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Direct electric curing of alkali-activated fly ash concretes: a tool for wider utilization of fly ashes

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ABSTRACT

Utilization of the fly ashes is a major problem in many developing countries and in South Africa only about 7% of the fly ash produced annually by coal-fired power stations, is being utilized. Although, fly ashes can be used as an alternative binder in alkali-activated concretes, strength development of these concretes at room temperature is slow limiting application of the material. Direct electric curing is proposed for heat curing of alkali-activated fly ash concrete which will open new opportunities for in-situ applications of these concretes in the construction industry thus increasing the amount of beneficially utilized fly ash. Alkali-activated fly ash concretes containing unclassified low calcium fly ash, sodium hydroxide and sodium silicate solutions were cured at 60 °C by means of direct electric curing. The electric resistivity and compressive strength development of the concretes were investigated. The resistivity strongly depends on the type of activator used. Compressive strength up to 33.8 MPa and 48.5 MPa at 2 and 28 days respectively, can be achieved after a short period of direct electric curing. This opens new opportunities for wider application of alkali-activated fly ash concretes and for more extensive utilization of fly ash.

1. Introduction

In many developing countries, electricity is generated by coal-fired power plants producing significant amounts of fly ash. Utilization of the fly ash is a major problem which needs a solution. In South Africa more that 40 million tonnes of ash is produced annually. Sasol (an international integrated energy and chemicals company) produces about 8 million tonnes of gasification ash per year (Matjie et al., 2005), while Eskom (the largest power utility in Africa) produces in excess of 30 million tonnes of fly ash annually. Only about 7% of all fly ash produced by Eskom is beneficially used and millions of tonnes of ash are being stored and disposed in ash dams and landfill sites annually (Eskom Integrated Report, 2014).

On the other hand, the increasing awareness of the environmental impact of Portland cement production has driven an intensive search for alternative binding systems for concrete. Alkali-activated cements are amongst the most researched binders, attracting increasing interest for their potential to enable the construction industry to operate within the limitations placed on CO_2 emissions (Kajaste and Hurme, 2016). According to Yang et al. (2013), the reduction rate for the CO_2 emissions of alkali-activated cement concrete relative to ordinary Portland cement concrete commonly ranges between 55 and 75%, while according to Van Deventer et al. (2010) the reduction can be as big as 80%. Heath et al. (2014) believe that the use of multiple initial aluminosilicate sources and complex mix design of alkali-activated materials has the potential to reduce the global warming effect compared to Portland cement. Alkali-activated cements utilize different raw materials including fly ashes (Torres-Carrasco and Puertas, 2015), slags (Abdalqader et al., 2015), kaolin (Longhi et al., 2015), rice husk ash and different soils (He et al., 2013; Mejía et al., 2016; Nimwinya et al., 2016). Alkali-activated cements based on fly ash probably have the greatest opportunity for commercial utilisation due to the worldwide presence of coal-fired power plants, as well as the more favourable rheological properties and lower water demand when compared to mixes based on calcined clays (Van Deventer et al., 2012). McLellan et al. (2011) emphasised that the Australian alkali-activated fly ash (AAFA) cements can provide an estimated 44–64% reduction in the CO_2 emissions over ordinary Portland cement. Therefore, a large amount of fly ash, disposed in ash dams and landfills at the moment, could be beneficially utilized in alkali-activated cements.

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There are however a few obstacles preventing the adoption of AAFA cements, which include the variability in the chemical and mineralogical composition of fly ashes (Fernández-Jiménez and Palomo, 2003), and, despite the fact that the alkali activation of fly ash is an exothermic reaction (Palomo et al., 1999), slow strength development at ambient temperatures (Puertas et al., 2000; Somna et al., 2011). Dry or steam heat curing in a wide range of temperatures is normally used to accelerate the alkali activation process in order to obtain an adequate early age compressive strength for AAFA cements and concretes (Bakharev, 2005; Kovalchuk et al., 2007). Although energy sources like microwave and solar radiation have been used for curing AAFA cements and mortars. Somaratna et al. (2010) showed that volumetric heating provided by microwave curing results in faster property development of NaOH activated fly ash mortars as compared to conventional heat curing. Chindaprasirt et al. (2013) also confirmed that short microwave curing accelerates reaction in AAFA cement resulting in improved compressive strength. Diop and Grutzeck (2008) showed that solar radiation can be used to produce bricks made of alkali-activated material. Microwave and sun curing are promising techniques but they are rather energy or time consuming respectively and, in case of microwave curing, are difficult to implement for big structural elements on a construction site.

Efficient heat curing of AAFA concrete on construction sites would open new opportunities for in-situ application of the material resulting in increased utilization of fly ash. Externally applied heat curing techniques such as steam curing, autoclaving, etc. are not easy to implement on construction sites. However, most construction sites have electric power supply which can be used for direct electric curing (DEC) of concrete when an alternating electric current is passed through the fresh concrete to accelerate the curing process by means of direct ohmic heating (Bredenkamp et al., 1993; Heritage et al., 2000). Direct electric curing can be energy efficient, with less initial capital investment and lower running cost than that required for externally applied heat curing (steam, autoclave, etc.) (Wadhwa et al., 1987). Portland cement concretes can gain as much as 60–70% of the 28-d strength in 24 h when cured by means of direct electric current Wadhwa et al. (1987) reported. Heritage et al. (2000) found that electrically cured Portland cement concretes can also achieve higher compressive strengths than that of concretes cured normally. Portland cement concretes have been cured for decades by means of DEC but very limited information could be found on DEC of alkali-activated concretes (Kovtun et al., 2015).

This paper provides information on the response of AAFA concretes to DEC. The main objectives of the study include investigating electric resistivity, temperature coefficient and compressive strength development of AAFA concrete cured by means of DEC. The influence of type and concentration of activator, as well as duration of pre- and isothermal curing on the electric and mechanical properties of AAFA concretes was studied. It is believed that DEC is an effective curing method which can be applied to in-situ AAFA concrete structures resulting in more extensive utilization of fly ash in the construction industry.

2. Materials and methods

2.1. Materials

The chemical and mineralogical composition of the unclassified low calcium fly ash used in this investigation is presented in Tables 1 and 2 respectively. The amount of amorphous SiO_2 and Al_2O_3, found by deduction of the oxide contents in the crystalline phases of fly ash from its chemical composition (Fernández-Jiménez et al., 2006a; Ward and French, 2006), are shown in Table 2. The particle size distribution is presented in Fig. 1. The specific gravity and Blaine fineness of the fly ash were 2240 kg/m^3 and 240 m^2/kg respectively.

Table 1
Chemical composition of fly ash.

SiO_2	Al_2O_3	CaO	Fe_2O_3	TiO_2	K_2O	MgO	P_2O_3	SO_3	Other	LOI
55.1	32.2	4.5	3.6	1.5	0.8	0.8	0.3	0.1	1.2	0.7

Table 2
Mineralogical composition and amorphous silica and alumina content of the fly ash.

Hematite	Mullite[a]	Quartz	Amorphous	Al_2O_3 amoph	SiO_2 amorph
0.9	25.8	11.6	61.7	13.5	36.4

[a] Powder diffraction file# 01–083–1881.

The suitability of fly ash as an aluminosilicate source for the production of alkali-activated materials depends on its characteristics, including particle size, amorphous phase, Fe_2O_3, CaO, reactive silica and alumina, and unburned material content (Diaz et al., 2010; Fernández-Jiménez and Palomo, 2003). Most of the characteristics of the fly ash are within the limits proposed by Fernández-Jiménez and Palomo (2003), but the particle size distribution is too coarse, with about 60% particles greater than 45 μm (Fig. 1). The relatively low content of amorphous alumina (13.5%) and silica (36.4%) in the fly ash composition must be noted (Table 2). Fernández-Jiménez and Palomo (2003) emphasised that the amorphous silica content of fly ash should be between 40 and 50%. Two fly ashes investigated by Fernández-Jiménez et al. (2006b) had 14.1% and 20.5% of amorphous alumina, and the fly ash with lower amorphous alumina was less reactive. Therefore the reactivity of the Lethabo fly ash used in this study may be relatively low. To increase the reactivity of fly ash, beneficiation by different methods has been used in previous studies. Somna et al. (2011) showed that milling of fly ash significantly increased compressive strength of NaOH-activated fly ash pastes cured at ambient temperature. The primary cause of the observed strength gain was the increased reactivity arising from the increased surface area of the milled fly ash. Van Riessen and Chen-Tan (2013a, 2013b) found that sieving, milling and magnetic separation increased the fraction of reactive amorphous material. The improved fly ash homogeneity and reactivity increased compressive strength of alkali-activated fly ash pastes by up to 32%. In this research, unclassified fly ash was purposely used as it would simplify the production process of alkali-activated materials (no beneficiation is needed) thus increasing the amount of beneficially utilized fly ash.

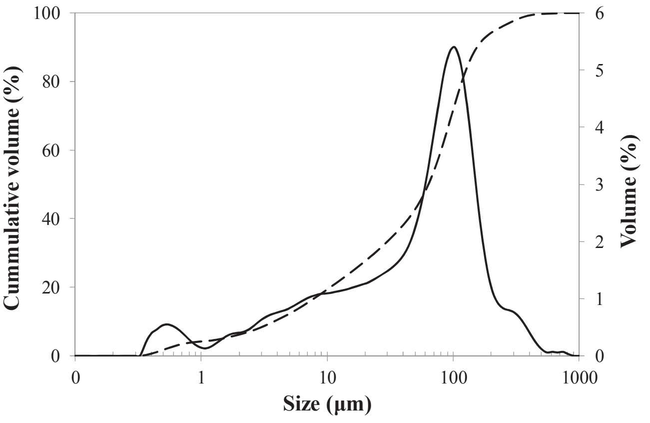

Fig. 1. Particle size distribution of the fly ash.