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Investigation of the compressive strength, time lags and decrement factors of AAC-lightweight concrete containing sugar sediment waste

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ABSTRACT

Sugar sediment waste was incorporated into the raw material mix for the production of Autoclaved Aerated Concrete, and was demonstrated by extensive testing to provide greater compressive strength than conventional materials, and an extended time lag. In addition, the use of this otherwise waste material was demonstrated to be highly beneficial both economically and environmentally. Sugar sediment is a waste product of the sugar refining industry in Thailand, and is available in huge quantities.

The optimum composition obtained had sugar sediment content of 30% by weight replacement of sand and 7.5% by weight of lime. The resultant product showed a maximum compressive strength of around 6.1 N/mm^2 and the highest proportion of tobermorite phase of 28.9%. The higher strength can be confirmed by a higher crystalline tobermorite phase. The surface of the Autoclaved Aerated Concrete is a finer needle-like crystalline morphology. The Autoclaved Aerated Concrete consisting of the optimum sugar sediment content also extended the time for the heat wave to propagate from the outer wall to the inner wall. This study also considered the environmental, economic and health impacts of removing a substantial quantity of the industrial waste product from landfill sites.

1. Introduction

Thailand is one of the main producers and exporters of sugar and sugar products. In 2012 its sugar exported volume was ranked 4th in the world [1,2]. Large amounts of sugar sediment waste (approximately 750,000,000 kgs per annum) is created during the process of sugar production which creates a significant problem in its environmental and subsequent human impact, especially in the landfill stage of disposal. Given the contribution of sugar and related products to the emission of greenhouse gases is significant [1,3], identifying and demonstrating the benefits of using this industrial waste product was considered to be an important matter to be investigated.

The production of Autoclaved Aerated Concrete (AAC) in Thailand and its use in construction work was around 28,000,000 m^2 in 2012 in high-rise buildings, offices and residential housing. Autoclaved Aerated Concrete is lightweight and has a highly porous structure (approximately 80% of the volume of the hardened material is made up of pores, 50% being air pores and 30% being micropores). It also has lower thermal conductivity, higher heat resistance and lower shrinkage than traditional concrete, and is easier and faster to use in construction and building processes [4–7]. Of further importance, AAC is the only type of wall material which exhibits the ability to meet building energy saving requests of about 50% without adding other affiliated thermal insulation materials [8].

2. Literature review

The uses of waste by-products from various industrial processes as a component of concrete have been investigated prior to this. To increase the range of waste materials reused as raw materials in concrete, and lower production costs, several previous works have investigated the possibility of traditional raw materials replacement in AAC by using industrial waste such as efflorescent sand and phosphorescent slag [9], iron ore tailings [10], air-cooled slag [11], siliceous crushed stone [12], lead–zinc tailings [13], coal bottom ash [14], copper tailings and blast furnace slag [15] and calcium fly ash and natural zeolite [16].

Wang et al. [10] applied the tailings from Chengchao Iron Ore Mine to the mixture in aerocrete that investigated the optimal proportion of cement and lime, dosage of the additional silicon-materials, calcium–silicon proportion, dosage of aluminum powder and other parameters. Their findings opened up a new way for

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Nomenclature

T_w	wall temperature (°C)
ϕ	time lag (min)
f	decrement factor
T_{room}	room temperature (°C)
$\tau_{qi,max}$	interior surface heat flux of the wall at a maximum
$\tau_{qe,max}$	exterior surface heat flux of the wall at a maximum
A_i	Amplitudes of the wave in the inner surfaces of the wall
A_e	Amplitudes of the wave in the outer surfaces of the wall
$q_{i,max}$	maximum heat flux of the interior surface of the wall
$q_{i,min}$	minimum heat flux of the interior surface of the wall
$q_{e,max}$	maximum heat flux of the exterior surface of the wall
$q_{e,min}$	minimum heat flux of the exterior surface of the wall
k	thermal conductivity (W/m °C)

the exploitation of low-silicon iron ore tailings. Mostafa [11] studied lime and sand replacement up to 50% by air-cooled slag in Autoclaved Aerated Concrete to enhance the compressive strength. This optimum condition showed compressive strength of around 3.8 N/mm^2. Wang et al. [12] further used clayish crushed stone for making aerated concrete and indicated that the hydration products were poorly crystalline C—S—H, tobermorite and hydrogamet. Subsequently, Li et al. [13] produced aerated concrete using lead–zinc tailings which explained the effects of water–binder ratio, casting temperature and aluminum powder content on the gas forming behavior, and those of lead–zinc tailing content, cement content and conditioning agents on the compressive strength of the aerated concrete. Kurama et al. [14] examined the use of coal bottom ash from Tuncbilek thermal power plant as an aggregate to produce aerated concrete. The Autoclaved Aerated Concrete with 50% coal bottom ash usage also had the beneficial effect of a strength gain to 2.78 N/mm^2. Huang et al. [15] investigated the lime replacement by copper tailings and blast furnace slag in Autoclaved Aerated Concrete, which exhibited a dry density of 0.61 g/cm^3 and compressive strength of 4.0 N/mm^2. Further, Jitchaiyaphum et al. [16] found that by replacing the Portland cement content by fly ash and natural zeolite, each 10% by weight, resulted in a lightweight concrete that showed relatively good compressive strengths of 3.65 and 4.51 N/mm^2, respectively.

The enhancement of the thermal effectiveness of AAC material as thermal insulation is one of the most valuable tools which meets power reduction requirements and thereby promotes both energy conservation in construction and economic sustainability in energy generation [17]. Reducing the environmental impact and improving the mechanical and physical properties of AAC by utilizing waste from various industrial processes as a component of concrete provides a major approach to such enhancement, and consequential economic and environmental benefits. Increasing thermal resistance or reducing thermal conductivity of envelope materials is of primary importance in reducing transmission loads, leading to the achievement of energy conservation goals in buildings. Although insulation materials are not a heat storage medium, they have been shown to give similar effects on time lag (increase time between occurrence of peak temperatures at wall outer and inner surfaces) and decrement factor (reduce wall inner surface temperature fluctuation) [18].

Furthermore, there are many studies analysing improvements to the thermal properties of insulative walls in buildings [19–24]. Asan and Sancaktar [19] studied the effect on the thermophysical properties of different building materials at 2.5 cm thickness on time lag and decrement factor. They demonstrated large time lags of concrete block (density of ∼1.4 g/cm^3) that has thermal conductivity value of around 0.51 W/m °C, and brick block (density of ∼1.8 g/cm^3) that has thermal conductivity value of around 0.62 W/m °C, which appeared at around 0.44 h and 0.46 h. Both materials demonstrate a small decrement factor; concrete block approximately 0.588 and brick block 0.609. Al-Sanea et al. [20] investigated the optimization of the thickness of a single insulation layer in cavity walls using different insulation materials located at various positions in the cavity. Kontoleon and Bikas [21] showed that solar absorptivity had a profound effect on time lag and decrement factor of insulated walls during cooling periods. Results showed that the maximum time lag was obtained with two insulation layers; one placed on the outside surface and the cavity surfaces, while the minimum decrement factor was obtained by placing the insulation layers on both outer and inner surfaces. Bojic et al. [22] demonstrated that providing thermal insulation in the envelope of residential buildings would lead to a reduction of the yearly maximum cooling demand, and largest reduction of around 10.5% was found when this thermal insulation was put either at the indoor side or at the outer side. Kossecka and Kosny [23] analyzed insulation locations on heating and cooling for six characteristic exterior wall configurations. They showed that the best thermal performance was obtained when massive material layers were located at the inner side and directly exposed to the interior space. The effect of wall orientation and exterior surface solar absorptivity on time lag and decrement factor for several insulated wall configurations was investigated by Kontoleon and Eumorfopoulou [24].

Notwithstanding this previous research, into the use of waste industrial materials in the component mix of aerated concrete, investigations into traditional raw materials substitution by sugar sediment waste has not been previously undertaken. Being available in abundance, it seems an ideal material for investigation. The second area of prior research has been regarding the thermal properties of building materials. AAC has previously been seen as an already effective building material in this regard. To bring these two areas of research together the use of waste sugar sediment in AAC, and the effect on the compressive strength, time lags and decrement factors of AAC-lightweight concrete was the main thrust of this research. Furthermore, the correlation between the crystallinity of tobermorite phase and the strength in AAC has been insufficiently tested to demonstrate any increase of the tobermorite crystalline proportion thereby increasing the strength in AAC. Importantly, the time in heat transmissibility from the outer wall to the inner wall has also not been tested, further supporting the research.

Given that the choice of construction materials can have significant implications economically and environmentally, the reduction in economic, environmental and human impact of utilizing this otherwise waste material was calculated.

3. Experimental methodology

3.1. Raw materials and procedure of AAC production

In AAC production, the starting materials are commercially and readily available: lime (CaO), Portland cement, aluminum (Al), anhydrite ($CaSO_4$), fine sand (less than 90 μm in size). The mixture composition of AAC is lime (17.167% by weight), Portland cement (17.870% by weight), aluminum (0.094% by weight), anhydrite (2.352% by weight) and fine sand (62.517% by weight). Waste sugar sediment is also available in quantity, and can be seen as an essentially free input. Chemical analyses of the raw materials (fine