Effect of addition of OPC on Performance characteristics of Self-compacting Alkali activated slag concrete mixes

Manjunath R* and Mattur C.Narasimhan
Department of Civil Engineering,
National Institute of Technology Karnataka, Surathkal, Mangalore-575 025, India

E-mail: *rmanju301@gmail.com

Abstract: An attempt has been made in the present research to develop construction friendly, self-compacting, alkali-activated slag concrete mixes with ground granulated blast furnace slag (GGBFS) as the major source of binder material. In an effort to make the concrete mixes more eco-friendly and sustainable, by-products from Iron and Steel Industry such as steel slag sand and Electric Arc Furnace (EAF) slag aggregates, were used as the fine and coarse aggregates respectively. While the total binder content has been varied in the range of 700 – 800 kg/m³ (in increments of 50 kg/m³), all the trial mixes had a constant w/b ratio of 0.40. Different amounts of sodium silicate solutions, with specified amounts of sodium hydroxide flakes dissolved in them, are used as alkaline solutions, with the combined Na₂O percentage in them varying between 6% - 8%. Test specimens were cast with mixes which showed enhanced flow-properties as per relevant EFNARC guidelines and were tested for their mechanical strength and durability characteristics. Effect of admixing of ordinary Portland cement (OPC) in smaller percentages (2.5% - 10 %, in increments of 2.5%), on the performance characteristics of this novel class of AAC mixes is evaluated. Increased cement contents are found to lead to better flow ability properties as per relevant guidelines and higher strengths values with lower sorptivity values in all the Cement-Admixed, Self-compacting, Alkali-Activated Slag Concrete mixes (CASAASC mixes) tested herein. Studies with a scanning electron microscope have shown more densified morphologies developed, accounting for better performances of these mixes.

Keywords: Self-compacting; High strength; Portland cement; Alkali activated slag concrete; Industrial wastes.

1. Introduction

1.1 General

In recent years, alkali-activated cementitious materials, often referred to by alternate names as inorganic polymers, alkali-bonded ceramics, geo-polymers etc., are claiming to have comparable performance to ordinary Portland cement (OPC), as a binder, in a range of applications. The advantages claimed by them include reduced carbon footprints [1], higher compressive strengths [2] and higher durability [3]. Calcium Aluminosilicate hydrates (C-A-S-H) and Calcium silicate hydrates (C-S-H) are the main hydration products found in AAS concrete mixes. These C-S-H gels are found with low Ca/Si ratios, which are similar to the ones in C-S-H gels formed when higher percentages of GGBFS are incorporated into an OPC paste. Further the structures of C-S-H in AAS will, quite likely, get modified by Al substitution of Si [4, 5]. Admixtures have been playing a pivotal role in the development of self-compacting concrete mixes for varied field-applications. Commercially available admixtures are generally compatible with Ordinary Portland (OPC)/Portland Pozzolana (PPC)/Portland Slag (PSC)-cement based systems only[6]. It is professed that the compatibility of a high-range water reducing admixture (HRWR) with the OPC could facilitate production of self-compacting, alkali-activated slag concrete mixes at lower w/b ratios and would lead to enhanced mechanical strength of these mixes. Hence smaller percentages of GGBFS of SAASC mixes (in a range of 2.5-10%) have been further replaced with OPC for developing Cement Admixed
Self-compacting Alkali Activated Slag Concrete (CASAASC mixes) and effects of such addition of OPC on the performance characteristics of the resulting mixes have been evaluated.

2. Materials
2.1 Binders
Ground granulated blast furnace slag obtained from M/s JSW, Bellary, India, conforming to IS: 12089-1987 and OPC-53 grade confirming to IS: 12269-2013 were used as the binders in the present investigation. The GGBF slag had a specific gravity of 2.9 and Blaine’s fineness of about 370 m²/kg, with the corresponding values for OPC being 3.15 and about 340 m²/kg respectively. Fine amorphous quartz powder having a specific gravity of 2.65, and a higher Blaine’s fineness of 450 m²/kg was also used in these mixes in order to further improve the microstructure within the binder phase of the AAS concrete mixes.

2.2 Alkaline Solution
Combination of NaOH flakes and Na₂SiO₃ solutions with a constant activator modulus (ratio of SiO₂/Na₂O) as 1.0, along with three different percentages of sodium oxide namely 6%, 7% and 8% are used as the alkaline solutions having a constant w/b = 0.40 in the present research. The sum of Na₂O present in sodium silicate solution and NaOH are considered for the total mass of Na₂O present in the alkaline solution. The percentage of water present in the liquid sodium silicate solution is also taken into consideration during the calculations for preparation of alkaline solution. In order to reduce the heat liberated and to prevent the quick setting of slag during mixing, the prepared alkaline solution is allowed to cool and mature for 24 hours prior to mixing.

2.3 Aggregates
Combinations of processed steel slag sand and quartz sand, in the ratio 3:1 were used as fine aggregates in our present investigation. The fine quartz sand was procured from a local dealer. While both Slag sand and Quartz sand, were having the same specific gravity of 2.65, their fineness moduli were 2.75 and 2.4 respectively. EAF slag aggregate, 12.5mm downsize, used as coarse aggregate was having a specific gravity of 2.9. The fine aggregates and coarse aggregates, conformed to the specifications of IS: 383-1970 based on the results obtained from the sieve analysis.

3. Mixture Proportioning, Preparation and casting of mixtures
A total of fifteen CASAASC mixes were developed with GGBFS as a major binder, taken in the range of 700kg/m³ – 800kg/m³. A constant water/binder ratio of 0.40 was maintained in all these mixes. While a constant alkaline modulus (ratio of SiO₂/Na₂O) of one was maintained in the alkaline activator solutions, the percentages of Na₂O in them were varied in the range of 6% to 8%. All the trial mixes carried out herein were proportioned based on the absolute volume method, due to the absence of any national code or general guidelines for the design of AASC mixes. The ratio of proportions of fine to coarse aggregates in all the mixes was maintained constant at 60:40. The details of proportions of concrete mixtures are shown in Table 1. A Ribbon-type mixer with a horizontal shaft was used for mixing of all the materials in order to provide better mixing. The workability characteristics of the self-compacting mixes were determined and ascertained. In order to evaluate the compressive strength and durability characteristics of these mixes, cube specimens were cast with the size of the mould being 100mmx100mmx100mm. All the test specimens could be de-moulded immediately after one day of casting and were then subjected to ambient curing under the lab-environment. In order to facility compressive tests at the age of 3-, 7-, 14- and 28-days, sufficient number of specimens were cast for all the mixes. In each case, the averages of test results for three test specimens were considered. After the 28-days age of testing, broken samples from all the 15 CASAASC mixes were collected and analysed for further micro-structural studies.
4. Results and discussions

4.1 Tests on Fresh CASAASCmixes

Flow-ability tests such as Slump flow, V- funnel, L- box, J ring and Visual stability Index, are generally prescribed for SCC mixes, were performed on all the fifteen CASAASC mixes.

The slump flow tests were carried out using the Abram’s cone, to evaluate the filling ability of the different CASAAS concrete mixes. Binder contents in the range of 700 to 800 kg/m³ were used for developing CASAASC mixes. Binder content of 700 - 800 kg/m³ (CASAASC 1 - CASAASC 15) showed slump flows in the range of 670 mm – 820 mm as observed from the results shown in Table 2. Thus satisfying the EFNARC guidelines, wherein a slump flow ranging from 650 – 800 mm. A slight increase in the flow have been observed with the increase in the percentage of OPC, which may due to the synergic effect in the presence of a compatible super-plasticiser, as observed from the results. From the results of V–Funnel tests carried out, given in Table 2, it can be seen that, for binder contents varying between 700 kg/m³ – 800 kg/m³, the times taken for emptying the V – Funnel at 5.5 – 11.0 seconds are all satisfying the EFNARC guidelines (values to range between 6-12 sec). The trial CASAASC mixes were tested for their passing ability also by conducting the L–Box tests. It was observed that all the fifteen candidate mixes tested herein have excellent abilities to pass through the reinforced bars, the blocking ratios $H_3/H_1$ being in the range 0.86 - 0.96 satisfying the relevant EFNARC guidelines, as observed in Table 2. Increase in the binder content showed an increase in the values of blocking ratio due to its simultaneous decrease in coarser materials.

Again from the results of the J–Ring tests it is observed that differences in the heights of concrete between the inside and outside of the ring were ranging from 5–10 mm for all the fifteen mixes satisfying the EFNARC guidelines (< 10mm). Again it is also observed that there was no significant decrease in the spread values associated with these tests (differences in the range of 5mm -10mm) as compared to the values of original slump flows, as seen in Table 2. From these results, it is clearly evident the CASAASC mixes developed are quite suitable even for areas with congested reinforcement. Again, the results of Visual stability index tests conducted, as per ASTM C 1611–2014 clearly show that all the candidate CASAASC mixes tested herein are quite stable, with no signs of segregation or bleeding, and hence having a VSI value of zero. Thus, in general, better flowability behaviours have been exhibited by all the CASAASC mixes tried here. This can be attributed to the synergic effects caused due to higher volumes of finer powdery materials (including the fine quartz powder) which have been incorporated in the CASAASC mixes. Admixing of increasing amounts of OPC (as a replacement to slag-content), with its good compatibility with the high range water-reducing admixture used herein, has further enhanced the flow-ability of these mixes.
4.2 Compressive strength of CASAASC mixes

The cube strength values for all the CASAASC mixes tested herein, as per IS 516:1959 at different ages (3-28 days) have been tabulated in Table 2. It can be observed that relatively higher compressive strengths, in the range of 70 – 95 MPa, have been achieved by 28-days of curing under ambient laboratory conditions. The highest 28-days compressive strength of about 95 MPa was achieved in the mix CASAASC-15 with a maximum total binder content of 800 kg/m³ (which then includes higher amounts of fine quartz powder and OPC, than other mixes). Similar behavior has been observed in case of all the CASAASC mixes tested herein, due to the early activation of slag occurring in the presence of alkaline solution leading to the early formation of C-A-S-H gels. Also, the unreacted CaO, present in GGBFS, might have reacted with the reactive SiO₂ present in the fine amorphous quartz, leading to the formation of additional C-S-H gels [7, 8] all accounting for higher early-age strengths. The Portland cement contents added herein also get hydrated with the available water leading to the formation of additional C-S-H gels. The crystalline quartz sand added to the steel slag sand, as a partial fraction of fine aggregate, also might have provided for effective pore filling effect inside AASC system leading to the decreased porosities and hence higher strength values. The higher dosage of Na₂O (%) made available in the alkaline solution also might have led to faster activation of the GGBFS. Hydration of possibly all the OPC, added as an additive, as partial replacement to GGBFS, especially in the presence of reactive silica available in quartz powder/activated slag, along with effective filling of even the smallest of the pores by finer quartz sand particles has also led to denser microstructure. Increase in the percentage of OPC has simultaneously caused an increase in strength characteristics due to the ternary formation of C-S-H gels in the candidate mixes tested herein. In the early ages, the enhanced strength is attributed to the early activation of slag grains with the available alkaline solution causing the formation of C-A-S-H gels. Similar behaviour has been observed for all the mixes.

4.3 Sorptivity Tests on CASAASC mixes

It is the characteristics of the pore-space within a hardened concrete system that actually decides, quite often, their strength and durability aspects. The total volume of pores, their relative size distribution, and their interconnectivity – all contribute towards the strength-durability performance of the mixes. Thus results of sorptivity tests can give an idea of relative durability performance of a set of candidate mixes. In order to evaluate the rate of penetration of water into the pores by the action of capillary action, sorptivity tests were conducted on all the fifteen CASAASC mixes as per ASTM C 1585 – 13. Cube specimens were tested after 28 days of ambient (laboratory) curing. The test
specimens were then kept in a temperature controlled oven at 105–110ºC for 24 hrs and were then cooled until they reach ambient room temperature. Four sides of these specimens are sealed with two opposite sides left unattended. The initial masses of these samples were noted down. The sealed specimens were immersed in a water bath with water upto 5–10 mm of water in it. The mass-gains for all the specimens were measured at a regular interval of 30 min over a period of 2 hours. The cumulative volume of water that has penetrated per unit surface area of exposure is plotted against the square root of time of exposure. The slope of the straight-line fit of the graph is measured as sorptivity and is a measure of the movement of water through the capillary pores [9].

Figure 1 shows the sorptivity values in the range of 5.1 – 3.3 (cm/min\(^{0.5}\)) for all the CASAASC mixes tested herein.

Increased percentages of OPC, along with the total binder contents, have resulted in decreased sorptivity values in the CASAASC mixes tested here. The values recorded are marginally lower than those of normal AAS concrete mixes [10]. Further mix CASAASC 15 has recorded the lowest sorptivity value of 3.3 cm/min\(^{0.5}\), caused due to the dual effect of both hydration products (C-A-S-H and C-S-H gels) produced, which substantially decreases the pores in that mix. It can be appreciated that the same mix CASAASC mix-15 has recorded the highest compressive strengths in all the successive test-ages as well. Relatively higher contents of GGBFS have led to the dissolution of slag grains causing activation in the presence of alkaline solution, leading to an early formation of strength-giving C-A-S-H gels. The reaction between CaO present in GGBFS with the reactive SiO\(_2\) present in the fine amorphous quartz admixed, leading to the formation of C-S-H gels, again contribute to denser microstructure. The hydration of additionally admixed OPC herein forming additional C-S-H gels along with the pore-filling or/and pore-refinement effects brought about by finer materials like fine amorphous quartz and quartz sand, have led to further reduction in the capillary porosities of these CASAASC mixes. Such reduced capillary porosities of these mixes should result in their better durability in aggressive environments.

4.4 Studies on Microstructures of CASAASC mixes

All the fifteen CASAASC mixes with their respective total binder contents and hence with varying OPC contents, were tested for analysing their microstructural details. Typical micrograms of all these mixes, obtained from powdered samples, as at 28-days of age, are shown in Figure 2-4. It can be easily seen that all the mixes have developed dense microstructures. Such dense microstructures are resulting from synergy of effective activation of the GGBFS slag in the high alkaline environment of alkaline solutions coupled with effective hydration of both fine quartz powder and OPC fractions of the binder system.
While stratified, layer-like formations, most possibly of C-A-S-H and C-S-H gels are visible in some cases, hydration products formed in the form of denser clusters are seen in other cases. Micro-cracks, along with small void-places are also observed in micrograms of some of the mixes. Addition of Quartz sand and any amorphous fine quartz left unreacted in the mixes could also provide the pore-filling effect, leading to lower porosities. Such denser morphologies formed lead to enhanced mechanical and durability properties in all the CASAASC mixes tested herein.

The elemental compositions along with their percentages of O, Ca, Si, Na and Al obtained from the results of EDX analysis are shown in Table 3. Generally these elemental atomic ratios - Ca/Si, Na/Si, and Al/Si are the major factors that govern the various mechanical and durability characteristics of the AAS concrete mixes. The values of these ratios of Ca/Si, Na/Si, and Al/Si, calculated for all candidate mixes, are shown in Table 3. Here, in the present set of CASAASC mixes, these ratios are predominantly in the narrow ranges, 0.60 – 1.1, 0.33 - 0.83 and 0.24 – 0.39 respectively[11, 12].

Thus it can be said that in all the candidate mixes, the main elements do occur, mass-wise, in the order Si > Ca > Na > Al, possibly as constituents of C-A-S-H and C-S-H gels. The XRD plots for all the CASAASC mixes tested herein are shown in Figure 5. Quartz, Calcium alumino silicate hydrate, Calcium silicate hydrate, Hydrotalcite and calcite etc., are different reaction products identified from these plots. Significant formation of Calcium alumino silicate hydrate and Calcium silicate hydrate gels has been clearly identified along with other reaction products. These Calcium alumino silicate hydrate and Calcium silicate hydrate gels, mostly in nano-crystalline phase, are largely responsible for the enhanced mechanical and durability properties of all the CASASSC mixes tested here in.
5. Conclusions
Efforts were made to incorporate Slag sand and EAF slag, two by-products from the steel industry, as fine and coarse aggregates respectively to develop self-compacting, alkali activated slag concrete mixes. Effects of addition of OPC, in increasing percentages, as a partially replacement to the GGBFS content in the mixes, on the performance characteristics of these mixes are studied in detail. Addition of OPC herein has caused an enhanced flowability in all the mixes tested herein due to the good compatibility of admixture with the cement, even at lower w/b ratios. Good gains have been achieved in the strength characteristics at all ages, due to synergy of efficient alkali-activation of GGBFS slag, effective hydration of both of OPC and fine quartz powder, and effective pore filling by increased finer materials in these concrete systems. Good amounts of both Calcium alumino silicate hydrate and Calcium silicate hydrate gels are getting formed as products of various reactions that are taking place, most often, simultaneously. An increased total binder content (GGBFS + amorphous quartz powder + OPC) varying between 700 kg/m³ – 800 kg/m³ has proved to be quite effective for developing these CASAASC mixes. While appreciable enhancements have been recorded in the flowability and strength-gain characteristics ranging between 75– 95 MPaat 28days and are accompanied with lower sorptivity values in the range of 5.1 - 3.3 cm/min⁰.5, indicating possible improvement in their durability characteristics too. The SEM micrograms of the various candidate CASAASC mixes tested herein depict very dense micro-structures with lesser amount of pores and lesser number of micro-cracks, with higher strengths in them.
References

[1] Gartner E 2004 “Industrially interesting approaches to “low –CO2” cements”. Cement Concrete Research, 34 (9): 1489–98.

[2] Chindaprasirt P, Chareerat T and Sirivivatnanon V 2007 “Workability and strength of coarse high calcium fly ash geopolymer”. Cement Concrete Composites, 29(3): 224–29

[3] Chaitanya S T and GunneswaraRao T.D 2018. “Effect of mix design parameters on mechanical and durability properties of alkali activated slag concrete”. Construction Building Materials, 193: 173-88.

[4] Wang S D, Scrivener K.L, and Pratt P.L 1994“Factors affecting the strength of alkali-activated slag”. Cement Concrete Research, 24(6):1033–43.

[5] Puertas F, Palacios M, Manzano H, Dolado J.S, Rico A and Rodriguez J.2011 “A model for the C-A-S-H gel formed in alkali-activated slag cements”. Journal of European Ceramic Society, 31(12): 2043-56

[6] Manjunath.R and Rahul M (2019). "Studies on Fresh and Hardened Properties of Sugarcane Bagasse Ash Blended Self-Compacting Concrete Mixes”, Springer Nature, 24.

[7] Fernandez-Jimenez A, Puertas F, Sobrados I and Sanz J (2003) “Structure of calcium silicate hydrates formed in alkaline-activated slag: influence of the type of alkaline activator”. Journal of American Ceramic Society, 86 (8): 1389-94.

[8] WangSDand ScrivenerK.L. 2003 “29Si and 27Al NMR study of alkali-activated slag”. Cement Concrete Research, 33 (5):769-74

[9] Ganesan N, Ruby Abrahamand Deepa Raj S (2015). “Durability characteristics of steel fibre reinforced geopolymer concrete”. Construction Building Materials, 93: 471–76.

[10] Susan BA, Ruby Mejía de Gutiérre, Alba Pedraza L, John Provis L, Erich .Rodriguez Dand Silvio D. 2011 “Effect of binder content on the performance of alkali-activated slag concretes”. Cement Concrete Research, 41(1): 1-8.

[11] Manjunath.R and Narasimhan M C. 2018. “An Experimental Investigation on Self-Compacting Alkali Activated Slag Concrete Mixes”. Journal of Building Engineering, 17:1-12.

[12] Manjunath. R., Mattur C Narasimhan, Umesh K.M,Shivam Kumar and BalaBharathi U.K. 2019. “Studies on development of high performance, self-compacting alkali activated slag concrete mixes using industrial wastes”, Construction Building Materials, 198, 133 – 47