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Optimizing mix proportion and properties of lightweight concrete incorporated phase change material paraffin/recycled concrete block composite

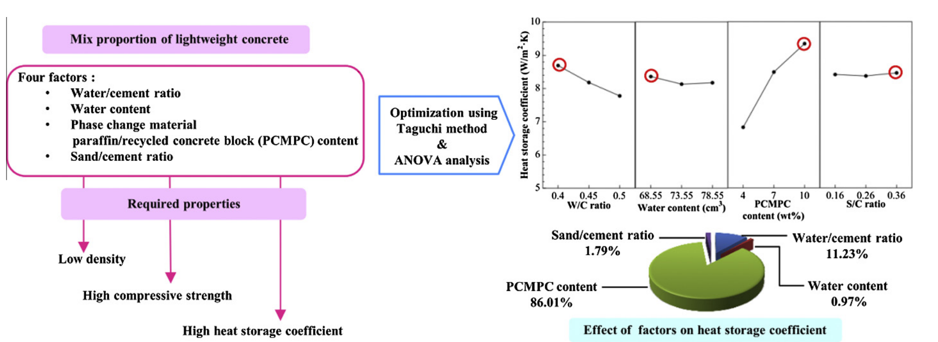
Pattaraporn Suttaphakdee [a], Nattakan Dulsang [a], Narubeth Lorwanishpaisarn [a], Pornnapa Kasemsiri [a,*], Patcharapol Posi [b], Prinya Chindaprasirt [c]

[a] Sustainable Infrastructure Research and Development Center and Department of Chemical Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand
[b] Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology, Isan Khon Kaen Campus, Khon Kaen 40000, Thailand
[c] Sustainable Infrastructure Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand

HIGHLIGHTS

- Mix proportions of LWC were designed by Taguchi method.
- Multi-linear regression models were developed to predict properties of samples.
- The concrete can be classified as structural LWC for structure.
- Thermal performance of LWC substantially improves by addition of PCMPC.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, the phase change material paraffin/recycled concrete block composite (PCMPC) was prepared and used as fine aggregate in manufacturing of lightweight concrete (LWC). The mix proportions of LWC were designed using Taguchi method. L_9 orthogonal array with four factors viz., water/cement (W/C) ratio, water content, PCMPC content and sand/cement (S/C) ratio were selected for the optimization of LWC. The most important factors influencing the properties of LWC were investigated using analysis of variance (ANOVA). Based on the results, the phase transition and latent heat of PCMPC showed good thermally reliable and chemically stability after thermal cycling test. The density and compressive strength of samples containing the PCMPC were in the range of 1711–1812 kg/m^3 and 33–53 MPa, respectively. The density and compressive strength of samples can meet the requirement of lightweight concrete for structure application according to ASTM C330/C330M-14. The results also showed that PCMPC was the most significant factor for heat storage coefficient. The thermal energy absorption and release characteristics of LWC containing PCMPC were significantly better than those of the control sample. The fine PCMPC aggregate is thus another novel building material for use in thermal conditioning of building which can reduce and save electricity consumption.

1. Introduction

One of the most important renewable energy is solar energy. It has been used for various applications such as of solar-thermal,

* Corresponding author.
E-mail address: pronkas@kku.ac.th (P. Kasemsiri).

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solar-electrical and solar-chemical conversion [1–5]. Recently, solar thermal applications have attracted much attention due to their high photo-thermal conversion efficiency [6,7]. However, the solar thermal system has some limitations from seasonal and climate variation. To overcome this problem, phase change materials (PCMs) have been developed to store thermal energy collected from solar radiation [8,9]. PCMs are considered as the most effective materials for thermal energy storage, and have been applied for wide application in energy conservation [10,11]. PCMs can absorb and release latent heat during a phase change process i.e. solid to solid or solid to liquid over a narrow temperature range [12–14]. Many researchers have shown that PCM based paraffin has excellent properties i.e. large amount of heat storage, high latent heat storage capacities in the range of 200–250 J/g and good thermal and chemical stability [1,10,15–17]. However, the application of paraffin is limited to certain area due to the leakage of paraffin during phase transition. To overcome this problem, the compounding paraffin with porous materials to obtain form-stable composite PCM is applied [12,18]. Various types of building materials such as diatomite [1,19,20], calcined diatomite [10], cement paste [21], expanded perlite [21], gypsum [22] have been tried as supports for paraffin form-stable composite PCM. The recycling of waste from building structure such a recycled concrete block was also used as support material for paraffin impregnation. The optimum adsorption ratio of paraffin in recycled concrete block was 25 wt% which produced phase transition temperature of 52.85 °C and latent heat of 30.88 J/g. These thermal properties are comparable with other form-stable PCMs. The form stable PCMPC composite is thus a promising PCM for energy storage with ecological utilization of building waste [23].

Form-stable PCM has been widely used for building applications [1,22,24,25]. The incorporate the PCM in building can enhance human comfort by reducing the frequency of internal building temperature swings and keeping the desired temperature for a long period [26–28], improving energy conservation and saving electric energy [29]. Ramakrishnan [25] studied expanded perlite coated with silicone as a support for paraffin impregnation. The modified expanded perlite containing paraffin up to 50 wt% showed a good leakage prevention during phase change process and the thermal energy storage and reliability of panel incorporating paraffin/modified expand perlite was significantly improved. The addition of PCM paraffin/diatomite composite can improve the overall thermal properties such heat capacity and thermal conductivity [24]. The presence of paraffin in cementitious composite can also decrease the thermal conductivity with some effects on the mechanical properties. The maximum reductions in compressive and flexural strengths with incorporation of PCM composite are almost 50% [2].

Generally, the main factors affecting the targeted properties of cementitious composite depend on the mixtures such as W/C ratio, S/C ratio and aggregate content [30–33]. It is a daunting task to investigate all parameters in a particular experiment. Therefore, a suitable design of experiment method (DOE) can take into account some of the factors. Taguchi experiment design is one of the most famous methods for designing the optimum concrete proportions with minimum number of experiments. This approach can determine the effective parameters on the properties of concrete [30,31]. Taguchi's method has been successfully used to develop the modern construction material such as LWC [32,33]. In comparison with ordinary concrete, LWC shows some excellent properties such as low density, high specific strength and great thermal insulation. LWC is used to reduce the unit weight and dead weight of a structure by replacing the conventional aggregate with lightweight aggregate. The application of LWC in construction industry offers many advantages i.e. high strength/weight ratio, saving in dead load for structural design and foundation, superior heat and sound insulation characteristics, low thermal conductivity and good durability [32,34,35].

Currently, there is no information about the optimization of mix proportion of LWC integrated with PCMPC. Therefore, this research aims to use the PCMPC as fine aggregate to produce LWC. The mix proportions of LWC are designed by Taguchi's method. The thermal energy storage and thermal reliability of PCMPC are studied. The heat storage coefficient, thermal conductivity, and physical and mechanical properties of the LWC are also studied.

2. Materials and methods

2.1. Materials

Commercially available Ordinary Portland cement (OPC) and paraffin from Chemipan Co. Ltd., Thailand were the materials used. Recycled concrete block was supplied from Concrete Precision Unique Co. Ltd., Thailand. The concrete block was crushed to fine particles. The fine particle was then passed sieve No. 8 and retained on sieve No. 16 to obtain a single size fine aggregate of 1.19–2.38 mm. The PCMPC used in this work was prepared by impregnation method. The melted paraffin was impregnated into recycled concrete block by continuous mixing with overhead stirrer at 120 rpm for 30 min with a vacuum pressure of 80 kPa [23]. The 25 wt% paraffin impregnation level was optimum and was thus used to prepare fine aggregate for LWC. The physical properties of materials are concluded in Table 1.

2.2. Mix proportions

The four factors viz., W/C ratio, water content, PCMPC content and S/C ratio with three level each were used for the optimization of LWC as summarized in Table 2.

The mix proportions of LWCs were derived from L_9 orthogonal array as shown in Tables 3 and 4. For mixing of LWC, cement and sand were first mixed for 1.5 min to obtain homogenous mixture. Then, water was added and the mixing was done for 1.5 min. In the final step, PCMPC was added and mixed for another 1.5 min. The fresh mixtures were cast in steel molds. The samples were covered with damped cloth and plastic sheet and left in a controlled 25 °C room for 24 h before demoulding. The obtained samples were wrapped with cling film and kept in a controlled 25 °C room. At the age of 28 days, the samples were tested for density, compressive strength, thermal conductivity, heat storage and thermal performance under heating and cooling systems.

2.3. Characterization of thermal and chemical stability of PCMPC

The thermal cycling test consisted of 150 melting and freezing cycles using thermal cycler (Biometra T1 Thermocycler, Whatman Biometra, UK). The sample was placed in plastic tube connected to thermocouple. Water at a constant temperature of 80 °C was circulated for melting process through the tube. After that, the sample was immediately subjected to solidification process by circulating water at a constant temperature of 5 °C. The thermal and chemical stability of sample after thermal cycling were investigated by Differential scanning calorimeter (DSC) and Fourier transform infrared (FTIR). The temperature of melting and freezing and latent heat were analyzed by DSC (Perkin Elmer Diamond) at a heating rate of 5 °C/min under nitrogen atmosphere. The chemical structures of sample were determined using Bruker Tensor 27 spectrometer in the range of 4000–650 cm^{-1}. All spectra were recorded as a function of time with 64 scans at a resolution of 4 cm^{-1}.