



Contents lists available at ScienceDirect

Construction and Building Materials

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

Strength development and durability of alkali-activated fly ash mortar with calcium carbide residue as additive

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HIGHLIGHTS

- CCR replacement has an effect on strength and microstructure of alkali-activated FA.
- Incorporation of CCR in alkali-activated FA decreases the setting time of the binder.
- Strength increases due to additional formation of C-S-H and N-A-S-H gel.
- Alkali-activated FA mortar incorporated with CCR shows an excellent durability performance.

ARTICLE INFO

Article history:

Received 26 June 2017

Received in revised form 15 October 2017

Accepted 6 December 2017

Keywords:

Alkali-activated Fly ash
Calcium carbide residue
Strength development
Microstructure
Durability

ABSTRACT

The strength development and durability of alkali-activated fly ash (FA) mortar with calcium carbide residue (CCR) as additive cured at ambient temperature were investigated in this paper. CCR was used to partially replace FA as additional calcium in the alkali-activated binder system by a weight percentage of 0%, 10%, 20% and 30%. Sodium hydroxide and sodium silicate solutions were used as liquid alkaline activation in all mixtures. Test results show that the incorporation of CCR has an effect on the strength development of alkali-activated FA mortar with CCR. The setting time of alkali-activated FA mortar with CCR has decreased whereas its strength development has increased. This is further confirmed by XRD, SEM, and FTIR analyses, which show that the reaction products were increased when the alkali-activated FA incorporated with CCR. The highest 28-day compressive strength of alkali-activated FA mortar was found in the mix of 70% FA and 30% CCR, which is about 40.0 MPa. In addition, the resistances of alkali-activated FA mortar incorporated with CCR to tap water, 5% H₂SO₄ solution, and 5% MgSO₄ solution are found to be superior to those of alkali-activated FA mortar without CCR as indicated by the relatively low strength loss. For the samples immersed in 5% H₂SO₄ solution and 5% MgSO₄ solution for 120 days, the alkali-activated FA incorporated with 30% CCR showed a low strength reduction of around 71% and 53%, respectively.

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1. Introduction

Nowadays, Portland Cement (PC) is still widely used for construction work although its manufacturing produces a significant amount of greenhouse gas. It was reported that, about one ton of carbon dioxide is created for every one ton PC produced. To solve

this problem, attempts have been made in recent years [1,2] to find alternative cementitious materials to replace PC in concrete. One of these alternative cementitious materials is the alkali-activated binder which uses sodium hydroxide and sodium silicate solutions [3]. The alkali-activated binder has received great attention in recent years due to its low carbon dioxide emission although it has some disadvantages. According to the reports of Turner and Collins [4] and Teh et al. [5], the low carbon footprint of the alkali-activated bind is only when it is used with sodium hydroxide solution [6].

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Alkali-activated binder is made from aluminosilicate materials such as fly ash (FA), calcined kaolin and blast furnace slag, activated with high alkali solutions [7]. Alkali-activated binder has emerged as one of the possible alternative cements to PC binder because it has an excellent properties, e.g., high compressive strength, low shrinkage, and good durability against chemical attacks [1–3]. In Thailand, FA from Mae Moh power station is suitable to be a good source material for making alkali-activated binder [8–10]. However, this FA needs a temperature curing at around 40–75 °C for improving the degree of geopolymerization, though its strength when cured at ambient temperature is sufficiently used in construction work as reported by researchers [9,11]. Although alkali-activated FA cured at ambient temperature could be used in real construction, the mechanical properties and durability of alkali-activated FA are generally not good in terms of strength, shrinkage and durability against chemical attacks. To improve these properties, some additives have been used to help the geopolymerization of alkali-activated FA. One of such additives is the material that consists of calcium oxide [12–14]. For example, Pangdaeng et al. [15] investigated the use of PC to replace alkali-activated high calcium FA for making alkali-activated binder under different curing conditions. They reported that the CaO from PC could improve the properties of alkali-activated high calcium FA due to additional reaction products within the matrix. Phoo-ngernkham et al. [16] investigated the properties of alkali-activated high calcium FA paste with PC as additive. They found the reactive CaO from PC is essential for the strength development of alkali-activated binder, which is consistent with what was reported by Pangdaeng et al. [15]. Many researchers [15–21] claimed that an exothermal process at ambient temperature from PC and water is important for accelerating the geopolymerization within the matrix. Also, coexistences of calcium silicate hydrate (C-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels resulted in a high strength developed in the alkali-activated binder [14]. Recently, FA-based alkali-activated binder has been considered as a sustainable future construction material. For example, recycled asphalt pavement (RAP) and FA were used to produce a road construction material [22]. Alkali-activated FA incorporated with slag was used to stabilize the pavement base/subbase applications [23]. More recently, novel low-carbon masonry units by using alkali-activated FA with recycled glass were developed by Arulrajah et al. [24].

Over the past few years, calcium carbide residue (CCR) has been very attractive for using as a promoter similar to the use of PC because it has rich calcium hydroxide ($\text{Ca}(\text{OH})_2$) [25]. CCR is a by-product of acetylene production process through the hydrolysis of calcium carbide (CaC_2) regarded as a sustainable cementing agent [26–29]. In Thailand, approximately 21,500 tons CCR is produced annually and is mainly disposed in landfills, which causes a huge local environmental problem due to its high alkalinity [26]. Currently, some researchers have used the CCR with rice husk ash [30], bagasse ash [31], and FA [32–35] as new cementitious materials used in construction work. This is because its main reaction product is calcium silicate hydrate (C-S-H), which is similar to the hydration products of PC. For example, a combination of CCR and FA without PC has been used by Makaratat et al. [35] for producing concrete, and for improving the strength characteristics of silty clay and soil [33,34]. Somna et al. [36] reported that CCR-FA blends at the ratio of 30:70 as a binder without PC gave sufficient strength in construction work and also had the reaction products similar to the pozzolanic reaction. Other by-products have been also used as the alkali-activated binder. For instance, Arulrajah et al. [37] investigated recycled demolition aggregates such as the recycled concrete aggregates and crushed brick, stabilized by alkali activation of CCR with supplementary components of FA and slag for pavement base/subbase applications. Phummiphon

et al. [38] studied the sustainable pavement based material made from marginal lateritic soil stabilized with alkali-activated FA with CCR, in which CCR replacement was recommended for low sodium hydroxide system because calcium hydroxide from CCR could enhance the strength development of alkali-activated binder similar to FA-PC blends activated with alkali solutions. Note that the use of CCR in construction materials is not only helping the strength development of the materials; but more importantly, it has the economic and environmental perspectives. Phetchuay et al. [39,40] have used a combination of CCR and FA as a precursor for making alkali-activated binder to stabilize strength development in soft marine clay. Hanjitsuwan et al. [25] presented a comparative study by using PC and CCR as a promoter in alkali-activated bottom ash (BA) mortar. It was found that the use of CCR to replace BA provided high compressive strength of alkali-activated BA mortar similar to the use of PC. However, the FA with PC provided more reaction products and the geopolymerization degree was better than that of CCR.

In regard to the durability of alkali-activated binders, several researchers [41–45] reported that the alkali-activated binder has excellent resistance to sulfate and acid, which is superior to that of normal PC mortar and concrete. For example, Bakharev [42] did the 5-month resistance test of alkali-activated low calcium FA to 5% sulfuric acid. Ariffin et al. [41] did the one-year resistance test of alkali-activated binder concrete made from pulverized flue FA and palm oil fuel ash to 2% sulfate acid. Sata et al. [46] did the resistance test of alkali-activated BA mortar to sodium sulfate and sulfuric acid solutions. It was reported that alkali-activated BA under different particle sizes showed less susceptible to the attack by sodium sulfate and sulfuric acid solutions than that of PC mortar. Chindaprasirt et al. [47] reported that the alkali-activated binders made from ground fluidized bed combustion FA and silica fume have both good strength and resistance to sulfate and sulfuric acid attack. In addition, Chindaprasirt et al. [48] also investigated the resistance of microwave-assisted alkali-activated high calcium FA to acid and sulfate attack. However, in the literature the durability of alkali-activated FA with CCR has not been discussed. In this paper the mechanical and durability properties of alkali-activated FA mortar with CCR as an additive were investigated using various different experimental methods. The work includes the setting time test, compressive strength test and immersion test of alkali-activated FA mortar incorporated with CCR, while the material characterization of alkali-activated FA paste incorporated with CCR was analysed using XRD, SEM, and FTIR techniques. The experimental details are described in Section 2 and corresponding results are presented in Section 3. The results show that the binder made from alkali-activated FA incorporated with CCR has the advantages of high compressive strength, short setting time and good resistance to H_2SO_4 and MgSO_4 attack. It can potentially be used, for example, as the binder for the precast structural members, pavement of roadworks, and repair materials for replacing the damaged concrete in existed RC structures.

2. Experimental details

2.1. Materials

The precursors used in this study are the lignite coal FA and CCR. The FA is the by-product from the Mae Moh power plant in northern Thailand with a specific gravity of 2.65 and the mean particle size of 15.6 micron, respectively. The CCR is the by-product from acetylene gas process in Sai 5 Gas Product Co., Ltd. It was oven-dried at 100 °C for 24 h and then ground by a Los Angeles abrasion machine. After that, it was passed through a sieve No. 100 (150 μm) before used as the precursor. The specific gravity

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