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Comparative study using Portland cement and calcium carbide residue as a promoter in bottom ash geopolymer mortar

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H I G H L I G H T S

- Sustainable masonry units using waste materials.
- Role of calcium promoter on strength development of BA geopolymer.
- PC provided more reaction products and degree of geopolymerization than CCR.
- Both PC and CCR replacement met the strength requirement for masonry units.

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This article presents the comparative study using Portland cement (PC) and calcium carbide residue (CCR) as a promoter on properties of bottom ash (BA) geopolymer cured at ambient temperature. Two calcium promoters: PC and CCR were used to replace BA at the amount of 10%, 20%, and 30% by weight of binder. Sodium hydroxide and sodium silicate solutions were used as liquid alkaline activation in all mixtures. The setting time and strength development of BA geopolymer mortars were studied. XRD, SEM and FTIR analyses were used on the BA geopolymer pastes with calcium promoters for investigating the reaction products. The results showed that the use of calcium promoters to replace BA resulted in decreasing of setting time whereas its strength development enhanced. The highest compressive strength of BA geopolymer mortars could be observed at the BA replacement with 30% of PC and 30% of CCR which were 13.8 and 11.4 MPa, respectively. The difference in strength development of BA geopolymer mortars with calcium promoters was due to degree of geopolymerization. The results of XRD, SEM and FTIR analyses agreed well with strength behaviors that the use of PC provided more reaction products and degree of geopolymerization than that of CCR. The 28-day compressive strengths of both PC and CCR replacement met the strength requirement for non-load-bearing and load-bearing brick masonry units as specified by ASTM standard. In addition, the outcome of this research could help divert significant quantity of waste materials from landfills and considerably reduce environmental damage caused by carbon emissions due to PC production.

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1. Introduction

The production of Portland cement increases every year all over the world and this process causes the emission of CO₂ which is a primary problem of global warming. Turner and Collins [1] mentioned that every ton of Portland cement production released approximately 0.82 ton of CO₂ to the atmosphere. To solve this

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problem, alternative pozzolanic materials were used to reduce the Portland cement content in concrete mixture [2]. Other efforts have made to develop a new binding material. This is called “alkali-activated aluminosilicate material” and also known as “geopolymer”, which consists of SiO₄ and AlO₄ tetrahedral with highly alkaline conditions to form three-dimensional structures.

In Thailand, by-product or waste materials from coal combustion for electricity generation such as fly ash and bottom ash are produced approximately 3 and 0.8 million tons, respectively, each year [3–5]. Fly ash is comprised of fine particles that are dispelled

of the incinerator and captured by electrostatic precipitators. Ash that falls in the bottom of the incinerator called bottom ash. Nowadays, bottom ash has been less used in concrete/geopolymer materials compared to fly ash. So, it is mainly disposed of to landfill which leads to environmental problems as reported by previous studies [5,6]. Both fly ash and bottom ash contain a large amount of silica, alumina and calcium oxide; thus, these waste materials can be used for producing geopolymer. Over the past few years, there have been several studies on fly ash and bottom ash geopolymer, for instance, two different types of precursors were used to manufacture geopolymer masonry units. One was made from fly ash and water treatment sludge [7] and another was produced from fly ash based geopolymer incorporating recycled glass [8]. Chindaprasirt et al. [6] reported that fly ash geopolymer had a higher strength development than bottom ash geopolymer, due to the difference of geopolymerization degree. Another reason is due to large particles and high porous of bottom ash resulting in lower reactivity [5,6]. To improve the reaction degree of bottom ash, Jaturapitakkul and Cheerarot [9] improved the pozzolanic reaction of bottom ash by grinding into small particles. The results showed that bottom ash with higher fineness obtained high strength of concrete. However, the use of bottom ash as source material for producing geopolymer is in low strength compared to fly ash geopolymer [6]. Recently, many researchers [10–17] have tried to improve the properties of geopolymer matrix cured at ambient temperature to obtain higher strength. It is known that geopolymerization reaction can be improved by curing at temperature of 40–75 °C [18,19] but this is not practical to use in construction work except in precast system. As mentioned previously, some studies [12,15] claimed that the use of Portland cement as a promoter could enhance the strength development of geopolymer cured at ambient temperature and resulted in good geopolymer properties.

Calcium carbide residue is also one of waste materials consisting of substantial calcium oxide; therefore, it is interesting to use as a promoter in similar to Portland cement. Calcium carbide residue is a by-product of acetylene production process through the hydrolysis of calcium carbide (CaC_2) regarded as a sustainable cementing agent. Calcium carbide residue is mainly composed of calcium hydroxide in a slurry form [20–23]. In Thailand, the demand of calcium carbide for producing acetylene gas is about 18,500 tons/year, consequently this implies that more than 21,500 tons/year of calcium carbide residue is released [20,23,24]. Usually, calcium carbide residue is mainly disposed in landfills, which causes various environmental problems due to its high alkalinity. Recently, calcium carbide residue was used as a new cementitious material with rice husk ash to form calcium silicate hydrate (C-S-H) similar to the hydration products of Portland cement [25]. Makaratat et al. [26] investigated the use of calcium carbide residue and fly ash in concrete without Portland cement and found that the properties were satisfactorily compared to normal concrete. Moreover, calcium carbide residue was also used to improve strength characteristics of soil [21,22]. For instance, Phetchuay et al. [23] used calcium carbide residue combined with fly ash as a binder for making geopolymer matrix to stabilize strength development in soft marine clay, and calcium carbide residue was also employed as an alkaline activator in fly ash geopolymer for subgrade stabilization [27]. In addition, other by-products have been recently used in geopolymer cements. For example, a novel geopolymeric material comprised of spent coffee ground as a base material together with blast furnace slag and fly ash as precursors was used to stabilize subgrade soil [28]. The stabilization of recycled demolition aggregates used in pavement base/subbase by geopolymers was investigated by Mohammedinia et al. [29]. The results showed that both the resilient modulus and compressive strength were improved by geopolymer binders. The

similar results were found by Arulrajah et al. [30] that the strength properties of pavement were enhanced by fly ash-slag-calcium carbide residue based geopolymer.

However, from the above review, several works have been investigated on fly ash based geopolymer but there is no research investigated on the utilization of bottom ash as a binder stabilized by calcium admixtures to improve the strength of geopolymer. Thus, this research focuses mainly on a comparison between Portland cement and calcium carbide residue as a promoter for enhancing the strength development of bottom ash geopolymer. The setting time, compressive strength, X-ray diffractometry (XRD), scanning electron microscopic (SEM) and Fourier transform infrared spectroscopy (FTIR) were examined. The results of this study would lay a foundation for the future use of bottom ash geopolymer with calcium promoters as non-load-bearing and load-bearing brick masonry units as described in ASTM C129 [31] and ASTM C90 [32], respectively, instead of treating bottom ash and calcium carbide residue as waste materials. Also, the outcomes from this study could help divert significant quantity of waste materials from landfills and considerably reduce environmental damage caused by carbon emissions due to Portland cement production.

2. Experimental details and testing analysis

2.1. Materials

The starting materials used in this study were bottom ash (BA), Portland cement type I (PC) and calcium carbide residue (CCR). The BA was obtained from the Mae Moh power plant in the northern Thailand. The BA was ground by a Los Angeles abrasion machine, and passed through a sieve No. 100 (150 μm) with a specific gravity and median particle size of 2.12 and 32.3 μm , respectively. The CCR was oven-dried at 100 °C for 24 h and then it was ground by a Los Angeles abrasion machine. The CCR passed through a sieve No. 100 (150 μm) with a specific gravity and median particle size of 2.25 and 21.2 μm , respectively. While, the commercial PC used in this study has a specific gravity and median particle size of 3.15 and 14.6 μm , respectively. Fig. 1 shows the scanning electron micrographs (SEM) of ground BA and CCR. The BA consists of irregular shapes whereas the CCR particles are generally irregular in similar to the previously published results [33]. The chemical compositions of BA, PC and CCR are summarized in Table 1. The BA mainly consists of SiO_2 , Al_2O_3 , CaO and some impurities. The sum of SiO_2 , Al_2O_3 and Fe_2O_3 is 56.25%, with 28.51% of CaO content, thus BA used in this study conformed to Class C as per ASTM C618-15 [34]. The PC comprises of CaO and SiO_2 whereas the major component of CCR is CaO . River sand with a specific gravity of 2.63 and fineness modulus of 2.05 in saturated surface dry condition was used as fine aggregate for mixing BA geopolymer mortars (BAGMs).

2.2. Sample preparation for bottom ash geopolymer mortars

Commercial grade sodium silicate solution (Na_2SiO_3) with 13.45% Na_2O , 32.39% SiO_2 , and 54.16% H_2O by weight and 10 M sodium hydroxide solution (NaOH) were used to produce the BAGMs. The 10 M NaOH solution was selected for this study because it provided high-strength geopolymer as reported by Rattanasak and Chindaprasirt [35] and Somna et al. [36]. The 10 M NaOH was obtained from 400 g of sodium hydroxide pellets in 1 L of distilled water and then allowed it to cool down for 24 h before use [3]. The ratios of liquid to solid binder, Na_2SiO_3 to NaOH , and sand to binder were fixed at 0.70, 2.0, and 1.5, respectively.

The BA and promoters were mixed at various BA:PC and BA:CCR ratios of 100:0, 90:10, 80:20 and 70:30 with an abbreviation of

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