Applied Energy 139 (2015) 43–55

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Utilization of macro encapsulated phase change materials for the development of thermal energy storage and structural lightweight aggregate concrete

Shazim Ali Memon [a,b,*], H.Z. Cui [a,*], Hang Zhang [a], Feng Xing [a]

[a] Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, College of Civil Engineering, Shenzhen University, China
[b] Department of Civil Engineering, COMSATS Institute of Information Technology, Pakistan

HIGHLIGHTS

- Compressive strength of LWAC with Paraffin–LWA was higher than 15 MPa.
- Shrinkage strain with Paraffin–LWA reduced by 41.8%.
- For outdoor testing, temperature at room center with Paraffin–LWA reduced by 2.9 °C.
- Recovery period with Paraffin–LWA was less than average life span of building.
- A reduction of 465 kg CO_2-eq/year or 12.91 kg CO_2-eq/year/m^2 was achieved.

ARTICLE INFO

Article history:
Received 14 June 2014
Received in revised form 26 September 2014
Accepted 10 November 2014

Keywords:
Phase change material
Macro encapsulation
Thermal energy storage concrete
Lightweight aggregate concrete
Thermal performance

ABSTRACT

Structural–functional integrated materials are one of directions of rapid development for saving-energy materials. Phase Change Materials (PCMs) are latent thermal storage materials possessing a large amount of heat energy stored during its phase change stage. Porous lightweight aggregate (LWA) can serve as the carrier for PCM. In this research, a structural concrete with function of indoor temperature control were prepared by using macro encapsulated PCM–LWA. The indoor and outdoor tests were performed to determine the thermal performance of the lightweight aggregate concrete (LWAC) containing macro encapsulated Paraffin–LWA. The compressive strength and shrinkage strain of LWAC with macro encapsulated PCM–LWA were evaluated. Finally, the economic and environmental aspects of application of macro encapsulated Paraffin–LWA in a typical floor area of public housing rental flat in Hong Kong were assessed.

From indoor thermal performance test, it was found that LWAC incorporated with macro encapsulated Paraffin–LWA has a function of reducing the energy consumption by decreasing the indoor temperature; flatten the fluctuation of indoor temperature and shifting the loads away from the peak periods. Moreover, from outdoor thermal performance test, it was found that the performance of macro encapsulated Paraffin–LWA in adjusting the room temperature was optimized when there was a remarkable temperature difference between the day and night. Test results showed that the compressive strengths of LWAC incorporating macro encapsulated Paraffin–LWA at 28 days was higher than control LWAC (without macro encapsulated Paraffin–LWA) and was found to be over 15 MPa. The shrinkage strain reduced with the incorporation of macro encapsulated Paraffin–LWA in LWAC and therefore has a beneficial effect on the volume stability of LWAC. From simple economic evaluation of macro encapsulated Paraffin–LWA in a typical floor area of public housing rental flat in Hong Kong, the recovery or payback period was found to be less than the average life span of a residential building in Hong Kong. Therefore, incorporation of macro encapsulated Paraffin–LWA in LWAC building walls is economically feasible. Finally, from environmental prospect, a reduction of 465 kg CO_2-eq/year or 12.91 kg CO_2-eq/year/m^2 was achieved. This

Abbreviations: LWA, lightweight aggregate; LWAC, lightweight aggregate Concrete; MIP, mercury intrusion porosimetry; SEM, scanning electron microscopy; PCM, phase change material; OR, outer surface; IR, inner surface; $W_{LWA-PCM}$, weight of LWA with Paraffin; W_{LWA}, oven dried weight of LWA; η, the mass percentage of Paraffin in LWA; ΔH_{comp}, measured latent heat of macro encapsulated Paraffin–LWA; ΔH_{pcm}, measured latent heat of pure Paraffin respectively.

* Corresponding authors at: Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, College of Civil Engineering, Shenzhen University, China. Tel.: +86 755 26733213 (S.A. Memon), tel.: +86 755 26916424 (H.Z. Cui).

E-mail addresses: shazim@ciit.net.pk, shazimalimemon@gmail.com (S.A. Memon), h.z.cui@szu.edu.cn (H.Z. Cui).

http://dx.doi.org/10.1016/j.apenergy.2014.11.022

reduction would contribute to mitigate Greenhouse Gases emissions over the life span of building. It can therefore be concluded that the developed macro encapsulated PCM LWAC can be used for thermal and structural applications in buildings.

1. Introduction

Concrete is the most widely used construction material with annual production of around 11 billion metric tonnes. Man consumes no material except water in such tremendous quantities [1]. The large thermal mass of the concrete walls can be advantageous especially in moderate climates where it can be used to store energy during the day and release it during night time therefore reducing the need for auxiliary cooling and heating [2]. The energy storage capacity of concrete can further be enhanced by the incorporation of PCM into the concrete mixtures. Thermocrete, a PCM enhanced concrete, combines an appropriate PCM with a concrete matrix producing concrete with structural and thermostatic properties [3,4]. Concrete is considered suitable for incorporation of PCM because (a) they are most widely used construction materials; (b) they can be formed into a variety of shapes and sizes; (c) they have larger heat exchange area and smaller heat exchange depth; (d) production and quality control can be easily achieved; (e) ease of testing, etc. [5]. Some of the other advantages of incorporating PCM in concrete are (a) it can be used to reduce temperature rise of a massive concrete section to minimize thermal cracking during curing [2]; (b) it can be used extend the service life of bridge decks by reducing the freeze/thaw damage [6].

The PCM can be incorporated in concrete by direct incorporation and immersion [2,6–8], form-stable composite PCM [9,10] and encapsulation [11–16]. For the direct incorporation and immersion technique, which are most practicable and economical, the leakage of PCM especially after large number of thermal cycling may interfere with the hydration products and may also affect the mechanical and durability properties [17–20]. To overcome the leakage issue, many form-stable composite PCMs were developed [21–24]. In form-stable composite PCM, the PCM after being confined into the porous media is utilized to produce thermal energy storage mortar or concrete. However, the incorporation of form-stable composite PCM has been found to affect the mechanical properties of cement based composites [9,10]. Moreover, the PCM sticking to the surface of form-stable composite PCM may interfere with the hydration products. For example in Zhang et al. [10] research, the incorporation of only 2.5 wt% of n-octadecane/expanded graphite composite PCM in cement mortar reduced the compressive strength by 55%. In order to overcome some of the above issues, researchers have successfully developed micro encapsulated PCM [13–16,25–29]. Hunger et al. [13] incorporated different percentages of micro encapsulated PCM (1%, 3%, 5%) in self compacting concrete and found that micro encapsulated PCM significantly improved the thermal performance of concrete. However, the incorporation of just 5% PCM reduced the compressive strength by up to 69%. The reduction in compressive strength of concrete incorporating micro capsule is due to (a) significant disparity between the intrinsic strength of the microcapsules and the concrete constituents and (b) damage of micro capsules during mixing resulting in leakage of PCM and subsequent interference with the surrounding matrix [13]. Due to these reasons, macro encapsulation with strong shell is preferred. Zhang et al. [11,12] developed thermal energy storage concrete by incorporating PCM in porous LWAs. Thermal energy storage aggregates (expanded clay, normal clay and expanded shale aggregates) were prepared with vacuum impregnation technique. Test results showed that the maximum absorption of PCM by porous aggregates was 68 wt%. It was found that porous aggregates and PCM are chemically compatible, have large thermal energy storage density and are feasible for large scale processing. However, the following issues still need to be addressed.

(a) The indoor and outdoor tests were not performed to evaluate the thermal performance of macro encapsulated PCM in concrete.
(b) Macro encapsulated PCM embedded in concrete, may affect the compressive strength of resulting concrete. Furthermore, the literature on the mechanical properties of concrete incorporating macro encapsulated PCM is scarce.
(c) No data is available on the shrinkage of concrete incorporating macro encapsulated PCM.
(d) An economic and environmental assessment/analysis of the application of macro encapsulated PCM in buildings have never been documented.

Therefore, in order to address these issues, we focused on the application of macro encapsulated Paraffin–LWA in LWAC. The compressive strength and shrinkage strain of thermal energy storage LWAC were evaluated. Moreover, indoor and outdoor tests were carried out to evaluate the thermal performance of LWAC containing macro encapsulated Paraffin–LWA. The economic feasibility of application of macro encapsulated Paraffin–LWA in a typical selected floor area for public housing rental flat in Hong Kong was assessed. Finally, the reduction in CO_2-eq/year for this selected flat was determined.

2. Experimental investigation

2.1. Materials, preparation and characterization of the developed macro encapsulated Paraffin–LWA

Technical grade Paraffin (procured from China) having latent heat storage capacity of 149.1 J/g was used as PCM, a synthetic LWA manufactured from expanded clay (Table 1) was used as container for PCM while epoxy resin adhesive and hardener complying

Table 1
Physical properties and chemical composition of LWA.

Density	600 kg/m^3
Porosity (MIP)	77.75%
Water absorbing capacity by simple immersion (1 h)	18%
Water absorbing capacity by vacuum immersion (1 h)	73.85%
Chemical composition	*(%)*
Silicon dioxide (SiO_2)	53.39
Aluminum oxide (Al_2O_3)	21.50
Iron oxide (Fe_2O_3)	15.84
Potassium oxide (K_2O)	2.56
Calcium oxide (CaO)	2.30
Magnesium oxide (MgO)	1.42
Titanium dioxide (TiO_2)	1.17
Manganese oxide (MnO)	0.80
Sulfate as SO_3	0.58
Sodium oxide (Na_2O)	0.43