UNIVERSITI PUTRA MALAYSIA

NANO-ENCAPSULATED ORGANIC PHASE CHANGE MATERIAL AS THERMAL ENERGY STORAGE MEDIUM

TUMIRAH KHADIRAN

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By

TUMIRAH KHADIRAN

Thesis Submission to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement of the degree of Doctor of Philosophy

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August 2015

Chairman : Professor Mohd Zobir Hussein, PhD
Faculty : Institute of Advanced Technology

In this study, two types of supporting materials, namely porous carbon-based material and polymer were used to encapsulate organic phase change materials (OPCM). The supporting material based on porous carbon is activated carbon (AC) derived from tropical peat soil using physical activation method (PSAC-P), AC derived from tropical peat soil using phosphoric acid (H_3PO_4) chemical activation method (PSAC-C) and commercial activated carbon (CAC), while supporting material based on polymer consists of mixtures of monomer styrene (St) and methyl methacrylate (MMA) at mass ratio of 4:1. The OPCM encapsulated into the pores of AC is known as shape-stabilised OPCM nanocomposite, while OPCM encapsulated into nano-sized St-MMA copolymer shell is known as OPCM nanocapsules. The shape-stabilised OPCM nanocomposite was synthesised using the one-step impregnation method, while OPCM nanocapsules was synthesised using the one-step miniemulsion *in-situ* polymerisation method. n-Octadecane and n-nonadecane were chosen as OPCM due to their phase transition temperatures are close to human comfort temperature (18 – 33 ^{o}C), thus they are suitable to be used for thermal comfort building applications.

The latent heat and encapsulation efficiency of shape-stabilised OPCM increased as the BET specific surface area of AC increased. The increasing of latent heat and encapsulation efficiency of shape-stabilised OPCM nanocomposite are in order of shape-stabilised OPCM/PSAC-P < OPCM/CAC < OPCM/PSAC-C. The higher the BET specific area of AC, the more OPCM can be infiltrated into the pores of AC, thus increase the latent heat value. The latent heat of fusion of shape-stabilised OPCM/PSAC-P, OPCM/CAC and OPCM-PSCA-C was 95.4 J/g, 101.3 J/g and 107.2 J/g, respectively. For the encapsulation of OPCM using polymer, it was found that the mass ratio of shell to core, shell to initiator, St to MMA and thermo-chemical properties of OPCM plays an important role in the morphology, latent heat and encapsulation efficiency of the OPCM. The n-octadecane nanocapsules was successfully prepared with diameter size of 102 ± 11 nm, while n-nonadecane nanocapsules was 160 ± 16 nm. The latent heat of fusion of n-octadecane and n-nonadecane nanocapsules was found to be 107.9 J/g and 76.9 J/g, respectively. Thermal cycling tests of both shape-stabilised OPCM nanocomposite and OPCM nanocapsules showed good thermal and chemical stability even after 1000 heating/cooling cycles. This indicates that both shape-stabilised OPCM nanocomposite and OPCM nanocapsules could be used as thermal energy storage (TES) medium for at least of 3 years.

The shape-stabilised OPCM nanocomposite and OPCM nanocapsules with the highest latent heat was chosen as TES medium to develop thermally regulated gypsum composite board (smart gypsum composite board). The thermal performance test of thermally regulated gypsum composite boards were carried out in order to understand their ability in reducing the internal building temperature fluctuation. The results show that both shape-stabilised OPCM nanocomposite and OPCM nanocapsules play an important role in reducing the indoor building temperature, which could help to maintaining internal building comfort, thus believed could decrease the energy consumption. The results and the information generated from this study could be very beneficial to the local building industries as well as those who are concerned about internal building comfort, environmental protection and energy sustainability.

All the works presented in the thesis have been accepted and published in the journals of the international repute, which reflect the quality of this research work.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

NANO-PENGKAPSULAN BAHAN ORGANIK BERUBAH FASA SEBAGAI MEDIUM PENYIMPANAN TENAGA HABA

Oleh

TUMIRAH KHADIRAN

Ogos 2015

Pengerusi : **Profesor Mohd Zobir Hussein, PhD**
Fakulti : **Institut Teknologi Maju**

Dalam kajian ini, dua jenis bahan sokongan iaitu bahan karbon berliang dan polimer telah digunakan untuk pengkapsulan bahan organik berubah fasa (OPCM). Bahan sokongan karbon berliang yang digunakan ialah karbon teraktif (AC) daripada tanah gambut tropikal yang disediakan menggunakan kaedah pengaktifan fizikal (PSAC-P), karbon teraktif daripada tanah gambut tropikal menggunakan kaedah pengaktifan kimia asid fosforik (H_3PO_4) (PSAC-C) dan karbon teraktif komersial (CAC), sementara bahan sokongan polimer terdiri daripada gabungan monomer stirena (St) dan metil metakrilat (MMA) pada nisbah berat 4:1. Pengkapsulan OPCM ke dalam liang AC dikenali sebagai nanokomposit OPCM terstabil bentuk, manakala pengkapsulan OPCM ke dalam saiz-nano kopolimer St-MMA dikenali sebagai OPCM nanokapsul. Nanokomposit OPCM terstabil bentuk telah disediakan dengan menggunakan kaedah pengisitepuan satu langkah, manakala nanokapsul OPCM disediakan menggunakan kaedah pempolimeran in-situ miniemulsi satu langkah. n-Oktadekana dan n-nonadekana dipilih sebagai OPCM kerana mempunyai perubahan fasa menghampiri suhu selesa manusia iaitu di antara 18-33 ^oC, di mana ianya sesuai digunakan untuk kegunaan bangunan selesa suhu.

Haba pendam lakuran dan kecekapan pengkapsulan nanokomposit OPCM terstabil bentuk meningkat dengan peningkatan luas permukaan spesifik BET bagi AC. Peningkatan haba pendam lakuran dan kecekapan pengkapsulan nanokomposit OPCM terstabil bentuk adalah mengikut susunan nanokomposit terstabil bentuk OPCM/PSAC-P < OPCM/CAC < OPCM/PSAC-C. Semakin luas permukaan spesifik BET AC, semakin banyak OPCM boleh menyerap masuk ke dalam liang AC menyebabkan peningkatan nilai haba pendam lakuran. Haba pendam lakuran nanokomposit terstabil bentuk OPCM/PSAC-P, OPCM/CAC dan OPCM/PSAC-C ialah masing-masing 95.4 J/g, 101.3 J/g dan 107.2 J/g. Manakala untuk pengkapsulan OPCM menggunakan polimer, nisbah berat petala/teras, petala/bahan pemula, St/MMA dan sifat thermo-kimia OPCM memainkan peranan penting kepada morfologi, haba pendam lakuran dan kecekapan pengkapsulan OPCM. n-Oktadekana nanokapsul telah berjaya disediakan dengan saiz garispusat 102 ± 11 nm, sementara n-nonadekana nanokapsul ialah 160 ± 16 nm. Haba pendam lakuran n-oktadekana dan n-nonadekana nanokapsul masing-masing ialah 107.9 J/g dan 76.9 J/g. Ujian ulangan terma yang dilakukan pada kedua-dua nanokomposit OPCM terstabil bentuk dan OPCM nanokapsul menunjukkan kedua-duanya mempunya kestabilan terma dan kimia yang baik walaupun selepas melalui 1000 kali putaran pemanasan/penyejukan. Ini menunjukkan kedua-duanya boleh berfungsi sebagai medium penyimpanan tenaga haba (TES) sekurang-kurangnya untuk 3 tahun.

Nanokomposit OPCM terstabil bentuk dan OPCM nanokapsul yang mempunyai haba pendam lakuran yang tertinggi dipilih sebagai medium TES untuk pembangunan haba terkawal-papan gipsum komposit. Ujian prestasi terma telah dijalankan terhadap haba terkawal-papan gipsum komposit bagi tujuan memahami keupayaannya untuk mengurangkan turun naik suhu dalam bangunan. Keputusan menunjukkan nanokomposit OPCM terstabil bentuk dan OPCM nanokapsul memainkan peranan penting dalam mengurangkan turun naik suhu dalam bangunan, di mana ianya akan membantu mengekalkan keselesaan dalam bangunan, seterusnya dipercayaai akan membantu menurunkan penggunaan tenaga dalam bangunan. Keputusan ujian dan maklumat yang diperolehi daripada kajian ini akan dapat memberi manfaat kepada industri bangunan tempatan, juga kepada individu yang mengambil berat tentang bangunan selesa suhu, perlindungan alam sekitar dan kemampanan tenaga.

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I certify that a Thesis Examination Committee has met on 12 August 2015 to conduct the final examination of Tumirah bt. Khadiran on her thesis entitle “Nano-Encapsulated Organic Phase Change Material as Thermal Energy Storage Medium” in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A)106] 15 March 1998. The Committee recommends that the student be awarded the Doctoral of Philosophy.

Members of the Thesis Examination Committee were as follows:

Khamirul Amin Matori, PhD
Associate Professor
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Faculty of Science
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Nor Azah Yusof, PhD
Professor
Department of Chemistry
Faculty of Science
University Putra Malaysia
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Mohd Zaizi Desa, PhD
Pusat Asasi Sains Pertanian
Universiti Putra Malaysia
(Internal Examiner)

In Woo Cheong, PhD
Associate Professor
Department of Applied Chemistry
Kyungpook National University
Republic of Korea
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 22 September 2015

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

Mohd. Zobir Hussein, PhD
Professor
Institute of Advanced Material
Universiti Putra Malaysia
(Chairman)

Zulkarnain Zainal, PhD
Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

Rafeadah Rusli, PhD
Senior Research Officer
Forest Product Division
Forest Research Institute Malaysia
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School of Graduate Studies
Universiti Putra Malaysia

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Name of Member of Supervisory Committee	: Professor Dr. Zulkarnain Zainal

Signature	:______________________________
Name of Member of Supervisory Committee	: Dr. Rafeadah Rusli

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LIST OF ABBREVIATIONS

AC	activated carbon
AIBN	2,2-azobisisobutyronitrile
ASAP	Accelerated surface area and porosimetry
BET	Brunauer-Emmert-Teller method
BJH	Barret-Joyner-Halenda method
CAC	commercial activated carbon
DLS	dynamic light scattering
DSC	differential scanning calorimetry
EPCMs	eutectic phase change materials
FESEM	field emission scanning electron microscopy
FTIR	Fourier transforms infrared spectroscopy
ΔH_m	enthalpy of melting
H_3PO_4	phosphoric acid
HNO_3	nitric acid
IOPCMs	inorganic phase change materials
J/kg K	joule per kilogram Kelvin
J/m^3 K	joule per cubic meter Kelvin
J/g	joule per gram
kJ	kilo joule
kJ/kg	kilojoule per kilogram
kg/m^2	kilogram per square meter
K	Kelvin
MMA	methyl methacrylate
$MgSO_4$	magnesium sulphate
nm	nanometer
NaOH	Sodium hydroxide
OPCMs	organic phase change materials
PSAC	peat soil activated carbon
PSAC-C	PSAC prepared using H_3PO_4 chemical activation method
PSAC-P	PSAC prepared using physical activation method
PSAC-Z	PSAC prepared using $ZnCl_2$ chemical activation method
PCM	phase change material
PSD	particle size distribution
PSt	polystyrene
rpm	revolution per minute
SSOAC	shape-stabilised octadecane/AC
SOAC	shape-stabilised octadecane/AC
SDS	sodium dodecyl sulphate

SiO_2	silicone dioxide
SEM	scanning electron microscope
ΔT	temperature change
Triton-X 114	polyethylene glycol tert-octylphenyl ether
T_m	temperature of melting
T_c	temperature of cooling
TGA	thermal gravimetric analyzer
TGA/DTG	Thermal gravimetric analyzer/derivative thermogravimetry
TEM	transmission electron microscopy
TES	Thermal energy storage
V	volume of storage material
ρ	density
W/mK	watt per meter Kelvin
W	watt
XRD	x-ray diffraction
$ZnCl_2$	Zinc chloride
µm	micrometer

CHAPTER 1

INTRODUCTION

1.1 Background of research

Buildings are responsible for about 40 % of the total world energy consumption, in which a large portion of energy is used for heating and cooling purpose of the buildings. It is responsible for one-third of green gas emission around the world which cause depletion of the conventional energy resources (Waqas and Din, 2013; Tyagi et al., 2011). In addition, the energy consumption by buildings was targeted to be increased to 60 % in the future due to increasing of the urbanization worldwide. One way to combat this problem in the future is to design buildings with a combination of green and smart technology. Therefore, it is a great demand to develop building materials with improving energy efficiency, which has a function to maintain internal building comfort, reduce the energy usage and indirectly could protect the environment from CO_2 emission. To achieve this, thermal energy storage (TES) based on organic phase change materials (OPCM) could offer the solution.

TES based on OPCM is a material which has ability to absorb, store and release a large amount of heat at small temperature fluctuation (Zhang et al., 2012a; Abhat, 1983). These properties could be used to improve the mismatch between the energy supply and demand in buildings. The incorporation of TES based on OPCM into building components likes walls, ceilings, roofs, and floors shows a potential to shift the electricity peak load which is beneficial to reduce energy usage in buildings. This technology provides realistic solution to improve the efficiency of the energy utilization and management in buildings, which would reduce the dependency towards conventional energy resources.

However, a good incorporation technique of OPCM into building materials is required to make sure that the OPCM are function. There are varies ways to incorporate OPCM into building materials either for passive or active energy storage systems applications. Passive energy storage system has advantages to the buildings, because it can be automatically absorb, store or release energy if the surrounding temperature is above or below the melting point of OPCM. In addition, passive energy storage system provided large heat transfer area, easily fabricated and installed with existing building facilities (Zhou et al., 2012). These properties will improve the thermal inertia of the buildings by minimizing internal building temperature fluctuation, in which it would increase the potential of energy saving (Schossig et al., 2005; Alawadhi, 2008). Therefore, passive energy storage system attracts worldwide attention to be researched further.

In passive energy storage system, OPCM can be integrated directly (direct incorporation or immersion) into the building materials or can be incorporated as separate components in buildings. Direct incorporation is the method in which OPCM are directly mixed with the building materials for example gypsum, cement, mortar or concrete during construction work (Hawes et al., 1989; Feldman et al., 1991). Dipping processes of building materials for example wall boards into the liquid OPCM refer to the immersion technique. Both techniques are the simplest, practicable and economical, but the OPCM may leak, especially after subjected to large number of thermal cycles

(Zhou et al., 2012; Soares et al., 2013) in which this may affect the mechanical properties and durability of the building materials.

Previous technology used macroencapsulation of OPCM to incorporate OPCM into building materials. Macroencapsulation technology refers to the encapsulation of OPCM using any type of container such as tubes, spheres, cylinder, cell or panels which can be integrated into building materials (Raj and Velraj, 2010; Cabeza et al., 2011). Example of this technique includes phase change material panels installed below finished flooring (Rodriguez-Ubinas et al., 2012). This technique could overcome the liquid leakage problem of OPCM during phase change processes, but it suffers from low thermal conductivity which cause low heat exchange. In addition, the complicated integrating processes to the building materials making this system more expansive, and could also disturb the mechanical strength of the building materials due to the big size of the capsule, and has to be protected against the destruction while the building is in used, such as cannot be simply drilled holes or nails. Due to all the problems, none of these technologies was successfully available in the wider markets.

Microencapsulation of OPCM has extensively developed to overcome the problem mentioned above. Other advantages of micro-encapsulated OPCM include the increased of surface area, which could increase the heat transfer. Incorporation of micro-encapsulated OPCM into building materials reported can reduce indoor temperature fluctuation (Shossig et al. 2005; Su et al., 2012) and do not need additional protection from destruction (Tyagi et al., 2011), but tend to be costly (Borreguero et al., 2010a). In addition, the diameter of micro-encapsulated phase change material is same size with most of the building materials, which could be adversely affected the structure integrity (Norvell et al., 2013).

Recently, studies focus on the development of shape-stabilised OPCM. Shape-stabilised OPCM refer to the composite OPCM which retain a maximum percentage of OPCM in the pores of porous materials such as expanded graphite (EG) (Zhang et al., 2013), graphene oxide (GO) (Li et al., 2013), carbon nanotube (CNT) (Wang et al., 2009a), etc., and maintained the OPCM shape (no leakage) even above melting temperature of OPCM. This shape-stabilised OPCM materials have reported can improve thermal conductivity (Sari and Karaipekli, 2009; Wang et al., 2009a). Unfortunately, the study about incorporation of this material into building materials is scarce. In addition, preparation of shape-stabilised OPCM using EG, GO and CNT incur high cost, which make this system expansive, thus not practical and not economical for building applications. Other porous material use for preparation of shape-stabilised OPCM is porous building materials including expanded clay (EC), expanded perlite (EP), expanded fly ash (EF), etc. However, different type of OPCM infiltrated into the porous building material has different melting and freezing properties. For example, OPCM based fatty acid will have strong interaction with porous building material due to the functional group (-COOH) in fatty acids, which will effect on increasing or decreasing the melting or freezing temperatures.

Not all OPCM can be used as TES medium for building application. Among OPCM, paraffin (n-alkanes) is more preferred to be used as TES material especially for building applications (Zalba et al., 2003; Farid et al., 2004). This is because it offers a lot of advantages. The advantages of n-alkanes includes high latent heat of fusion, high density, congruent melting, small volume changes during phase transition, little or no supercooling during freezing, chemical stability, low vapor pressure, non-corrosive, non-toxic, commercial availability, abundant and low cost (Dincer and Rosen, 2011; Zalba et al., 2003). Unfortunately, OPCM based n-alkanes suffer from liquid leakage during their phase change processes, low thermal conductivity which will leads to low and decreasing heat storage and discharge powers and flammable. This weakness will limit their application for TES medium (Farid et al., 2004).

Considering the problems mentioned above, therefore various encapsulation technology should be explored. Encapsulation of OPCM using the pores of activated carbon (AC) has a good promising for TES application. AC can be used as an alternative to EG, CNT and GO. AC can be produced from a variety of carbonaceous materials including agricultural waste (González-Garía et al., 2013) and industrial waste (Kong et al., 2013). AC is relatively cheap and easy to prepare compared to EG, CNT and GO. Therefore, the shape-stabilised OPCM/AC nanocomposite has a good future to be used as TES medium for building application.

Recently, nanoencapsulation technology has attracted a lot of attention by researcher worldwide (Fang et al., 2014a). This technology is relatively new and able to produced novel phase change material. No report was found on the utilization of nanoencapsulated OPCM as TES medium on the building application. An ultra-small size of the nanocapsules (<1000 nm) could provide interesting thermo-physical and chemical properties. In addition, due to their ultra-small diameter, they can easily incorporate and penetrate into the matrix of building materials (Pasupathy et al., 2008). Due to the ultra-small diameter of the OPCM nanocapsules, the surface area to volume ratio is very high, therefore higher heat transfer speed.

1.2 Problem Statements

Recently, various encapsulated OPCM have been developed using both porous carbon-based material and polymer. Among porous carbon-based material used as a framework to encapsulate OPCM are expanded graphite (EG) (Py et al., 2001; Sari and Karaipekli, 2009), graphene oxide (GO) (Mehrali et al., 2013a), graphene nanoplatelets (Mehrali et al., 2013b) and carbon nanotube (CNT) (Yu et al., 2014). Porous carbon-based material offers a lot of advantages, such as low density, good thermal conductivity, chemical stability, well-defined pore structure, and high specific surface area. However, they are difficult to synthesis, therefore fairly expensive, thus not economical to be used for building applications.

AC shows a promising property as porous carbon-based material framework for the preparation of shape-stabilised OPCM nanocomposite due to its easy to synthesis and low cost. However, the effectiveness of AC as porous carbon-based material depends on their pore size distribution, geometrical shape, network inner-connection and the functional groups on the internal surface (Zhang et al., 2007a). Nevertheless, these properties depend on the type of carbon precursor and activation method (González-Garía et al., 2013). In addition, very limited study was reported on the use of AC as porous carbon-based material framework to encapsulate OPCM. Previous studies indicate that they used commercial AC (Feng et al., 2011, Chen et al., 2012), which lack with the information regarding the carbon precursor and type of activation method used. The information on the carbon precursor and type of activation method is important in the preparation of a shape-stabilised OPCM/AC nanocomposite. This is because different type of carbon precursor and activation method could give different physico-chemical properties of the resulting AC, which later would affect the physico-chemical and thermal properties of the shape-stabilised OCPM/AC nanocomposite. Furthermore, the study on shape-stabilised OPCM/AC nanocomposite as TES medium for building application has not yet reported. Therefore, the preparation of AC from tropical peat soil using physical and chemical activation method as porous carbon-based material framework for preparation of shape-stabilised OPCM nanocomposite will be reported. Commercial AC was used as comparison. Then, the ability of the shape-stabilised OPCM nanocomposite obtained in maintaining internal building temperature will be also verified.

On the other hand, the encapsulations of OPCM into micro-sized polymer shell have been frequently reported (Rahman et al., 2012; Qiu et al., 2014), however the works on the encapsulated OPCM into nano-sized polymer shell are still lacking. In addition, the encapsulation method that was developed previously was non-selective because the size of the capsules obtained is non-homogeneous composed of mixtures of micro- and nano-capsules (Sari et al., 2014a; Bayes-Garcia et al., 2010). Non-homogeneous particle size of the capsule is believed to later disturb the TES performance. In addition, some of the polymer materials which were previously used as capsules may exist ineluctable remnant formaldehyde, especially polymer-based melamine- and urea formaldehyde, which will cause health and environmental problems. These could limit their used, especially for building applications (Norvell et al., 2013).

Encapsulation of OPCM into micro-sized (Micro-encapsulated OPCM) has been reported to be not effective to be used as TES medium when they are incorporated into building materials (Borreguero et al., 2014a). Borreguero et al. (2014a) used commercial micro-encapsulated OPCM with the average particle size of 7.10 ± 2.32 µm, and the latent heat of fusion was 116.20 ± 4.11 J/g to prepare gypsum composite board. The result obtained shows that the microcapsules were not completely melt thus given lower value of TES. In addition, most of the average particle sizes of the micro-encapsulated OPCM are similar to the particle size of the building material. This could be adversely affects the structure integrity of the buildings (Norvell et al., 2013). Therefore, nano-encapsulated OPCM is more preferred. Due to the ultra-small diameter of the nanocapsules, the surface area to volume ratio is very high, therefore higher heat transfer speed, and can be easily incorporated and penetrated into the matrix of the building materials (Pasupathy et al., 2008) or other matrix such as textiles.

The used of polystyrene (PSt) to encapsulate OPCM, based n-alkanes has been extensively discussed previously (Sánchez et al., 2007; Fang et al., 2013a). Nevertheless, to obtained encapsulated n-alkanes into nano-sized with high encapsulation efficiency is difficult, due to the fact that both n-alkanes and PSt have high hydrophobicity properties (Chen et al., 2012a). Therefore the designated styrene-methyl methacrylate (St-MMA) copolymer shell is the way of compromised. Studies have shown that the n-alkanes have been successfully encapsulated into micro-sized capsules using St-MMA copolymer shell by suspension-like polymerization method (Sánchez-Silva et al., 2010). Combination of St and MMA at certain ratio will reduce the interfacial surface tension, which could overcome the hydrophobicity of PSt. Moreover, the higher solubility of MMA in water compared to St would improve the efficiency of n-alkanes encapsulation (Tiarks et al., 2001). In addition, the final capsules morphology obtained is strongly dependent on the hydrophilicity and reactivity ratios between the monomers (Stubbs and Sundberg, 2008). The use of MMA as the shell system of this study could improve the characteristic of n-alkanes capsules. However, the encapsulation of n-alkanes into nano-sized capsules using St-MMA copolymer shells by one-step miniemulsion *in-situ* polymerization has not yet reported. The encapsulated OPCM into nano-sized polymer capsules could benefit in term of the increasing of the heat transfer rate of the n-alkanes as TES materials.

1.3 Scope of study

Previous study shows that porous carbon-based material and polymer are suitable to be used to encapsulate OPCM. Unfortunately, there are a lot of barriers, which make the encapsulated OPCM products either in the form of shape-stabilised or capsule fail to function as TES medium for building applications, due to expensive encapsulation processes, and therefore not economical to be used for building applications. Other barrier is the size of capsule, which fail to provide enough surface area, thus decrease the heat transfer rate during melting and freezing processes of OPCM due to poor heat transfer coefficients (poor conductivity) of OPCM. Therefore this study was carried out to find out the way to reduce the barriers.

The scope of this study is to prepare and characterize porous carbon-based material, which is AC derived from tropical peat soil to be used as frameworks to encapsulate OPCM. The AC was prepared using the physical and chemical activation methods. Different activation methods are expected could produce AC with different physico-chemical properties. These properties would be very beneficial to study their physico-chemical and thermal behavior of the OPCM, after they were infiltrated into the pores of AC. The commercial AC was also used as framework for comparison. n-Octadecane was used as OPCM throughout this study. The samples obtained from this study are known as shape-stabilised OPCM nanocomposites.

Other scope of this study is to encapsulate OPCM into nano-sized styrene (St)-methyl methacrylate (MMA) copolymer shell. The parameters of polymerization processes; St to MMA mass ratio, shell to core mass ratio and shell to initiator mass ratio were extensively studied. Two different n-alkanes (n-octadecane and n-nonadecane) were used as a core. The study also covers the ability of polymerization method developed in this study (one-step miniemulsion *in-situ* polymerization) to encapsulate two n-alkanes (n-octadecane and n-nonadecane) with different thermo-chemical properties. The term OPCM nanocapsules was used for OPCM encapsulated into nano-sized St-MMA copolymers shells.

The shape-stabilised OPCM nanocomposite and OPCM nanocapsules samples with high latent heat of fusion were chosen to develop the thermally regulated gypsum composite board (smart gypsum board). The thermal behaviour of the thermally gypsum composite boards was characterized using in-house method, which was developed for this study.

The n-alkanes with C_{18} (n-octadecane) and C_{19} (n-nonadecane) were chosen as an OPCM because both n-alkanes are the most suitable n-alkanes used for building industries application. This is because their melting temperatures are within the human comfort temperatures zone of 18-36 ^{o}C (Khosrojerdi and Mortazavi, 2013).

1.4 Objectives

The main objective of this study is to prepare novel nano-encapsulated OPCM based on shape-stabilised and core-shell nano-capsules materials with excellent physico-chemical and thermal properties for thermal energy storage. The specific objectives are as listed below:

1) to prepare and characterize activated carbon (AC) derived from peat soil using physical and chemical activation methods, to be used as porous carbon-based frameworks.
2) to prepare and characterize shape-stabilised organic phase change materials (OPCM) using AC prepared in (1) by one-step impregnation method.
3) to prepare and characterize shape-stabilised OPCM using commercial AC by one-step impregnation method as comparison with the shape-stabilised OPCM prepared in (2).
4) to synthesis and characterize nano-encapsulated OPCM using styrene (St)-methyl methacrylate (MMA) copolymer shell by one-step miniemulsion *in-situ* polymerization method.
5) to explore the physico-chemical behavior of the shape-stabilised OPCM and OPCM nanocapsules incorporated with gypsum board.
6) to investigate the thermal performance effect of thermally regulated gypsum composite board prepared in (5) in maintaining the internal building temperature.

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