International Journal of Smart Grid and Clean Energy

Functionality assessment of concrete containing a dual-layer coated macro-encapsulated PCM

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Abstract

In this study, a structural lightweight concrete with function of indoor temperature control was developed by using thermal energy storage aggregates (TESA). TESA was made of porous structural lightweight aggregate (scoria) impregnated with liquid phase change material (PCM) and was coated with epoxy resins and mineral admixtures. TESA concrete mixes were prepared by substituting coarse aggregates with varying amounts of TESA. The properties of TESA concrete were investigated through thermal performance and water absorption analyses. The results concluded that the concrete with macro-encapsulated PCM can be used to improve the thermal performance of building, particularly during the summer the energy consumption for cooling can be significantly reduced. It was found that PCM in LWA was appropriately encapsulated and did not have negative impact on the properties. The coating materials covered the surface of porous aggregates significantly resulted in the reduction of permeability.

Keywords: Dual-layer coating, Phase change Materials, Macro-encapsulation, Thermal energy storage aggregate

1. Introduction

The rapid world economic growth has led to an increase in the energy consumption. The fossil fuels dominate the world energy market, with a share of about 81% [1, 2]. However, not only are the fossil fuels running out and present high costs, but its use is also associated with the emission of detrimental gases into the environment [3, 4]. Consequently, application of the efficient energies and the feasibility of using renewable energy sources become significant ever more. The energy efficiency of buildings is now one of the principal targets for energy policy at regional, national and international levels [5]. Buildings are one of the leading sectors in energy consumption in developed countries. According to the information from the Government of South Australia [6], the most energy used in a typical Australian home is for heating and cooling, which is 38% of the total energy use.

Embedding phase change materials (PCMs) in a concrete matrix has been considered as a means to enhance energy efficiency of buildings [7] and to reduce the risk of thermal cracking [8]. PCMs are able to store or release thermal energy in the form of latent heat through a reversible phase transition between solid and liquid states, actions which superimpose onto the sensible heat capacity of the concrete [9]. The aim of implementing composite PCM building elements such as walls is to substantially decrease and time-shift the maximum thermal load on the building in order to subtract and smooth out the electricity demand for heating and cooling.

Cement mortar and concrete as cementitious materials are most widely used construction material and not only does incorporation of PCM into cementitious materials enhance the thermal energy storage (TES) capacity of this popular building material, but also facilitates energy conservation and savings in buildings [10, 11]. Among the wide variety of cementitious materials, concrete is one of the well-known construction material which its large thermal mass can be advantageous for reduction of the heating and

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doi: 10.12720/sgce.8.5.517-521

cooling energy demands in buildings. TES capacity of concrete can be also further improved by the incorporation of PCM into concrete. Incorporation of PCM in construction materials should be selected properly to mitigate the problems associated with the application of these materials.

Several application methods has been applied to foster the TES capacity of cement-based materials with PCM. A direct impregnation method that involved directly mixing the cementitious composite with PCMs was initially adopted to develop TES concretes. Nonetheless, in practice, leakage of PCMs during phase transition will happen should they are employed directly in building materials without being encapsulated [1]. To overcome these issues, encapsulation techniques such as micro and -macro encapsulation are introduced into cementitious composites. For such methods, the encapsulated PCM by polymer shells or porous supporting materials are either replaced for aggregates or added as cement admixture in cementitious composites.

A large usage of micro-/nano-encapsulated PCM is of a higher cost and has an obvious adverse effect on the mechanical strength or thermal conductivity of the resulting building materials [12]. In contrast, macro-encapsulated PCM stored into comparatively larger form factors can be applied into building elements without influencing the structural function of these elements in buildings [13, 14]. Macro-encapsulated PCMs usually allows a higher content fraction of PCM to be incorporated into construction materials and also permit a higher encapsulation ratio of PCM [14]. Over the last few years, macro-encapsulation method has received great research attention due to its major merits of easily and low-cost production and direct use in concrete as aggregates or elements. For buildings, the macro-encapsulated PCM can be incorporated into the building wall as a thermal storage layer. Different macro-encapsulation techniques including polymer encapsulation [15] and impregnation into porous aggregates [16] were widely investigated for integration into cement-based materials. However, the main shortcomings of this macro-encapsulation method are associated with its low thermal conductivity and PCM leakage problems.

In this research, a novel dual-layer coating system is introduced. The first layer of coating consists of a mixture of epoxy resins which is directly applied to the surface of aggregate aiming to prevent the loss of PCM from the aggregate. The second layer of coating is made of silica fume as a mineral admixture aiming to improve the interfacial transition zone (ITZ) and thermal conductivity. The effectiveness of this coating system will be verified by thermal performance and water absorption tests.

2. Experimental Procedure

In the current study, the integration of PCM into structural-functional concretes was experimentally investigated. Scoria as a lightweight aggregate (LWA) having density 1581 kg/m^3 and porosity of 60% was used as the container for PCM. Commercial PCM with a melting temperature of 22 ℃ was used as the PCM. It is believed that PCM with such melting temperature is suitable for achieving good temperature control in moderate climates. TESA was prepared using vacuum impregnation method. After impregnation, epoxy resin adhesive and hardener, were used to coat the surface of TESA to prevent the loss of PCM from the aggregate. Moreover, silica fume was used to separate the PCM-LWA particles after epoxy coating. Ordinary Portland cement complying with AS2350.2-1991 was used in all mixtures. River sand and crushed granite with the same density of 2600 kg/m^3 were used as the fine aggregate and coarse aggregate. Furthermore, a locally available superplasticiser was used to attain the required workability of concrete mixes. Five mixes were designed for the investigation. The control sample is containing normal aggregates without any PCM. The abbreviations for labelling specimens were adopted in such a way that the letters LWA and TESA stand for samples with lightweight aggregate and thermal energy storage aggregates, respectively. The number before the letters shows the percentage of materials replaced into the mixture. All the mixtures were designed for a constant water cement ratio of 0.35. The details of the mix proportions are given in Table 1. Thereafter, the mixing procedure and casting the samples were carried out according to the explained procedure discussed in previous article [17]. The specimens were de-molded after 24 h and keep in the fog room at 23 ± 3℃ until they were tested. The water absorption of the 10*20^{cm} cylindrical specimens were determined as per AS1012.21 after 28 and 90 days of curing.

Table 1. Mix proportion of samples (kg/m^3)

Mix Code	Cement	Fly ash	Water	Sand	Normal aggregate	Lightweight aggregate	TESA
Control	300	70	140	780	1080	0	0
50LWA	300	70	140	780	540	330	0
100LWA	300	70	140	780	0	660	0
50TESA	300	70	140	780	540	0	346
100TESA	300	70	140	780	0	0	692

Five different room models with dimensions of 200 x 200 x 200 mm^3 were placed together inside a self-designed environmental chamber with an internal dimension of 1000 x 1000 x 1000 mm^3 [17]. Type K thermocouples (±0.3℃ resolution) were placed in each room model at three different positions (outer and inner surfaces of the concrete panel, and the centre of the room) for temperature measurements. An additional thermocouple was placed at the centre of the environmental chamber (the area to which the concrete panels were exposed) to measure the environmental temperature. The internal temperature of the chamber was raised and lowered by the portable air conditioner. Consequently, the thermal responses of the different panels under different temperature conditions were measured with temperature cycles between 15℃ and 35℃ at a ramping rate of 0.04℃/min, which could also be assumed as a typical summer daily temperature variation in Australia. Temperature measurements were recorded by a data-logger at a frequency of 30 s.

3. Results and Discussion

The water absorption results of specimens have been shown in Fig. 1. As the figure indicates, the presence of LWA increased the absorption of concretes by about 42% and 52% in 50LWA at 28 and 90 days, respectively and by about 93% and 128% at 28 and 90 days, respectively in 100LWA compared to the control sample. This expectable increased absorption is mainly due to the porous nature of LWA. Although the replacement of TESA increased the water absorption compared to the control sample, it was decreased in comparison to the samples with same level of LWA. The reduction of the water absorption in specimens with macro-encapsulated TESA can be attributed to the coating material, i.e., epoxy and inclusion of silica fume as a layer of coating material [18]. The coating materials covered the surface of porous aggregates resulted in the reduction of permeability. Thus, it can be concluded that PCM in LWA was encapsulated properly.

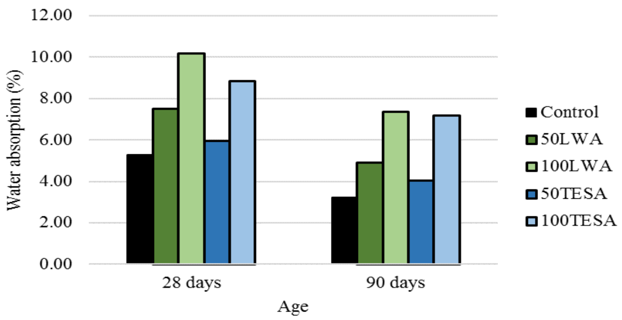

Fig. 1. Water absorption of samples with and without macro-encapsulated PCM-LWA

The thermal performance of concrete panels with and without PCM-LWA were assessed via monitoring the temperature variation at the centre of the panels during a period of 9 h tests which are plotted in Fig. 2. In comparison with the control sample, the room with TESA concrete panel indicated a lower indoor temperature during the heating and cooling process. The maximum temperature values were 25.3, 25 and 24.3 ℃ for the control, 50TESA and 100TESA, respectively. It can be inferred from the results that part of the heating load has been taken by the PCM macro-encapsulated in the LWA.

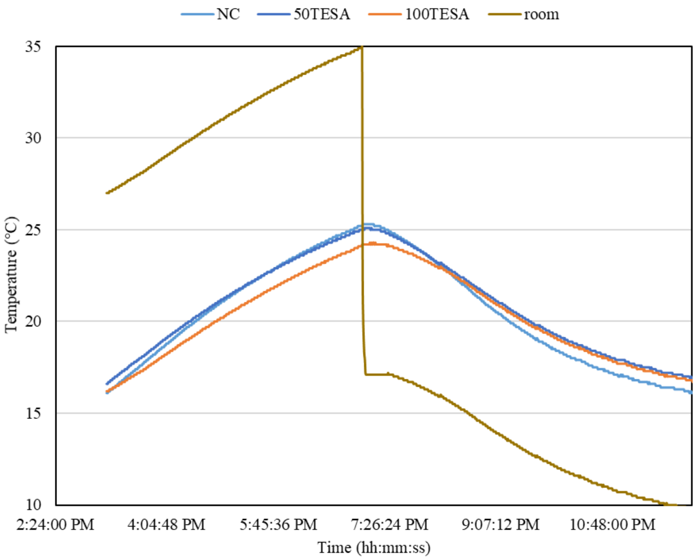

Fig. 2. Thermal performance of concretes

It can be confirmed that macro-encapsulated TESA is capable of reducing the indoor temperature fluctuations, thus TESA has the ability to reduce the energy consumption by decreasing the indoor temperature and shifting the loads away from the peak periods, and the implication of functional integrated concrete on economic impact, environmental sustainability, and quality of life is expected to be significant.

4. Conclusion

According to the experimental test results, the conclusions of this study are as follows:

- Water absorption of specimens with TESA (macro-encapsulated PCM) reduced compared to the mixtures with same level of LWA.
- From water absorption results, it can be concluded that PCM in LWA was appropriately encapsulated and did not have negative impact on the properties. The coating materials covered the surface of porous aggregates significantly resulted in the reduction of permeability.
- From the thermal performance tests, it can be inferred that macro-encapsulated TESA was capable of reducing energy consumption by decreasing the indoor temperature and shifting the loads away from the peak periods.

Acknowledgement

The work described in this paper was supported by the Australian Research Council Discovery Project (No.: G1500225).

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