



Matrix hybridization using waste fuel ash and slag in alkali-activated composites and its influence on maturity of fiber-matrix bond

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ABSTRACT

With growing environmental concerns due to huge carbon foot prints of different industries, particularly, cement industry which is about 7% of the global CO₂ emissions, the use of industrial by-products such as fuel ash and slag to replace cement in construction industry has been considered one of the most effective approaches for recycling these waste materials. One alternative is to use these industrial by-products to fully replace cement in the alkali-activated materials. This study is aimed to investigate the feasibility and influence of hybridization of pulverized fuel ash and ground granulated blast-furnace slag at different proportions on maturity of strength properties and bond strength of alkali-activated composites reinforced with different macro fibers cured at ambient temperature. Slag was replaced as 0% (reference), 10%, 20% and 30% of the total binder and activated by sodium silicate and sodium. Working life and strength of alkali-activated composites were determined. Single fiber pull-out tests were conducted with different macro steel fibers (straight, hooked end-deformed, sinusoidal end-deformed, length-deformed) and polypropylene fibers (length-deformed) embedded in dog-bone shaped specimens and cured at ambient temperature for 7 and 28 days to evaluate the bond-slip behavior. In addition, an optimal mix proportion of pulverized fuel ash-slag-based alkali-activated composites was cured at elevated temperature of 60 °C (24 h) for comparison. The results are compared to the bond-slip behavior of the same fibers in alkali-activated composites without slag as control condition. Finally, an improvement in compressive and tensile strengths of pulverized fuel ash-slag-based alkali-activated composites cured at ambient temperature achieved with the effect of hybridization of pulverized fuel ash and slag along with prolonged curing. Results also demonstrate that the maximum fiber-matrix bond strength of pulverized fuel ash-slag-based alkali-activated composites to different fibers was obtained within 7-day ambient curing which is almost the same as the ones obtained after 28-day ambient- and heat curing.

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1. Introduction

In cement manufacturing, carbon dioxide (CO₂) is emitted as a result of both fuel combustion and process-related emissions. In 2017, the amount of CO₂ released by the cement industry is about 7% of the global CO₂ emissions, and with the world-wide increase in the demand for the cement, the emissions of CO₂ in the production of the cement may reach about 10% of total CO₂ emissions in the near future (Habert et al., 2011). Furthermore, cement manufacturing process also brings a huge amount of the kiln dust each year, these kiln dusts make the atmosphere polluted which

can induce respiratory diseases and physical health problems (Huntzinger and Eatmon, 2009; Yang et al., 2015). Therefore, cleaner production is a persistent concern to minimize carbon foot prints and environmental pollution globally.

One alternative to solve these problems is to use the industrial waste by-products as alternate materials to replace the cement in the alkali-activated materials (geopolymers). These are relatively new materials that can be regarded as both sustainable and economical construction materials by virtue of the fact that they are produced from industrial by-products such as pulverized fuel ash (PFA) and ground granulated blast-furnace slag (slag) replacing 100% of cement in concrete (Juenger et al., 2010; Yang et al., 2013). These binders are gaining greater interest for their low carbon foot prints in comparison to cement (Altan and Erdoğan, 2012; Shojaei et al., 2015). They are inorganic

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alumino-silicate polymers synthesized from alkaline activation of various alumino-silicate materials of geological origin such as metakaolin or by-product materials like fly ash, and blast-furnace slag (Davidovits, 2008). Alumino-silicate chemically reacts with source materials such as PFA and slag along with alkaline solutions resulting in a three dimensional polymeric chain (Duxson et al., 2007). Although the alkali activation mechanism is still ambiguous, the chemical composition of the alkaline activators and source materials are known to influence the final products of geopolymerization (Yip et al., 2008; Swanepoel and Strydom, 2002).

PFA is a by-product generated during combustion of pulverized coal in thermal power plants, and essentially contains silica (SiO_2) and alumina (Al_2O_3) along with other compounds. Due to abundant availability, alumino-silicate composition, low water demand and high workability, PFA has become the material of interest for geopolymer synthesis. However, the drawback of using PFA in alkali-activated materials, is its low reactivity with alkaline solution at ambient temperature, which often leads to slow setting and strength development. In many cases, the dissolution of PFA is not complete before the final hardened structure is formed (Diaz et al., 2010). Chindaprasirt et al. (2009) described in SEM-EDX analysis that a large portion of PFA does not completely react, especially the large particles. Lloyd et al. (2009) also stated in a microscopy and microanalysis of remnant PFA particles in alkali-activated pastes that the multiple particles of PFA remain unreacted and that calcium appears to be active in the process of alkali activation of ash/slag blends. Different approaches have been adopted to overcome the problem of low reactivity of fly ash; such as mechanical processing of fly ash, blending of slag to PFA and heat curing. Most of the previous studies were conducted on heat-cured alkali-activated concrete which is considered to be ideal for precast concrete products. Maturity of both Portland cement composites and alkali activated materials are known to be a function of time and temperature (Ferreira et al., 2015). Although, heat curing at elevated temperatures has been proven to have a beneficial effect on strength enhancement and durability performance of alkali-activated materials. Nevertheless, heat curing process is not cost-effective and not practically applicable at the construction site, therefore, elimination of heat curing can reduce the cost and energy associated with the heat curing process. Different other additives such as silica fume, rice husk ash, metakaolin, nanoparticles used in fly ash-based alkali-activated composites have been reported in the literature (Rashad, 2014). These materials also exhibit good mechanical and durability properties. The addition of slag (a by-product of iron and steel making) in PFA is more economical and quick method to enhance setting time and early strength development of fly ash-based alkali-activated materials at ambient curing. Tests involving addition of slag along with PFA to produce an alkali-activate binder have shown some promising results, however the fly ash/slag ratio, type, concentration and composition of activator varied widely in the mixtures (Kumar et al., 2010; Chi and Huang, 2013; Li and Liu, 2007; Puertas et al., 2000; Shi and Day, 1999; Guerrieri and Sanjayan, 2010). This is attributed to the development of calcium alumino silicate hydrate (C-A-S-H) and calcium sodium alumino silicate hydrate (C-N-A-S-H) gels resulting from the activation of slag in addition to the sodium alumino silicate hydrates (N-A-S-H) in fly ash geopolymer (Criado et al., 2016; Ismail et al., 2013, 2014). The chemical reaction and the rate of strength development of alkali-activated composites are influenced by several factors based on chemical compositions of the source materials, alkaline activators and curing condition (Diaz et al., 2010; Yip et al., 2008; Wang et al., 2004).

Islam et al. (2014) reported that the compressive strength of geopolymer mortar increased with the increase of slag content in the binder containing PFA and palm oil fuel ash. The inclusion of calcium from other sources such as calcium hydroxide in geopolymer based on metakaolin improved its mechanical strength (Sarker et al., 2013). Puertas et al. (2000) studied the strength behavior and hydration products of fly ash/slag pastes and found that the compressive strength reached more than 50 MPa at 28 days by the mix having a high fly ash/slag ratio of 1.0, and cured at the temperature of 25 °C. Shi and Day (1999) concluded that addition of a small amount of hydrated lime could also enhance the early-age strength of fly ash/slag mixtures activated by sodium hydroxide and sodium silicate.

Many studies have shown that fiber addition is an efficient technique to improve tensile and flexural strengths, particularly, fracture toughness and crack growth resistance of brittle materials based on alkaline-activated binders. Sarker et al. (2013) stated that higher fracture energy of geopolymer concrete can be achieved at elevated temperature curing which has same compressive strength as cement concrete. There are studies on geopolymer composites incorporating slag report only on workability, setting, strength development and durability properties (Nath and Sarker, 2014). Few studies have reported a significant improvement in toughness and crack strength in alkali-activated slag concretes reinforced with fibers (Bernal et al., 2010; Silva and Thaumaturgo, 2003). However, there is still very little available on the fracture behavior of fly ash-slag-based alkali-activated composites reinforced with different fibers during flexural or single fiber pull-out tests (Bernal et al., 2010; Bhutta et al., 2017a).

1.1. Research significance

As mentioned above, the performance of PFA-based alkali-activated materials is inferior due to low reactivity of PFA with alkaline activator at ambient curing, therefore, different percentages of slag are partially replaced with PFA in alkali-activated systems to investigate. For that purpose the effect of slag hybridization with PFA on the bond strength of alkali-activated composites reinforced with different macro fibers is examined.

It is well known that deforming the fiber is essential to maximize the pullout resistance (and effectiveness) of the steel- and polymeric macro fibers. The amount of fiber deformation is quantified as the deformation ratio (Bhutta et al., 2017a). The sinusoidal end-deformed and length-deformed steel fibers are the most widely used fibers in cementitious composites, however, a different trend in interfacial bond-slip response between fiber and alkali-activated materials compared to cementitious materials was noticed. Therefore, the choice of fibers used in the present study was updated from previous research (Bhutta et al., 2017a, 2017b). The bond between different types of fibers and alkali-activated matrices is a critical aspect that needs to be explored to optimize the performance of fiber-reinforced alkali-activated composites, thus a wide range of deformation ratios (0, 0.06, 0.12 and 0.27) were investigated by employing the following steel fibers: straight steel, hooked end-deformed, sinusoidal end-deformed, and length-deformed. Additionally length-deformed polypropylene (PP) fibers were also investigated.

Single fiber pull-out tests were conducted on steel and polypropylene macro fibers embedded in alkali-activated composites incorporating different slag contents and cured at ambient and elevated temperatures. The influence of maturity due to prolonged curing in PFA-based alkali-activated composites with and without addition of slag on strength and bond strength development is studied.

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