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A sustainable cold bonded lightweight PCM aggregate production: Its effects on concrete properties

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HIGHLIGHTS

- Lightweight thermal aggregates enhanced by PCM were produced using pelletization.
- Using by-products, eco-friendly materials were produced for a sustainable development.
- PCM reduced the pelletization tendency while duration of the production process increased.
- The lowest density values were measured in slag-based aggregates.
- Over use of PCM caused non-uniform, improper products with reduced performance.

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ABSTRACT

Due to the responsibility of building sector for a large portion of the energy consumed, it is necessary to prioritize the energy efficiency along whole lifecycle of a building. Designing buildings to provide maximum benefit from renewable energy sources, and reusing the by-products such as fly ash and blast furnace slag makes a significant difference with regard to sustainability and energy efficiency. In this study, artificial lightweight aggregates (LWAs) were produced utilizing phase change materials (PCMs) which are prominent in literature with their contribution to energy efficiency via their high thermal capacity. Supplementary cementitious materials (SCMs) were utilized as part of binder of LWAs. Pelletization method was used in production of LWAs. Effect of binder material composition and PCM amount to the production process and physical, mechanical and thermal properties of produced aggregates were investigated. As the amount of PCM increased, lighter aggregates with higher thermal capacities were obtained. The strength decreased significantly with use of PCM. Use of PCM at high amounts negatively affected the pelleting process as well. Concrete samples were produced using LWAs and tested to determine the effect of aggregates to concrete performance. The minimum compressive strength obtained was 33.9 MPa, which is accepted as satisfactory for many structural applications.

1. Introduction

Sustainability has long been a universal development goal in many fronts. Sustainable development is improvement of the present by prioritizing next generations' ability to meet their own needs, calls for concerted efforts for an inclusive, sustainable and resilient future. Universal access to affordable, reliable, sustainable and modern energy and efficient use of it is one of the sustainable development goals declared by the United Nations (UN) in the 2030 Agenda for Sustainable Development. Energy production and use are also closely related to several other goals determined by UN and they form the basis of a more sustainable world plan [1,2]. On the other hand, energy consumption of the world has been increasing dramatically during the last century resulting a depletion in energy costs and environment degradation. This increase has reached over 30% in the last two decades [3–7]. Moreover, as projected by the U.S. Energy Information Administration (EIA), the demand in energy will continue increasing progressively through the forthcoming thirty years and total world energy consumption will rise from 549 quadrillion Btu in 2012 to 815 quadrillion Btu in 2040, with an increase of 48% [8]. The current energy demand has mainly been supplied by fossil fuels, which are well-known with their contribution to the greenhouse effect, promoting global warming. Besides, the world is running out of fossil fuels and the supply is not economically reliable [3,9]. Building sector accounts for around 40% of world's energy consumption

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and one third of associated global greenhouse gas (GHG) emissions [10]. This consumption and emission are notable in all stages of a building lifecycle from construction to demolition. Furthermore, it is known that operational emissions are higher than embodied emissions [11]. Therefore, limitation of the building based energy consumption by improving the energy efficiency of both new and refurbished buildings, remains at the forefront of the governmental plans and building codes in order to ensure a sustainable development strategy [12].

Considering that approximately 60% of the energy consumed in buildings is associated with climatization operations such as heating, ventilating and air conditioning (HVAC). Lowering the energy used for these purposes are essential for sustainable buildings concepts. Passive cooling strategy is an alternative method in building climatization which makes construction material work as natural climatization agent. In this concept, there is no energy input except for renewable energy sources. Unlike the traditional HVAC systems, in passive cooling, the energy available in nature is utilized instead of conventional energy resources. It is also possible to enhance the total efficiency of the building by using the passive techniques along with the conventional HVACs, reducing the burden of them. Such applications are called "hybrid" systems in literature [13,14]. Phase change materials (PCMs) which have considerable latent heat capacity are very advisable components for passive buildings. It is possible to store energy or to control the indoor temperature fluctuations (to the extent permitted by the phase transition range of the chosen PCM) with the use of PCMs [15,16]. When the environmental temperature rises above the PCM's melting point, PCM transitions from solid to liquid by absorbing the excessive heat and it solidifies upon a drop in the temperature while releasing the heat to the indoor. PCM remains at an almost constant temperature during the transition and prevents overheating or overcooling of the interior [17,3]. Integration of the PCM into the building fabric provides enhanced thermal storage effects and improved thermal comfort. Although PCMs can be integrated with almost all kinds and components of building envelopes, the PCM integration in wallboards, roof & ceiling, and windows is most commonly studied, due to its convenience and efficiency [13].

Concrete can be considered for utilization of PCM since it is the most widely used construction material. It is a practical material with its design indulgence, ease of production and testability. More importantly, concrete offers large areas for heat exchange with smaller heat exchange depth which promotes performance of the PCM [18]. It is reported that PCM use may help to minimize thermal cracking of massive concrete sections and to reduce the freeze/thaw damage [19,20]. Different techniques, such as direct incorporation, immersion [20–24], and encapsulation [25–30] have been used for the utilization of PCM in cementitious composites. Direct incorporation and immersion technics are addressed in the literature for their practicability and economy but leakage possibility of PCM after large number of thermal cycling makes these methods ineffective. Besides, the leaked PCM may interfere with hydration products and can cause mechanical and durability problems [18]. For the case of microencapsulation technique, desired PCMs with an appropriate melting point is enclosed in microscopically small polymer capsules and then incorporated in building materials like plasterboards, mortars or concrete. Waxes can be used as PCM to obtain melting points that can be flexibly adjusted to the application. The encapsulation process protects the wax from any deterioration and wax can stay in its pure form with its high heat storage capacity.

Although the microencapsulation method was preferred by many researchers [31–33], problems like leakage of PCM from damaged micro capsules still continue to be a matter of debate [34]. Macro encapsulation methods have been proposed to address this problem [26,35–37] but extensive studies addressing the effect of PCM use to the mechanical performance of concrete are needed to add on the current findings [18]. In this project, we utilize microencapsulated PCM with some by-products like fly ash and blast furnace slag to develop a cementitious lightweight PCM aggregate using pelletization method. By these ready-to-use PCM aggregates structural concretes with improved thermal properties can be made more accessible.

Pelletization is a frequently used method [38–46] for production of artificial aggregates. In this method, the fines are agglomerated in a rotating disc or drum with the help of moisture and an additional binder if the need arises. Pelletization can be practiced via cold bonding or thermal treatment methods such as sintering, autoclaving and steam curing may be applied to improve the pellet characteristics. In cold bonding method, pozzolanic ability of ingredients is employed at ambient temperature. It is a preferred procedure of producing artificial aggregate by many researchers [41–43,46–48] due to its energy efficiency [49]. Theory of pelletization can be found in the work by Baykal and Döven [50]. Artificial aggregates may have customized properties and they can be reproduced consistently according to manufacturer purpose. They are also promising materials in terms of ensuring sustainability by allowing the already existing natural aggregate resources to be consumed in a controlled manner. Moreover, the use of waste materials such as fly ash, blast furnace slag or reservoir sediments in aggregate production is both economically and environmentally beneficial [47]. The technical benefits such as lower density of these by-products are also taken.

This paper explains the experimental study carried out for the development of lightweight thermal aggregate (LWTA) products enhanced by microencapsulated PCM. With different mix designs containing by-products such as fly ash and blast furnace slag, eco-friendly materials were produced supporting the sustainable development strategies with the efficient use of energy. Physical, mechanical and thermal characterization of cold bonded aggregates were studied systematically. Performance of lightweight aggregate concretes (LACs) comprising these PCM aggregates was also investigated to observe the efficiency of LWTA in concrete.

2. Experimental work

2.1. Material properties

An ordinary Portland cement (CEM I – 42.5 R) with a density of 3.15 g/cm^3 was used. Physical and mechanical properties of the cement are presented in Table 1. The fly ash used in the mixture

Table 1
Physical and mechanical properties of the Portland cement.

Density (g/cm^3)	3.15	Specific surface – Blaine (cm^2/g)	3942
Setting time start (min)	129	Compressive strength (2 days)* (MPa)	29.6
Setting time finish (min)	191	Compressive strength (7 days)* (MPa)	45.8
Volume expansion (Le Chatelier) (mm)	1	Compressive strength (28 days)* (MPa)	56.4

* Average test results of the prism samples with dimension of 40x40x160mm produced using 1-part cement, 3-parts CEN ref. sand, 0.5 water/cement ratio.