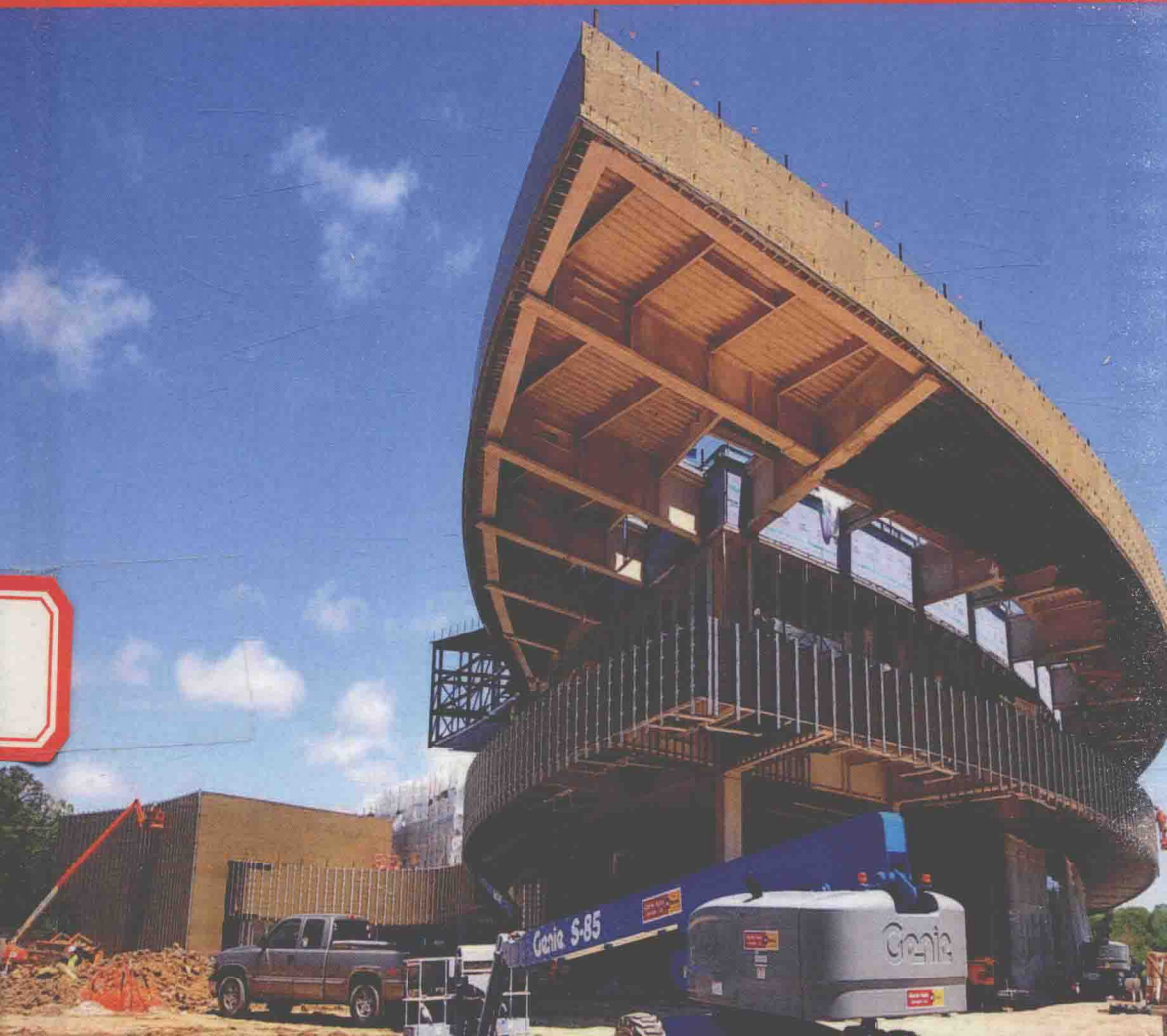
Handbook of
MODERN EARTH BUILDINGS:
Materials, Engineering, Constructions and Applications

Contributors:
Jessica Giro-Paloma, Refat Al-Shannaq et al.



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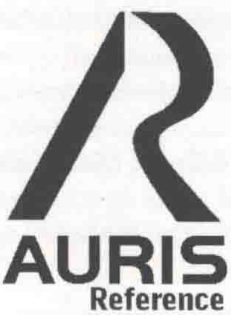

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List of Abbreviations

ADP	Abiotic depletion potential
AHP	Analytical hierarchy process
AAC	Autoclaved aerated concrete
BOQ	Bill of quantities
BIM	Building information model
BIM	Building information modeling
BM	Building materials
BRE	Building research establishment
CVA	Change vector analysis
CSW	Compressed shopper waste
CFD	Computational fluid dynamics
CSM	Continuous stiffness measurement
DSI	Depth-sensing indentation
EUE	End-use of energy
EIR	Environmental impact report
FLIS	Fuzzy logic inference systems
GSA	General services administration
GWP	Global warming potential
HR	Human resources
LA	Lauric acid
LOD	Level of detail
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life-cycle inventory
LECA	Light expanded clay aggregate
LOS	Line of sight
MCI	Marginal cost increase
MPCM	Microencapsulated phase change materials
NCM	National calculation methodology
PCM	Phase change material
PCM	Phase change materials
PCMs	Phase change materials
POCP	Photochemical oxidant creation
POCP	Photochemical ozone creation potential
PCA	Principle component analysis
SBS	Sick building syndrome
SA	Stearic acid
SVM	Support vector machine
SPD	Suspended particle devices
SD	Sustainable development

TES	Thermal energy storage
TIF	Thermal integrity factor
TP	True positives

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Preface

The construction of earth buildings has been taking place worldwide for centuries. With the improved energy efficiency, high level of structural integrity and aesthetically pleasing finishes achieved in modern earth construction, it is now one of the leading choices for sustainable, low-energy building. The text *Handbook of Modern Earth Buildings: Materials, Engineering, Constructions and Applications* provides an essential exploration of the materials and techniques key to the design, development and construction of modern earth buildings.The purpose of first chapter is to develop, prepare, characterize, study, and compare thermal and mechanical properties of microcapsules containing organic phase change materials (PCM) in order to assess their suitability for use in buildings and other applications. The goal of second chapter is to demonstrate the feasibility of using EP-based composite PCM in cement boards to increase their thermal inertia and to reduce the energy demand of the building. Third chapter aims to analyze recent advances in the area of non-metallic building materials (BM) and outlines future prospects and challenges. Fourth chapter outlines and draws conclusions about different aspects of the material efficiency of buildings and assesses the significance of different building materials on the material efficiency. Fifth chapter develops a template for evaluating the embodied environmental impact of using a building information modeling (BIM) design tool as part of BIM-based building life-cycle assessment (LCA) technology development. In sixth chapter, we explain the Delphi method as a group decision-making technique, including its uses, underlying assumptions, strengths and limitations, potential benefits to qualitative higher education research, and key considerations in its use. In seventh chapter, a CFD-based model has been proposed to analyze the effect of phase change materials (PCMs) on the thermal behavior of the walls of a cubicle exposed to the environment and on the resistance of the walls to climate changes. In eighth chapter, we evaluate the thermal performance of a range of modern wall constructions used in the residential buildings of Tehran in order to find the most appropriate alternative to the traditional un-fired clay and brick materials. Ninth chapter presents a method for detecting and classifying changes to buildings by using classified and well registered (strip difference <10 cm) laser data from several epochs. A review of energy conservation properties in earth sheltered housing has been presented in tenth chapter. The aim of last chapter is to analyze large slope movements in conjunction with radar interferometry and damage data in order to investigate the state of the activity of such phenomena and to describe the resulting level of damage as a function of the ground surface rate of movement.

Contents

Chapter 1

PREPARATION AND CHARACTERIZATION OF MICROENCAPSULATED PHASE CHANGE MATERIALS FOR USE IN BUILDING APPLICATIONS

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ABSTRACT

A method for preparing and characterizing microencapsulated phase change materials (MPCM) was developed. A comparison with a commercial MPCM is also presented. Both MPCM contained paraffin wax as PCM with acrylic shell. The melting temperature of the PCM was around 21 °C, suitable for building applications. The M-2 (our laboratory made sample) and Micronal® DS 5008 X (BASF) samples were characterized using SEM, DSC, nano-indentation technique, and Gas Chromatography/Mass spectrometry (GC-MS). Both samples presented a 6 μm average size and a spherical shape. Thermal energy storage (TES) capacities were 111.73 $J \cdot g^{-1}$ and 99.3 $J \cdot g^{-1}$ for M-2 and Micronal® DS 5008 X, respectively. Mechanical characterization of the samples was performed by nano-indentation technique in order to determine the elastic modulus (E), load at maximum displacement (P_m), and displacement at maximum load (h_m), concluding that M-2 presented slightly better mechanical properties. Finally, an important parameter for considering use in buildings is the release of volatile organic compounds (VOC's). This characteristic was studied at 65 °C by CG-MS. Both samples showed VOC's emission after 10 min of heating, however peaks intensity of VOC's generated from M-2 microcapsules showed a lower concentration than Micronal® DS 5008 X.

INTRODUCTION

Thermal energy storage (TES) using phase change materials (PCM) has shown a significant increased attention because of its important role on energy conservation in buildings [1,2,3,4]. PCM can be used for TES in buildings [5] either in passive [6] or active systems [7,8,9], aiming to improve the thermal managements of these buildings. In most of the applications, PCM were used either in macroencapsulated [10,11] or microencapsulated [12,13,14] forms, for heating [15], air-conditioning [16], ventilation [17], refrigeration [18], and heat exchangers [19] for building applications [3,20,21,22].

Microencapsulation process is defined as a technique in which small particles or droplet are enclosed by a coating, or surrounded in a homogeneous or heterogeneous matrix, to provide microcapsules (1–100 μm). For this reason, the microencapsulated phase change materials (MPCM) are composed of PCM as a core and a polymer as a shell used to preserve the spherical shape of the microcapsule and avoid PCM leakage during phase change [12,23]. The use of MPCM in buildings [24,25,26,27] can decrease daily inner temperature fluctuation during summer and winter [28]. The suitability of the shell used in encapsulating specific core PCM is a key issue in order to ensure proper thermal performance of the MPCM [13,29,30], especially in preventing PCM leakage when it melts. Additionally, MPCM can be easily incorporated in gypsum board [31,32], plaster [33], and concrete [34] used in buildings.

The complete characterization of materials used in indoor environments like MPCM is very important. The exposure to chemical compounds could cause health problems (nausea; dry skin; eye, nose or throat irritations; headache; irritated eyes; dizziness; difficulty in concentrating; psychological stress) in indoor environments [35,36,37,38] (buildings, for example [39,40,41,42,43,44,45,46,47]) or outdoor environments [48]. These problems are known as sick building syndrome (SBS) [37,49,50,51]. Volatile organic compounds (VOC's) are defined as any organic compound having an initial boiling point less than or equal to 250 °C at a standard pressure of 101.3 kPa [52]. VOC's are one of the most important groups of trace contaminants in the atmosphere known for its photochemical, toxic, and radioactive effects. For this reason there are some studies, guides [53,54], and database [55,56] related to this effect. Formaldehyde [39,46,57] and benzene [58] are some of the most studied pollutants since they are classified in Group 1 of human carcinogens by the IARC 2004 (International Agency for Research on Cancer). Other chemicals known for their health hazard are acetaldehyde, toluene, and xylenes [59]. By this way, VOC's evaluation of the outdoor and indoor air quality has been evaluated [28,29,30,31] in materials for buildings like gypsum

base PCM composites [60] but it has not been reported for building materials containing MPCM. For this reason, the characterization of VOC's of MPCM is an important contribution to the state of the art of the environmental properties of MPCM.

The main purpose of this research is to develop, prepare, characterize, study, and compare thermal and mechanical properties of microcapsules containing organic PCM in order to assess their suitability for use in buildings and other applications. The samples under study are commercial MPCM (Micronal® DS 5008 manufactured by BASF, Berlin, Germany) and a laboratory prepared one by us (M-2). Micronal® DS 5008 sample has been used extensively in concrete, gypsum, lime plaster, and gypsum plaster, without being fully characterized for fire hazards. The comparison includes fire retardancy and gas emission released to environment from upon fire. It is important to establish a characterization methodology, which will include both volatile emission measurements and nano-indentation technique to measure the shell mechanical strength of the microcapsules. This is very important issue in the selection of PCM products, especially for use in building application. PCM microcapsules should have high phase change enthalpy, uniform spherical shape, acceptable thermal stability, good mechanical properties, and low release of hazardous gases in the form of volatile organic compounds.

MATERIALS AND METHODS

Materials

The chemical preparation of microcapsules required the following reagents:

- Shell: Methyl methacrylate (MMA) (99%, contains $\leq$ 30 ppm monomethyl ether hydroquinone (MEHQ) as inhibitor, Sigma Aldrich, Auckland, New Zealand) and pentaerythritol tetraacrylate (PETRA) (contains 350 ppm (MEHQ), Sigma Aldrich, Auckland, New Zealand) were used as a monomer and cross-linking agent respectively in order to obtain proper shells for MPCM.
- Free radical thermal initiator: Luperox® A75, Benzoyl peroxide (BPO) (75%, contains 25% water, Sigma Aldrich, Auckland, New Zealand) was used as free radical thermal initiator.
- Surfactants: Polyvinyl alcohol (PVA) (M_w 85,000–124,000, Sigma Aldrich, Auckland, New Zealand) and sodium dodecyl sulfate (SDS) (BioXtra, 99%, Sigma Aldrich, Auckland, New Zealand) were used as a non-ionic and ionic surfactant, respectively.
- PCM: a commercial paraffinic PCM, Rubitherm® RT 21 (T_m = 21 °C,

ΔH_m = 135 J·g^{-1}, Rubitherm® Technologies GmbH, Berlin, Germany) was used.

The bulk density of M-2 microcapsules is 0.496 g·mL^{-1}. The commercial MPCM, Micronal® DS 5008 X (BASF®), was also selected for characterization and was compared with the microcapsules produced in this work. This sample is also composed by an acrylate shell and organic PCM in the core [13], and its bulk density is 0.445 g·mL^{-1}.

Synthesis of PCMs Microcapsules

Emulsification

A standard procedure was used as reported elsewhere [61]. Wherein, an aqueous solution of surface-active agent (called aqueous phase) and a mixture of MMA, PETRA, BPO, and PCM (called organic phase) were prepared separately. The organic phase was added to the aqueous phase and emulsified mechanically using a high shear mixer (Silverson L5M-A laboratory Mixer, Silverson LTD, East Longmeadow, MA, USA). A stirring rate of 3000 rpm for 5 min was chosen to achieve the required emulsification.

Polymerization

The produced emulsion was transferred to a 2-L four-neck glass reactor (LR-2.ST laboratory reactor-IKA-Werke, Gmbh@Co.KG, Staufen, Germany) consisting of EUROSTAR 200 control P4, Anchor stirrer LR 2000.1, HBR 4 digital heating bath. The agitation speed was set at approximately 300 rpm, and the temperature of the water bath was maintained at 70 °C for 2 h, and then adjusted to 85 °C for another 4 h. The water bath was then switched off and allowed to cool down naturally to room temperature. After cooling, the suspension of PCM microcapsules was transferred to a clean glass beaker and washed three times with distilled water to remove the unreacted monomers and the non-encapsulated PCM. The separated microcapsules were spread on a tray and placed in an oven at 50 °C for 48 h for drying. The dried microcapsules were then collected for testing.

CHARACTERIZATION OF MICROCAPSULES

Scanning Electron Microscopy (SEM)

To study the shape and size of microcapsules SEM was used (a FEI Quanta 200 FEG-Field Emission Gun with an EDS Detector SiLi (Lithium drifted) with a Super Ultra-Thin window, FEI Company, Hillsboro, OR, USA). The sputter

coater used was a Quorum Q150RS (FEI Company, Hillsboro, OR, USA), and it is designed to give an appropriate thin, slight metal coating proper for SEM observation, using Pt as a target. The coating thickness and uniformity of the sample depends on different factors: distance between sample and target, topography of the sample, and affinity of the material with the metal coating.

Differential Scanning Calorimetry (DSC)

Phase change properties of the fabricated PCM microcapsules and the pure PCM (such as melting and solidification temperatures and their phase change enthalpies) were determined using a SHIMADZU DSC-60 differential scanning calorimeter (Shimadzu Company, Kyoto, Japan). The measurements were performed by varying the temperature between −15 °C and 40 °C with heating and cooling rate of 3 °C·min^{-1}. Each sample was analyzed for three times and the average was taken. Consequently, the percentage PCM encapsulated can be determined using DSC results and the following Equation (1) [62,63]. The mass content obtained by DSC measurements does not provide accurate measure of the core mass content. Equation (1), which was used to estimate the mass content from DSC measurements, does not take in account the sensible heat of coating materials. The TGA method provides more accurate measure of the core material mass content than DSC. In our previous publication [63] the core material mass content of sample M-2 obtained by TGA is 77.5 wt%, which is less than the one obtained by DSC.

$$\%\ \text{PCM in microcapsules by mass} = \Delta H_{\text{microcapsules}}/\Delta H_{\text{Pure PCM}} \times 100\% \quad (1)$$

where $\Delta H_{microcapsules}$ (J·g^{-1}) is the latent heat of the microcapsule containing PCM; and $\Delta H_{purePCM}$ (J·g^{-1}) is the latent heat of pure PCM (before encapsulation). In Equation (1), it is assumed that the latent heat of the microcapsule without PCM is zero, which is true if phase change does not occur in the shell does.

Nano-Indentation Technique

To characterize the mechanical properties of M-2 and commercial Micronal® DS 5008 X samples, a nano-indentation technique was used. Nano-indentation is identified as an appropriate technique to test the strength of individual microcapsules [64]. MTS Nano Indenter XP (MTS Company, Eden Prairie, MN, USA) was the instrument used. Aluminium stubs of 20 mm height and 30 mm diameter were needed to stick the samples at the top to characterize them using a red glue to stick the samples as shown in Figure 1. The instrument parameters were set the same for the two studied samples for a more accurate comparison.

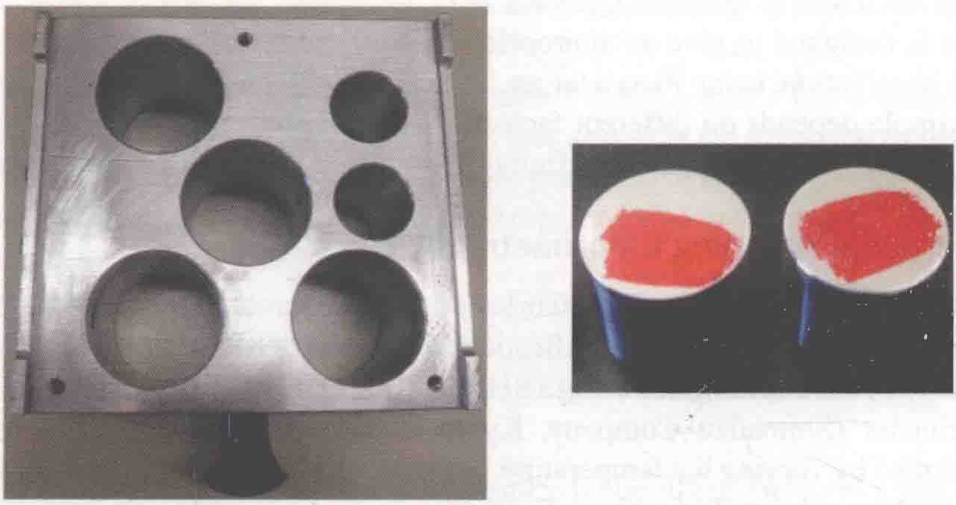

Figure 1: Holder and aluminum stubs with the sample over the red glue.

There are some required inputs to set before starting the experiments: strain rate target of 0.05 s^{-1}, allowable drift rate of 0.05 $nm \cdot s^{-1}$, a Poissons' ratio of 0.18 for the tip indenter [65,66] a peak hold time of 10 s, a surface speed of 10 $nm \cdot s^{-1}$, 25% of surface approach sensitivity, 90% to unload, an approach distance to store of 1000 nm, a surface approach distance of 1000 nm, and finally, a depth limit of 5000 nm.

To determine the elastic modulus (E) of the studied samples, a Berkovich tip TB-13288 (Micro Star Technologies, Huntsville, TX, USA) was used. The use of nano-indentation for the characterization of mechanical properties of materials has been extensively studied by several authors. Oliver and Pharr developed extensively the methodology for characterizing ceramic materials [66,67]. They described the typical load *vs.* displacement curve, where increasing the load (P) increases the displacement (h) until reaching a maximum load (P_{max}) and a maximum displacement (h_{max}). Following that, the indenter is removed out of the material (unloading section), the load will be zero, and the final displacement (h_f) will be measured. After that, the E value for each sample can be calculated. Hochstetter *et al.* [68] presented results for glassy polymers and Giro-Paloma *et al.* [69] compared both methodologies using continuous stiffness measurement (CSM) by applying a small oscillation to the quasi-static component of loading using different thermoplastics suitable as containers for PCM. They concluded that Loubet's method produce lower values of H and E because it uses a dynamic approach for stiffness measurements and the contact depth is larger due to the contribution of the apparent tip effect. In the light of these findings, it was concluded that Loubet's method should be used only with polymeric materials having a low viscous character ($T_g > T_{measurement}$).