Durability of concrete incorporating GGBS activated by water-glass

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Received 29 July 2006; received in revised form 24 July 2007; accepted 24 July 2007

Available online 24 September 2007

Abstract

The environmental concerns related to the production of cement in terms of the energy consumption and the emission of CO₂ lead to the search for more environmentally viable alternatives to cement. One of those alternative materials is ground granulated blast-furnace slag used not only as a partial replacement to cement but also as the sole binder in the form of alkali-activated slag (AAS) to produce concrete. In addition to a control OPC mix, an OPC/slag mix with 60% cement replacement by GGBS, and also AAS mixes were prepared with slag as the sole binder, activated with water glass at two dosages, 4% and 6% Na₂O (by weight of slag). Two types of water glass were used, one in a solution form and the other in a solid granules form. The two forms of the activator used were also of different silicate modulus (\( M_s \)); 1.65 for the solution form and 1.0 for the granule form. All the mixes had the same binder content and w/b = 0.48.

This paper presents the results of the durability related tests that were carried out which included, chloride penetration resistance, porosity, carbonation, and alkali–silica reaction. The effect of the different parameters including the activator type and dosage are discussed. The results give indications on the good durability of alkali-activated slag concrete compared to conventional OPC concrete.

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Keywords: Slag; Alkali; Activator; Silica modulus; Durability; Porosity; Chloride permeability; Alkali–silica reaction

1. Introduction

Blast-furnace slag refers in particular to the slag produced from the manufacture of pig iron. If the molten slag is quenched sufficiently rapidly it forms a glassy material, when finely ground, called “ground granulated blast-furnace slag” or GGBS [1]. GGBS has been used in composites and as a cementitious component of concrete for many years and it can be expected that the expansion of GGBS use will continue for the foreseeable future [2]. As an example, in the year 2000 GGBS accounted for about 10%, of the total cementitious material used throughout UK [3]. On the other hand alkali-activated slag cements using granulated blast-furnace slags were invented by Glukhovsky and patented in 1958. A review given by Glukhovsky [4] commented that alkali-activated slag cements had been introduced into construction practice in the USSR in 1960 and in Poland in 1972. Alkali-activated slags have been employed on a limited scale as oilwell cements and as a roof support system in mine applications in South Africa and Canada. Industrial experience of precast products utilizing these cements is widespread in Eastern Europe, Finland and France [5]. Research in China has confirmed the high strength of these systems [6].

The use of slag as supplementary cementitious material improves the durability of concrete as it reduces the permeability of GGBS concrete and significantly inhibits the ingress of sulfates [7]. The reduction in chloride penetration achieved by GGBS has been confirmed by many different investigators [8–12].

Wang [6] cited some research carried out in China showing AAS mortars to be very impermeable. They also state that the pores in hardened AAS concrete are distinctly smaller than those in OPC concrete. Alkali-activation ensures long-term alkalinity of AAS concrete, which prevents corrosion.

Researchers Glukhovsky [4] and Pu et al. [14] and Wu et al. [15] showed that the strength of AAS mortars increased after 1 year in 1–2% MgSO₄ solution and stayed constant for 2 years in dilute acids, HCl and H₂SO₄, while OPC samples deteriorated in six months. Byfors et al. [16] used an activator (called F-activator) composed of 2.75% NaOH plus 1.0% Na₂CO₃ and reported that for the same w/b ratio AAS concrete showed more carbonation than OPC. They attributed this to the small content of hydrated CaO, which may react with incoming CO₂ and also to the microcracking in their F-concrete. Neville [1] stated that blended cement with high replacement levels of slag exhib- its high carbonation rate. But since carbonation and pore structure are interrelated, good curing, which resulted in a more compact structure, helped to reduce carbonation. This also means the higher the strength, the lower the carbonation.

Douglas et al. [17] reported AAS concrete having good resistance to chloride ion penetration with ion penetration ranging from 1311 to 2547 C for 28 days curing and from 676 to 1831 C at 91 days.

Shi [18] presented rapid chloride permeability test (RCPT) results for AAS mortars using water-glass as an activator. These results were very high for the early ages 20,000 C at 3 days reducing to 12,000 C at 7 days and further to a value around 5000 C at 28 and 90 days.

Although the hydration of OPC slag blended and AAS in concrete produces low Ca(OH)₂, which is responsible for carbonation in OPC concrete, some researchers [19,20] had reported higher carbonation with AAS concrete especially with low grade concretes in comparison with OPC concrete. This might be due to carbonation of the C–S–H.

Some researchers report studies made on alkali-aggre- gate in AAS concrete and observed only slight expansion in the first period and no expansion after 28 days. Wang et al. [20] cited Krivenko [21] stating that AAS concrete suffers no AAR because hydration products bind 80% of the alkali at one year. Metso and Kajaus [22] carried out an AAR study of AAS sand mortar by the measurement of expansion rate and found a maximum expansion for about 8% opal content (reactive aggregate) by total aggregate weight. Gifford and Gillot [23] reported results on alkali–silica reaction (ASR) and alkali–carbonate reaction (ACR) in alkali activated slag concrete.

2. Research significance

Alkali-activated slag is not a widely known and used construction material. Most of the research done has been at the material development stage dealing with paste and mortar specimens to study the material’s chemistry and microstructure and the strength and engineering properties. Information pertaining to the concrete durability of AAS concrete is limited. This paper is part of research work carried out as a contribution to knowledge at this level.

3. Experimental investigation

3.1. Materials

The same types of ordinary Portland cement, ground granulated blast-furnace slag, lime, alkali activators, fine and coarse aggregates have been used throughout the investigation with one exception when a special reactive fine aggregate was used for the alkali-aggregate reaction test. Details of each material used are given below.

3.1.1. Cement

Ordinary Portland cement conforming to the requirements of BS 12:1996 class 42.5 N, was used in this investigation. The chemical and physical properties of the cement, as provided by the manufacturer, are given in Table 1.

3.1.2. Slag

The ground granulated blast-furnace slag (GGBS) used complied with BS 6699:1992. Typical chemical and physical properties provided by the manufacturer are shown in Table 2.

3.1.3. Lime

Hydrated lime of commercial grade was used in the alkali-activated slag mixtures to control the setting. The lime was added in a slurry form of equal parts (by weight) of lime and water.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical and physical properties of cement a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide</td>
<td>Percent</td>
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<tr>
<td>SiO₂</td>
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<td>Al₂O₃</td>
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<tr>
<td>Fe₂O₃</td>
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<tr>
<td>CaO</td>
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<tr>
<td>MgO</td>
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<tr>
<td>SO₃</td>
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</tr>
<tr>
<td>Na₂O</td>
<td>0.19</td>
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<tr>
<td>K₂O</td>
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</tr>
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</table>

a Provided by the manufacturer.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Chemical and physical properties of GGBS a</th>
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<td>Oxide</td>
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<tr>
<td>Al₂O₃</td>
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<tr>
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<td>SO₃</td>
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<tr>
<td>Na₂O</td>
<td>0.35</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.5</td>
</tr>
</tbody>
</table>

a Provided by the manufacturer.
3.1.4. Sodium silicate (water-glass)

The alkali activator used was a sodium silicate (water-glass). Two forms of the activator were used: The first was sodium silicate solution with a molecular ratio SiO$_2$:Na$_2$O ($M_s$) = 1.65 with 31.8% SiO$_2$ and 20.2% Na$_2$O by weight. The second was sodium metasilicate solid granules from with a molecular ratio SiO$_2$:Na$_2$O ($M_s$) = 1.00.

Medium graded sand and 20-mm uncrushed gravel complying with BS 882:1992 were used in this investigation. Potable tap water was used throughout the investigation.

3.1.5. Concrete mixes

The mixes were as follows:

- CM2: PC control mix with w/c = 0.48;
- SLG60: 60% GGBS + 40% OPC mixture with w/c = 0.48;
- SS4: Sodium silicate alkali-activated slag mixture with Na$_2$O content of 4% with w/c = 0.48;
- SS6: Sodium silicate alkali-activated slag mixture with Na$_2$O content of 6% with w/c = 0.48;
- MET4: Sodium metasilicate alkali-activated slag mixture with Na$_2$O content of 4% with w/c = 0.48;
- MET6: Sodium metasilicate alkali-activated slag mixture with Na$_2$O content of 6% with w/c = 0.48.

The details are shown in Table 3.

3.2. Testing procedure

3.2.1. Compressive strength

100 $\times$ 100 $\times$ 100 mm$^3$ cubes were prepared to determine the compressive strength according to BS 1881:1983.

3.2.2. Porosity

The porosity for the concrete specimens investigated was determined using a vacuum saturation apparatus ($RILEM$ CPC-11.3, 1984) at 7, 14, 28, 90, 180 and 365 days.

3.2.3. Rapid chloride permeability

This test followed the ASSHTO T277 or ASTM C 1202. Cylinders of 100 mm $\otimes$ 50 mm long were used to determine the rapid chloride permeability. The rapid chloride permeability test procedure was applied at 7, 14, 28, 90 and 180 days.

3.2.4. Carbonation

Measurement of the carbonation of concrete specimens was carried out following. The procedure is prescribed by $RILEM$ (1988) using phenolphthalein in ethanol solution.

3.2.5. Alkali-silica reaction

A set of three prisms 75 $\times$ 75 $\times$ 280 mm for each mix were prepared and tested according to BSI Draft DD218: (1995).

3.2.6. Aggregate reactivity testing

Reactive sand from Greywacke type rock source provided by BRE was used as fine aggregate in the concrete mixes for this test.

Two mixes were designed initially to assess the reactivity of the aggregates. They were intended to promote ASR expansion therefore they had high binder content.

TEST 1: A control mix designed exactly according to the standard using specified high alkali cement and added alkalis to the required Na$_2$O level of 1% of the weight of cement by adding potassium sulphate. The Na$_2$O equivalent of the cement originally was 0.68%. The purpose of this mix is to cause ASR and accelerate the reaction.

TEST 2: Replacing 60% of the cement in TEST 1 by GGBS and maintaining the alkali content of the cement at 1%.

3.2.7. ASR for AAS mixes

The mixes used have the same proportions as the mixes used throughout the investigation for OPC, OPC/slag, and AAS concrete, replacing the sand by the reactive aggregate and tested for ASR expansion.

4. Experimental results and discussion

4.1. Compressive results and discussion

It can be seen in Fig. 1 that SS6 mix with a dosage of 6% Na$_2$O achieved higher gain in compressive strength in comparison with all the other mixes. The 28 day compressive strength for SS6 was 79 MPa while it was 51 MPa for CM2 mix and 57.5 MPa for SS4 mix having the dosage of 4% Na$_2$O. This clearly shows the effect of the Na$_2$O dosage on the early compressive strength gain. In a similar

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>Slag (kg/m$^3$)</th>
<th>OPC (kg/m$^3$)</th>
<th>Activator (Na$_2$O %)</th>
<th>Activator (kg/m$^3$)</th>
<th>Lime (%)</th>
<th>Lime slurry (kg/m$^3$)</th>
<th>Water (kg/m$^3$)</th>
<th>Total water (kg/m$^3$)</th>
<th>Total binder (kg/m$^3$)</th>
<th>Fine Agg. (kg/m$^3$)</th>
<th>Coarse Agg. (kg/m$^3$)</th>
<th>w/b (%)</th>
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<tbody>
<tr>
<td>CM2</td>
<td>375</td>
<td>180</td>
<td>186</td>
<td>375</td>
<td>600</td>
<td>1215</td>
<td>0.48</td>
<td></td>
<td></td>
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<tr>
<td>SLG60</td>
<td>225</td>
<td>150</td>
<td>180</td>
<td>186</td>
<td>375</td>
<td>591</td>
<td>1215</td>
<td>0.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS4</td>
<td>326.39</td>
<td>0</td>
<td>4</td>
<td>64.63</td>
<td>4</td>
<td>30</td>
<td>133.97</td>
<td>180</td>
<td>375</td>
<td>591</td>
<td>1215</td>
<td>0.48</td>
</tr>
<tr>
<td>SS6</td>
<td>305.34</td>
<td>0</td>
<td>6</td>
<td>90.69</td>
<td>6</td>
<td>45</td>
<td>113.96</td>
<td>180</td>
<td>375</td>
<td>591</td>
<td>1215</td>
<td>0.48</td>
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<tr>
<td>MET4</td>
<td>333.15</td>
<td>4</td>
<td>4</td>
<td>47.93</td>
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<td>30</td>
<td>144.38</td>
<td>180</td>
<td>375</td>
<td>591</td>
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<td>MET6</td>
<td>314.49</td>
<td>6</td>
<td>6</td>
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<td>0.48</td>
</tr>
</tbody>
</table>
manner the MET6 mix had higher compressive strength gain (61 MPa at 28 days) in comparison to MET4 (48 MPa at 28 days) which is lower than the control mix CM2. The results in Fig. 6, representing early strength development under dry curing, show a similar trend and indicate that the AAS mixes having 6% Na₂O gave higher early strength gain than the mixes with 4% Na₂O.

The long-term strength development is clearly slower after 28 days. SS6 and MET6 (Na₂O = 6%) at later ages achieve the highest strength followed by SS4 and MET4 (Na₂O = 4%) and then come CM2 then SLG60 and. It is worth noting that MET4 and SLG60 concrete strengths started lower than OPC CM2 but they caught up and exceeded the control mix strengths after 90 days. This is attributed to the continuing pozzolanic reaction in slag concrete.

4.2. Porosity

Fig. 2 shows the porosity of the concrete mixes at different ages (7, 14, 28, 90, 180 and 365 days) under water curing condition. CM2 has the lowest value of porosity for all.

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Fig. 1. Compressive strength development for the different mixes.

Fig. 2. Porosity results.
ages. Replacing 60% of the cement by (GGBS) in mix SLG60 resulted in an increase in the porosity of concrete compared to the OPC concrete mix (CM2) with the same w/c of 0.48. But when comparing the slag mix with the OPC control mix having w/c of 0.55 the results show the SLG60 having lower porosity. These results are in agreement with results presented by Lynsdale and Sit [24] where they indicated that 70% slag replacement of OPC resulted in an increase in porosity in the early age up to 28 days. The comparison was done on equal w/c ratio but when the comparison was done on equal slump the slag concrete eventually had lower porosity after 28 days.

On the other hand, looking at the results of the AAS concrete mixes it can be noted that the increase in the Na$_2$O dosage of the activator from 4% to 6%, that was expected to produce lower porosity, did not do so in the case of the SS4 and SS6 mixes, where the activator has an $M_s = 1.65$, but did so in the case of MET4 and MET6 mixes, with the activator having an $M_s = 1.00$. The porosity of concrete is generally reduced with age as is clearly shown in the results.

4.3. Chloride permeability

The results shown in Fig. 3 for the water cured mixes show that CM2 gave higher results than SLG60 in all ages. The RCPT values at 7 days are 2490 and 1650 C for CM2 and SLG60 respectively, decreasing with age to reach 1811 and 690 C at 182 days. These values indicate low chloride ion penetrability for CM2 and very low chloride ion penetrability for SLG60 after 28 days according to the AASHTO test classification.

This clearly demonstrates that the incorporation of GGBS as a replacement for OPC leads to a reduction in RCPT values.

It can be noticed from the results that Na$_2$O dosage of the activator plays a role influencing RCPT values for AAS concrete mixes. Comparing SS4 (with Na$_2$O = 4%) to SS6 (with Na$_2$O = 6%) indicate that from 7 to 90 days SS6 gave the higher result with the difference between the values decreasing with age until SS6 gave the lower result at 182 days. Similarly it can be noted that MET6 (with Na$_2$O = 6%) gave results higher than MET4 (with Na$_2$O = 4%) decreasing with age until it gave lower results from 90 days onward.

The AAS concrete gave generally lower RCPT results in comparison with the control mix CM2 except for the MET6 mix at the first 28 days.

The increase in RCPT results with the higher Na$_2$O dosage at the early ages is not an indication of the low quality of the concrete, but it directs attention to a shortcoming in the test itself. The test measures the current passed and not the actual permeability of the concrete. Hence the presence of high concentration of alkalis probably gives misleading results. At later ages the alkalis are supposedly bound in the hydration products and this leads to reduction in their influence on the results in addition the effect of hydration progress on the permeability.

It can be noted from the results of Fig. 3 also that with AAS concrete having the same Na$_2$O dosage, the silica modulus $M_s$ has an effect on the chloride permeability. The higher the $M_s$ the lower the RCPT values, thus the SS4 gave lower values than the MET4 and the SS6 gave lower values than the MET6 at all ages.
4.4. Carbonation

Results of carbonation depth measurement after 1 year of age are presented in Fig. 4. These results show that CM2, which is the OPC mix with w/c = 0.48, having a carbonation depth of 4.5 mm. The OPC/slag mix SLG60 had carbonation depth of 6 mm depth grater than CM2 which has similar w/c ratio.

The AAS mixes differ in their depth of carbonation, as the lowest depth of carbonation was achieved by SS6 with a depth of only 4 mm of carbonation followed by MET6 with depth of 7.5 mm then SS4 which had a carbonation depth of 9 mm and the highest carbonation depth which was with MET4 having 12 mm.

Although hydrated slag blended and AAS concrete produce low Ca(OH)₂ which is the main reactant for carbonation in OPC concrete, some researchers have reported higher rate of carbonation with AAS concrete especially with low grade, low strength concretes. This might be due to carbonation of C–S–H [20,25].

4.5. Alkali–silica reaction

The results of the alkali–silica reaction expansion test carried out in this investigation on the prisms of the concrete mixes cast and treated in accordance with the relevant standard detailed in previous sections are discussed in detail to reach an understanding of the behaviour and potential for ASR to occur in AAS concrete.

4.5.1. Reactivity of the aggregate

The Thames valley sand used in this investigation was identified by Blackwell et al. [26] being of greywacke source as having deleterious expansion attributed to AAR. This finding is confirmed in this investigation. Results shown in Fig. 5 show that the TEST 1 mix exhibited high expansion up to 0.185% after 1 year of exposure. Greywacke some times is the only available source for aggregate for construction. That is the case with certain areas in the UK. The potential reactivity of such aggregates can still be avoided by several means, including controlling the alkali or using cement replacing binders such as fly ash or slag. The results in Fig. 5 show that the OPC/slag mix having high binder content and 60% cement replacement by GGBS (TEST 2) achieved a reduction in the expansion reaching only 0.027% after 1 year, which is below the 0.04% limit. This result is in agreement with Hobbs [27] who stated that incorporation of GGBS for 50% of OPC in concrete results in a reduction in the expansion of concrete in the presence of reactive aggregate. Sims [28], Thomas and Innis [29] stated that the addition of slag had a beneficial effect in reducing expansion. Also reached similar conclusions to the reduction in expansion in mortar bars and concrete prisms made with alkali–silica reactive aggregates. It can be noted from Fig. 6 that the OPC/slag mix SLG60 reached a maximum value of expansion 0.02%, which is lower also than the limit and lower than the TEST 2 mix probably because of the high cementitious content and the alkali content of the latter. The role of slag in reduction of expansion due to ASR in OPC and GGBS blends containing at least 50% slag was attributed by the BRE digest [30] to the greatly reduced ability of hydroxyl ions to diffuse within the cement paste. Glasser [31] stated that the products of hydration of blended cements have higher binding power for alkalis resulting in less potential for reaction with aggregate.

4.5.2. ASR potential in AAS concrete

The results in Fig. 6 show that AAS concrete had overall a low expansion indicating less susceptibility to ASR. Comparing the mixes based on the Na₂O dosage shows that the higher the Na₂O content the higher the expansion,
as SS6 shows higher expansion than SS4, and MET6 shows higher expansion than MET4. On the other hand, comparison based on the $M_s$ of the activator indicates that the higher the $M_s$, the lower the expansion, when the Na$_2$O is the same since, the SS4 expansion was lower than that of MET4, and SS6 expansion was lower than that of MET6. The control OPC mix CM2 also showed low values for expansion reaching 0.0165% at 1 year. The available literature is contradictory. Some researchers pointed out there is no susceptibility for ASR with AAS in agreement with what was found in this investigation. Some of those researchers stated that it is not possible for ASR to take place in the activated slag mortar because all, or almost all, the alkalis (more than 80%) are combined in the different hydration products [5]. Gifford and Gillot [23] proposed that AAS concrete is less susceptible to ASR because of the pessimum effect, which results in the consumption of the reactive silica during the early period of
hardening. On the other hand others reported potential for ASR in AAS mortars and concrete. Metso [22] reported expansion in AAS mortars. Wang [6] reported some work done in China that found ASR expansion about 0.1–0.15% using 3% granulated silica in AAS mortars. Bakhre-rov et al. [32] tested AAS concrete where slag was activated by a mixture of Na2SiO3 and NaOH having an Ms = 0.75. They reported high expansion starting from 0.04% at 90 days, increasing to 0.045% after 12 months, reaching 0.1% after 22 months. They recommended that ASR testing with AAS concrete should continue for over 2 years as they noticed slower expansion at early ages where it is mitigated according to the researchers by rapid strength development. This suggestion is probably reasonable as the results of this investigation, shown in 6, show a trend of probable increase in the future for the AAS mixes having 6% Na2O although the expansion is still below the 0.04% limit after 1 year.

Glasser [31] as mentioned earlier stated that OPC/slag blends among other blended cements have higher binding power for alkalis in their hydration products, which can also be true for AAS concrete resulting in less potential for ASR. The results of this investigation can be explained following the same logic. The effect of Ms of the activator on the expansion as it decreases with higher Ms can be due to the binding of the alkali fraction to the silicate fraction of the activator in forming part of the hydration products. SS4, having lower alkali and higher Ms showed the lowest expansion.

5. Conclusions

1. The choice of the type of activator and dosage is very important in AAS concrete with the higher dosage resulting in higher strength and the higher silicate modulus of the activator resulting in higher strength.
2. Replacing 60% of OPC by GGBS results in an increase in porosity compared to the OPC mix of the same w/c ratio while it results in lower porosity when compared to the OPC mix with the same workability level.
3. The increase of the Na2O dosage in AAS concrete, where the activator has an Ms = 1.0, results in a decrease in porosity. But in the case of the AAS concrete, with the activator having Ms = 1.65, the porosity increases with the increase of the Na2O dosage.
4. Slag/OPC concrete undergoes higher carbonation than OPC concrete with the same w/c ratio.
5. AAS concrete with low compressive strength around 40 MPa shows higher carbonation depth compared to OPC concrete of the same grade.
6. Replacing 60% of the OPC by slag reduces the alkali–silica reaction expansion of concrete prisms containing reactive aggregates.
7. AAS concrete has low susceptibility to ASR expansion possibly because of binding of alkalis in the hydration products.

References


