STUDIES ON ECO-FRIENDLY CONCRETE MIXES INCORPORATING INDUSTRIAL BY-PRODUCTS

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ABSTRACT. With the continuing increase in demand for concrete infrastructural facilities, the demand for Ordinary Portland Cement (OPC) and so also the natural aggregates are increasing unabated, resulting in continuous depletion of natural resources. Also associated with the increased industrial activities are the growing concerns over the ill-effects being caused due to increased emission of green-house gases, including CO_2, to the atmosphere. Hence, an attempt has been made herein to produce good and durable, eco-friendly concrete mixes using industrial by-products only, both for their binder part and the aggregates. The paper reports the fresh and hardened properties of a class of **sustainable, eco-friendly, alkali activated slag concrete (SE_AASC)** mixes produced using ground granulated blast furnace slag (GGBFS) as the only source material. The binder (GGBFS) content in these mixes was varied between 550 kg/m^3 – 650 kg/m^3. The net w/b (water to binder) ratio of the mixes was varied between in a narrow range of 0.36 – 0.40. Alkali-activation of the GGBFS fractions of the mixes were due to different mixtures of sodium silicate solutions, with specified amounts of sodium hydroxide flakes dissolved in them were used as alkaline activator solutions. The combined Na_2O percentage in these mixtures were varied between 4- 8%; however a constant activator modulus of 1.0 was maintained in all the trial mixes. In order to reduce the actual experimental efforts, Taguchi's design of experiments methodology was adopted. The test results indicate satisfactory workability properties; but vastly improved mechanical strength properties, for all the candidate mixes, as compared to normal OPC-based concrete mixes containing conventional aggregates.

Keywords: Eco-friendly, Ground Granulated Blast Furnace Slag, Alkali activated slag concrete, Slag sand, Electric Arc Furnace slag, Taguchi Method.

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INTRODUCTION

Concrete is the ***numero uno*** construction material in the world. Due to continued increase in the amount of cement concrete being used for infrastructure development, world-wide, there have been growing concerns expressed about the associated global environmental issues. Cement concrete industry is responsible for large-scale depletion of many natural resources – lime-stones and clays for cement production, broken chips of stones like granites and gneisses, sand stones and lime stones for aggregates, river-bed sand for fine aggregates and coal for power generation. Based on the survey carried out by International Energy Authority (IEA), cement industry is responsible for the production of approximately 6 to 7 percent of global, annual CO_2 emission to the atmosphere **[1].** Under these circumstances, special efforts are being made towards making concrete constructions more sustainable – less energy intensive with reduced consumption of virgin raw materials and having lower carbon foot-print. One of the effective methods to make concrete constructions more sustainable is to minimize the use of Portland cement (PC) in them. Fly ashes, Rice husk ash, GGBFS, Metakaolin are some of the materials being used as supplementary cementitious materials. Some of them are pozzolanic in nature **[2].**

Again, Fly ash and GGBFS are the most commonly used cement-replacement materials, even in blended cements, due to the higher percentages of alumina and silica available in them. GGBFS itself can be used as a sole-binder in the production of concrete, if it is activated by an alkaline solution of higher pH such as Sodium Hydroxide (NaOH) and/or Sodium Silicate (Na_2SiO_3) **[3,4].** This has led to the production of alkali activated slag concrete mixes which have exhibited higher mechanical strengths and also greater resistances to aggressive environments **[5 -7].** These properties of AAS concrete mixes have made them very promising alternatives to OPC-based concrete mixes, taking into account sustainability issues as well **[8,9]**.

These binder-systems have the potential of using of larger volumes of GGBFS, which otherwise may lead to safe disposal problems; thus proving themselves to be more eco-friendly and economical **[10, 11].** Again GGBFS can be used as a part replacement to fly ash in alkali-activated geo-polymer concrete systems also, to avoid heat curing in them **[12].**

Alkali activated slag concrete mixes, however, tend to exhibit workability-related problems in that, due to the early activation of the slag, following mixing, they tend to stiffen at faster rates, quite often within 15-20 minutes **[13].** Natural rocks and sand reserves resources are being continuously exploited, due to the exponential growth in the construction industry, for use as the coarse and fine aggregates also **[14].** These natural resources also need to be carefully managed. Many alternative materials, most of which are industrial by-products/solid wastes are being tried as aggregates in alkali activated concrete mixes.

In the present paper, an attempt has been made to develop **S**ustainable, **E**co-friendly, **A**lkali **A**ctivated **S**lag **C**oncrete mixes **(SE_AASC mixes**) using three major industrial wastes-GGBFS as the principal binder, steel slag sand (in lieu of river sand) as fine aggregate and EAF slag aggregate (as replacement to broken granite chips) as the coarse aggregate respectively. Thus the present paper discusses results of a detailed study into the mechanical strength properties of such SE_AASC mixes. The results suggest that such mixes with better mechanical properties, as compared to the available OPC based mixes, can indeed be developed.

EXPERIMENTAL PROGRAM

Materials

Ground granulated Blast furnace slag (GGBFS)

Due to its higher hydraulic activity, Ground granulated Blast furnace slag is generally preferred as the main binder material used in AAS systems. GGBFS used in the present investigation, was sourced from M/S Jindal Steel Works, Bellary, India, and it conformed to the requirements in IS: 12089 -1987 **[15].** This slag had a Blaine's fineness of about 370 m^2/kg and its specific gravity was 2.9. CaO (33.7%), SiO_2 (32.42%), Al_2O_3 (16.7%) and MgO (9.65%) were the principal oxide constituents in this slag.

Alkaline Solution

In the present study, mixtures of sodium hydroxide and sodium silicate solutions, having different percentages of Sodium oxide (Na_2O) content in them; but with a constant activator modulus (ratio of SiO_2/Na_2O = 1.0), were used as alkaline solutions. The constant activator modulus was obtained by adding prescribed quantities of commercial grade NaOH flakes to specified quantities of liquid sodium silicate solution **(LSS)** (containing 14.7% Na_2O +32.8 SiO_2 + 52.5% H_2O, by mass and with a density 1570 kg/m^3). The tap water available in the laboratory was used for preparing the alkaline solutions, with their water to binder (W/B) ratios maintained at 0.36, 0.38 or 0.40. The water present in the LSS was also taken into consideration in calculations for preparation of alkaline solutions. The alkaline solutions prepared were 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.

Aggregates

In the present study, processed steel slag sand was used as fine aggregate and processed EAF slag (Electric arc furnace slag), 12.5mm downsize, was used as the coarse aggregate in all the AAS concrete mixes, with specific gravity 2.65 and 3.0 respectively. Slag sand and EAF slag aggregates, shown in **Figure 1 and 2**, were industrial by-products procured again from M/s Jindal Steel Works, Bellary, India. Both the fine aggregates and coarse aggregates used herein are pre-processed ones, in that chances of expansion reactions due to the presence of any free lime in resulting concrete mixes has been eliminated. The chemical composition of both the fine and coarse aggregates used are given in **Table 1**. The water absorption and fineness modulus values for EAF-Slag were 1.5 % and 6.9, while fine aggregates had values of 1% and 2.75 respectively for them. The results of the sieve analyses carried out, shown in **Table 2** for both fine aggregates and coarse aggregates, indicate that they conform to the specifications of IS: 383- 1970 **[16].**

Figure 1 Slag Sand

Figure 2 EAF slag

Table 1 Chemical Composition of Slag Sand and EAF slag

CHEMICAL CONSTITUENTS	WEIGHT (%)$	
	SLAG SAND	EAF SLAG
CaO	34.30	34.70
Al_2O_3	17.29	4.19
Fe_2O_3	0.73	24.20
SiO_2	36.01	19.12
MgO	6.20	6.20
Minor Minerals	5.47	1.63
Insoluble Residue	-	9.70
LOI	-	0.26

$As given by the manufacturer

Table 2 Results of Sieve Analysis

SIEVE SIZE	CUMULATIVE PERCENTAGE FINER									
	20mm	16mm	12.5mm	10mm	4.75mm	2.36mm	1.18mm	600µm	300µm	150µm
Slag Sand	-	-	-	100	100	99.6	85.45	34.5	17	4.6
EAF Slag	100	100	97.6	59.0	1.96	-	-	-	-	-

Optimum Mix design of AASC mixes

In the present research, Taguchi's design of experiments methodology was adopted for the development of SE_AAS Concrete mixes). Taguchi method is generally used for optimising the number of experiments to be carried out, when it is known that the results do depend on larger number of parameters. Herein, the three factors – Binder content, W/B Ratio and the Na_2O content in the alkaline solution, were considered as the principal factors deciding the properties of resulting mixes. Each of them were considered at three levels so that an initial set of only nine trial mixes were formulated using the L-9 orthogonal array, as shown in **Table 3** and the performance of these mixes were tested in the laboratory.

Table 3 Levels and Factors - L-9 orthogonal array

LEVELS	FACTORS		
	A Binder Content (kg/m^3)	B W/B Ratio	C Na_2O (%)
LEVEL 1	550	0.36	4
LEVEL 2	600	0.38	6
LEVEL 3	650	0.40	8

Mixture Proportioning, Preparation and Casting of mixtures

The details of proportions of concrete mixtures are shown in **Table 4**. Test specimens were cast and tested, using nine different trial mixes, designated as AASC -1 to AASC-9.

Table 4 Details of Trial Concrete Mixes Tested based on L-9 array - quantities in kg/m^3

MIX ID (A-B-C OF L9)	BINDER	ALKALINE SOLUTION			AGGREGATES		TOTAL WET WEIGHT
	GGBFS	Sodium silicate solution	NaOH Flakes	Water	Slag Sand	EAF Slag	
AASC -1 (1-1-1)	550	67	16	163	972	733	2501
AASC -2 (1-2-2)	550	101	24	157	916	692	2440
AASC -3 (1-3-3)	550	135	32	150	875	660	2402
AASC -4 (2-1-2)	600	110	26	159	883	666	2444
AASC -5 (2-2-3)	600	147	34	152	748	564	2245
AASC - 6 (2-3-1)	600	73	14	202	875	660	2424
AASC -7 (3-1-3)	650	159	37	152	779	588	2365
AASC -8 (3-2-1)	650	80	19	206	827	624	2406
AASC -9 (3-3-2)	650	119	28	198	779	588	2362

In the absence of any code of practice/user manuals, the above proportions for the ingredients of all the SE_AASC mixes were arrived at 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. A constant activator modulus of 1.0 was adopted in the calculations for design of these various concrete mixes. Alkaline solutions were prepared one day prior to mixing, based on the quantities of the ingredients given above.

The mixing of all the materials for all the mixes was done in a Ribbon-type mixer with a horizontal shaft, for better mixing. The resulting homogeneous concrete mixes were then subjected to slump test to check their workability. Then cube (100mm-size) and cylindrical (100mm in diameter x 200 mm height) test specimens were cast, for evaluating the mechanical strengths and water absorption characteristics. All the test specimens were de-moulded after one day of casting and were then air-cured in ambient lab-environment.

RESULTS AND DISCUSSION

Fresh and Hardened properties of AASC mixes

The workability was basically targeted for achieving pumpable AASC mixes which were measured using Abram's slump cone as per EFNARC guidelines **[17].** It can be seen, that all the nine mixes have shown good workability values with their slump flow values ranging between of 300mm – 400mm, however not satisfying the guidelines for SCC mixes as shown in **Figure 3**. It can be clearly observed that, increase in the volume of paste content has shown an increase in the slump flow values for all the AASC mixes clearly indicating a pumpable concrete very much adoptable for the current RMC technology.

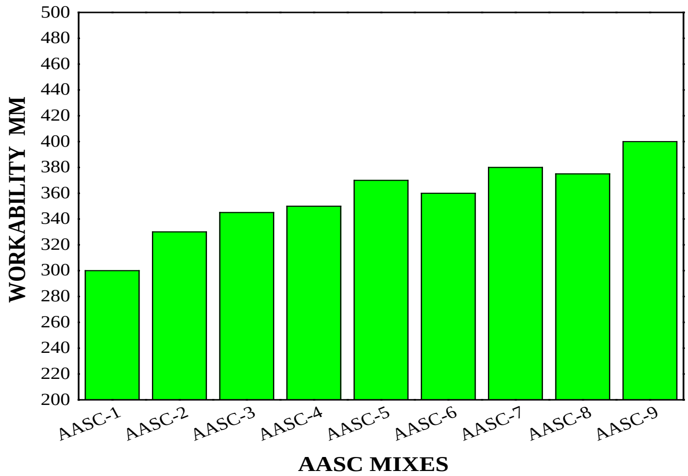

Figure 3 Variation of slump flow values for different AASC mixes

Compressive strength of AASC mixes

Compressive strength results for all the nine candidate mixes tested herein, at all the four representative ages are pictorially presented in **Figure 4**. All the sustainable eco-friendly alkali activated slag concrete mixes were tested as per IS 516:1999 **[18].** It was observed that compressive strengths values obtained were in the range of 50MPa to 60MPa at age of 28-days were obtained, for a binder-content of about 550 – 650 kg/m^3. As generally observed in an alkali-activated slag concrete system, higher early-strengths (3-days) have been obtained in case of AASC mixes. The average value of the ratios of 3-day and 7-day strengths to 28-day strengths were in the range of 0.74 -0.96 and 0.78 -0.92 respectively. This is due to the early activation of slag which takes place in the presence of alkaline solution leading to an early formation of, most probably, C-A-S-H gels. The highest 28-days compressive strength of about 60MPa was achieved for the mix AASC-7 with the highest binder content of 650kg/m^3 used. Again, from **Table 4,** it is observed that for this mix, the quantity of alkaline solution used also is slightly higher as compared to the other mixes. The higher amounts of OH^- ions available in these mixes, due to increased amount of the alkaline solution, ensures activation of the larger percentages of the slag used as compared to other mixes. Hence the concrete micro-structure becomes denser, with the formation of more amounts C-A-S-H gels which fill the very minute pores present, leading to higher strengths.

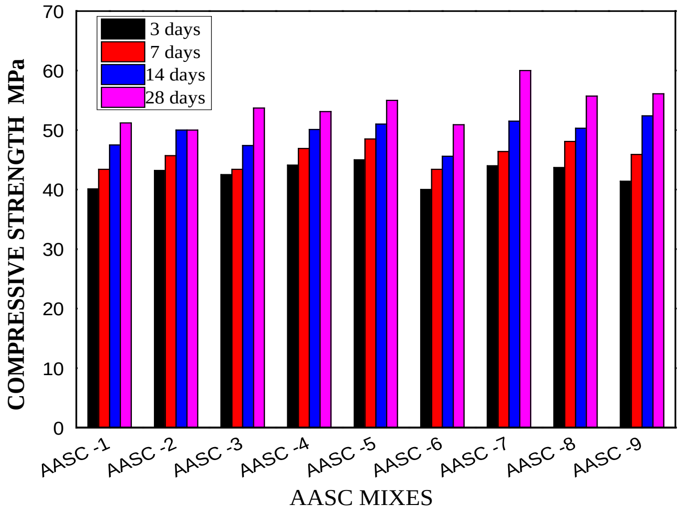

Figure 4 Compressive strength-gain characteristics for AASC mixes

Split Tensile strengths of AASC mixes

The split tensile strength tests were performed according to IS 5816 -1999 **[19].** The values of split-tensile strengths of the various mixes, at different ages are ranging from 2.0 MPa to 3.0 MPa, as shown in **Figure 5,** for the varying binder contents. The fact that the ratios of split-tensile strength to compressive strength, for any of these AASC mixes, even at 28-days of age, are in the range of 0.048 - 0.055, suggest that these mixes are relatively much weaker in tension (vis-à-vis compression), than their OPC-based counterparts.

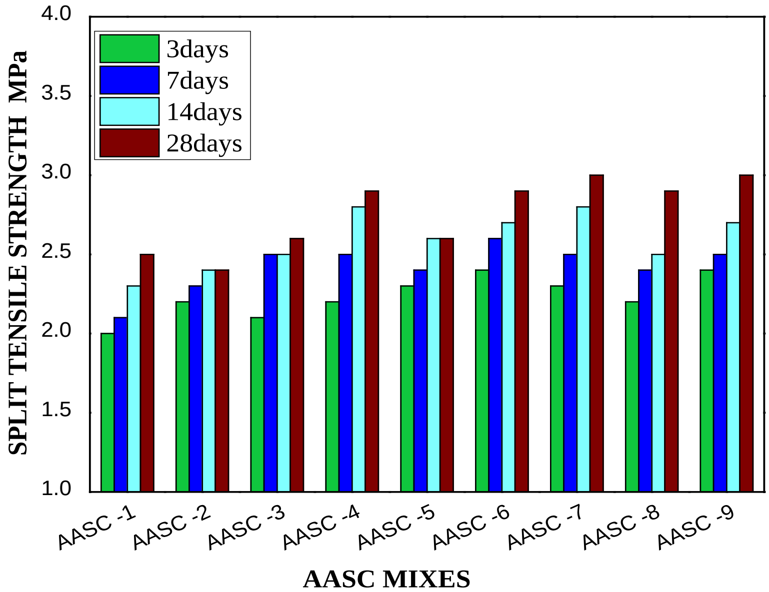

Figure 5 Variation of split tensile strength values for different AASC mixes

Water Absorption of AASC mixes

Specimens of all the nine AASC mixes were subjected to water absorption tests as well, to know the amount of pores present inside the hardened concrete mixes. It can be observed from **Figure 6**, that water-absorption values recorded at low 4 –3 % (at different ages) are marginally lower than normal OPC-based concrete mixes **[6].** AASC-5 mix has shown relatively lower water absorption value, in the range of 3.3 - 3.0 %, as compared to the other mixes tested herein. Initially, in the early ages, possibly all the pores are not completely filled up with the C-A-S-H gels, leaving many minute pores filled up with only water. With higher binder contents and with increase in age, reaction of slag may take place at a faster rate, with more alkaline solution available, forming more of strength-inducing gels which effectively fill up the pores present leading to very low porosity and denser microstructures.

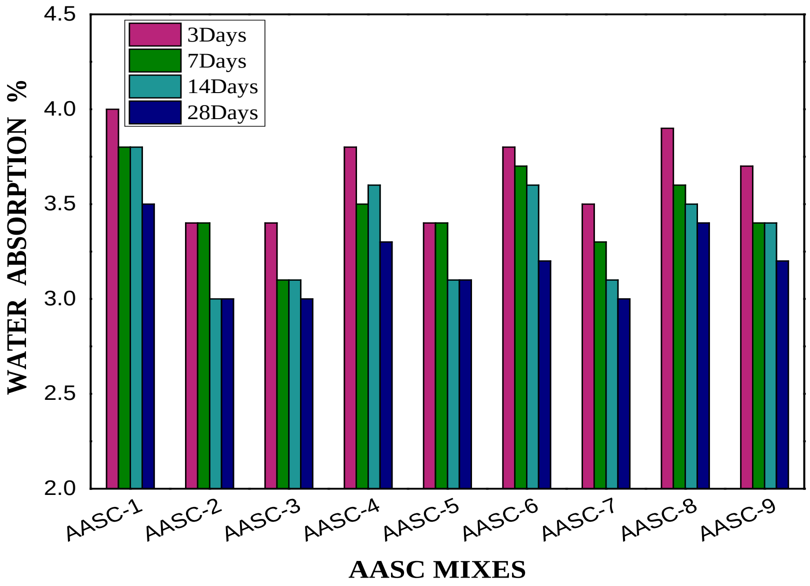

Figure 6 Variation of water absorption values for different AASC mixes

CONCLUSIONS

1.0 Sustainable, Eco- friendly, Alkali activated slag concrete (SE_AASC) mixes were developed, with very effective use of three industrial wastes, all from Iron and Steel Industry – GGBFS as binder, Steel slag sand and EAF slag, (both at 100% replacement levels), as fine aggregates and coarse aggregates.

2.0 A binder content (GGBFS) varying between 550kg/m^3 – 650 kg/m^3 has proved to be quite effective for developing the SE_AASC mixes. Appreciable enhancements in workability and compressive strength**s** and lower water absorption have been obtained. However slightly lower split tensile strengths have been achieved in all the alkali activated slag based concrete mixes tested herein.

3.0 SE_AASC mixes tested herein have shown a compressive strengths, ranging between 40MPa – 60MPa, without affecting the pumpable properties for all the mixes developed herein. Lower split tensile strengths values, ranging between 2.0 MPa – 3.0 MPa, have been obtained, with marginally lower water absorption values as compared to normal OPC based concrete mixes.

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