Contificat	Table of Contents	::
Declaratio		
Declaratio	on by the candidate	111
Copyright	t transfer certificate	iv
Acknowle	dgement	v
Preface		xix
СНАРТЕ	R:1 INTRODUCTION	1-18
1.1 Back	rground	1
1.2 Ther	mal energy storage in buildings	5
1.2.1	Sensible thermal energy storage	6
1.2.2	Latent thermal energy storage	8
1.2.3	Thermochemical energy storage	9
1.3 Phas	e Change material	10
1.3.1	Types of PCM	10
1.3.2	Thermo-physical properties of PCM	11
1.4 Tech	iniques of incorporation of PCM in buildings	15
1.5 Oper	cating principle of PCM in buildings	17
СНАРТЕ	R:2 LITERATURE REVIEW	19-104
2.1 Mici	coencapsulation	19
2.1.1	mPCM integrated in building material	25
2.2 Mac	roencapsulation	37
2.2.1	MPCM embedded directly in the construction material	41
2.2.2	MPCM incorporated in air handling unit	50
2.2.3	Performance enhancement of MPCM	55
2.2.4	Compatibility with shell/container material	61
2.3 Shap	be stabilized PCM	64
2.3.1	Porous material used for improvement of thermo-physical properties	65
2.3.2	Porous carbon	66
2.3.3	Graphite schaffolds	69

2.3.4	Polyurethane foam	72	
2.3.5	Silica scaffolds	75	
2.3.6	Clays	78	
2.3.7	Nanoparticles	82	
2.3.8	Application of shape stabilized PCM in buildings	87	
CHAPTE	R:3 MATERIAL AND METHODS	105-119	
3.1 Meth	nodology	105	
3.2 Mate	erial for field testing	108	
3.3 Expe	erimental setup	112	
3.4 Mate	erial and equipment for evaluating thermal energy storage performance	116	
3.4.1	Materials	116	
3.4.2	Preparation of PCM/EV/EG ss-CPCM	117	
CHAPTE	R:4 RESULT AND DISCUSSION	120-161	
4.1 Shor	t duration field testing (One day analysis)	120	
4.1.1	Indoor temperature profile	120	
4.1.2	Heat flux and cooling load reduction	127	
4.1.3	Thermal analysis using infrared thermography	131	
4.2 Long duration field testing (Yearly/Seasonal analysis		134	
4.2.1	Annual indoor temperature profile	134	
4.2.2	Annual average cost saving in peak heat flu	146	
4.3 Ther	mal energy storage performance analysis	149	
4.3.1	Thermal energy storage	149	
4.3.2	Thermal stability analysis	153	
4.3.3	Transient thermal response	156	
4.3.4	Thermal conductivity	158	
4.3.5	Leakage proof performance of the ss-CPCM	160	
CHAPTE	R:5 CONCLUSION AND SCOPE FOR FUTURE WORK	162-167	
5.1 Conc	cluding remarks	162	
5.2 Reco	ommendation for future work	166	
References	References168		
List of pub	lications	205	

LIST OF FIGURES

Figure no.	Caption Pag	e no.
Figure 1.1	Final energy consumption by sector	2
Figure 1.2	Primary energy uses in US residential and commercial buildings in 2010) 3
Figure 1.3	Share of end-uses (by appliances) in electricity consumption in Delhi	3
Figure 1.4	Three steps of thermal energy storage	5
Figure 1.5	Thermal energy storage methods in Buildings	6
Figure 1.6	Classification and properties of PCM	10
Figure 1.7	Incorporation methods of PCM in building envelope	15
Figure 1.8	Operating principle scheme of the PCM	18
Figure 2.1	Microencapsulation of paraffin as core material having polymer shell	19
Figure 2.2	Energy gain and loss using mPCM	20
Figure 2.3	Methods of preparation of mPCM	21
Figure 2.4	(a) Textile reinforced concrete panel with MPCM (b) Real weather testing	25
Figure 2.5	Developed cubicles using MPCM for analysis	26
Figure 2.6	(a) Schematic of lightweight PCM wall (b) Full-size test room at Fraunhofer ISE	27
Figure 2.7	Full size test room with and without MPCM on left and schematic of test room on the right	28
Figure 2.8	Compressive strength of prepared mortar-PCM samples	29
Figure 2.9	Developed reference test cell and composite PCM test cell	30
Figure 2.10	(a) Developed test buildings under outdoor environment condition(b) Fabricated composite panel	31
Figure 2.11	Sectional view (Left) of composite timber and experimental setup	33

outside view (Right)

Figure 2.12	Perforated MPCM plasterboard with holes	33
Figure 2.13	Gypsum powder, MPCM and prepared gypsum-MPCM panel	34
Figure 2.14	(a) New combination of hybrid PCM gypsum wallboard (b) Dimension of gypsum wallboard	35
Figure 2.15	Commonly used container shape for macroencapsulation	38
Figure 2.16	commonly used MPCM in buildings	39
Figure 2.17	Hollow bricks with MPCM	41
Figure 2.18	Bricks with PCM macrocapsules	42
Figure 2.19	Inside view of composite PCM room and ordinary room	42
Figure 2.20	(a) Encapsulation used for PCM(b) Test room and perforated brick(b) Test room and perforated brick	44
Figure 2.21	(a) Outdoor and indoor temperature in free cooling(b) Outdoor and indoor temperature during open window and door at night(c) Outdoor and indoor temperature during forced ventilation at night	45 nt
Figure 2.22	(a) Location of macroPCM wall tile (b) Physical model of macroPCM wall tile (Not to scale)	45
Figure 2.23	(a) PCM packed in aluminum foil sheet (b) Test houses developed for Study	46
Figure 2.24	Wall assembly used for experimentation in the dynamic wall simulator	48
Figure 2.25	(a) Experimental setup of the developed test rooms with PCM in 48 aluminium containers (b) Encapsulated PCM in aluminium containers	8-49
Figure 2.26	Test room with PCM encapsulation	50
Figure 2.27	Schematic of the concrete slab	51
Figure 2.28	Thermal energy storage unit developed by using MPCM for free cooling	52
Figure 2.29	Schematic of the experimental setup	53
Figure 2.30	Air-PCM heat exchanger having MPCM	54

Figure 2.31	Schematic of heat exchanger having MPCM	55
Figure 2.32	Commercially available MPCM panel	55
Figure 2.33	Layout of Hollow Steel Ball (HSB) with metal clamp	56
Figure 2.34	HSB without metal clamp, metal clamp and HSB with metal clamp (From top to bottom)	57
Figure 2.35	(a) PCM-HSB ball secured with rivet and epoxy (b) Cut section of HSB	58
Figure 2.36	Samples of concrete block prepared by using various shapes of encapsulation (a) Superimposed elongated plates 1 design (b) Adjacent setup elongated plates 2 design (c) Separated plates 3 design (d) Complex plate 4 design (e) Spherical shape (f) Cylinder 1 design (g) Cylinder 2 design (h) Cuboid 1 with 1 kg pcm (i) Cuboid 2 with 1.5 kg pcm	59
Figure 2.37	(a) Melting time (b) Crystallization time of various prepared concrete block samples	60
Figure 2.38	Weight loss of (a) Aluminum (b) Stainless steel (c) Copper in inorganic PCM	62
Figure 2.39	Scheme of preparation of shape stabilized composite PCM	65
Figure 2.40	Scheme of preparation of porous carbon supporting material from fresh Potato	67
Figure 2.41	Scheme of preparation of succulent based carbon aerogel	68
Figure 2.42	Synthesis scheme of N-doped porous carbon	69
Figure 2.43	SEM images of expanded graphite with different magnification	70
Figure 2.44	SEM images of (a) Raw PUF (b) PUF with PCM	72
Figure 2.55	Scheme of preparation of shape stabilized PCM using polyurethane	73
Figure 2.56	Preparation procedure of Polyurethane/wood powder/GO based shape stabilized composite PCM	74
Figure 2.57	Schematic of preparation of dye-polyurethane/hexadeconal shape stabilized PCM	75
Figure 2.58	In situ one-step preparation of monolithic silica aerogel based composite PCM	76

Figure 2.59	Scheme of preparation of shape stabilized composite PCM using mesoporous silica and two different diatomite	77
Figure 2.60	One pot method for preparation of LA/SiO ₂ shape stabilized PCM	78
Figure 2.61	(a) Normal concrete block (left) concrete-based CPCM block (right) (b) Experimental setup for thermal performance of the concrete blocks	88
Figure 2.62	Shape stabilized PCM sheets	88
Figure 2.63	(a) Preparation of shape stabilized composite PCM(b) Developed gypsum board/shape stabilized composite PCM	89
Figure 2.64	Experimental setup of climate cycling test chamber	91
Figure 2.65	Developed (a) PCM wall using shape stabilized PCM bricks (b) Regular wall	92
Figure 2.66	(a) Shape stabilized PCM (b) Concrete loaded with shape stabilized PCM	93
Figure 2.67	(a) Test room photograph (b) Wallboard with shape stabilized PCM on the roof (c) Wallboard with shape stabilized PCM on the wall	94
Figure 2.68	(a) PCM room and Reference room (b) Schematic of the south wall with shape stabilized PCM wallboard	95
Figure 2.69	Experimental setup for evaluating the temperature regulating Performance of SEP/FEAM/Cement plaster	97
Figure 2.70	Images of tested room (a) South view (b) Tested wall (c) Indoor view	98
Figure 2.71	Image of hollow concrete panel	99
Figure 2.72	Shape stabilized PCM location in the wall	100
Figure 2.73	Shape stabilized PCM location in the wall	100
Figure 2.74	Schematic of under floor heating system	101
Figure 2.75	Proposed double layer shape stabilized PCM wallboard (b) Reference wallboard without shape stabilized PCM	102
Figure 3.1	Commercially available OM37 PCM	109
Figure 3.2	Prepared macrocapsules	111

Figure 3.3	Various pictures of the experimental site during the construction (a) Embedding MPCM on the roof (b) Embedding MPCM in the wall (c) Installations of thermocouple inside the cubicles (d) Photograph of the construction site	113 ne
Figure 3.4	Schematic of the building structure	114
Figure 3.5	Schematic diagram of the experimental cubicle with macroencapsulated PCM	114
Figure 3.6	(a) Section view of the wall containing MPCM (b) Aluminum pipe used as Macrocapsule	115
Figure 3.7	Experimental setup photographs of developed experimental and reference cubicle	116
Figure 3.8	Schematic of thermal conductivity test using hot disk technique	119
Figure 4.1	South wall temperatures of reference and experimental cubicle on 12 th July 2018	121
Figure 4.2	West wall temperature of reference and experimental cubicle on 12 th July 2018	122
Figure 4.3	North wall temperature of reference and experimental cubicle on 12^{th} July 2018	122
Figure 4.4	East wall temperature of reference and experimental cubicle on 12 th July 2018	123
Figure 4.5	Roof temperature of reference and experimental cubicle on 12 th July 2018	123
Figure 4.6	Indoor ambient temperatures of reference and experimental cubicle on 12 th July 2018	124
Figure 4.7	Time lag of experimental cubicle compared to the reference cubicle	123
Figure 4.8	Heat flux across (a) South wall (b) West wall (c) North wall (d) East wall (e) Roof	129
Figure 4.9	Peak heat flux and corresponding percentage reduction of both the Cubicles	130

Figure 4.10	(a) Thermal image of South wall of experimental cubicle at 9:00 a.m.(b) Thermal image of South wall of reference cubicle at 09:00 a.m.	132
Figure 4.11	(a) Thermal image of South wall of experimental cubicle at 12:00 p.m.(b) Thermal image of South wall of reference cubicle at 12:00 p.m.	132
Figure 4.12	(a) Thermal image of South wall of experimental cubicle at 3:00 p.m.(b) Thermal image of South wall of reference cubicle at 3:00 p.m.	133
Figure 4.13	(a) Thermal image of South wall of experimental cubicle at 6:00 p.m.(b) Thermal image of South wall of reference cubicle at 6:00 p.m.	133
Figure 4.14	Temperature profile of 1 st Jan 2019 of reference and experimental Cubicle	134
Figure 4.15	Temperature profile of 2 nd February 2019 of reference and experimental Cubicle	135
Figure 4.16	Temperature profile of 3 rd March 2019 of reference and experimental cubicle	135
Figure 4.17	Temperature profile of 4 th April 2019 of reference and experimental Cubicle	136
Figure 4.18	Temperature profile of 5 th May 2019 of reference and experimental Cubicle	136
Figure 4.19	Temperature profile of 6 th June 2019 of reference and experimental Cubicle	137
Figure 4.20	Temperature profile of 7 th July 2019 of reference and experimental Cubicle	137
Figure 4.21	Temperature profile of 8 th August 2019 of reference and experimental Cubicle	138
Figure 4.22	Temperature profile of 9 th September 2019 of reference and experimental Cubicle	138
Figure 4.23	Temperature profile of 10 th October 2019 of reference and experimental Cubicle	139
Figure 4.24	Temperature profile of 11 th November 2019 of reference and experimental cubicle	139

Figure 4.25	Temperature profile of 12 th December 2019 of reference and experimental cubicle	140
Figure 4.26	Monthly time lag of experimental cubicle in comparison to the reference Cubicle	145
Figure 4.27	Monthly decrement factor of the reference and experimental Cubicle	145
Figure 4.28	DSC testing results of PCM (OM37)	150
Figure 4.29	DSC testing results of ss-CPCM without thermal cycles	150
Figure 4.30	DSC testing results of ss-CPCM after 1000 thermal cycles	151
Figure 4.31	TGA results of ss-CPCM	155
Figure 4.32	TGA results of ss-CPCM after 1000 thermal cycles	155
Figure 4.33	Melting curve of ss-CPCM	156
Figure 4.34	Freezing curve of ss-CPCM	156
Figure 4.35	Leakage proof performance of ss-CPCM at 30 °C for 10 minutes and at 40 °C for 30 minutes	161

LIST OF TABLES

Table no.	Illustration Pa	ige no.
Table 1.1	Potential sensible thermal energy storage material for building application	7
Table 1.2	List of PCM which can be used in buildings for improving energy Efficiency	13-14
Table 2.1	Characteristics features of MPCM techniques	22
Table 2.2	List of manufacturers of MPCM	24
Table 2.3	Commercial manufacturers of MPCM	40
Table 2.4	Composition of prepared concrete panel samples	58
Table 2.5	Comparative analysis chart on chemical compatibility of PCM with container material for encapsulation	61
Table 2.6	Rate of corrosion $(mg/cm^2/yr)$ of different metals and alloys with all combinations of PCM for cooling application	63
Table 2.7	Rate of corrosion (mg/cm ² /yr) of different metals and alloys with all combinations of PCM for heating application	64
Table 2.8	Classification and properties of porous supporting material for PCM	66
Table 2.9	Thermo-physical properties of EG	70
Table 2.10	Summary of studies published using EG as supporting material	71
Table 2.11	Composition of clay materials used for preparation of shape stabilized PCM	l 79
Table 2.12	Summary of published literature on thermal characterization of Shape stabilized PCM using clays	80-82
Table 2.13	Thermo-physical properties of nanoparticles used to prepare shape	83-84

stabilized organic PCM

Table 2.14	Summary of published literature on thermal properties of shape stabilized PCM loaded with nanoparticles	85-87
Table 2.15	Comparative analysis of various methods of incorporating PCM in building envelope	104
Table 3.1	Thermo-physical properties of the PCM (Provided by the manufacturer)) 110
Table 3.2	Thermo-physical properties of aluminum 8011 alloy (Provided by the manufacturer)	110
Table 3.3	List of sensors used for the data collection	111
Table 3.4	Composition of building material used to develop cubicles	112
Table 3.5	Weight and percentage amount of various components of ss-CPCM	117
Table 4.1	Comparison of peak temperature of reference cubicle and experimental cubicle walls	125
Table 4.2	Comparison of thermal amplitude of reference and experiment cubicle	126
Table 4.3	Monthly peak temperature reduction of reference and experimental Cubicle	141
Table 4.4	Comparison of the monthly thermal amplitude of the reference and experimental cubicle	143
Table 4.5	Comparison of the peak heat fluxes of the RBS and EBS and corresponding cost savings	148
Table 4.6	Comparison of experimental result with previous published literature	148
Table 4.7	DSC analysis of PCM and ss-CPCM	152
Table 4.8	Thermal decomposition (%) of the PCM and ss-CPCM in different temperature ranges	153
Table 4.9	Thermal conductivity measurement of ss-CPCM with corresponding percentage improvement	159
Table 4.10	Comparison of thermal properties of PCM/EV/AO ss-CPCM of this study with previously published studies on similar ss-CPCMs.	160