Construction and Building Materials 110 (2016) 201–210

Contents lists available at ScienceDirect

Construction and Building Materials

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

Development and optimisation of phase change material-impregnated lightweight aggregates for geopolymer composites made from aluminosilicate rich mud and milled glass powder

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HIGHLIGHTS

- PCM vacuum impregnation is very successful for expanded clay lightweight aggregate.
- Polyester resin coating is able to retain all of the impregnated PCM from leakage.
- Resin coating is chemically stable and neutral, also improving thermal conductivity.
- Novel combination of geopolymer and thermal energy storing aggregates evaluated.
- ME-LWA has a high energy storage capacity of 157 J/g.

ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 24 December 2015
Accepted 10 February 2016
Available online 17 February 2016

Keywords:
Geopolymer
Alkali-activated
Mining waste
Lightweight aggregate
Expanded clay aggregate
Thermal conductivity
Phase change material
Paraffin
Impregnation
SEM

ABSTRACT

Macro-encapsulated aggregates (ME-LWAs) consisting of expanded clay lightweight aggregates (LWAs) impregnated with a paraffin wax phase change material (PCM) was produced. To fully exploit the thermal energy retaining properties of PCM, it is fundamental to retain as much of the PCM as possible within the pores of the LWA. This paper investigates 3 different commercial materials to create a total of 14 different coating regimes to determine the most efficient coating method and material regarding its ability at retaining the PCM. The ME-LWAs are then further used as aggregates in geopolymer binders made from a combination of aluminosilicate rich mud and waste glass. Physical properties such as thermal conductivity and mechanical strength are determined for the geopolymer binder with and without the addition of the ME-LWA. A polyester resin was determined to be the most suitable choice of coating material for the ME-LWA, producing a practically leak-proof coating. The ME-LWA was also determined to be chemically neutral, showed a 42% higher thermal conductivity than the LWA in their raw state and maintained a latent heat of 57.93 J/g before and after being used in the geopolymer binder. Carbon fibres and graphite spray were used to improve the thermal conductivity of the resin coating, however no significant increase was detected. Finally, the compressive strength and thermal conductivity results achieved are acceptable for applications in buildings for enhancement of their energy efficiency.

1. Introduction

In our current time, large proportions of energy are still supplied from the exploitation of fossil fuels that are finite natural resources. Exploitation and usage of fossil fuels bring a negative impact on the environment. In response to this, different techniques have been studied related to space cooling and heating in buildings to improve their energy efficiency using 'active methods' [1–3]. It is also evident that more focus should be placed on the use of renewable energy sources that reduce environmental pollution and, at the same time, improve our quality of life [4]. According to the European Commission, buildings account for 40% of EU final energy demand, and the Horizon 2020 EU Framework Programme for Research and Innovation has made it a priority to deliver innovative, affordable and applicable technologies for energy efficiency for building envelopes [5]. The initiative aims to reduce the total primary energy consumption of a building by at least a factor of 2, with great emphasis being placed on the

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http://dx.doi.org/10.1016/j.conbuildmat.2016.02.029

development of prefabricated components with the re-use of recycled and residue materials from the construction and industrial sectors. By the end of 2020, all new buildings should meet the Energy Performance of Buildings Directive obligations and thus reach 'nearly zero-energy' performance levels using innovative, cost-efficient solutions while also integrating renewable energy sources. One of the most effective 'active methods' to reduce a building's energy consumption is to incorporate a phase change material (PCM) as an additive into the desired building component. The building components used for the incorporation of PCM have ranged from actual cement powder [6], mortar [7] concrete [8], plastering mortar [9] and many others [10,11,12]. PCM's have high latent heat storage densities and can, therefore, absorb thermal energy when transforming from solid to liquid or release it when turning back to solid [13]. This property allows the PCM to function as a heating and cooling system for a building since, during the daytime, the PCM in a building component absorbs surplus thermal energy by melting and at cooler temperatures during the night, will solidify and release thermal energy back into the environment. Incorporation of PCM's into building components can be achieved primarily in three different ways: The first method is direct incorporation at the time of mixing. The second method is the immersion of the building component in liquid PCM. The third method is micro/macro encapsulation of the PCM [14]. The latter method is considered to be the most advanced and popular because it allows for better dispersion, eliminates direct interaction between PCM and host material and reduces the external volume changes [15,16]. Microencapsulation of PCM has been transformed into an industrialised process that at the moment is very expensive, and production is limited to only a few companies worldwide [17]. Alternatively, macro encapsulation using fine and lightweight aggregates (LWAs) has been studied recently however very little research focus has been concentrated on ensuring the PCM, once impregnated, does not leak out during its phase change, which may cause contamination of the host material. Researchers who have impregnated lightweight aggregates with PCM have either incorporated the aggregates into building materials without applying any protective coating [18] or have applied a coating without establishing thoroughly its effectiveness at preserving the PCM [19]. The coating is an integral part of impregnated LWAs as it is the boundary between the PCM and host building material and must, therefore, be made as leak proof as possible. This study aimed to uncover the effectiveness of different types of coating materials, fine tune their composition and means of application.

Paraffin PCM has an inherently low thermal conductivity so for it to take advantage of its capabilities to absorb and release large amounts of thermal energy, its ability to exchange heat with the surroundings must be enhanced. Carbon based fillers have been used to successfully improve the thermal performance of the PCM itself [20] and resins [21]. Results show that with the addition of 7 wt% of carbon fibres to PCM, the thermal conductivity can be quadruplicated [22] while the addition of 71.7 wt% of silicon carbide to epoxy can improve its thermal conductivity by 20 times [23].

In this research, the impregnated aggregates with the best performing coating were incorporated into square panels made from a geopolymeric binder to establish their thermal performance. A geopolymeric binder was chosen because the authors felt that using coated lightweight PCM impregnated aggregates as an addition to a geopolymeric binder is a unique combination and has not yet been explored. Another reason was to promote the use of geopolymeric binders as an alternative to cement-based binders and initiate innovative uses for it such as the development of sustainable and energy-saving concrete, mortar plaster and facade panels.

2. Experimental investigation

2.1. Materials and preparation of coated PCM-LWA

For the production of the coated PCM-LWA, commercially available and conforming to EN 13055-1 expanded clay LWA supplied by Argex S.A were used. Table 1 shows physical properties, and chemical compositions of the LWA and Fig. 1 shows the microscopic images of the LWA. The numerous small and large pores can be clearly seen. The LWA was sieved to reduce it to the maximum dimensions of 8 mm. This limit was chosen to take into account the increase in radius after coating and the radius of aggregates would not be above 10 mm after coating. They were also blow dried with compressed air to remove surface dust before impregnation. Technical grade paraffin was chosen as the PCM with the following thermophysical properties according to the producer: phase change temperature in the range of 22–26 °C, thermal energy storage capacity of 230 kJ/kg, specific heat capacity of 2 kJ/kg K, density 0.77 kg/L at 40 °C, thermal conductivity of 0.2 W/m K and a maximum operation temperature of 60 °C. The different coating materials used are the following: commercial synthetic rubber emulsion (Sika Latex) provided by Sika S.A., commercial liquid waterproof membrane (Weber dry-lastic) supplied by Saint Gobain-Weber S.A. and polyester resin adhesive (Palatal P 4-01) combined with hardener and catalyser. The mixing ratio was determined after preparing trial mixes. The adhesive: harder: catalyser ratio that provided the most manageable working time, in this case, 15 min, was determined to be 1:0.02:0.03 by mass. Moreover, the milled carbon fibre powder (SIGRAFIL) was supplied by SLG Group and has a mean fibre length of 80 microns. Finally, the powders used to separate the LWA after coating with polyester resin were obtained directly from the quarry in the case of granite and quartz or made in the laboratory in the case of powdered glass.

PCM was introduced into the pores of the LWA using vacuum impregnation (Fig. 2). First a weighed sample of LWA was placed into vacuum chambers, which were then sealed using vacuum gel. After air entrapped within the pores of the LWA were removed under a vacuum pressure of −860 mbar for 30 min. Liquid paraffin was then allowed to enter the chambers and completely submerge the LWA. The air was then allowed to enter the chambers to help force the paraffin into the pores. After this, the sample was permitted to rest for a further 30 min. An attempt was made to keep the sample at approximately 50 °C during the rest stage to improve the PCM absorption as suggested by other researchers [24]. However in our experiment, only a 1.3% gain was made, so it was decided not to include this in the final impregnation process. Finally, the sample was taken out, and the surface was dried using absorbent towels to remove excess paraffin. The sample was immediately placed in the climatic chamber at a temperature below phase change to allow the PCM to solidify. The mass increase after impregnation and subsequent

Table 1
Physics properties and chemical composition of LWA.

Type of PCM	Organic paraffin
Bulk particle density	555 kg/m^3
Bulk particle SSD density	689 kg/m^3
Apparent density	648 kg/m^3
Bulk (tap) density	327 kg/m^3
Porosity (MIP)	61.55%
Water absorbing capacity by immersion (24 h)	26.45%
PCM absorbing capacity by immersion (1 h)	9.5%
PCM absorption capacity by vacuum impregnation (1 h)	95%

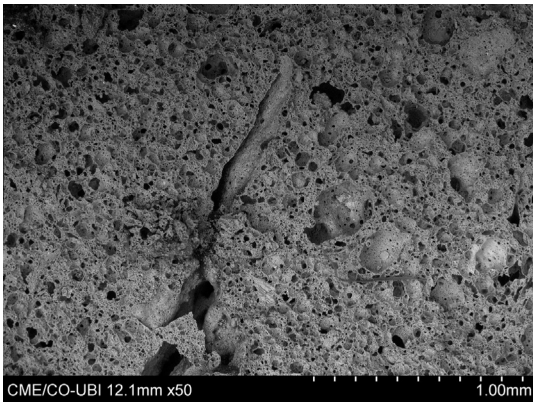

Fig. 1. Microscopic image of the LWA ×50.