A study of the properties of alkali activated cement concrete with potassium carbonate activator.

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Abstract. Alkali-activated cements (AAC) have recently attracted the vivid interest of the civil engineering industry as promising innovative alternatives to Portland Cement (PC) which is responsible for 8% of anthropogenic CO_2 emissions. In this context, this paper studies concrete produced using potassium carbonate (K_2CO_3)-activated slag cements, on which there is paucity of information. A preliminary study included one-part versus two-part cements and different liquid/solid ratios. Following this, mechanical property and durability testing of the resulting concrete was performed for different curing conditions. The results indicated that strengths would be suitable for C20/25 concrete (i.e., suitable for domestic uses); these strengths were gained early in the curing process (already at 7 days) in most cases. However, by lowering the liquid/solid ratio of the mixes, higher 28-day strengths of up to C30/37 concrete were achieved. Ongoing work is investigating durability of this type of concrete with results so far showing good promise.
Keywords: concrete sustainability; alkali-activated cements; potassium carbonate; ground granulated blast furnace slag; waste management

1. Introduction

To mitigate climate change and achieve net zero carbon, novel cements are actively researched to replace partly or fully Portland Cement (PC), which accounts for 8% of anthropogenic CO_2 emissions (Mavroulidou et al, 2015). Amongst these cements, alkali-activated cements (AAC) have been introduced as promising alternatives to PC towards potentially lowering CO_2 emissions; moreover, in many cases AAC were shown to enhance concrete mechanical properties and durability. AAC are produced by the activation of an aluminosilicate precursor by the use of a soluble alkaline substance, supplying alkali metal ions (hydroxides, carbonates, sulphates, aluminates or oxides), which is commonly referred to as the 'activator'. The activator raises the pH of the mixture and accelerates the dissolution of the solid precursor. The precursor may be a natural or a waste material, of high aluminosilicate content.

Following on previous work on AAC for concrete carried out at London South Bank University, using different alkaline activators (Mavroulidou and Martynková, 2018;

Mavroulidou and Shah, 2021; Mavroulidou et al, 2023), this paper studies the feasibility of producing AAC concrete using potassium carbonate (K_2CO_3) as an activator of Ground Granulated Blast Furnace Slag (GGBS), an industrial by-product of the steel production industry, which is used as the precursor. Whilst a number of other activators such as Na_2SiO_3, NaOH, KOH, have been widely used in the production of AAC (Mavroulidou and Martynková, 2018; Mavroulidou et al, 2023), there is paucity of information on the potential of using K_2CO_3 as an activator in AAC. However, there are advantages of using K_2CO_3 in the context of sustainability and circular economy, as it can be potentially obtained from various waste material sources, in particular food/plant waste, which can be found in any part of the world. Additionally, activator systems with K_2CO_3 would have a lower pH compared to other alkaline activators such as sodium hydroxide, making the material safer for handling on site.

The following sections of the paper present indicative results of salient mechanical and durability properties of these little researched systems, considering the effect of mixing and curing conditions, as AAC properties are highly dependent on these conditions (Bernal et al, 2014; Mavroulidou et al, 2023).

2. Materials and methods

To make the alkaline binder (AAC), analytical grade K_2CO_3 activator was used (Fisher Scientific) supplied in the form of anhydrous potassium carbonate pellets (≥99% purity) and GGBS precursor provided by Hanson Regen; the suitability of this GGBS for AAC and its chemical composition were discussed in Mavroulidou and Martynková (2018). In addition to the AAC binder, the other concrete mix ingredients were river sand of 5mm maximum size and gravel of 10 mm maximum size (used as fine and coarse aggregate respectively). The concrete mixes used are shown in Table 1.

A preliminary study on 7-day cubes performed in duplicate included one-part (K_2CO_3 supplied in powder form in the concrete mix) versus two-part (K_2CO_3 supplied in solution form in the concrete mix) AAC and two different sequences of mixing as these can affect the results. Following this, mechanical property testing of the resulting

concrete was performed using the best mixing procedure for the one-part and two-part systems respectively (based on mixes giving the best 7-day strengths and good concrete finish). This was done using different curing conditions and times and two different liquid/solid ratios in the mixes (see Table 1). Note that for the two-part mixes part of the total water in the concrete mix mentioned in Table 1 was used to make the K_2CO_3 solution considering the solubility in water of K_2CO_3 (111 g/100 g at 20 °C). For example, to dissolve 37 g of K_2CO_3 33.5 g of water would be required as a minimum.

Table 1. Mix design (kg/m^3)

MIX ID	GGBS	River sand	Coarse aggregate	K_2CO_3 powder	Water (total)	liquid/solid
Mix1	415	784	1039	37	249	0.55
Mix2	415	784	1039	37	203.5	0.45

Curing conditions followed the protocol of previous works at LSBU (Mavroulidou and Shah, 2021; Mavroulidou et al, 2023). Namely four different curing methods were studied: (a) Method 1: curing in moulds at room temperature for 72h, demoulding and water-curing at 20ºC, until required for testing; (b) Method 2: constant humidity curing, where samples were kept in moulds and covered by an impermeable membrane to preserve their original moisture content; (c) Method 3: curing at 65°C for 5.5 hours, then, after cooling overnight, demoulding and water-curing at 20ºC; (d) Method 4: high humidity curing i.e., at a relative humidity of 95% and a temperature of 25°C. The cube compressive strength of 100 mm cubes and the tensile/splitting cylinder strength were determined using a Zwick Roell ToniPACT II 2000kN compression test plant according to BS EN 12390-3:2019 (BSI, 2019a,b respectively). Water absorption by immersion of 70 mm cube specimens was conducted according to BS1881-122:2011 (BSI, 2011). Accelerated corrosion tests by the impressed current density method and equipment described in Mengasini et al (2021) were performed on 100mm cube specimens with a pre-weighed standard carbon steel rebar (8 mm diameter), embedded at the centre of the cubes (see Fig. 1), which were cured for 7 days and then immersed into the NaCl solution and subjected to accelerated corrosion testing for 21 days. At the end of the testing, embedded rebar corrosion was assessed.

3. Results

Table 2 summarises indicative results from different mixes (solution vs powder and different liquid/solid ratios). These refer to compressive and tensile strengths as well as indicative water absorption results, which usually give an indication of concrete porosity and hence an indication of the durability of conventional PC concrete. Indicatively, concrete with CEM-II (CEM-II/A-L 32,5R) results of a water/cement ratio (w/c) of 0.55 from tests at LSBU and the literature are also shown in Table 2. It can be seen that 28-day strengths (the design strength for concrete) may not reach CEM-II results but would be suitable for C16/20 and in most cases C20/25 concrete (i.e., suitable for domestic uses); these strengths were gained early in the curing process (already at 7 days) in most cases. However, by lowering the liquid/solid ratio of the mixes, higher 28-day strengths of higher-grade concrete, i.e., of up to C30/37 were achieved (depending on the curing method). However, as in most cases C20/25 was achieved one could safely consider that concrete of C20/25 will be produced.

Concerning the effect of curing method on the strength, for early strengths, generally the two best curing methods for the K_2CO_3 solution were 3 (temperature) and 4 (high humidity); this is very consistent with observations that we have made on different AAC mixes without K_2CO_3 activator (see e.g., Mavroulidou and Shah, 2021 or Mavroulidou and Martynková, 2018 for NaOH, KOH and Na_2SiO_3 activators or Mavroulidou et al, 2023 for AAC mixes with Na_2CO_3 activator).

For the powder mix of lower liquid/solid ratio, all methods except method 1 had a similar performance (considering concrete batch variability, +/-1MPa cannot be considered a significant difference).

Regarding method 1, it was generally difficult to obtain 7-day compressive strength results, as the concrete had not hardened sufficiently within this period of curing; consequently, during demoulding, handling and placement in water, specimens could get damaged. For this reason, the curing method had to be subsequently adjusted for the mixes with lower liquid/solid ratio which were problematic in this respect, and all new method 1 samples were demoulded and placed in water after 7 days. This is why no 7-day strength value is reported for method 4 for mix 2 (see Table 1).

For the 28-day strength, i.e., the nominal strength used for concrete design, method 3 led to a limited further strength development if any at all (in fact for mix 1 an apparent slight reversal in strength is seen at 28 days of curing for method 3 but as noted earlier, +/-1 MPa is not a significant difference for concrete). This is again consistent with previous observations we made for the different alkali-activator systems listed above (i.e., in Mavroulidou and Shah, 2021, Mavroulidou and Martynková, 2018 and Mavroulidou et al, 2023). For 28-day strength method 2 was generally the best overall in terms of strength evolution/gain followed by method 4. Note that for mix 1 there was an apparent reversal in the 28-day strength of the triplicate cubes in method 4. This is why the value is marked as N/A, because we intend to repeat the tests to have some further evidence and confirmation, as this reversal would be difficult to explain, especially for curing method 4.

Table 2. Indicative results

| MIX ID | Curing Method | Average Compressive Strength (MPa) | | | Average Tensile strength (MPa) | Tensile/ Compressive (%) | Absorption by immersion (%) |
		7 Days	28 days	7/28 day strength ratio	28 days	28 days	28 days
Mix1 (solution)	1	13	17.5	0.74	2.05	11.7	2.7
	2	14.5	24.5	0.59	2.25	9.18	10
	3	24	23	~1	2.15	9.3	3.95
	4	23	N/A	N/A	2.15	N/A	6.03
Mix2 (powder)	1	-	21	N/A	2.6	12.4	9.56
	2	23	38.5	0.6	2.25	5.84	9.61
	3	22	25	0.88	2.95	11.8	6.91
	4	21.5	34.5	0.62	2.3	6.67	8.47
CEM-II 32,5R (w/c=0.55)	1	25	32	0.77	2.3	7.19	3
C20* w/c=0.55)	1	22	30	0.77	2.6	8.7	-

*Results from Keykha and Najmaddini (2020)

It is also observed that tensile strengths are generally higher than expected for regular PC concrete, considering the respective cube compressive strengths obtained. Tensile strengths are linked to the initiation of cracking in concrete. For regular concrete (not AAC concrete) there is a rule of thumb that tensile strength is about 10% of the compressive strength; however, the percentage depends on the testing method, and for indirect tensile strength measurements (i.e., flexural strength or splitting cylinder strength) usually the 10% is seen in flexural strength testing, whereas in splitting cylinder strength testing lower percentages (around 6-7%) of the compressive strength are usually achieved. Moreover, the trends of the splitting cylinder strength values are generally not consistent with the compressive strength trends, especially for specimens with lower solid/liquid ratio, unlike what was expected. In some cases, there was however a discrepancy between the values of duplicate specimen results, especially in the drier mixes of 0.45 solid/liquid ratio for which samples could occasionally suffer more damage when they were taken out of the moulds. This will be further investigated by replicating the series of tests. There is also an indication that exposure to water (method 1) may favour the development of tensile strength, which will need to be further investigated and the reason for this understood, for example by supporting the mechanical testing by material analysis.

The water absorption results were variable. Generally, absorption was lower than 10% (except in one case where values equaled 10%) which is acceptable for concrete quality (Neville, 1995).

As for the accelerated corrosion testing, indications are that rebars did not suffer high mass losses (see the clean area around the steel rod in Figure 1, showing no signs of corrosion of the rod or concrete damage). In a few cases where the rod was not firmly embedded in the concrete, some higher mass loss of the rod was observed. It is suspected that this was due to ingress of water from the top of the sample in the unsealed area of the poorly fitted steel rod. Overall, however, there was no visible negative effect on the concrete (e.g., cracked concrete due to expansive rust forming). The tests are ongoing for firm conclusions.

Figure 1. Example of steel reinforcement embedded in the concrete, after accelerated corrosion testing.

4. Conclusion

The paper assessed the feasibility of K_2CO_3-activated GGBS AAC concrete, on which there is paucity of information. The results indicate that good concrete of C20/25 grades (i.e., suitable for domestic uses) could be safely obtained; these strengths were gained early in the curing process, already at 7 days in most cases. Indications so far are that this concrete would have appropriate durability. Upon further mix optimization it appears possible to obtain higher grades of such AAC concrete, as with lowering the liquid/solid ratios, strengths of up to C30/37 were achieved. This is encouraging, as there are advantages of using K_2CO_3 in the context of sustainability and circular economy; K_2CO_3 can be potentially obtained from various waste material sources, in particular food/plant waste, thus

reducing AAC production costs, especially important for lower income countries and providing a waste management solution. Ongoing and future work is planned to replicate the tests shown here, extend the durability investigations with further testing (sulphate resistance, effective porosity testing etc) and perform material analysis to interpret the findings. We also intend to specifically test AAC with K_2CO_3 obtained from plant waste.

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