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Resistance of alkali activated concretes to sulphate attack

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ABSTRACT

The article highlights the resistance of two types of alkali activated material (AAM) concretes to sulphate attack. AAM considered were made of 100% ground granulated blast furnace slag (GGBS) and a blend of GGBS and pulverised fuel ash (PFA). Sodium hydroxide and sodium silicate based activator was used for this study. The material presented here is part of a wider study into Alkali Activated Materials to characterise them for their durability performance. Although it is accepted that AAM based concretes had superior strength characteristics to Portland cement based concretes, there is still debate over the durability of AAM. The mass loss, strength and expansion of four mixes were studied for a period of 56 days. Concrete cubes were exposed to water, magnesium sulphate, sodium sulphate and calcium sulphate solutions and a sulphuric acid solution. Mass and ultrasonic pulse velocity across each sample were measured once a week. For studying expansion concrete prisms were immersed in water and the salt solutions and changes to the length of each sample was measured every week. Dry prisms kept in ideal condition were used as a reference. For the first 56 days of immersion the Blended samples appeared to perform better than the GGBS samples.

1. INTRODUCTION

The production of Portland cement (PC) for the construction industry is believed to contribute at least 5-8% of the world’s total carbon dioxide (CO2) emissions according to Provis and van Deventor [1] and use an estimated 10% of the world’s energy according to Arbi et al. [2]. With concrete already produced in volumes exceeding 10 billion tons annually according to Arbi et al., making it the second most consumed substance on Earth behind water [2]. These factors have led in recent years to an increase in research carried out trying to develop alternative binder systems for concrete.

Alkali Activated Materials (AAM) concrete is produced by combining a precursor which has a high aluminosilicate content such as GGBS and PFA with water and an activator and can be one of the alternative binder systems for concrete. AAM has the potential to replace PC as the binder in concrete for a wide range of construction purposes due to its superior strength characteristics, and its increased durability in selected exposure environments [1-3].

Sulphate attack is a complex phenomenon which is yet to be fully understood due to the many overlapping reactions taking place according to Skalny, Marchand and Odler [4]. What is known is that PC based concretes do not perform well in high sulphate environments so there is potential for finding a better alternative. Shi, Krivenko and Roy state that regardless of composition, GGBS based AAM is superior to PC concrete in all sulphate solutions and superior to sulphate resistant PC in Na2SO4 solutions. The reduction of the alkali content seemed to increase resistance to MgSO4 solutions according to Shi, Krivenko and Roy who also state that an increase in water to slag ratio decreased the AAM’s ability to resist sulphate attack [5].

While AAM has shown superior durability over PC concretes based on laboratory testing according to Shi, Krivenko and Roy and Provis and van Deventer there are still gaps in understanding how different AAM mixes perform when exposed to high sulphate environments [1, 5]. Arbi et al and Provis and van Deventer both agree that further research is required into the durability of AAM before they become commercially viable and are adopted for use in the construction industry on a wider scale. Therefore, this paper will focus on investigating the ability of PFA and GGBS based Alkali Activated Materials to resist sulphate attack as part of a wider study into AAMs to determine their durability [1, 2].
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 (Na₂O), 30.5% silicon oxide (SiO₂) 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 SiO₂/Na₂O) 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 of 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 the 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. From each concrete mix, sixteen 100 mm concrete cubes and five 75x75x285 mm concrete prisms were cast for the determination of compressive strength, mass loss and expansion measurement. After casting, all the moulded specimens were covered with plastic sheets and left in the casting room for 24h. They were then demoulded and kept in a sealed plastic zip bag for 28 days. These samples were placed in a humidity and temperature controlled chamber (20°C and 100% RH) for 24 hours before ponding. This was to achieve sufficient moisture to prevent the dominant capillary forces controlling the initial uptake of moisture.

Table 1 The details of mixes and their properties

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>GGBS/PFA (kg/m³)</th>
<th>Ms (kg/m³)</th>
<th>NaOH% (Na₂O/siO₂)</th>
<th>Slump (mm)</th>
<th>28days Comp. St. (MPa)</th>
<th>56days Comp. St. (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
<td>0.45</td>
<td>0.55</td>
<td>220</td>
<td>29.7</td>
<td>51.8</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>1.0</td>
<td>0.55</td>
<td>205</td>
<td>29.1</td>
<td>44.8</td>
</tr>
<tr>
<td>3</td>
<td>340/85</td>
<td>1.0</td>
<td>0.47</td>
<td>220</td>
<td>50.7</td>
<td>74.9</td>
</tr>
<tr>
<td>4</td>
<td>170/255</td>
<td>0.45</td>
<td>0.44</td>
<td>230</td>
<td>14.3</td>
<td>45.5</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSIONS

3.1 Fresh properties and compressive strength

As can be seen in Table 1, all the mixes have a slump greater than 200 mm and after 28 days Blended mix 3 is clearly the strongest with a compressive strength of 74.9 MPa while the other mixes all have similar strengths ranging from 44.8-51.8 MPa. This would support what was found in literature regarding the superior strength characteristics of AAC. The results would also indicate that the microstructure forms rather quickly in AAC therefore helping them to reach their maximum strengths faster than PC based concretes. This may not mean very refined low pore network structure.

3.2 Strength changes

The compressive strength resulted from crushing concrete samples was related to the UPV measured for the same samples before crushing. The below formulas related compressive strengths (CS) of the samples to the UPV measurements with more than 70% confidence:

\[ \text{CS} = -0.036(\text{UPV}) + 182.89 \quad \text{(for GGBS Mixes)} \]

\[ \text{CS} = 0.0502(\text{UPV}) - 132.28 \quad \text{(for Blended Mixes)} \]

The compressive strength of saturated samples before and after 56 days of ponding in different solutions were calculated based on applying the above formula to UPV measurements and is presented in Table 2.

Table 2 The compressive strength of saturated samples before(B) ponding and after(A) 56 days of ponding in various solutions (MPa)

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Water</th>
<th>MgSO₄</th>
<th>Na₂SO₄</th>
<th>CaSO₄</th>
<th>H₂SO₄ (pH=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>28.8</td>
<td>22.7</td>
<td>30.6</td>
<td>21.7</td>
<td>24.4</td>
</tr>
<tr>
<td>1A</td>
<td>18.3</td>
<td>22.7</td>
<td>23.2</td>
<td>25.8</td>
<td>32.4</td>
</tr>
<tr>
<td>2B</td>
<td>28.8</td>
<td>28.3</td>
<td>23.7</td>
<td>29.2</td>
<td>29.2</td>
</tr>
<tr>
<td>2A</td>
<td>21.1</td>
<td>34.6</td>
<td>21.6</td>
<td>25.2</td>
<td>33.0</td>
</tr>
<tr>
<td>3B</td>
<td>89.7</td>
<td>89.7</td>
<td>81.9</td>
<td>89.0</td>
<td>91.4</td>
</tr>
<tr>
<td>3A</td>
<td>101.1</td>
<td>71.7</td>
<td>85.6</td>
<td>87.1</td>
<td>76.5</td>
</tr>
<tr>
<td>4B</td>
<td>79.4</td>
<td>86.3</td>
<td>85.5</td>
<td>79.1</td>
<td>93.1</td>
</tr>
<tr>
<td>4A</td>
<td>89.7</td>
<td>86.3</td>
<td>97.4</td>
<td>94.3</td>
<td>74.5</td>
</tr>
</tbody>
</table>

It is obvious from Table 2 that the strength of GGBS based samples immersed in water has decreased while the same increased for blended based mixes. The reason can be since in the first reaction of precursor is matured, the leachate of activators may cause destruction of precursor while in the later absorbing more water causes to perform more reacted precursor and stronger
structure. Considering samples immersed in sulphate solution, this would indicate that for the GGBS samples performed best in sulphuric acid solution while the blended samples performed best in the 5% Na₂SO₄ solution as both of these showed the largest increase in pulse velocity indicating an increase in strength.

3.3 Mass loss

The saturation process has shown an increase in mass of 0.6-0.8% for mix 1 and mix 4, an increase of 0.2-0.5% for mix 3 and an increase of 1-1.2% for mix 2. A larger increase in mass during saturation indicate a more porous/connected microstructure for that concrete.

Figures 1-a to 1-d show the change in mass for cubes from each mix over the first 56 days of immersion. This duration, significant mass changes for Mixes 1-3 for H₂SO₄. There was a mass increase of 0.5%, 0.45% and 0.26% for samples of Mixes 1 to 3 and a reduction of 0.2% for samples of Mix 4 which immersed in pH 1 sulphuric acid. H₂SO₄ make a positive change in Mix 3 and a negative change in Mix 4. It means that there can be an optimum amount of GGBS/PFA ratio which causes the least mass changes. Nevertheless, these changes are minimal compared to GGBS based mixes. It seems when more GGBS exists in the mixes there is more calcium in contact with sulfuric acid to conform gypsum and causes more expansion.

The mass loss for samples in 5% MgSO₄, 5% Na₂SO₄ and 0.2% CaSO₄ solutions was similar (for mix 1) or less (for mixes 2, 3, and 4) than that of the reference samples kept in water. It is also clear that there is no comparative change in mass for mix 4. the samples in different sulphate solutions compared to a mass loss of 0.1% for the reference samples immersed in water. These all are agreeing with Provis and van Deventer findings that shows in AACs including an alkali silicate activator and blast furnace slag, little change occurs for the first months of sulphate exposure in magnesium (MgSO₄) and sodium sulphate (Na₂SO₄) solutions [1].

3.4 Expansion results

Figures 2-a to 2-d show the expansion for concrete prisms from each mix over the first 56 days of immersion. Prisms of each mix design were also kept dry to see how they performed. Since casting these samples showed shrinkage of between 0.05 and 0.2%.

Firstly, it should be noted that all the shrinkage and expansion of the samples immersed in water and different solutions was incredibly small and less than 0.08%. For all mixes immersion in 5% Na₂SO₄ solution appeared to cause the most expansion (except Mix4 which the most expansion occurs in 5% MgSO₄ solution) while immersion in 0.2% CaSO₄ solution appeared to cause the least.
MgSo4 is causing expansion in all cases, but not so obvious in Mix 3. Shrinkage occurred in all the samples immersed in water except for those of Mix 1 and water is doing the most damage in Mix 4.

Overall, expansion was less for Mix 1 than the other designs. It is also of note that the changes in lengths occurred gradually and didn’t appear to slow down after the first 3 weeks of immersion unlike the change in mass.

4. CONCLUSIONS

The work shows 56 days is too short a time to get an accurate idea of how the different mixes performs when exposed to a high sulphate environment.

For the first 56 days of immersion the Blended samples appeared to perform better than the GGBS samples when it came to mass loss while Mix 1 appeared to perform better than the other samples in terms of expansion.

The reactions between the solutions and the samples appeared to slow down or stop entirely after the first 3 weeks of immersion. This is likely due to the maximum ion exchange having occurred during this time and if the solutions were to be replenished a greater change in mass and length would likely be observed.

The samples immersed in pH 1 sulphuric acid showed the greatest change in mass over the first 56 days of immersion.

Acknowledgement

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References


