



Confined-Direct Electric Curing of NaOH-activated fly ash based brick mixtures under free drainage conditions: Part 1. Factorial experimental design



Mateusz Ziolkowski*, Maxim Kovtun

Department of Civil Engineering, University of Pretoria, Pretoria 0002, South Africa

HIGHLIGHTS

- The best induced design conditions produced a mixture with a compressive strength of 11.5 MPa in 7 min.
- The same mixture continued to increase in compressive strength to 20.1 MPa at 28 days.
- Under free drainage conditions, confined-DEC's potential is limited.

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ABSTRACT

The utilisation of fly ash is a global concern. Under conditions of mass production and rapid turnover in automated plants, a reduction in the curing duration of alkali-activated fly ash based mixtures is sought-after. An alternative accelerated curing technique, confined-DEC (Direct Electric Curing), with the binding mechanism of NaOH activation of fly ash was investigated for the rapid manufacture of fly ash based bricks. This concept is a potentially viable alternative solution for high-volume fly ash utilisation. The investigation revealed that the confined-DEC technique shows great promise in the rapid accelerated curing of NaOH-activated fly ash based brick mixtures. The best induced design conditions, a mixture consisting of 4.1% NaOH, 9% water and 86.9% fly ash by weight, simultaneously subjected to a confining pressure of 10 MPa and a voltage gradient of 0.8 V/mm, obtained a compressive strength of 11.5 MPa in 7 min and the mixture continued to increase in compressive strength after the application of confined-DEC, acquiring a compressive strength of 20.1 MPa at 28 days. The investigation also revealed the limitations of confined-DEC under free drainage conditions.

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1. Introduction

South Africa alone produces 40 million tons of coal ash per annum, of which approximately utilises only 7% of fly ash generated and the rest, including bottom ash, is stacked on dumps or ash dams, creating landfills [1]. Economic factors increasingly dictate that the industry should look towards recycling waste materials as opposed to landfilling and discarding [2]. Increase in production of fly ash across the globe compels one to increase the utilisation of fly ash in the construction industry [3]. One significant way to make use of waste in large quantities is by utilising it in brick manufacture [4]. The utilisation of fly ash to manufacture bricks can not only solve the storage and environmental issues, but

* Corresponding author.

E-mail addresses: mateusz.zski@gmail.com (M. Ziolkowski), max.kovtun@up.ac.za (M. Kovtun).

also reduce the exploitation of natural resources for brick production, for example, clay. Traditional brick manufacturing methods, firing process, consumes significant amount of energy and releases large quantity of greenhouse gases [5]. Today low-temperature accelerated curing techniques below 150 °C are possible and favourable since they are not as energy intensive as firing, and are capable of producing adequate fly ash based bricks [6,7].

Liu et al. (2005) [8] successfully manufactured bricks from high-calcium fly ash without the addition of a cementing agent. However, most South African fly ashes are low-calcium content [9], which has low self-cementing properties. Therefore, the addition of a cementing agent is needed, but regular cementing methods for producing bricks from waste materials have the disadvantages of high energy consumption and a large carbon footprint [5]. Using geopolymerisation to produce bricks from waste materials currently seems to be the most prevalent way to address energy and environmental concerns [5]. However, geopolymer binding tech-

nology used in fly ash mixtures is frequently associated with conventional thermal curing. The main drawback of conventional thermal curing is that it inevitably increases the energy consumption, offsetting the benefits that can be obtained from alkali-activated fly ash [10]. It is possible to synthesise an alkali-activated fly ash based binder at an ambient temperature, but it is impractical, due to delayed setting, intensive efflorescence formation, very slow mechanical strength development and relatively low strength at 28 days of age [11].

As with the traditional firing process, low temperature curing is also governed by long curing durations. With conventional heating techniques, heat is distributed in the specimen from the exterior to the interior leading to a uniform and long heating period to attain the required temperature [12]. Ahmari and Zhang (2012) [13] successfully manufactured adequate bricks from waste (tailings) through geopolymerisation, but their brick mixtures were oven cured for 7 days. The long duration of curing also does not aid the successful utilisation of fly ash. Under conditions of mass production and rapid turnover in automated plants, reduction in curing duration is sought-after. The temperature rise in conventional masonry units during curing is limited to a rate of 20 °C/h [14]. The coefficients of thermal expansion for aggregates and cement are of the same order of magnitude, but for water it is roughly 15 times, and for air 200 times, higher [15]. The different expansion characteristic of the constituents leads to differential expansion during curing, resulting in generated stresses within the mixture. Beyond the recommended curing rate, the early strength of concrete masonry units is not enough to counteract the generated stresses; cracks are formed from within the mixture, resulting in reduced later strength [15].

Compared to conventional thermal curing, such as oven curing, it is generally agreed that microwave curing is a low-energy heating source [10]. Chindaprasirt et al. (2013) [12] showed that early-stage microwave curing followed by conventional oven curing reduced the curing duration and energy consumption and, hence, the associated cost. However, mixtures prepared with microwave curing are also prone to thermally induced cracks at high heating rates. Somaratna et al. (2010) [16] observed severe cracking and deterioration within a few minutes of alkali-activated fly ash mixtures subjected to too high power levels of microwave curing.

An accelerated curing technique investigated by Davidovits and Legrand (1977) [17] shows that rapid hardening of a mixture in a matter of minutes is possible. A semi-dry mixture within a mould was compressed between two heated plates at 150 °C, and within minutes the strength of the material was approximately the same as a similar mixture that was cured in an oven for 1.5 h at the same temperature, 150 °C. This rapid accelerated curing was possible because the two heat plates suppressed the formation of cracks by preventing differential expansion within the mixture.

With the confinement of the mixture, curing duration is not governed by heating rates. However, one drawback of this curing technique by Davidovits and Legrand (1977) [17] is that it becomes ineffective for thicker mixtures. The semi-dry mixture that hardened in 3 min was only 3 mm thick, the redistribution of the heat from the plates into the mixture was rapid. However, the redistribution of heat will take longer with an increase in mixture thickness, especially with brick mixtures. Therefore, this curing technique is not as effective as conventional curing techniques when thicker elements are being cured.

This dilemma for rapid accelerating curing of thicker mixtures can simply be overcome by replacing the heated plates with another source of heat, with Direct Electric Curing (DEC). This method utilises the properties of the mixture to generate heat, and not its surroundings.

In DEC, an alternating electric current is directly induced through a mixture of relatively high resistivity between two

imbedded electrodes, and during this process heat volumetrically rises throughout the mixture, and also in a shorter time [15]. This heating mechanism is also known as Joule heating and ohmic heating; under the influence of an electric field, the resistance that the moving ions encounter results in the generation of heat. Alternating current is used to avoid the electrolysis of the mixture [18] and, generally, mains frequency supplies of 50 Hz are used for DEC [19]. Otherwise, under direct current (0 Hz), the formation and liberation of hydrogen gas at the electrodes results in the polarisation of the electrodes, which obstruct the flow of charges to the electrode surface [19–21]. This problem is eliminated by the use of alternating current [19–21].

The limitations encountered during the heated plate curing technique do not occur with DEC; voltage gradient input is adjusted to the thickness of the element. DEC is also one of the most energy-efficient methods for accelerated curing [21,22]. The combination of confinement and DEC, confined-DEC, introduces a potentially novel approach in rapid accelerating curing of masonry units. Confined-DEC, keeps the confinement aspect of Davidovits and Legrand's (1977) [17] method, but replaces the heated plates with electrodes.

This curing approach, confined-DEC, can also support mass production of fly ash bricks on an industrial scale. Fly ash does not have the physical plastic properties [23] to be extruded from a rectangular die like clay [24], which are commonly manufactured on a large scale. Belden et al. (2012) [25] explain that in order to commercialise bricks with more than 40% coal ash, it becomes necessary to press mould the brick mixture. Hence, on an industrial scale, confinement of the mixture and DEC can be introduced during the press moulding of fly ash based mixtures.

The semi-dry mixture mentioned earlier, which hardened in a manner of minutes, is what is known today as an 'alkali-activated material': kaolinite mixed with a solution of NaOH. Based on the findings by Davidovits and Legrand (1977) [17], with the appropriate induced curing conditions, the rapid manufacture of alkali-activated materials is possible. Of the two most commonly used alkali activators, NaOH and sodium silicate [26], NaOH-activated fly ash based mixtures have a smaller carbon footprint than sodium silicate-activated fly ash based mixtures [27]. Bakharev (2005) [28] observed that fly ashes activated with NaOH had more stable strength properties at later ages than fly ashes activated with sodium silicate. Previous work revealed that the NaOH present in the alkali activator provided an adequate conductive medium for generating heat in accelerated curing of NaOH-activated fly ash concretes [29]. The combination of confinement and DEC – confined-DEC – with the binding mechanism of NaOH activation of fly ash indicates that this novel approach in the rapid manufacture of bricks could be a viable alternative solution for high-volume fly ash utilisation.

The paper consists of two parts: Part 1: Factorial experimental design, and Part 2: Confined-DEC versus oven curing. The findings of Part 1 are presented in this paper. The objective of Part 1 is to investigate the capability of confined-DEC to rapidly manufacture NaOH-activated fly ash based brick mixtures of adequate compressive strength and also to provide insight into the influence of variables on rapid compressive strength development and the limitations of confined-DEC.

2. Experimental procedure and material properties

2.1. Experimental set-up

For safety reasons, the design of the confined-DEC set-up is based on the design of Davidovits and Legrand (1977) [17] with regards to relieving the internal water pressure build-up during curing; the compressed material is allowed a capillarity migration of water (free drainage conditions). This prevents dangerous steam outbursts when the confining pressure is removed after curing. Otherwise, in a closed

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