

# 1 Alkali activated slag concretes designed for a desired slump, strength and chloride diffusivity

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## 11 Abstract

12 Ground granulated blast furnace slag (GGBS) is the most common industrial by-product used as a  
13 precursor for alkali activated binders due to its fast setting, simple curing needs, and good early age  
14 strength gain. There are conflicting findings on the chloride penetration resistance of such binders and  
15 more information is required regarding the suitability of this type of binder material for chloride  
16 environments. This article outlines the findings of investigation of alkali activated slag concretes  
17 (AASC), to provide a comprehensive view of the effect of mix design variables on slump, strength, and  
18 chloride transport and binding. It is concluded that AASC can be designed for different workability and  
19 different grades of concrete. The diffusivity results demonstrate that the addition of excess water does  
20 not directly control the pore structure/connectivity in AASC as it does for Portland cement, and  
21 therefore AASC can be designed based on the water/binder ratio needed for a specified mechanical  
22 performance. The chloride binding capacity increased as the paste content of the concrete and/or the  
23 silica content of the activator was increased.

24 **Keywords:** alkali activated slag concretes (AASC); workability; strength; chloride diffusion and  
25 chloride binding capacity

## 26 1. Introduction

27 Alkali activated materials (AAMs) have been under consideration as an alternative binder system since  
28 1895 [1]. However, despite the engineering community having been aware of the potential of this  
29 material for over a century, there is still insufficient information available about the durability of AAMs,  
30 and the resistance to chloride ingress is particularly critical for materials intended to serve in reinforced  
31 concretes.

32 Several factors are known to affect the setting time, workability, strength and durability properties of  
33 alkali activated slag concretes (AASC), including: the type of alkaline activator, the means of adding  
34 the activator, the dosage of alkali, the SiO<sub>2</sub>/Na<sub>2</sub>O ratio (denoted *modulus*, Ms), the type and fineness of  
35 slag, the paste content of the concrete, and the water to solid ratio in the paste constituent of AASC.

36 Many of these factors are interdependent, and the effect of changing more than one in parallel is usually  
37 not additive. The optimum  $\text{Na}_2\text{O}$  dosage for AAS binders activated by sodium silicate solution under  
38 normal curing has been found to be 3% – 5% relative to the mass of slag, depending on the demand for  
39 high early age strength [2-4]. Slag cements activated by sodium silicate at modulus values between 0.6  
40 and 1.5 at appropriate dosages were reported to show high ultimate strength for engineering purposes.  
41 However, this optimum modulus for appropriate dosage of sodium silicate varied depending on the type  
42 of slag, i.e. 0.75 – 1.25 for acid slag, 0.90 – 1.3 for neutral slag, and 1.0 – 1.5 for basic slag [3-5].  
43 Activation by sodium silicate tends to give higher strength than when NaOH is used; the lower strength  
44 in the NaOH activated slag pastes may be explained by the much higher porosity found in these pastes  
45 than in the sodium silicate activated materials [6].

46 The effect of water to slag ratio on NaOH activated slag is similar to that of water to cement ratio on  
47 Portland cement [4]. However, an increase in water to slag ratio has a very marked effect to decrease  
48 the heat evolution of  $\text{Na}_2\text{SiO}_3$  activated slag [4]. In this case when the water to solid/slag ratio is lower  
49 than 0.45, there is an early and pronounced peak in the heat evolution curve, which then changes to a  
50 very diffuse peak with 15 hours delay for a water to slag ratio greater than 0.45 [4]. This can have a  
51 noticeable effect on the performance of AASC, especially on workability and setting time.

52 It has been reported [7] that by controlling mix design parameters, such as binder content and water to  
53 binder ratio, it is possible to produce AASC with mechanical strength and durability comparable to  
54 conventional Portland cement concretes. It has also been shown that a higher slag content leads to an  
55 increase in strength of AASC and improvement of the permeability, water absorption and carbonation  
56 resistance [7].

57 Park *et al.* [8], in their work using mortars, have reported that the corrosion behaviour of embedded  
58 steel in AAMs was strongly dependent on the type of alkali activator. According to their findings, AAS  
59 containing  $\text{Ca}(\text{OH})_2$  as the activator was most effective to reduce galvanic corrosion, while KOH and  
60 NaOH activators indicated corrosion levels similar to that of Portland cement mortar [8].

61 AASC has traditionally been known for its low slump, and this raises challenges in its design for  
62 different workabilities and different grades of concrete. Therefore, this article presents findings from  
63 investigations of the effect of water/slag ratio and binder content on workability, strength, chloride  
64 diffusion and chloride binding in AASC, with the aim of determining the suitability of AASC for use  
65 in chloride environments. The outcomes will help designers to select mix designs for AASC for required  
66 performance.

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## 70 **2. Materials and experimental procedures**

### 71 **2.1 Materials**

72 The granulated blast furnace slag used in this study was provided by ECOCEM, France. The basicity  
73 coefficient  $(\text{CaO}+\text{MgO}/\text{SiO}_2+\text{Al}_2\text{O}_3)$  and the quality coefficient  $(\text{CaO}+\text{MgO}+\text{Al}_2\text{O}_3)/(\text{SiO}_2+\text{TiO}_2)$  were  
74 calculated from the chemical composition (Table 1) to be 1.07 and 1.7, respectively. The particle size  
75 distribution of slag was determined by laser diffraction, the particle density was measured using a  
76 LeChatelier flask, and the water absorption was measured using the centrifugal consolidation method;  
77 these physical properties are presented in Table 2.

78 The aggregates used in this study were crushed basalt from local sources in Northern Ireland, and  
79 comprised 10 mm and 16.5 mm crushed aggregates, and 4 mm sand. In stage A of the experimental  
80 campaign, the proportion of 16.5:10:4 mm fractions were 32:32:36; in stage B the proportions were  
81 optimised for the best packing density at 48:12:40. The bulk specific gravity and water absorption of  
82 these materials were measured based on BS EN 1097-1, and are presented in Table 3. Potable tap water  
83 (i.e. drinking water quality) was used to make the concrete mixes.

84 Sodium hydroxide (NaOH) pellets were dissolved in water and used along with sodium silicate solution  
85 to act as alkaline activators in concrete production at specified concentrations and compositions, as  
86 shown in Table 4. The chemical composition of the as-received sodium silicate solution was 15.5%  
87 sodium oxide ( $\text{Na}_2\text{O}$ ), 30.5% silicon dioxide ( $\text{SiO}_2$ ) and 54% water, on a mass basis. NaOH was used  
88 to adjust the  $\text{Na}_2\text{O}$  content and Ms value to the required values.

### 89 **2.2 Mix details, mixing and casting of test specimens**

90 Twelve AAS concretes with alkali concentrations ( $\text{Na}_2\text{O}$  % by of mass of slag) of 4, 6, and 8 %, and  
91 modulus (Ms) values of the sodium silicate solution activator of 0.75, 1.00, 1.50, and 2.00, were studied  
92 in stage A. The water/binder mass ratio (w/b) was held constant at 0.47 in these concretes. A barium  
93 based retarder was used in this work for mixes A1-A12 for controlling the setting time. The content of  
94 the retarder was 0.3% of the mass of slag for all of these mixes and dry-blended with slag before mixing.  
95 For the purpose of comparison, one PC concrete mix was manufactured with the same total binder  
96 content as that of the AAS concretes. A w/b of 0.42 was specified for the PC concrete [9] to ensure that  
97 its performance in exposure classes XS3 and XD3 as defined in BS EN 206:2013 [10] would be  
98 acceptable. In stage B, ten further AAS concretes were studied with different w/b ratios, binder to  
99 aggregate ratios, alkali concentrations, and Ms values without using retarder. The details of the different  
100 mixes and their initial properties are presented in Table 4. Throughout this work, the total binder content  
101 is defined as the sum of GGBS and the solid component of the sodium silicate solution, and the water  
102 content of the sodium silicate solution was taken into account while determining the mixing water.

103 A laboratory pan-mixer of volume 50 L was used in this study. In stage A the mixing was conducted in  
104 accordance with BS 1881-125:2013 [11]. In Stage B, crushed basalt aggregates and sand were first dry-  
105 mixed together for one minute, and the GGBS powder was subsequently added, and mixed for a further  
106 2 minutes. The sodium hydroxide solution was then added and after a further 2 minutes of mixing, then  
107 sodium silicate solution was added and mixing continued for a further minute.

108 For both stages, fresh properties of concrete were measured according to BS EN 12350 [12], and nine  
109 100 mm cubes and one 250×250×110 mm slab were cast for determining compressive strength in  
110 accordance with BS EN 12390 [13], and chloride diffusion coefficients according to Nordtest NT Build  
111 443 [14]. After casting, all the specimens (still in moulds) were covered with plastic sheets and left in  
112 the casting room for 24 h. The demoulded slabs were wrapped with 3 layers of plastic sheets, and cube  
113 samples were kept in a sealed plastic zip bag, until the testing date. The storage room was maintained  
114 at 23°C and 65% RH.

### 115 **2.3 Testing procedures**

116 Chloride transport through AAS concretes was assessed using a non-steady state chloride diffusion test,  
117 Nordtest NT Build 443 [14]. One day before the test age of 91 days, three cores of diameter 100 mm  
118 per mix were drilled from the 250 x 250 x 110 mm concrete blocks. A slice with a thickness of 50 mm  
119 from the cast surface (trowel finished face) was cut off, and the rest was kept for carrying out the test.  
120 The vacuum saturation regime specified in the standard was used to precondition the slices so that the  
121 chloride flow is predominantly diffusive, and initial sorption or capillary forces are negligible. The  
122 vacuum was applied to remove air for three hours and released afterwards. Samples were wrapped in  
123 hessian saturated in deionised water to prevent leaching of ions, and placed in the container. The weight  
124 of the sample was noted after an hour ( $W_1$ ) and then vacuum was applied, followed by further saturation.  
125 Weight was checked again ( $W_2$ ). Usually after 6 hours, when  $W_i - W_{(i-1)}$  was less than 0.1%, the samples  
126 were considered fully saturated; if not, saturation was continued until this criterion was met. After  
127 conditioning to a surface-dry condition, an epoxy resin was applied onto the surfaces of the specimens  
128 in three layers except the exposure face (saw cut face). When the epoxy coating was dry, the cores were  
129 immersed in an NaCl solution of concentration 165 g/L (~2.82 M) for three months for samples tested  
130 in stage A, or six months for samples tested in stage B. After immersion, the cores were profile ground  
131 to obtain concrete dust from different depths up to a depth of 30 mm in stage A and 16 mm in stage B,  
132 measured from the exposed surface. The total chloride content of the dust samples was determined in  
133 accordance with the recommendations of RILEM TC 178-TMC [15] using a pre-calibrated  
134 potentiometric titration method. The concrete dust was dissolved in deionised water in accordance with  
135 RILEM TC 178-TMC recommendations [16] to measure the pH value of the suspension in both stages,  
136 and for the determination of water soluble chlorides in stage B. Chloride diffusivity and the surface

137 chloride content were determined by using curve fitting to the error function solution of Fick's second  
138 law of diffusion, as described in NT BUILD 443 [14].

### 139 **3. Results and discussion**

140 The following sections discuss the slump, compressive strength, chloride diffusivity, and chloride  
141 binding capacity of AAS concretes.

#### 142 **3.1 Slump**

143 AASC has often been characterised by a low slump value and rapid setting behaviour; slump values up  
144 to 60-120 mm have been reported in the literature [17]. The purpose of this testing programme was to  
145 demonstrate the range of slump values that AASC is capable of producing, and the changes to the  
146 governing variables that are necessary to achieve such high slump. The Stage A results shown in Table  
147 4 and Figure 1 indicate that a slump value between 55-180 mm can be achieved by varying the  
148 percentage Na<sub>2</sub>O and Ms while the w/b is fixed at 0.47. As the percentage of Na<sub>2</sub>O increased, the slump  
149 increased from 55-70 mm (Mixes A1, A5 and A9), and a further increase in modulus (A1-A4, A5-A8,  
150 A9-12) brought the slump values to 180 mm due to the plasticising effects of dissolved silicate anions.  
151 In order to design slump class  $\geq$  S3 specified in BS 8500-1:2015 [18], an Na<sub>2</sub>O dose of 8% is required.  
152 The role of parameters such as Na<sub>2</sub>O% and Ms in controlling the slump has been widely reported in the  
153 literature [19, 20] and is in agreement with the Stage A results.

154 In Stage B, tests were designed to consider the effects of other parameters such as w/b and binder  
155 content and did not use the retarder. Mixes in this stage were limited to Ms values of 0.45 or 1, as an  
156 increase in modulus means a proportional increase in the sodium silicate content, which is both costly  
157 and can have high negative environmental impacts. The main difference between the mix designs in the  
158 two stages is that w/b was increased to 0.55 in stage B, and its effect is very obvious on the slump as  
159 mixes B4, B6-B10 had slump values in excess of 135 mm. What is more interesting is that slump values  
160 >200 mm are achievable with low Na<sub>2</sub>O% and Ms by increasing w/b, so in this sense, the AASC behaves  
161 similarly to PC concretes without any observation of bleeding or segregation.

162 As is evident from Figure 1a and 1b, the AASC can be designed for all slump ranges. However, higher  
163 slumps in the range of S4-S5 require w/b ratios higher than those allowed in BS 8500 [18]. Whether  
164 such high w/b ratios are acceptable for concretes in different chloride exposure environments will be  
165 further discussed in section 3.3, after the diffusivity results are presented.

166 The contour map graphs in Figure 2 show the results obtained for slump as a function of sodium oxide  
167 (Na<sub>2</sub>O%) and silicate modulus (Ms), for different mixes with same binder content for both stages. Using  
168 a w/b ratio of 0.55 instead of 0.47 resulted in more workable mixes. It is obvious from Figure 2(b) that  
169 at higher w/b, both sodium oxide (Na<sub>2</sub>O%) & silica modulus (Ms) have a significant effect on  
170 workability, while for lower w/b, parallel lines in Figure 2 (a) indicates that only the effect of Na<sub>2</sub>O%

171 is significant. All AAS concrete mixes in stage 2 (i.e., 0.55 w/b) are in at least class S3 specified in BS  
172 8500-1:2015 [18], even for the minimum alkali content and silica modulus, which are 4% and 0.45,  
173 respectively in this stage, whereas in stage A the minimum alkali content to reach this class of  
174 workability was more than 7.5% and the minimum silica modulus is 1.0. It is evident from the results  
175 in stage B that for a silica modulus more than 0.8, increasing the sodium oxide increases the workability,  
176 as has been reported by previous investigators [18, 19].

### 177 3.2 Compressive strength

178 An overall comparison of the results between Stages A and B (Figure 3) makes the effect of w/b very  
179 apparent, with almost all (except one) Stage A mixes exceeding 45 MPa at 28 days. Stage B mixes with  
180 w/b between 0.55 and 0.7 offer 28-day compressive strengths in the range 21.5 to 64.4 MPa. From the  
181 Stage A results, it can also be stated that: (1) most mixes had approximately 20 MPa after 3 days curing,  
182 (2) higher modulus results in loss of early strength, but offers comparable strength in the long term, (3)  
183 in most cases 28 day strength is 80-90% of the 91 day strength, offering insight into the short and long  
184 term microstructural development in such binders. It is obvious that mixes with high modulus (i.e.,  
185 silicate content) need to be cured longer. Concretes with Ms values of 1.0 to 1.5 generally obtained the  
186 highest compressive strength (see Figure 3(a)), which is in agreement with the literature [21].

187 Figure 3b shows data for mixes with varying w/b. The comparable mixes B8-10 all offer better strengths  
188 than their Stage A equivalents (A2, A6, A10) after 28 days, despite their higher w/b. But as time  
189 progress, i.e., with 91 days curing, the aforementioned differences become negligible. Better strengths  
190 for Stage B could be due to their higher density. Due to these differences, it is best to summarise that  
191 strength in the range of 20-60 MPa is achievable by altering the binder content, w/b, Ms, and Na<sub>2</sub>O%.  
192 To aid with the design for strength, a contour map using 28 day compressive strength results as a  
193 function of sodium oxide (Na<sub>2</sub>O%) and silica modulus (Ms) is provided in Figure 4. An increase of  
194 Na<sub>2</sub>O% and Ms generally increases the compressive strength, which is in agreement with the results  
195 reported by others [19, 21]. This is due to the higher degree of reaction (indicating the extent to which  
196 the slag particles are reacted) caused by an increase in the alkali activator dosage [22]. More N-A-S-H  
197 (sodium aluminosilicate hydrate) gels are generated when the Na<sub>2</sub>O% and SiO<sub>2</sub> content are increased.  
198 The bottom right corner of Figure 4a (Stage A results) also shows that the strength value decreases as  
199 the silica modulus increases beyond 1.5 for Na<sub>2</sub>O doses below 5%, as the alkalinity of the activators in  
200 such systems is not sufficient to reach a very high degree of reaction.

201 The PC concrete in Stage A was designed as a reference that conforms to the BS EN 206:2013  
202 requirement for exposure classes XS3 and XD3. Therefore, it was designed for a minimum  
203 characteristic compressive strength of 45 MPa, which is equivalent to an average strength  $\geq 49.41$  MPa  
204 (calculated as  $45 + 1.48(3.15)$  MPa; where 3.15 is the standard deviation of the test results). Table 4 and  
205 Figure 3(a) both show that mixes no. A3(4%-1.5), A6(6%-1.0), A7(6%-1.5), A8(6%-2), A9 (8%-0.75),

206 A10 (8%-1.0), A11(8%-1.5), A12(8%-2) and the PC met the strength requirements for this exposure  
207 class. Additionally, most of the AAS concretes except mix A4(4%-2) met the strength requirement of  
208 41.66 (=37+1.48(3.15)) MPa for the lower-demand exposure classes XS1, XD1 and XD2. It should be  
209 noted that the w/b ratio used for AAS concretes (0.47) was higher than that for PC concrete (0.42) due  
210 to the lack of workability of the AAS at such a low water content [9]. The 28 day compressive strength  
211 results reported for stage B in Table 4 and Figure 3(b) show that mixes B7(8%-0.45), B9(6%-1) and  
212 B10(8%-1) also achieved the required strength  $\geq 51.11$  (=45+1.48(4.13)) MPa for the exposure classes  
213 XS3 and XD3 even at w/b = 0.55. However, for mix B10 the setting time was inconveniently short, at  
214 around half an hour. Mixes B6(6%-0.45) and B8(4%-1) seem to meet the strength requirements of 43.11  
215 (=37+1.48(4.13)) MPa for the exposure classes XS1, XD1 and XD2. Although it was evident that the  
216 strength requirement and w/b ratio of mixes B1, B2, B3 and B5 will not comply with BS EN 206:2013  
217 norms, the intention of including these mixes was to assess their performance against chloride ingress  
218 and compare that data against a conforming PC reference.

219 Figure 5 shows the 91-day compressive strength results as a function of the SiO<sub>2</sub> content of the activator,  
220 relative to the total slag content (calculated for each mix as Na<sub>2</sub>O% × Ms). When the 91-day compressive  
221 strength values of all the activated slag concrete mixes studied are plotted as a function of (Na<sub>2</sub>O% ×  
222 Ms), a two-term exponential relationship can be fitted, as shown in Fig. 5. In general, there is an increase  
223 in the 91-days compressive strength values with increase in the SiO<sub>2</sub> content, up to a value of ~ 9% of  
224 the total slag content. This parameter is significant because it has been shown that the later-age  
225 compressive strengths of activated slag concretes are proportional to the SiO<sub>2</sub> content of the activator  
226 [23], and a higher silicate content in the activator has been reported to lead to a higher degree of reaction  
227 [24]. In agreement with this observation, the results here support the use of the maximum SiO<sub>2</sub> content  
228 for optimising strength.

### 229 3.3 Chloride diffusivity through AASC

230 Figure 6 presents chloride diffusion coefficients,  $D_{\text{nsd}}$ , for mixes from both stages. Stage A mixes, at  
231 w/b = 0.47, show very low to low chloride diffusivity values as identified in the classification of RILEM  
232 TC 230-PSC [24], from  $1.88 \times 10^{-12}$  m<sup>2</sup>/s [A7 (8%-1.5)] to  $6.59 \times 10^{-12}$  m<sup>2</sup>/s [A1 (4%-0.75)]. Stage B  
233 mixes, with w/b values of 0.55-0.7, demonstrate low to very low chloride diffusivity values [25], from  
234  $5.09 \times 10^{-12}$  m<sup>2</sup>/s (B4) to  $1.18 \times 10^{-12}$  m<sup>2</sup>/s (B2). All of the coefficients obtained, with the exception of  
235 A1, were lower than  $6 \times 10^{-12}$  m<sup>2</sup>/s, which is the lowest limiting value specified for the equivalent  
236 durability approach in PD CEN/TR 16563 [26] for chloride environments. The coefficients obtained in  
237 this study are also similar to the non-steady state chloride migration coefficient values measured via NT  
238 Build 492 and reported elsewhere [27-29]. Comparing the results of the two stages illustrates that  
239 despite the high w/b ratio, stage B concretes offer lower diffusion coefficients. This could be due to  
240 better workability and compaction in the case of stage B mixes. All the  $D_{\text{nsd}}$  values for AAS concretes

241 were lower than the result shown for PC concrete in Figure 6(a), despite the higher water to binder ratio  
242 of the AASC mixes. This is possibly due to the influence of the activated aluminosilicates, chloride  
243 binding, pore size and pore connectivity of the concrete.

244 The effects of w/b and binder content are not directly obvious from the results. It seems that the excess  
245 water is not affecting the pore structure/connectivity of AASC as it does for PC concrete. Therefore, it  
246 can only be identified that mix design parameters and also reactivity of the aluminosilicate precursor  
247 [30] may have a larger influence on the diffusivity.

248 The contour plot in Figure 7(a) (stage A) indicates that for lower w/b an optimum can be achieved by  
249 increasing the  $\text{Na}_2\text{O}\%$  and bringing the modulus closer to 1.5. The information in Figure 7(b) for stage  
250 B gives a lower range: (i) for  $\text{Na}_2\text{O}$  doses less than 5%, the lowest value is observed at a higher  $M_s$ ,  
251 similar to the observations in Figure 7(a), and (ii) for higher  $\text{Na}_2\text{O}$  doses, this is reversed.

252 In summary, the  $D_{\text{nssd}}$  is comparatively low for all of the AASC mixes studied here.  $D_{\text{nssd}}$  is a measure  
253 of the rate of transport as modified by the chemical reactions leading to chloride binding. In order to  
254 distinguish these two effects, the binding capacity of the mixes in stage B was assessed to develop a  
255 more complete picture of the factors controlling chloride transport in AASC.

### 256 3.4 Chloride binding in AASC

257 There is limited information available on chloride binding of AASC in the literature. The available CSH  
258 and aluminate phases (C-(N)-A-S-H or two layered double hydroxides) in activated GGBS may  
259 contribute to the physical and chemical binding reactions [30, 31]. Figure 8 shows the total and water-  
260 soluble chloride concentrations measured for concrete mixes B8, B9 and B10, and the corresponding  
261 pH values are also provided for comparison. It is evident from Figure 8 that the surface region, Zone 1,  
262 is undergoing leaching-induced changes during  $\text{Cl}^-$  transport that result in a lowering of pH; there is  
263 also a skin effect which causes a near-surface dip in the total  $\text{Cl}^-$  content. The depth of zone 1 is between  
264 5-12 mm for the three mixes; the lowest depth is for the mix with 6%  $\text{Na}_2\text{O}$  and  $M_s = 1$ . In Zone 2, pH  
265 reduction is not significant. It is known that pH reduction can release the  $\text{Cl}^-$  otherwise bound to  
266 Friedel's salt [32] in PC based systems. It should be noted that the total  $\text{Cl}^-$  is composed of both bound  
267 and free chloride, and free chloride is represented here by the water soluble fraction which therefore  
268 will also contain a proportion of the adhered  $\text{Cl}^-$  physically bound to the aluminate phases. The ratio  
269 between total and water-soluble  $\text{Cl}^-$  seems to follow the general trends established for PC systems [33].  
270 The quantity of bound chlorides for all the mixes in stage B is shown in Table 5. This is computed by  
271 determining the area under the total and free chloride curves from the concentration vs depth graph  
272 (typical data shown in Fig. 8); the difference between the two areas gives the quantity of bound chloride.  
273 The values presented in Table 5 show that quantity of bound chlorides increased as the paste content of  
274 the concrete and/or the silica content of the activator was increased. As discussed, the main reaction  
275 product in AASC is an Na-Al substituted calcium silicate hydrate (C-(N)-A-S-H) gel which can bind



276 chlorides, while hydrotalcite-group minerals are a smaller constituent of the phase assemblage but have  
277 strong chloride binding capacity. Surface absorption is the main binding mechanism in these phases,  
278 responsible for around 90% of the total chloride uptake, with around 10% contribution from ion  
279 exchange [30, 31]. The binding capacity is comparable to the values reported for PC and high-volume  
280 blast furnace slag concrete [34]. This is likely due to the alkalinity reduction affecting the stability of  
281 the bound chlorides [34, 35] in zone 1.

282 In summary, the mass transport testing showed that AASC performed significantly better than  
283 conventional PC based binders in terms of restricting  $\text{Cl}^-$  transport. These concretes can be classified  
284 into two zones, based on the reduction of pH closer to the surface. While the overall binding capacity  
285 is deemed slightly lower than comparable PC systems, further study is needed to exclude the effect of  
286 pH reduction and to eliminate near-surface effects.

#### 287 **4. Conclusion**

- 288 • AAS concretes can be designed for different workability and strength grades of concrete. The  
289 key parameters at the disposal of the designer are  $\text{Na}_2\text{O}\%$ , Ms, and the paste content.
- 290 • For higher water to binder ratio, both sodium oxide ( $\text{Na}_2\text{O}\%$ ) and silica modulus (Ms) influence  
291 the workability, while for lower w/b only  $\text{Na}_2\text{O}\%$  seems to have a notable effect.
- 292 • The compressive strength values were strongly proportional to the  $\text{SiO}_2$  content in the activator.  
293 This will be useful as guidance to produce AASC of required strength.
- 294 • Chloride diffusion coefficients of AAS concretes are low. Measurement of chloride binding  
295 capacity was affected by the pH reduction due to leaching in the surface zone. The depth of the  
296 affected zone was in the range of 5-12 mm, so further study is required to discern the binding  
297 capacity of zones unaffected by this type of pH reduction.
- 298 • The diffusivity results demonstrate that the excess water is not affecting the pore  
299 structure/connectivity in AASC as it does for PC concretes; and AASC can be designed based  
300 on the w/b needed for a required mechanical performance.

301 As a closing remark the authors suggest adopting a performance-based approach to specifying such  
302 concretes, since the conventional wisdom of w/b and mix design features may not translate well [26].  
303 A performance-based approach is apt to give confidence to the suppliers, and also to convince clients  
304 of the beneficial aspects of AASC.

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308

309 Table 1: Oxide composition of the GGBS used, from X-ray fluorescence analysis

Precursor	Component (mass % as oxide)							
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	MgO	TiO <sub>2</sub>	Other	LOI*
GGBS	35.7	11.2	43.9	0.3	6.5	0.512	1.578	0.31

310 \* LOI is loss on ignition at 1000°C.

311 Table 2: Physical properties of the GGBS used

Fineness (particles $\geq 45\mu\text{m}$ )	7.74%
Particle density	2.86
Water absorption	35.14%

312

313 Table 3: Physical properties of aggregates

Aggregates	Bulk dry specific gravity	Bulk saturated surface-dry specific gravity	Water absorption (%)
Sand (0-4 mm)	2.72	2.73	0.75
Fine crushed agg. (5-10 mm)	2.67	2.75	3.14
Coarse crushed agg. (10-16 mm)	2.60	2.67	2.60

314

315 Table 4 (a): The details of the different Stage A mixtures and their properties

Mix No.	Mix details (Na <sub>2</sub> O%-Ms)	Wet density	Setting time (initial/final) (min)	Slump (mm)	3 days compressive strength (MPa)	28 days compressive strength (MPa)	Concrete grade
A1	4%-0.75	2245	30/39	55	22.3	44.7	C32/40
A2	4%-1	2217	11/14	55	21.8	46.7	C35/45
A3	4%-1.5	2229	15/22	55	1.7	49.5	C35/45
A4	4%-2	2186	18/24	55	1.4	33.3	C30/37
A5	6%-0.75	2222	28/38	65	31.7	47.3	C35/45
A6	6%-1	2219	12/22	65	37.3	53.6	C40/50
A7	6%-1.5	2221	14/22	65	20.3	60.8	C49/60
A8	6%-2	2236	32/42	75	8	59.6	C45/55
A9	8%-0.75	2208	16/26	70	32.3	51.9	C40/50
A10	8%-1	2230	46/58	105	32.7	53.6	C40/50
A11	8%-1.5	2233	37/56	145	34.1	59.3	C45/55
A12	8%-2	2241	-	180	11.7	55.4	C45/55
A13	PC	2257	-	50	35.4	58.9	C45/55

316 Note: all have water to binder ratio = 0.47, binder content = 400 kg/m<sup>3</sup>, sand = 670±16 kg/m<sup>3</sup> and aggregate = 1190±30  
 317 kg/m<sup>3</sup>, from [9]. The setting time of the alkali activated slag pastes with standard consistence (0.2<w/b<0.27) was studied in  
 318 satge A and the results are reported in the above Table. Due to the quick setting as observed, a retarder described in section  
 319 2.2 at a dosage of 0.3% of the mass of slag was used to control the setting of the AASCs. This dosage was the minimum one  
 320 guaranteeing all of the alkali activated slag mixes to meet the setting time requirement specified in BS EN 197-1 (2011)  
 321 [36, 37].

322

Table 4 (b): The details of the different Stage B mixtures and their properties

Mix No.	Mix (Na <sub>2</sub> O%-Ms)	Binder (kg/m <sup>3</sup> )	w/b	Sand (kg/m <sup>3</sup> )	Aggregate (kg/m <sup>3</sup> )	Wet density	Setting time (initial/final) (min)	Slump (mm)	2 days compressive strength (Mpa)	28 days compressive strength (MPa)	Concrete grade
B1	4%-0.45	300	0.60	772	1158	2426	120/175	40	15.3	27.1	C20/25
B2	4%-0.45	360	0.70	671	1007	2410	145/200	225	11.1	21.5	C16/20
B3	4%-0.45	400	0.60	669	1004	2390	165/230	215	15.3	26.4	C20/25
B4	4%-0.45	400	0.55	701	1051	2395	160/230	168	17.8	30	C25/30
B5	6%-0.45	400	0.60	669	1004	2389	130/200	215	21.2	35.8	C28/35
B6	6%-0.45	400	0.55	701	1051	2469	125/200	135	24.7	44	C32/40
B7	8%-0.45	400	0.55	701	1051	2464	90/150	225	38.4	53.6	C40/50
B8	4%-1	400	0.55	701	1051	2519	80/135	160	25.8	47.8	C35/45
B9	6%-1	400	0.55	701	1051	2447.5	60/110	203	33.9	62.7	C49/60
B10	8%-1	400	0.55	701	1051	2420	40/70	240	33.7	64.4	C49/69

324 Note: The setting time of the AASCs in sage B are reported in the above Table based on observations during casting  
 325 concrete.

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Table 5: Total Cl<sup>-</sup>, free Cl<sup>-</sup>, and bound Cl<sup>-</sup> values for stage B mixes

Mix No.	Mix details (Na <sub>2</sub> O%-Ms)	Binder (kg/m <sup>3</sup> )	w/b	Total Cl <sup>-</sup> (Quantity)	Free Cl <sup>-</sup> (Quantity)	Bound Cl <sup>-</sup> (Quantity)
B1	4%-0.45	300	0.60	7.08	2.93	4.15
B2	4%-0.45	360	0.70	7.14	2.59	4.55
B3	4%-0.45	400	0.60	10.32	4.02	6.30
B4	4%-0.45	400	0.55	13.53	3.54	9.99
B5	6%-0.45	400	0.6	12.71	4.54	8.17
B6	6%-0.45	400	0.55	10.69	4.01	6.68
B7	8%-0.45	400	0.55	7.72	3.14	4.58
B8	4%-1	400	0.55	11.37	4.62	6.75
B9	6%-1	400	0.55	11.36	3.69	7.67
B10	8%-1	400	0.55	9.32	3.53	5.79

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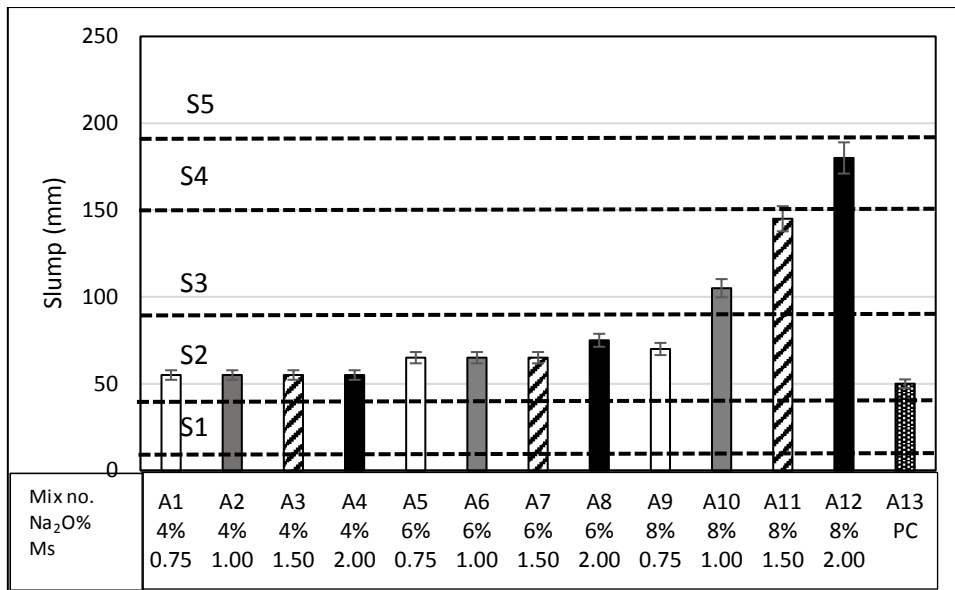
**Note:** Quantity of total Cl<sup>-</sup> and free Cl<sup>-</sup> was estimated by computing the area under the concentration vs depth curve. Maximum value for depth was 16mm for all mixes. Quantity of bound chlorides is therefore the difference between the total and free chlorides.

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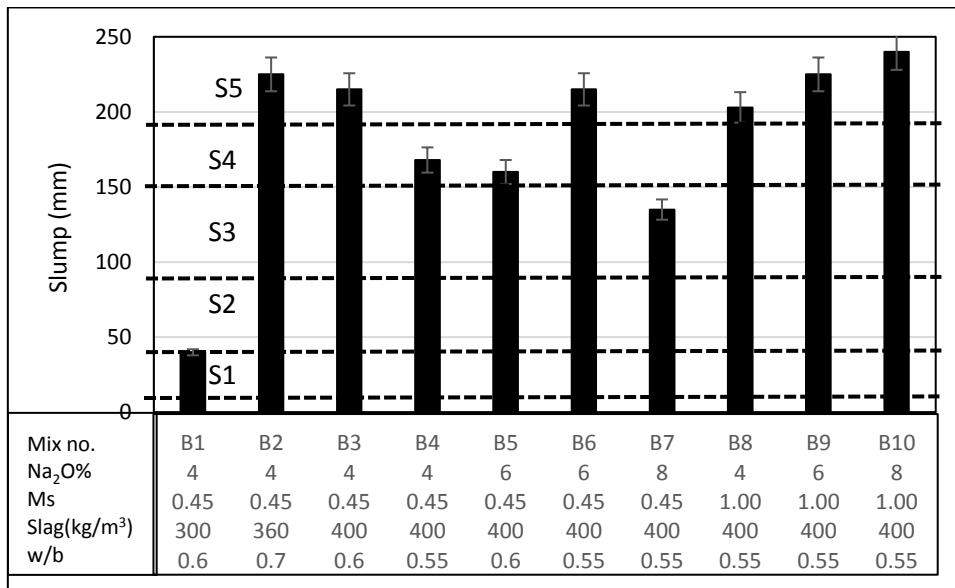
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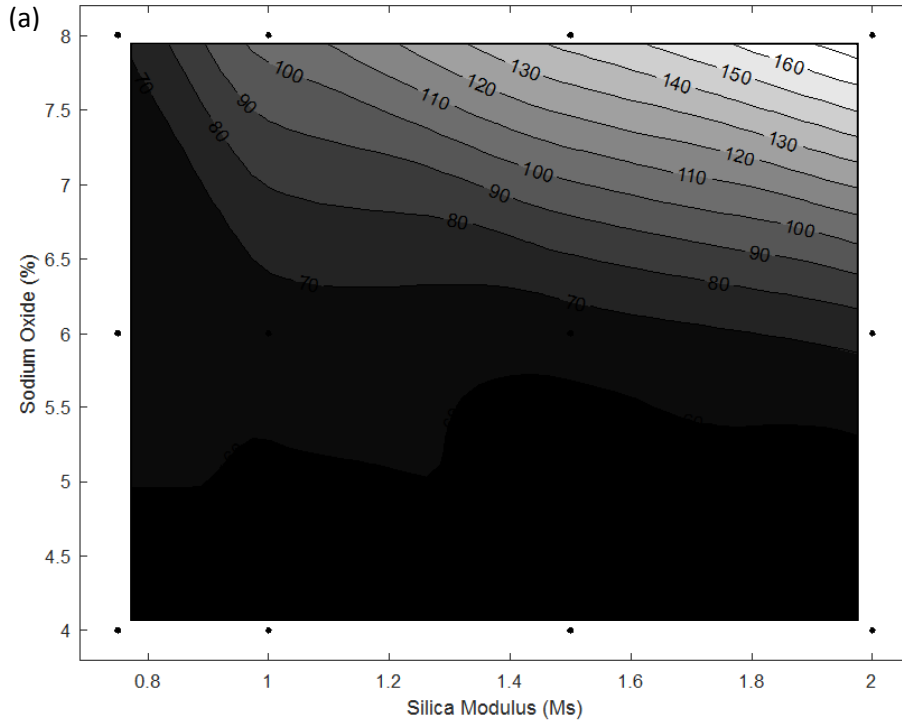


(a)

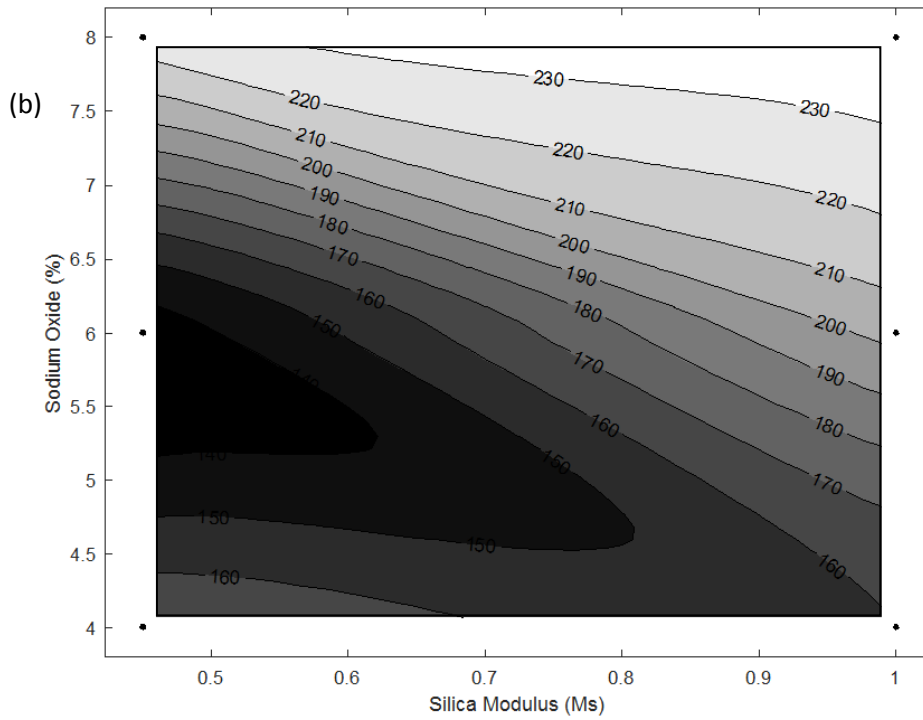


(b)

Figure 1. Slump results of AAS concretes: (a) Stage A, water to binder ratio = 0.47 and binder content = 400 kg/m<sup>3</sup>; (b) Stage B with various mix design parameters as marked



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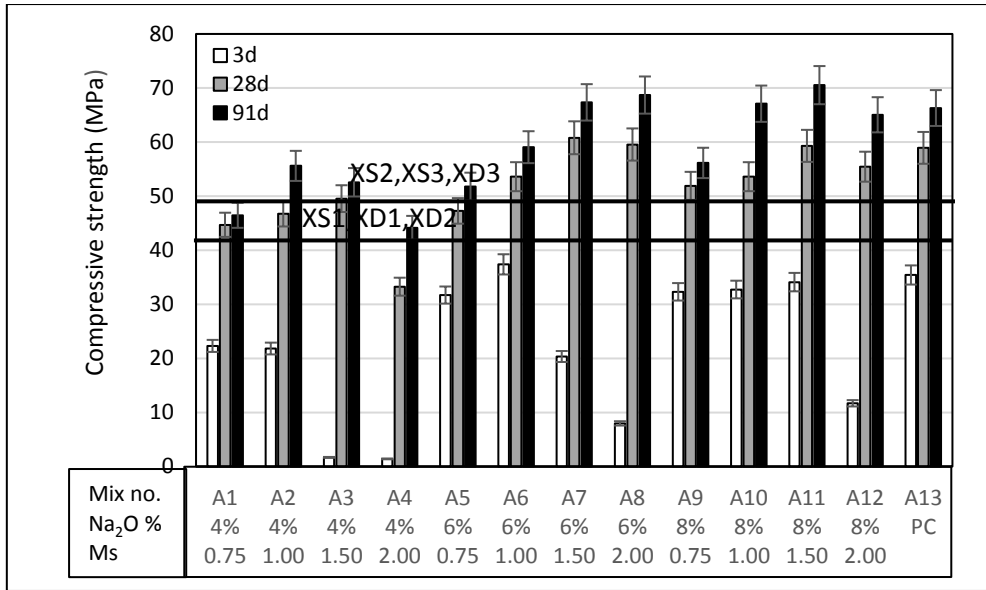


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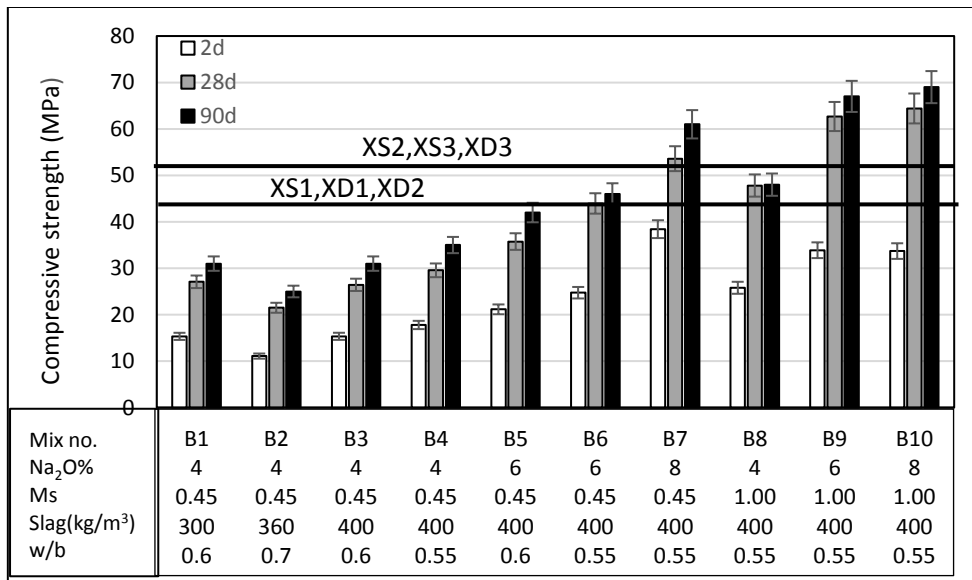
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Figure 2. Contour graph for workability of different mixes (binder content=400 kg/m<sup>3</sup>): (a) Stage A, water to binder ratio = 0.47; (b) Stage B, water to binder ratio = 0.55



(a)

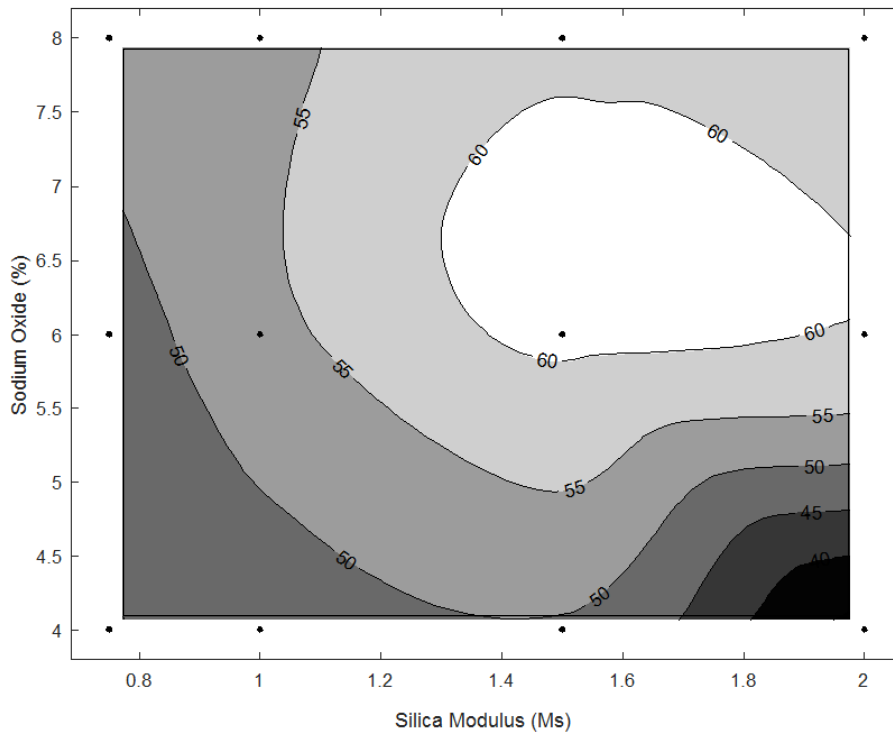


(b)

Figure 3. Strength results of AAS concretes at different curing ages: (a) Stage A, water to binder ratio = 0.47 and binder content = 400 kg/m<sup>3</sup>; (b) Stage B with various mix design parameters as marked. The error bar compare the difference between the mean with the amount of scatter within replicates.

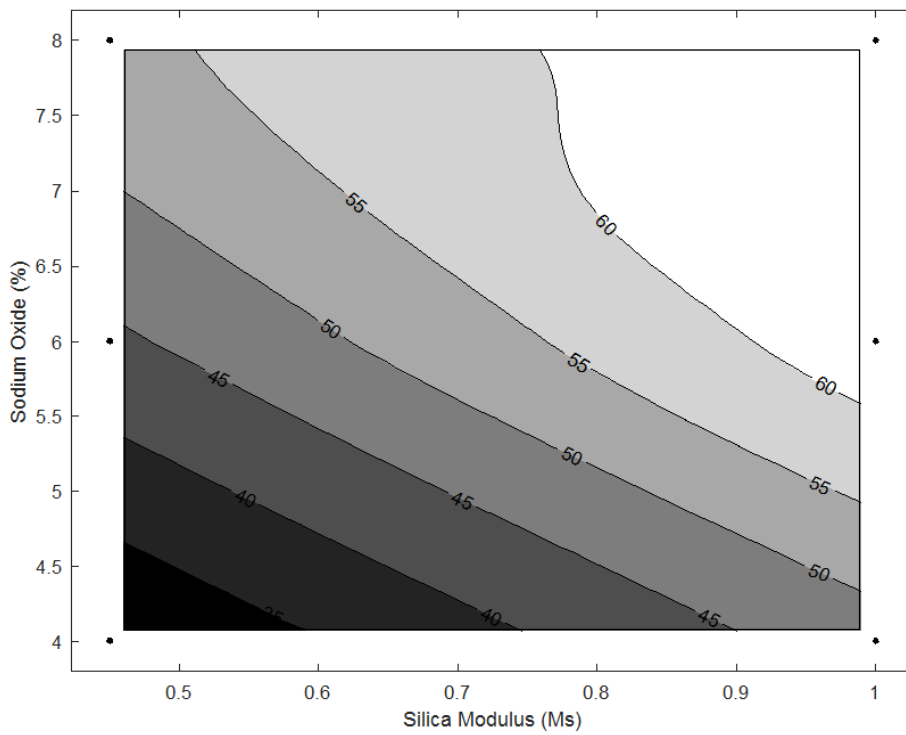
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(a)



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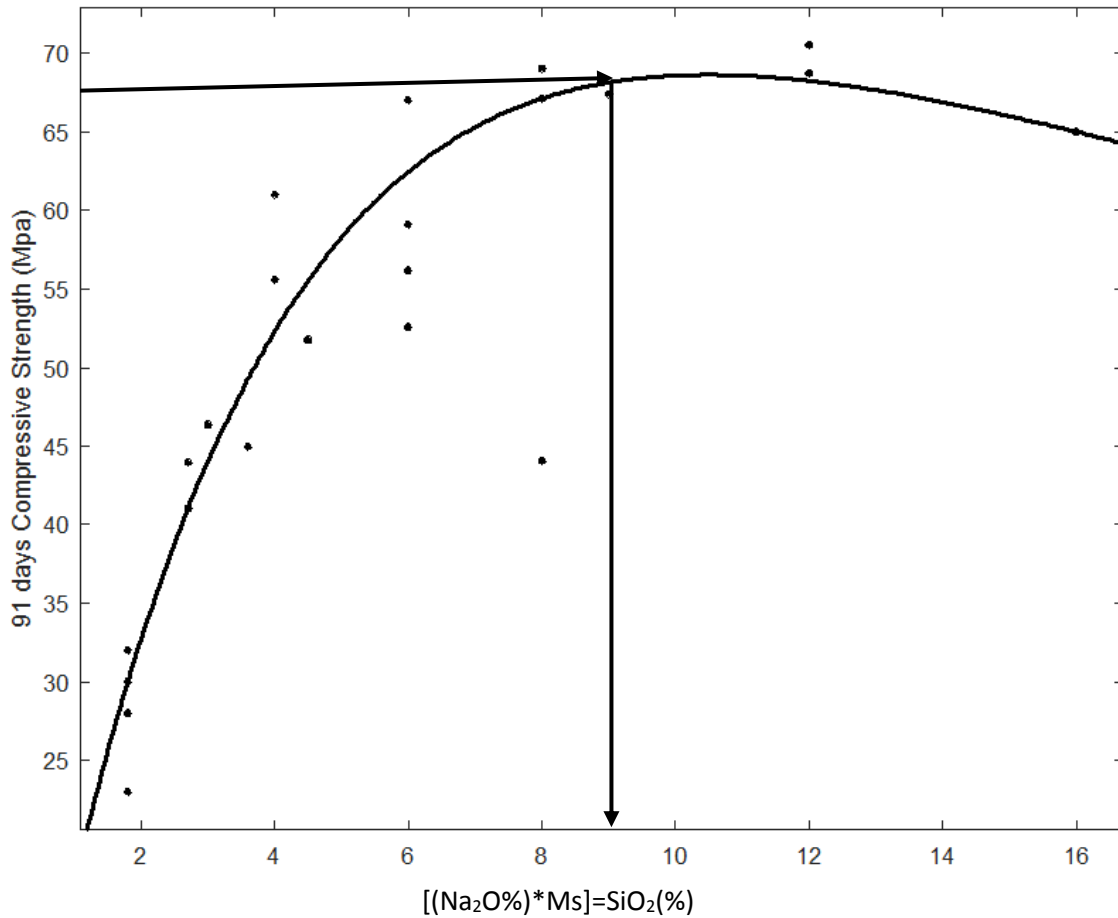
(b)



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365

366 Figure 4. Contour graph for 28 days compressive strength of different mixes (binder content = 400  
367 kg/m<sup>3</sup>): (a) Stage A, water to binder ratio = 0.47; (b) Stage B, water to binder ratio = 0.55.



368

369 Figure 5. Correlation of 91 days compressive strength and SiO<sub>2</sub> content in activator of AAS concrete

Fit found when optimization terminated:

General model Exp2:

$$f(x) = a \cdot \exp(b \cdot x) + c \cdot \exp(d \cdot x)$$

Coefficients (with 95% confidence bounds):

- a = 92.67 (16.16, 169.2)
- b = -0.02089 (-0.07184, 0.03005)
- c = -95.84 (-155.7, -35.99)
- d = -0.2671 (-0.539, 0.004749)

Goodness of fit:

- SSE: 312.5
- R-square: 0.9315
- Adjusted R-square: 0.9201
- RMSE: 4.166

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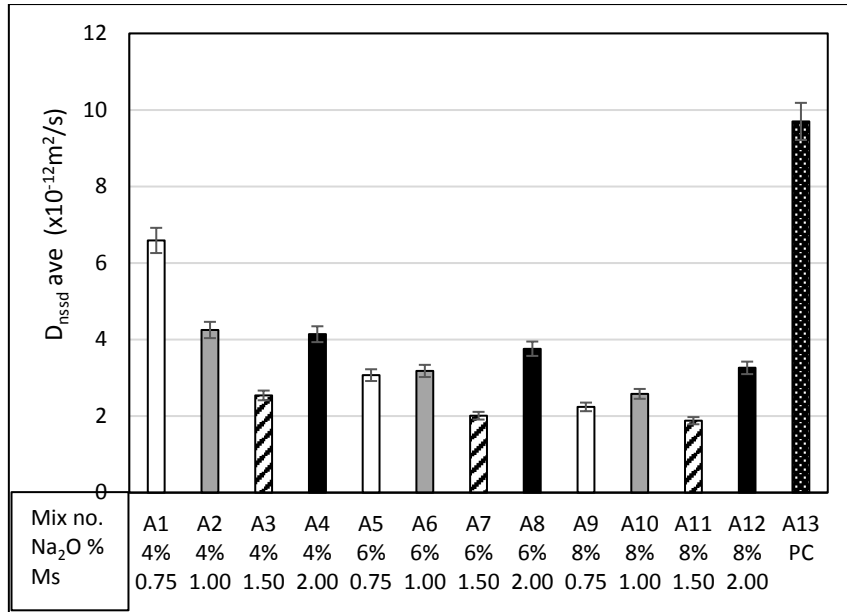
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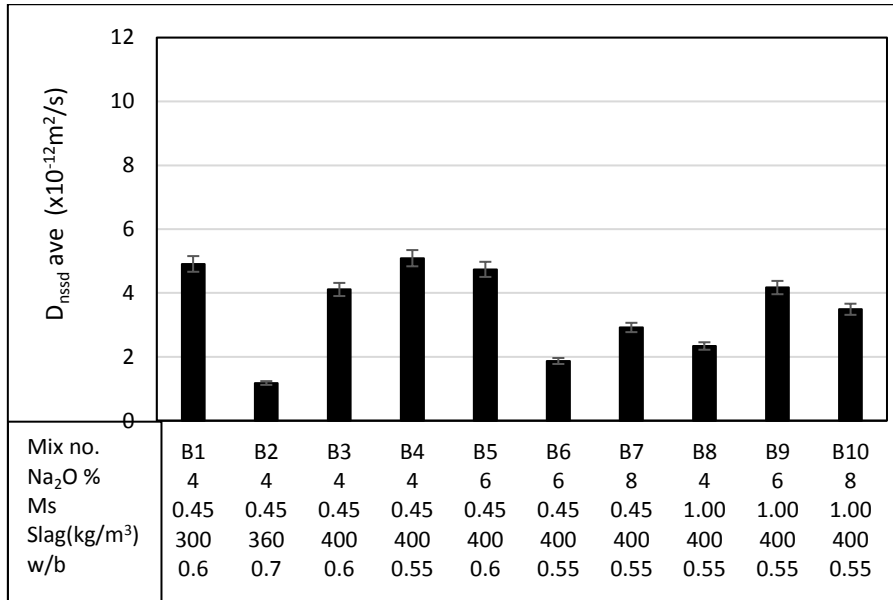




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(a)



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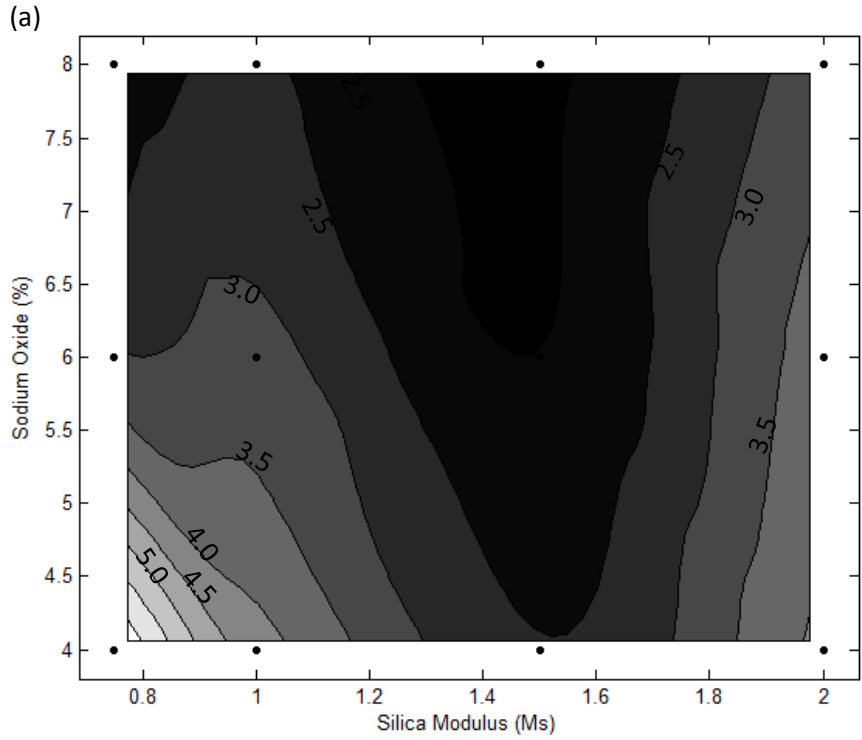
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(b)

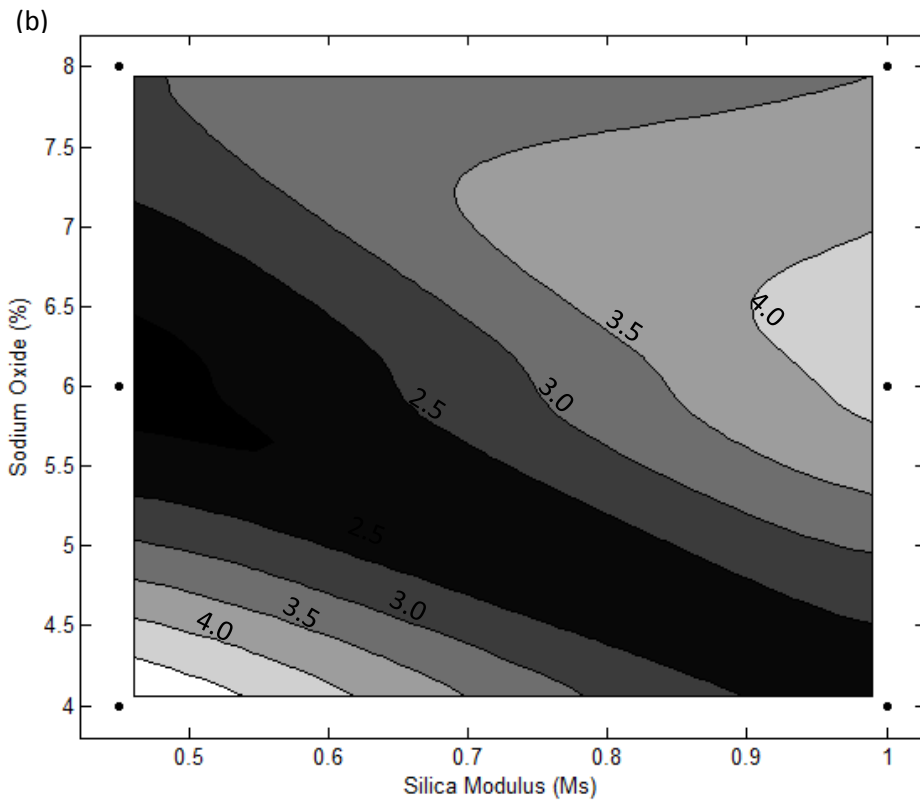
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Figure 6  $D_{nssd}$  values measured for AAS concrete mixes: (a) Stage A- water to binder ratio=0.47 and binder content = 400 kg/m<sup>3</sup> (b) Stage B



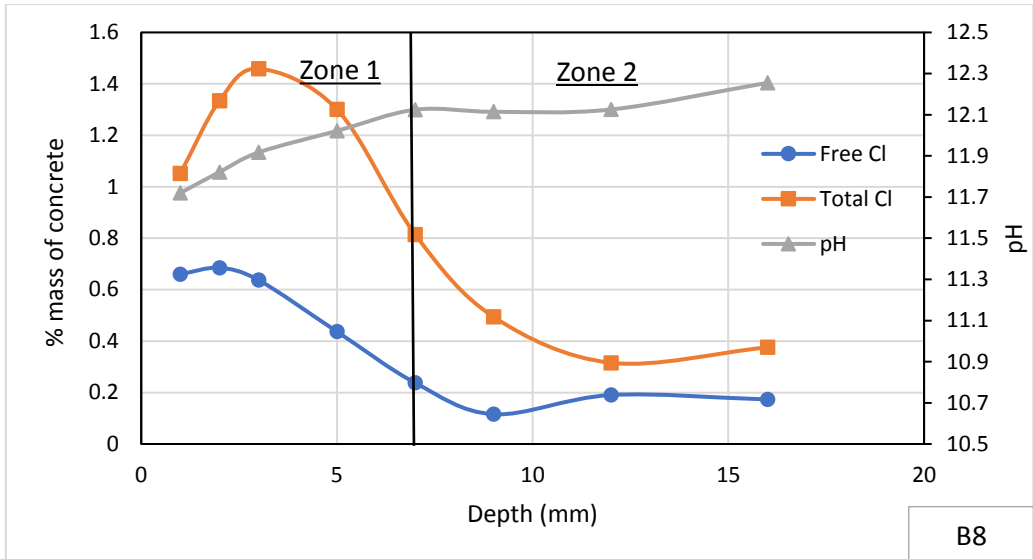
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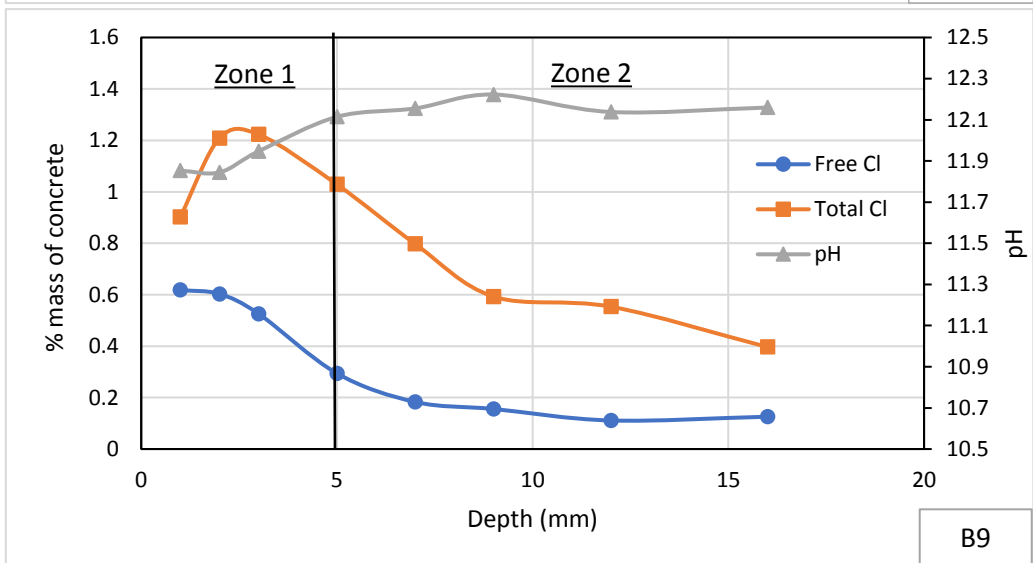
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383 Figure 7 Contour graphs for  $D_{nssd}$  ( $\times 10^{-12}$  m<sup>2</sup>/s) of different mixes (binder content = 400 kg/m<sup>3</sup>): (a)

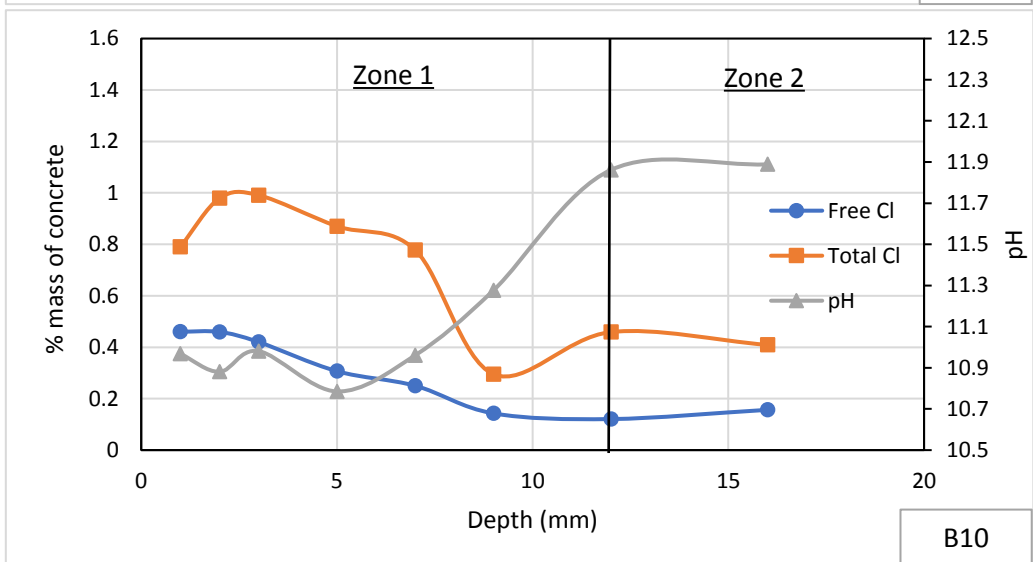
384 Stage A, water to binder ratio = 0.47; (b) Stage B, water to binder ratio = 0.55



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Figure 8 Total and water-soluble Cl<sup>-</sup> and pH of mixes B8, B9 and B10 of stage B

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395 A of this work.

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