



# Alkali activated slag concretes designed for a desired slump, strength and chloride diffusivity

Dali Bondar<sup>a,\*</sup>, Qianmin Ma<sup>b</sup>, Marios Soutsos<sup>a</sup>, Muhammed Basheer<sup>c</sup>, John L. Provis<sup>d</sup>, Sreejith Nanukuttan<sup>a</sup>

<sup>a</sup> School of Natural and Built Environment, Queen's University Belfast, BT9 5AG, UK

<sup>b</sup> Faculty of Civil Engineering and Mechanics, Kunming University of Science and Technology, 650500 Kunming, China

<sup>c</sup> School of Civil Engineering, University of Leeds, LS2 9JT, UK

<sup>d</sup> Department of Materials Science and Engineering, University of Sheffield, S1 3JD, UK

## HIGHLIGHTS

- AAS concretes can be designed for different workability and different grades of concrete.
- The compressive strength of AASC are strongly proportional to the SiO<sub>2</sub> content in the activator.
- Chloride diffusion coefficients of AAS concretes are low.
- Chloride diffusivity of AASC shows that the excess water is not affecting the pores in AASC as PC.
- AASC can be designed for a water/binder ratio needed for a specified mechanical performance.
- AASC binding capacity increases by increasing the paste and/or silica content of the activator.

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## ABSTRACT

Ground granulated blast furnace slag (GGBS) is the most common industrial by-product used as a precursor for alkali activated binders due to its fast setting, simple curing needs, and good early age strength gain. There are conflicting findings on the chloride penetration resistance of such binders and more information is required regarding the suitability of this type of binder material for chloride environments. This article outlines the findings of investigation of alkali activated slag concretes (AASC), to provide a comprehensive view of the effect of mix design variables on slump, strength, and chloride transport and binding. It is concluded that AASC can be designed for different workability and different grades of concrete. The diffusivity results demonstrate that the addition of excess water does not directly control the pore structure/connectivity in AASC as it does for Portland cement, and therefore AASC can be designed based on the water/binder ratio needed for a specified mechanical performance. The chloride binding capacity increased as the paste content of the concrete and/or the silica content of the activator was increased.

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## 1. Introduction

Alkali activated materials (AAMs) have been under consideration as an alternative binder system since 1895 [1]. However, despite the engineering community having been aware of the potential of this material for over a century, there is still insufficient information available about the durability of AAMs, and the

resistance to chloride ingress is particularly critical for materials intended to serve in reinforced concretes.

Several factors are known to affect the setting time, workability, strength and durability properties of alkali activated slag concretes (AASC), including: the type of alkaline activator, the means of adding the activator, the dosage of alkali, the SiO<sub>2</sub>/Na<sub>2</sub>O ratio (denoted *modulus*, Ms), the type and fineness of slag, the paste content of the concrete, and the water to solid ratio in the paste constituent of AASC. Many of these factors are interdependent, and the effect of changing more than one in parallel is usually not additive. The optimum Na<sub>2</sub>O dosage for AAS binders activated by sodium silicate solution under normal curing has been found to be 3%–5% relative to the mass of slag, depending on the demand for high early age

\* Corresponding author.

E-mail addresses: [d.bondar@qub.ac.uk](mailto:d.bondar@qub.ac.uk) (D. Bondar), [m.soutsos@qub.ac.uk](mailto:m.soutsos@qub.ac.uk) (M. Soutsos), [P.A.M.Basheer@leeds.ac.uk](mailto:P.A.M.Basheer@leeds.ac.uk) (M. Basheer), [J.Provis@Sheffield.ac.uk](mailto:J.Provis@Sheffield.ac.uk) (J.L. Provis), [s.nanukuttan@qub.ac.uk](mailto:s.nanukuttan@qub.ac.uk) (S. Nanukuttan).

strength [2–4]. Slag cements activated by sodium silicate at modulus values between 0.6 and 1.5 at appropriate dosages were reported to show high ultimate strength for engineering purposes. However, this optimum modulus for appropriate dosage of sodium silicate varied depending on the type of slag, i.e. 0.75–1.25 for acid slag, 0.90–1.3 for neutral slag, and 1.0–1.5 for basic slag [3–5]. Activation by sodium silicate tends to give higher strength than when NaOH is used; the lower strength in the NaOH activated slag pastes may be explained by the much higher porosity found in these pastes than in the sodium silicate activated materials [6].

The effect of water to slag ratio on NaOH activated slag is similar to that of water to cement ratio on Portland cement [4]. However, an increase in water to slag ratio has a very marked effect to decrease the heat evolution of  $\text{Na}_2\text{SiO}_3$  activated slag [4]. In this case when the water to solid/slag ratio is lower than 0.45, there is an early and pronounced peak in the heat evolution curve, which then changes to a very diffuse peak with 15 h delay for a water to slag ratio greater than 0.45 [4]. This can have a noticeable effect on the performance of AASC, especially on workability and setting time.

It has been reported [7] that by controlling mix design parameters, such as binder content and water to binder ratio, it is possible to produce AASC with mechanical strength and durability comparable to conventional Portland cement concretes. It has also been shown that a higher slag content leads to an increase in strength of AASC and improvement of the permeability, water absorption and carbonation resistance [7].

Park et al. [8], in their work using mortars, have reported that the corrosion behaviour of embedded steel in AAMs was strongly dependent on the type of alkali activator. According to their findings, AAS containing  $\text{Ca}(\text{OH})_2$  as the activator was most effective to reduce galvanic corrosion, while KOH and NaOH activators indicated corrosion levels similar to that of Portland cement mortar [8].

AASC has traditionally been known for its low slump, and this raises challenges in its design for different workabilities and different grades of concrete. Therefore, this article presents findings from investigations of the effect of water/slag ratio and binder content on workability, strength, chloride diffusion and chloride binding in AASC, with the aim of determining the suitability of AASC for use in chloride environments. The outcomes will help designers to select mix designs for AASC for required performance.

## 2. Materials and experimental procedures

### 2.1. Materials

The granulated blast furnace slag used in this study was provided by ECOCEM, France. The basicity coefficient ( $\text{CaO} + \text{MgO} / \text{SiO}_2 + \text{Al}_2\text{O}_3$ ) and the quality coefficient ( $\text{CaO} + \text{MgO} + \text{Al}_2\text{O}_3 / (\text{SiO}_2 + \text{TiO}_2)$ ) were calculated from the chemical composition (Table 1) to be 1.07 and 1.7, respectively. The particle size distribution of slag was determined by laser diffraction, the particle density was measured using a LeChatelier flask, and the water absorption was measured using the centrifugal consolidation method; these physical properties are presented in Table 2.

**Table 1**  
Oxide composition of the GGBS used, from X-ray fluorescence analysis.

Precursor	Component (mass % as oxide)							
	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{CaO}$	$\text{Fe}_2\text{O}_3$	$\text{MgO}$	$\text{TiO}_2$	Other	LOI*
GGBS	35.7	11.2	43.9	0.3	6.5	0.512	1.578	0.31

\* LOI is loss on ignition at 1000 °C.

**Table 2**  
Physical properties of the GGBS used.

Fineness (particles $\geq 45 \mu\text{m}$ )	7.74%
Particle density	2.86
Water absorption	35.14%

The aggregates used in this study were crushed basalt from local sources in Northern Ireland, and comprised 10 mm and 16.5 mm crushed aggregates, and 4 mm sand. In stage A of the experimental campaign, the proportion of 16.5:10:4 mm fractions were 32:32:36; in stage B the proportions were optimised for the best packing density at 48:12:40. The bulk specific gravity and water absorption of these materials were measured based on BS EN 1097-1, and are presented in Table 3. Potable tap water (i.e. drinking water quality) was used to make the concrete mixes.

Sodium hydroxide (NaOH) pellets were dissolved in water and used along with sodium silicate solution to act as alkaline activators in concrete production at specified concentrations and compositions, as shown in Table 4. The chemical composition of the as-received sodium silicate solution was 15.5% sodium oxide ( $\text{Na}_2\text{O}$ ), 30.5% silicon dioxide ( $\text{SiO}_2$ ) and 54% water, on a mass basis. NaOH was used to adjust the  $\text{Na}_2\text{O}$  content and Ms value to the required values.

### 2.2. Mix details, mixing and casting of test specimens

Twelve AAS concretes with alkali concentrations ( $\text{Na}_2\text{O}$  % by mass of slag) of 4, 6, and 8%, and modulus (Ms) values of the sodium silicate solution activator of 0.75, 1.00, 1.50, and 2.00, were studied in stage A. The water/binder mass ratio (w/b) was held constant at 0.47 in these concretes. A barium based retarder was used in this work for mixes A1–A12 for controlling the setting time. The content of the retarder was 0.3% of the mass of slag for all of these mixes and dry-blended with slag before mixing. For the purpose of comparison, one PC concrete mix was manufactured with the same total binder content as that of the AAS concretes. A w/b of 0.42 was specified for the PC concrete [9] to ensure that its performance in exposure classes XS3 and XD3 as defined in BS EN 206:2013 [10] would be acceptable. In stage B, ten further AAS concretes were studied with different w/b ratios, binder to aggregate ratios, alkali concentrations, and Ms values without using retarder. The details of the different mixes and their initial properties are presented in Table 4. Throughout this work, the total binder content is defined as the sum of GGBS and the solid component of the sodium silicate solution, and the water content of the sodium silicate solution was taken into account while determining the mixing water.

A laboratory pan-mixer of volume 50 L was used in this study. In stage A the mixing was conducted in accordance with BS 1881-125:2013 [11]. In Stage B, crushed basalt aggregates and sand were first dry-mixed together for one minute, and the GGBS powder was subsequently added, and mixed for a further 2 min. The sodium hydroxide solution was then added and after a further 2 min of mixing, then sodium silicate solution was added and mixing continued for a further minute.

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