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Carbonation resistance of alkali activated concretes

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ABSTRACT

One of the key drivers for the adoption of Alkali Activated Material (AAM) over recent years is the reduction in CO2 emissions compared to Portland Cement and it is well known that AAM based concretes have superior strength characteristics in comparison to Portland Cement based concretes. However, many consider the durability of AAMs to be an unproven issue and therefore in the past decade many tests and investigations like this one have been undertaken to obtain a better understanding of the durability of AAM based concretes. The purpose of this paper is to assess the carbonation resistance of AAM concretes based on Ground Granulated Blast-furnace Slag (GGBS) and Pulverised Fly-Ash (PFA). The carbonation depth and strength change of four mix designs has been measured; two based on GGBS and two based on a blend of GGBS and PFA. A combination of both Sodium Hydroxide and Sodium Silicate was used as activator solution for various mix designs. This was completed as part of a wider study of AAM based concretes properties and overall durability. For investigating the effect of differing percentages of relative humidity on the carbonation of AAM concretes under accelerated condition, a constant CO2 level of 5% which is greatly elevated from the atmospheric level, as well as a constant temperature of 20°C was considered. Then the carbonation depths and strength changes of all mixes were tested at 50%, 65%, 75% and 85% humidity levels.

1. INTRODUCTION

Concrete is used in substantial volumes worldwide, and according to Pierre-Claude Aïtcin, "concrete is presently the most widely used material after water" [1]. However, as concrete used for major infrastructure is left exposed to the surrounding environmental elements it is only natural that such structural concrete will succumb to some form of deterioration over its life-span. In recent decades an increased emphasis has been placed on ensuring longevity in the performance of concrete infrastructure. Dyer reports the increasing importance placed on the whole-life performance of structures means that there is a growing demand for long service lives with minimal maintenance requirements [2]. Carbonation is one of the different degradation processes for concrete. PC is not the sole binder used in the production of concrete, and one of the numerous alternative binder systems that can be availed of is Alkali-Acitvated Materials (AAM) which recent studies suggest that provide 25 to 50% reductions in CO_2 emissions and more than 40% reductions in embodied energy relative to PC concrete [3, 4]. According to Bernal *et al.* carbonation of concretes produced using PC has been widely studied. Whereas, in the case of concretes based on alkali-activated binders, there is limited existing knowledge about the long-term in-service stability of these materials, although the studies that have been published show generally moderate to low carbonation rates (0.5 mm/year), similar to the carbonation rate of Portland cement concretes [5]. In this paper, the effect of varying relative humidity on the rate of the carbonation process of AAM concretes based on Ground Granulated Blast-furnace Slag (GGBS) and Pulverised Fly-Ash (PFA) under accelerated conditions will be tested. Carbonation depths, strength and mass changes of all mixes for this project will be tested at 50%, 65%, 75% and 85% RH levels.

2. EXPERIMENTAL DETAIL

2.1 Materials

The primary raw materials used in this study were granulated blast furnace slag (GGBS) and low-CaO PFA, which were provided by ECOCEM – Ireland and Power Minerals Ltd, UK, respectively. Sodium hydroxide (NaOH) powders or pellets were dissolved in water to produce the alkaline solution. The chemical composition of the sodium silicate solution was 15.5% sodium oxide (Na_2O), 30.5% silicon oxide (SiO_2) and 54% water. Two mixes based on GGBS and two mixes based on a blend of GGBS and PFA were considered. The GGBS/PFA ratio, the percentage NaOH in the paste (NaOH%) and the silicate modulus (molar ratio SiO_2/Na_2O) for these mixes are shown in Table 1. The aggregates used in this study were crushed basalts from local sources in Northern Ireland, and comprised 16.5 mm and 10 mm crushed coarse and fine aggregates, and 4 mm of sand. These were combined in a ratio of 48:12:40 to get the maximum packing density in concrete mixtures. Potable tap water (i.e. drinking quality water) was used to make the concrete mixtures.

2.2 Mixing, casting, curing and preparation of the specimens

All the concrete mixtures were mixed in a laboratory pan-mixer. Fourteen 100x100mm cubes for each concrete mix were cast for the determination of compressive strength, mass and strength changes due to carbonation and carbonation depth measurement. After casting, all the moulded specimens were covered with plastic sheets and left in the casting room for 24h. Six samples were demoulded and kept in a sealed plastic zip bag until the compressive strength test date and the rest samples were kept in a sealed plastic zip bag for 28 days. Then for each mix, 2 cubes were placed in a humidity and temperature control chamber (20^{o}C and target RH) before putting in the carbonation chamber to get target moisture content 50%, 65%, 75% and 85%. Once samples had achieved the desired RH they were once again weighed and then transferred to a sealed carbonation chamber for a minimum of 30 days (720 hours). A CO_2 concentration of 5±0.2% was used, at a temperature 20±2^{0}C and RH values of 50±5, 65±5, 75±5 and 85±5 %. Then all the samples were removed from the carbonation chamber and weighed in order to analyse the effect of carbonation on the weight of AAM based concretes. All of the samples were crushed to find out the strength changes and then split in half along the longitudinal axis and all surface dust was removed for the freshly split surfaces and a film of phenolphthalein indicator solution was then sprayed upon the exposed surface and left for around one hour to allow for drying. Once all samples had dried sufficiently each result was reported as the average of eight depths measured using two replicate samples by a calliper (BS EN 14630:2006).

Table 1 The details of mixes and their properties

Mix No.	GGBS/PFA (kg/m^3)	Ms (=SiO_2/Na_2O)	NaOH (%)	W/B	Slump (mm)	2days Comp.St. (MPa)	28days Comp.St (MPa)
1	400/0	0.45	8	0.55	185	28.9	44.8
2	400/0	1.0	6	0.55	215	26.5	50.3
3	340/85	1.0	8	0.47	225	41.2	73.7
4	170/255	0.45	8	0.44	225	18.4	42.1

3. RESULTS AND DISCUSSIONS

3.1 Fresh properties and compressive strength

As can be seen in Table 1, all four mixes have slump greater than 150 mm and after 28 days blended mix 1 is clearly the strongest with a compressive strength of 73.7 MPa. The other mixes all have similar strengths, ranging from 42.1-50.3 MPa. This would support what is obvious from literature that AAC offers superior strength characteristics. The results point out that the microstructure formation (geopolymerisation) is quicker in AAC, meaning they reach their maximum strengths quicker than PC based concretes.

3.2 Depth of carbonation

Figure 1 shows the carbonation depth vs. RH for the different mixes. The overall trend indicates that there is a significant decrease in depth of carbonation when samples were tested at a higher relative humidity of 85% as opposed to the

50% and 65%. The trend stated above is evident for all mixes, with the highest rate of carbonation for those samples tested at a relative humidity of 50%, followed by 65%, 75% and then finally the 85%. Out of the four mixes, blended Mix 3 performed best, with GGBS Mix 2 performing poorly. According to a study undertaken by Atiş regarding the carbonation of concretes made with fly ash, it was found that low potential for the carbonation process could be produced by using fly ash [6]. Considering the mix designs used here Blended Mix 3 and blended Mix 4 where the only mixes consisting of PFA. In Blended Mix 3 the replacement level was 20% in comparison to a 60% replacement in Blended Mix 4. From Figure 1 it can be deduced that Blended Mix 3 performed better in resistance to the process of carbonation in comparison to Blended Mix 4. This was expected as the replacement level for Blended Mix 4 and the lower silica content.

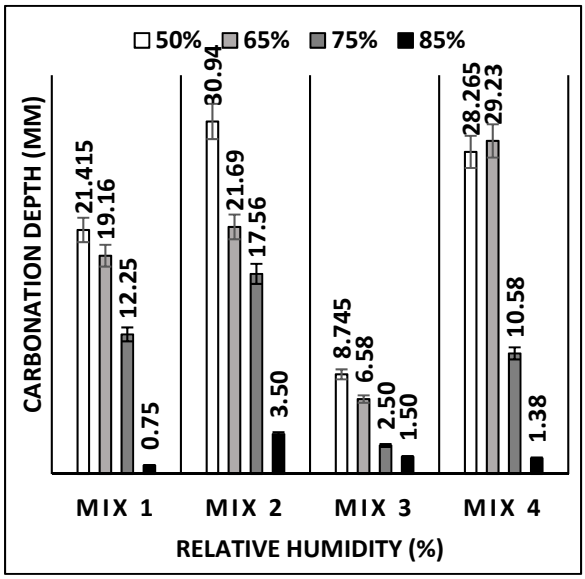

Figure 1- Depth of carbonation for concrete maintained at different relative humidity.

3.3 Strength changes

The residual compressive strength (Figure 2) represents the ratio of the strengths of the AA concretes before and after exposure to CO_2, providing a direct means of comparison of the samples which had different strengths before carbonation. Residual strength changes results for both GGBS Mix 1 and Blended Mix 4 indicated that the samples at relative humidity of 85% and 50% leads to strength gain. This is closely followed by the 75% cubes and then lastly the 65% cubes which are considerably weaker in comparison. The maximum reductions in the compressive strength relative to un-carbonated concretes happens at RH of 65% which is 8% and 15% for Mix 1 and Mix 4 respectively. This agree with the carbonation depth results while maximum carbonation depth happened at relative humidity of 65%. However, results for GGBS Mix 2 and Blended Mix 3 cubes samples tested at a relative humidity of 50% and 65% showed greater strength, followed by those tested at 85% and then the 75% cubes with maximum of 31% and 18% reduction due to carbonation. Therefore out of the four mixes, the poor performance of GGBS Mix 2 can be due to lower NaOH content and therefore less C-A-S-H (calcium alminosilicate hydrate) reacted product in the system. This can cause more calcium oxide available in the system to react with air CO_2 to produce calcium carbonate.

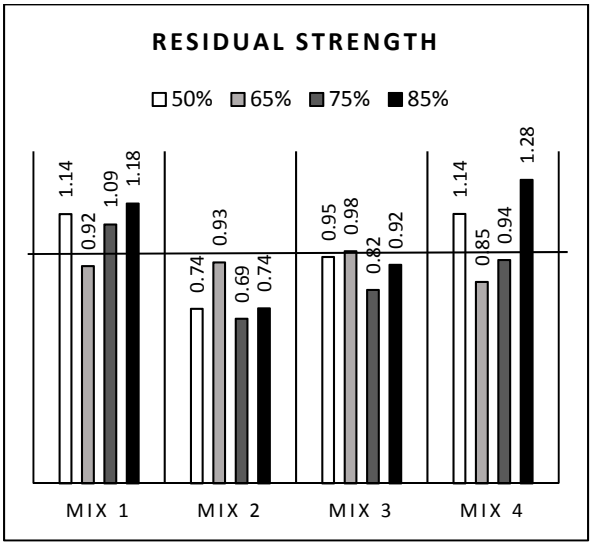

Figure 2- Residual compressive strength of the concretes post carbonation.

3.4 Mass changes

Generally after carbonation the mass should increase as the CO_2 uptake which is combined to $Ca(OH)_2$ exist in the concrete. While if there is any mass loss the possible reasons behind this weight loss can be due to the decomposition of $CaCO_3$ although this occurs from 530 to 950 °C [7].

Figure 3 shows the mass changes relative to un-carbonated samples. For Blended Mix 3 which performed better in resisting carbonation than others, the maximum mass increase happen at RH of 50% which has shown maximum carbonation depth as well. `While for other mixes, different factors such as evaporation of pore fluid and leachate of alkali makes mass change be a poor index for comparing different mixes. Although mass change is not a great measurement but it seems the least change is for Mix 3 which performed best.

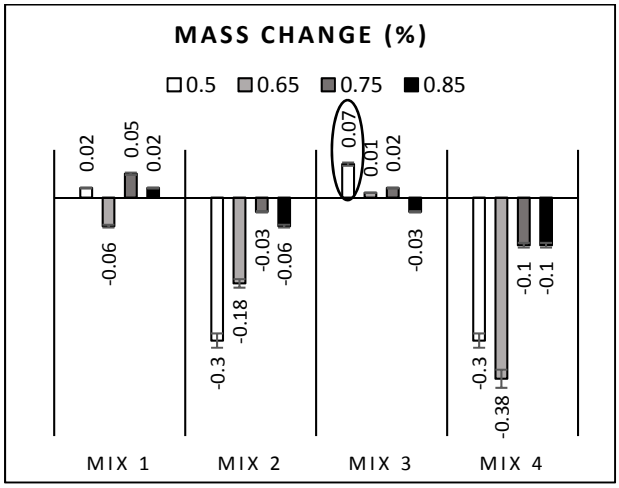

Figure 3- Mass changes (positives shows mass gain and negatives show mass loss) for various mixes in different relative humidity

4. CONCLUSIONS

The main findings of this work are:

Out of the four mixes cast for this project Blended Mix 3 performed best and can be recommended. While GGBS Mix 2 performing poorly and can therefore be considered as an undesirable mix.

Across relative humidity's at 85% all the mixes performed best in terms of resisting carbonation.

It is evident for all the mixes that the highest rate of carbonation for those samples tested at a relative humidity of 50%, followed by the 65% and 75% samples and then finally the 85% samples.

Mass change is not a great measurement but it seems the least change is for the best performed mix.

Acknowledgement

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