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Impact of Water Content on the Performance of Alkali-Activated Slag Concretes

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ABSTRACT

In this study, we report the effect of varying the water/binder (w/b) ratio on the performance of sodium silicate activated concretes. Compressive strength development and water transport properties of these concretes were assessed, along with their resistance to carbonation. The results demonstrate that varying the water content within a reasonable range induced negligible changes in the compressive strengths of these concretes, when a constant paste content was used. A direct correlation between the w/b ratio and the amount of permeable voids in the concretes was not identified. The carbonation behaviour of these concretes changes prominently depending on the CO₂ concentration of exposure, meaning that comparable accelerated carbonation rates were observed at varying w/b ratios, conversely to observations under natural carbonation conditions where w/b was significant in defining the carbonation rate.

Keywords: Alkali-activated slag concretes, water content, mechanical strength, transport properties, durability

INTRODUCTION

Alkali activated slags (AAS) are gaining significant attention as materials with great potential for replacing Portland cement for production of concretes (Provis, 2017). Despite the advantageous mechanical and durability properties AAS concretes can develop when properly formulated and cured, the lack of standardised methodologies for their design is one of the factor affecting their adoption.

Over the past decades a significant number of studies have focused on the development and optimisation of AAS binders. However, notably fewer studies have assessed the influence of conventional concrete mix design parameters such as the amount of binder (Bernal et al., 2011) or the water content on the performance of AAS concretes, as it is often assumed that these parameters will induce similar changes in properties to those expected in Portland cement based concretes.

The water content in concrete mixes is usually selected based on the workability required for casting. For Portland cement-based concretes, it is well known that higher contents of water in the mix lead to an increase in the porosity and consequently a reduction in mechanical performance (Hewlett, 1998). In the case of alkali-activated slag (AAS) concretes, an alkaline solution (referred to as the

alkali activator), rather than water, is required to promote the chemical reactions leading to the formation of the binding phases (Provis and Bernal, 2014) and its consequent hardening.

The workability and rheology of AAS are strongly dependent on mix design parameters including the type and amount of alkali activator (Puertas et al., 2014, Collins and Sanjayan, 1999) and the particle size distribution of the slag used (Kashani et al., 2013). Other parameters such as speed and duration of mixing (Palacios and Puertas, 2011), ambient conditions during the mixing and casting of fresh AAS, among others, can also influence the workability of these materials. Although increasing the amount of water is a common parameter used to adjust the workability of concretes, in the case of AAS this changes the alkali activator concentration and pore solution alkalinity, which can extend the setting time and modify the structure and amount of reaction products forming in these materials (Bernal et al., 2015).

A study in AAS pastes did not identify direct correlation between their water content and the kinetics of the alkali-activation reaction (Bernal et al., 2015), although an increased porosity has been identified in AAS pastes and mortars when increasing water content (Ismail et al., 2011, Wang et al., 1994). Despite this, it is largely unknown if a

direct correlation between the mechanical performance and porosity of these materials can be drawn, and how variation in water content might influence the permeability of AAS concretes, and consequently also their durability performance when exposed to aggressive agents.

Therefore, this study evaluates the influence of modifying the water content on the compressive strength, water permeability, and carbonation resistance of alkali silicate-activated slag concretes.

EXPERIMENTAL PROGRAMME

Materials

A commercial granulated blast furnace slag (GBFS) with a specific gravity of 2800 kg/m³ and a d₅₀ of 15 µm was used. The chemical composition of the slag is shown in Table 1.

Table 1. Composition of blast furnace slag (GBFS) from X-ray fluorescence analysis. LOI is loss on ignition at 1000°C

Component wt.% as oxide	CaO	Al ₂ O ₃	MgO	SiO ₂	Others	LOI
Slag	43.1	13.8	5.4	34.2	1.3	1.8

Commercial sodium metasilicate granules with a chemical composition of 50.5 wt.% Na₂O and 46.0 wt.% SiO₂ (balance H₂O) were dissolved in tap water and cooled for two hours before use as the activating solution.

Crushed gravel and sand were used as coarse and fine aggregates in the production of the concretes. The coarse aggregate was of 20 mm maximum size, with a specific gravity of 2830 kg/m³ and water absorption of 1.10%. The specific gravity and water absorption of the sand were 2550 kg/m³ and 0.90% respectively.

Sample preparation and tests conducted

Three sets of alkali-activated slag concretes were produced, with water/binder ratios of 0.40, 0.44 and 0.48. In this definition, the binder comprises anhydrous slag + solid activator. The concretes were produced using similar proportions of slag (400 kg/m³ of fresh paste) as the main binder component, and were mixed in an electric pan mixer following the Australian Standard AS 1012 (Standards Australia, 1994) The concretes were cast in 100 mm diameter × 200 mm height cylinder moulds, and vibrated until suitably consolidated. The concretes were then cured for 28 days in a water bath at ambient temperature (20-23°C), until testing.

Compressive strength and water absorption

An ELE ADR Auto 1500 compression testing instrument was used for compressive strength

testing of concrete cylinders according to the standard procedure ASTM C 39-10 (ASTM International, 2010), at a loading rate of 2.4 kN/sec, until failure. The results reported correspond to the average of three measurements. Volume of permeable voids (VPV) was determined according to the standard test ASTM C 642-06 (ASTM international, 2006) drying the specimens at 100°C until reaching constant weight, strictly following the standard recommendations. The results reported correspond to measurements of 4 slices taken from two cylinders, for a total of 8 measurements. Capillary sorptivity was assessed by applying the standard procedure EMPA-SIA 162/1 (Fagerlund, 1982), in which water is allowed to pass from a damp sponge into a dried cylindrical sample through a process of capillary suction, and the mass of the sample is monitored as a function of time.

Carbonation testing

To induce accelerated carbonation, cylindrical concrete specimens were stored in a chamber with a CO₂ concentration of 1.0 ± 0.2%, temperature of 23 ± 2 °C, and relative humidity (RH) of 65 ± 5%. For the natural carbonation study, concrete specimens were stored in an indoor warehouse in Melbourne, Australia, with an urban environment consistent during the testing time. The accelerated and naturally carbonated specimens were exposed to CO₂ for up to 90 days. Carbonation depths were determined periodically by treating the surface of freshly cleaved samples with a 1 % solution of phenolphthalein in alcohol.

RESULTS AND DISCUSSION

Compressive strength and water absorption of concretes

Concretes produced with w/b ratios of 0.40 and 0.44 (Fig. 1) presented comparable compressive strengths at 28 days of curing. Increasing the w/b ratio to 0.48 reduced the compressive strength by ~10 MPa compared to the concretes with lower w/b ratios. Specimens formulated with w/b = 0.44 had the lowest volume of permeable voids among those tested, while the concrete with the higher w/b ratio reported a VPV of 17%. According to the classification given in the ASTM C 642 standard, these concretes would not be classified as durable; however, the severe pre-conditioning stipulated by this testing protocol induced severe microcracking of the tested AAS concretes, increasing the permeability of the samples, causing the collection of results that do not represent the real porosity of undamaged concrete specimens.

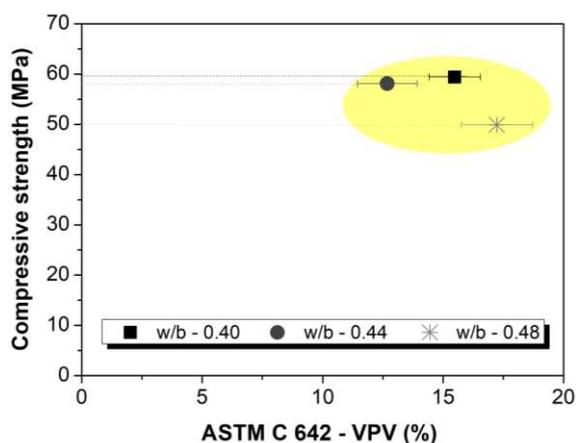


Fig. 1. Relationship between compressive strength and volume of permeable voids for 28-day cured alkali-activated slag concretes

A direct correlation between compressive strength and VPV is not identified in the concretes tested (Fig. 1.). However, the concretes produced with a w/b ratio of 0.48 did, as expected, show the lowest compressive strength and the highest VPV of the materials tested. This is consistent with the trends identified in pastes (Bernal et al., 2015) with similar compositions to the concretes tested in this study, where w/b ratios beyond 0.44 induced delayed formation of reaction products, hindering compressive strength development, and promoted formation of more porous materials.

Water sorptivity curves of the produced concretes (Fig. 2.) show that concretes formulated with a w/b ratio of 0.44 present the lowest total water penetration of the concretes tested, followed by concretes with w/b ratios of 0.40 and 0.48. These results are consistent with the VPV values recorded for these concretes (Fig. 1.) where concretes with a w/b ratio of 0.44 presented lower VPV values than the others. All the concretes reached saturation at comparable testing times, which might be indicating a comparable pore network tortuosity (Bernal et al., 2012).

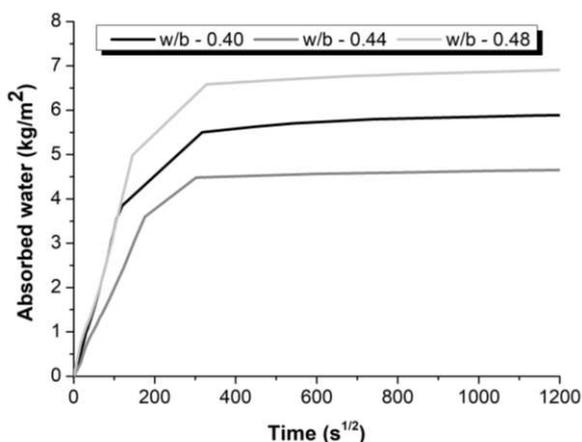


Fig. 2. Capillary sorptivity curves of 28-day cured alkali silicate-activated slag concretes

The capillary absorption coefficient (k ; initial slope of the sorptivity curves in Fig. 2) and resistance to water penetration (m , saturation time divided by the square of the penetration depth) are reported in Table 2.

Table 2. Capillary absorption parameters of alkali silicate-activated slag concretes

Water/binder ratio	k (kg/m ² s ^{1/2})	m ($\times 10^7$ s/m ²)
0.40	0.031	1.88
0.44	0.020	2.63
0.48	0.033	1.88

Concretes with w/b ratios of 0.40 and 0.48 presented similar k and m values, indicating that the total capillary porosities of these concretes are similar, despite presenting significantly different VPV (Fig. 1), which causes the uptake of larger amounts of water in concretes with w/b ratio of 0.48. Conversely, concretes with a w/b of 0.44 had a lower k value, indicating a more tortuous and refined pore network structure compared with the other concretes assessed; and a higher m value, consistent with the lower VPV (Fig. 1) of these samples.

Carbonation resistance

Under natural carbonation conditions (Fig. 3), concretes produced with a w/b ratio of 0.40 do not show observable carbonation during the first 40 days of storage, while specimens formulated with w/b ratios of 0.44 and 0.48 had comparable carbonation depths. Beyond this exposure time, all concretes were partially carbonated, and this was more noticeable as the w/b ratio increased. After 90 days of storage, the carbonation depths of all concretes were less than 4 mm.

Conversely, under accelerated carbonation conditions the carbonation depth increased at longer times of exposure, particularly when the w/b ratio of the concretes was higher. The carbonation results, either under natural or accelerated conditions, do not correlate neither with the VPV (Fig. 1) nor with the sorptivity (Fig. 2) measurements for the concretes assessed, where a reduced permeability was identified in concretes with a w/b ratio of 0.44. This suggests that the microstructural differences induced by varying alkalinity of these concretes as water content increases, particularly the crystallinity of the reaction products forming (Bernal et al., 2015), might be influencing the kinetics of carbonation of these materials.

A linear correlation between natural and accelerated carbonated specimens was not able to be identified (Fig. 3); instead, it seems that there is a 'skin' effect where the accelerated carbonation starts immediately, while the CO₂ under natural carbonation conditions, takes a longer time to pass the surface layer of the concrete to induce a sufficiently measurable carbonation depth.

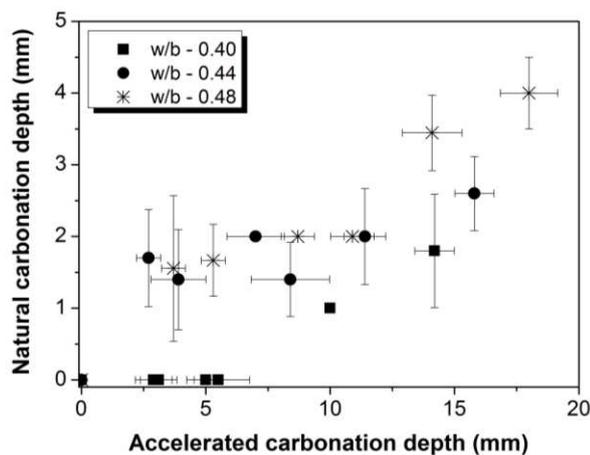


Fig. 3. Correlation between natural and accelerated carbonation of silicate-activated slag concretes

CONCLUSIONS

The water content in alkali-activated slag concretes strongly influences the mechanical strength and permeability of these concretes. Conversely to what is expected for conventional Portland based concretes, a direct correlation between water content of the concrete, compressive strength and porosity cannot be drawn for the AAS concretes assessed. This demonstrates that the changes in activating solution concentration induced by slight modification in the w/b ratio of AAS concretes can significantly impact how these materials will perform, particularly at an early age of curing.

There is not a direct correlation between natural and accelerated carbonation results of AAS concretes, and the water permeability measured in these concretes, elucidating the complexity of the carbonation process in these materials, and the need to understand in detail the competition between chemical reactions vs. gas transport mechanisms in the extent of carbonation of AAS materials.

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