High Strength Flowable Alkali Activated Slag Concrete Mixes produced using industrial wastes

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Abstract: A new class of High–Strength Flow able Alkali activated Slag Concrete (HSFASC) mixes is developed using steel slag sand and EAF (Electric Arc Furnace) slag aggregates, respectively, as the fine and coarse aggregates. These mixes use the ground granulated blast furnace slag as the source material. Thus it is to be recognized that all the three materials used—GGBFS, slag sand and EAF slag aggregates are by-products of the Iron and Steel Industry, and are available in very large quantities demanding safe disposal. Different amounts of Sodium silicate solutions, with specified amounts of Sodium Hydroxide flakes dissolved in them, are used as alkaline solutions. Test specimens were cast using a total of nine HSFASC mixes, (based on Taguchi’s Method), each of which satisfied the relevant EFNARC guidelines with respect to their rheological properties. The test results indicate higher compressive strengths values for all the mixes tested herein. Microstructure studies are conducted on samples from the fractured surfaces of test specimens of different mixes, using advanced SEM, EDX and XRD analyses and the results are discussed.

Keywords: Flow ability; High strength; Alkali activated slag concrete; Slag sand; EAF slag.

1. Introduction
1.1 General
Alkali-activated concretes are a new generation of alternative building materials, whose main difference from traditional Portland cement-based concretes is the use of a relatively alkali-rich, clinker-free binder matrix such as alkali-activated slag or geopolymer. Compared with conventional concretes, the production of alkali-activated concretes is associated with low energy consumption and low CO2 emission, and they have a potential to gain higher mechanical strengths at early ages of curing, higher stability in aggressive environments and better resistance to elevated temperatures, among others [1–4]. The structure of C-S-H in AAS has been fairly well understood in the recent years. The main hydration product found in AAS is calcium silicate hydrate (C-S-H), but with a low Ca/Si ratio, it is similar to C-S-H formed when GGBFS was incorporated into OPC paste at higher levels of replacement; the structure of C-S-H in AAS gets modified by aluminium substitution of silicon [5].

The present paper reports on the efforts made for developing a novel class of High Strength Flowable alkali activated slag concrete mixes (HSFASC mixes). In order to make such mixes with a greener technology, industrial by-products are used as aggregates in these mixes. Thus, steel slag sand and EAF-slag aggregates are used as the fine and coarse aggregates respectively. Further, in order to develop the HSFASC mixes, 15% of GGBFS-binder content has been replaced with fine amorphous quartz powder; 25% of the total fine aggregates is replaced by quartz sand; conventionally used granite chips are completely replaced by EAF-slag in the coarse aggregate fraction of the mixes. The present experimental work aims at achieving economical AASC mixes with higher mechanical strength properties as compared to the current, state-of-art, AASC mixes.
2. Materials

2.1 Binders
In the present investigation, GGBFS, obtained from M/S Jindal Steel Works, Bellary, India, conforming to IS: 12089 -1987 was used. The slag had a specific gravity of 2.91 and Blaine’s fineness of about 370 m²/kg. As a possible measure to improve the micro-structure within the binder phase of the concrete mixes, 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.

2.2 Alkaline Solution
In the present study, mixtures of sodium hydroxide and sodium silicate solutions, keeping a constant activator modulus (ratio of SiO₂/Na₂O) as 1.0, but for three different percentages of Na₂O namely 7%, 8% and 9%, are used as alkaline solutions. The total mass of Na₂O present in the alkaline solution is then the sum of Na₂O present in sodium silicate and that in NaOH. The water present in the LSS is also taken into consideration in calculations for preparation of alkaline solution. The alkaline solution prepared is allowed to cool and mature for 24 hours prior to mixing, to reduce the heat liberated and to prevent the quick setting of slag during mixing.

2.3 Aggregates
In the present study, combinations of processed steel slag sand and quartz sand, in the ratio 3:1 were used as fine aggregates. 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 results of the sieve analyses carried out, for both fine aggregates and coarse aggregates, indicate that they conform to the specifications of IS: 383-1970 [6].

3. Mixture Proportioning, Preparation and casting of mixtures
In order to reduce the experimentation in the development of High Strength Flowable Alkali-Activated Slag Concrete mixes (HSFASC mixes), Taguchi’s design of experiments was adopted. The binder content (700 – 800 kg/m³), W/B ratio (0.47 – 0.48) and dosage of Na₂O (%) (7 - 9) were identified as the primary parameters affecting the strength performance of this class of HSFASC mixes (at constant modulus of the alkali activator). These three factors were considered at three levels. An initial set of only nine trial mixes were formulated using the orthogonal L-9 array, and the performance of these mixes were tested in the laboratory. In the absence of any national code or general guidelines for the design of AASC mixes, the trial-mixes herein were proportioned on the basis of absolute volume method. 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.

The mixing of all the materials was done in a Ribbon-type mixer with a horizontal shaft for better mixing. The workability characteristics of the self-compacting mixes were determined and ascertained. The cube specimens were then cast using 100mmx100mmx100mm moulds; for evaluating the compressive strength characteristics. All the test specimens could be de-moulded after one day of casting and were then subjected to ambient curing under the lab-environment. Sufficient number of specimens were cast for facilitating compressive tests at 3-, 7-, 14- and 28-days. 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 9 HSFASC mixes were collected and analysed for further microstructural studies.
The slump flow tests were carried out using the Abram’s cone, to evaluate the filling ability of the different HSFASC concrete mixes. Binder contents in the range of 700 to 800 kg/m$^3$ were used for developing HSFASC mixes. It is observed from the results in Table 2 that mixes with a binder content of 700 kg/m$^3$ showed a slump flow of about 690 mm. Thus they satisfy the EFNARC [7] guidelines wherein a slump flow ranging from 650 to 800 mm is prescribed. With higher binder contents of 750 kg/m$^3$ and 800 kg/m$^3$ decreased slump flows ranging between 650–670 mm were recorded. This decrease in the flow with the increase in binder content is mainly due to the large increases in the surface area of solids resulting on addition of higher amounts of finer quartz powder material, which use larger amounts of water just for wetting the smaller size particles.

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/m$^3$ – 800 kg/m$^3$, the times taken for emptying the V – Funnel at 10.0 - 11.5 seconds are all satisfying the EFNARC guidelines (values to range between 6-12 sec). Based on V–funnel test results, it can be concluded again that the HSFASC mixes can easily fill the areas with larger congestion of rebar’s leading to better structural conditions. It is clearly evident from the V-Funnel test results that availability of relatively higher volumes of pastes and smaller size of the aggregates used also favour higher flowing ability of these mixes. The HSFASC mixes were tested for their passing ability by conducting the L–Box tests. It was observed that all the nine candidate mixes tested herein have excellent abilities to pass through therebar’s at the bottom of the L-box, the blocking ratios H$_2$/H$_1$ being in the range 0.88 - 0.94 satisfying the relevant EFNARC guidelines, as observed in Table 2. 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 7–9 mm for all the nine mixes satisfying the EFNARC guidelines (< 10 mm). Again it is also observed that there was no significant decrease in the spread values associated with these tests (differences in the range of 15 mm – 20 mm) as compared to the values of original slump flows, as seen in Table 2. From these results, it is clearly evident the HSFASC 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 [8]. clearly show that all the candidate HSFASC mixes tested herein are quite stable, with no signs of segregation or bleeding, and hence having a VSI value of zero.

| MIX ID | Flow ability | Segregation Resistance | Compressive Strength (MPa) |
|--------|--------------|------------------------|---------------------------|
|        | Filling ability | Passing ability | Compressive Strength (MPa) |
|        | Slump Flow Test | V–Funnel Test | L–Box Test | J–Ring Test | 3 days | 7 days | 14 days | 28 days |
| HSFASC-1 | 690 | 10.0 | 0.88 | 685 | 8.0 | 0 | 60.5 | 73.0 | 75.5 | 77.5 |
| HSFASC-2 | 690 | 10.3 | 0.88 | 685 | 8.4 | 0 | 62.5 | 63.0 | 72.5 | 79.0 |
| HSFASC-3 | 685 | 10.5 | 0.89 | 677 | 8.9 | 0 | 62.5 | 72.0 | 77.0 | 84.5 |
| HSFASC-4 | 685 | 10.5 | 0.92 | 678 | 8.9 | 0 | 67.5 | 74.0 | 75.0 | 80.0 |
| HSFASC-5 | 670 | 10.9 | 0.91 | 665 | 9.0 | 0 | 67.0 | 72.5 | 73.5 | 80.5 |
| HSFASC-6 | 665 | 10.9 | 0.91 | 658 | 9.4 | 0 | 67.5 | 77.0 | 79.0 | 84.0 |
| HSFASC-7 | 650 | 11.0 | 0.93 | 650 | 10.0 | 0 | 68.0 | 70.0 | 76.5 | 84.5 |
| HSFASC-8 | 650 | 11.2 | 0.92 | 651 | 10.0 | 0 | 65.0 | 68.0 | 72.5 | 78.5 |
| HSFASC-9 | 650 | 11.5 | 0.94 | 650 | 9.9 | 0 | 66.5 | 74.0 | 74.5 | 79.0 |

4.2 Compressive strength of HSFASC mixes

All HSFASC mixes tested herein have shown higher strength values on testing as per IS 516:1959 [9] as shown in Table 2. It can be observed that compressive strengths in the range of 77 MPa – 85 MPa have been obtained as shown in Table 2 for a binder-content of about 700 kg/m$^3$ - 800kg/m$^3$. As generally observed in any alkali-activated slag concrete system, higher strengths have been obtained at as early an age as 3-days. This is due to the early activation of slag which takes place due to the presence of alkaline solution leading to early formation of C-A-S-H gels and also the unreacted CaO generally present in GGBFS reacts with the additional amount of reactive SiO$_2$ present in the fine amorphous quartz leading to the formation of additional C-S-H gels, all accounting for higher early-age strengths. The crystalline quartz sand added to the steel slag sand as a as a partial fraction of fine aggregate appears to have provided for effective pore filling effect inside AASC system leading to the decreased porosities and hence denser microstructures accounting for higher strength values. The highest 28-days compressive strength of about 85 MPa was achieved in the mix HSFASC-7 with a binder content of 800kg/m$^3$. Again, from Table 2, it is observed that the quantity of alkaline solution is about 45% in this HSFASC-7 mix, as compared to the other mixes, and also the amounts of fine amorphous quartz (binder) as well as the quartz sand (filler) are higher along with the slag content.

4.3 Studies on Microstructures of HSFASC mixes

All the nine HSFASC mixes with the three different binder contents, w/b ratio and % Na$_2$O were tested for analysing their microstructural details shown in Figure 1 and Figure 2. The micrograms of all these mixes distinctly show a dense microstructure due to the activation of the slag along with the smaller percentages of amorphous fine quartz available in them. While densified formations, most possibly of C-A-S-H in the form of sheets are visible in some cases, hydration products formed in the form of clusters are seen in other cases[10]. Micro-cracks, along with small void-places are also observed in micrograms of some of the mixes. The results of EDX analyses with their percentages of atomic weights obtained for all the mixes as shown in Table 3. It is suggested that it is generally the range of values shown in Table 3, of the three elemental atomic ratios - Ca/Si, Na/Si, and Al/Si, that govern the various mechanical and durability characteristics of the AAS concrete mixes.
5. Conclusions
A new class of High-StrengthFlowable Alkali activated slag concrete mixes (HSFASC mixes) were developed using two industrial wastes. Efforts were made to incorporate Slag sand and EAF slag, both by-products from the steel industry, as fine and coarse aggregates respectively. The mixes are shown to be satisfying the EFNARC guidelines, with enhanced flow ability and strength characteristics. HSFASC mixes developed herein have shown relatively higher compressive strength values ranging between 77 MPa – 85 MPa with desired level of rheological properties. The enhanced compressive strengths are possibly due to the higher binder contents employed leading to formation of amorphous phase.
more amounts of the C-A-S-H and C-S-H gels. The fine amorphous quartz powder having the highly reactive silicafurther reacts withCaO present in the slag grains, leading to additional formations of C-A-S-H and C-S-H gels. It is clearly evident from the SEM micrograms, EDX analyses and XRD charts that the HSFASC mixes herein have developed denser micro-structures with lesser micro-cracks and lesser amount of minute pores, leading to better strength performances from them.

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