thermal energy storage in buildings. A detailed discussion on the thermo-physical properties of PCM, methods of integrating the PCM in the building envelope, and principal of operation of PCM, when integrated in the building envelope was also done. In chapter 2, a detailed and robust literature review on indirect methods of integration of the PCM in the building envelope was conducted. Based on this literature review, a suitable method of integrating the PCM in the building was identified for experimentation work. Chapter 3 presents the methodology opted to conduct the experiments. This chapter also elaborates about the material used and experimental set up in detail. Chapter 4 presents the results of all the experiments and discusses about the parameters which affects the indoor thermal comfort of the building. Chapter 5 presents the concluding remarks and recommendation for future work.

The scope of this study is to develop energy efficient building envelope by integrating the PCM with the building element. This study will be beneficial in improving the indoor thermal behavior of the building by using thermal energy storage technique through Phase Change Material. The improvement in the indoor thermal comfort will reduce the usage of electrical appliances and consequently results in energy savings.