International Journal of
Advanced Structures and Geotechnical Engineering
ISSN 2319-5347, Vol. 03, No. 04, October 2014

Experimental Investigation on Air-cured Alkali activated GGBFS-Fly ash concrete mixes

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Abstract: Alkali Activated Binders are eco friendly produced by activating industrial waste products such as ground granulated blast furnace slag (GGBFS), Fly Ash (FA) etc. using alkaline solutions. The present research aims to investigate the effect of the alkaline activators on the strength characteristics of air-cured alkali activated concrete mixes using indigenous GGBFS-FA. The research highlights the effect of the sodium oxide dosages (Na_2O, in the range of 4 to 6%) and the activator modulus (Ms) (i.e. the SiO_2/Na_2O ratio, in the range of 0.75 to 1.75) of the alkaline solutions, on the workability and strength characteristics of alkali activated GGBFS-FA concrete mixes for different ratios of GGBFS: FA (i.e.100:0, 75:25, 50:50 and 75:25). Further the flexural and split tensile strength were evaluated for optimal mixes for each dosage of Na_2O. It was observed that the optimal Ms was 1.25 for GGBFS: FA ratios of 100:0, 75:25, 50:50 and 1.5 for GGBFS: FA ratio of 25:75. Increase in dosage resulted in increase in compressive strength and corresponding increase in split-tensile strength and flexural strengths, both at the early and later ages. A reduction in the compressive strength was observed with the increase in FA content.

Keywords: *GGBFS-FlyAsh, Activator Modulus, Sodium Oxide Dosage, Strength Characteristics*

Introduction:

The production of Portland cement emits green house gases into the atmosphere creating global warming and climatic changes. Several efforts are in progress to minimise the use of cement in concrete in order reduce the global warming issues. With a vision of minimising the ill effects occurring from cement production, the hunt for alternative binder material has gained importance in the past few decades. Alkali activated binder system can be considered as a promising alternative which possess the potential to replace cement in concrete. Such binders are prepared by activating industrial aluminosilicate waste materials such as Ground granulated blast furnace slag (GGBFS), Fly ash (FA) with highly alkaline solutions [1-3]. GGBFS is an industrial waste product obtained during the processing of iron ore while FA is waste product obtained from thermal power plants. These binders are having low impact on the environment and exhibit superior performance in terms of strength and durability [4-6]. Alkali Activated Slag (AAS) and Alkali Activated Slag-Fly Ash (AASF) are few examples of alkali activated binders. AAS concrete are produced by incorporating 100% GGBFS as binder where as AASF include a combination of GGBFS and FA as binders. However, the reaction products of AAS and AASF are similar i.e. low Ca/Si ratio C-S-H [7, 8] which is the main reaction product in Ordinary Portland Cement (OPC) concrete. Alkali Activated Slag Concretes (AASC) are characterised by superior mechanical properties as compared to OPC concrete. The compressive and tensile strength of AAS activated with sodium silicate were greater than OPC concrete [9-12]. The strength of AASC mixes depends upon the type, concentration, dosage and activator modulus of the alkaline solution [13].The strength of the AASC increase with the increase in the dosage of the alkaline activator. The activator modulus ($Ms=SiO_2/Na_2O$) of the activator solution plays an important role in the strength development of AASC [13]. A combination of sodium hydroxide and sodium silicate has proved to provide the better properties to AASC [14].

Replacements of GGBFS with FA in AASCs result in the reduction of compressive strength but increases setting time [15]. AASFCs with FA content upto 50% develop considerable amount of strength at ambient temperature but replacement of FA beyond 50% will require a higher dosage of alkali activator [16]. Increase in the FA content in AASFC mixes increases the workability [14, 17, 18]. The ratio of Slag/FA plays major role in the strength development of AASFC mixes. Garcia et al [19] prepared pastes of slag and FA in proportions of 100:0, 75:25, 50:50, 25:75 and 0:100, by weight, activated with sodium silicate wit activator modulus of 0.75, 1, 1.5 and 2 for Na_2O dosages at 4%, 6% and 8% binder weight. The pastes were cured at 75^oC for 24 h and then at 20^oC up to 28 days. The results indicated that the best modulus for all the mixes were in the range 1 to 1.5.

In this paper, the effect of activator modulus on the mechanical properties of air cured AASC and AASFC mixes at different GGBFS/FA ratios are investigated in detail. The GGBFS/FA ratios of 100:0, 75:25, 50:50 and 25:75 by weight were considered. Sodium oxide dosage of 3%, 4% and 5% of weight of binder with activator modulus in the range 0.75 to 1.75 were used to activate various GGBFS/FA mixes. Properties such as workability, compressive strength, flexural strength and split tensile strength were evaluated. The present study is aimed to endeavour the possibility of utilization of industrial waste products in construction industry. The consumption of GGBFS and FA in concrete will reduce the ecological hazard occurring from the dumping of such wastes into the environment.

Experimental Investigation

Materials: The materials required for the preparation of mixes were sourced from local industries. The Class C fly ash (in accordance to IS: 3812-2003 [21]) was procured from Raichur Thermal Power Station (RTPS) and the GGBFS (in accordance to IS 12089-1987 [22]) was obtained from Jindal Iron and Steel Plant, Bellary. The chemical composition and physical properties of GGBFS and FA are presented in Table I. The sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) flakes together are adopted as alkaline activators. The liquid sodium silicate [Na_2O=14.7%, SiO_2=32.8%, H_2O=52.5% by mass] having density of 1570kg/m^3 and NaOH flakes (97% purity) with a density of 2110 kg/m^3 was supplied by a local available industry. Potable tap water available in the institution was used for the preparation of alkali solution. The coarse aggregates used were crushed granite aggregates with a maximum size of 20mm, while the river sand meeting the requirements of IS: 383-1970[23] was used as fine aggregates. The physical properties of aggregates are presented in Table II.

Table I: *Chemical Composition and Physical Properties of GGBFS and Fly Ash [(%) By Weight]*

Constituents	GGBFS	FA
CaO	34.77	0.79
Al_2O_3	16.7	32.17
Fe_2O_3	1.2	2.93
SiO_2	32.52	58.87
MgO	9.65	0.92
Na_2O	0.16	0.37
K_2O	0.07	1.14
SO_3	0.88	0.49
Insoluble Residue	4.03	2.31
Loss of Ignition	0.04	0.03
Specific gravity	2.9	2.2
Blaine Fineness (m^2/kg)	370	425
Basicity Coefficient, K_b=[(CaO+MgO)/SiO_2+Al_2O_3)]	0.88	-

Table II*: Physical properties of aggregates used in the present study*

S. No	Test	Crushed granite aggregate	Fine aggregate	Method of Test, reference
1	Specific Gravity	2.69	2.64	IS 2386 (P-III) - 1963
2	Bulk Density a) loose	1494 kg/m^3	1478 kg/m^3	
	b) compact	1655 kg/m^3	1550 kg/m^3	
3	Aggregate Crushing Value	24%	-	IS 2386 (PIV)- 1963 -
4	Los Angeles Abrasion Test	20%	-	
5	Aggregate Impact value	21%	-	
6	Water Absorption	0.50%	0.80%	

Mix proportion and specimen details: Sixty different mixes with different GGBFS: FA ratios, various activator moduli for different sodium oxide dosages were prepared and tested for their compressive strengths at different ages. The AASC and AASFC mixes were proportioned to contain total binder content of 425 kg/m^3 with a total water/binder ratio of 0.4. The total water content included the sum of water readily present in liquid sodium silicate solution along with the extra water added to achieve the required water/binder ratio (0.4). The GGBFS: FA ratios of 100:0, 75:25, 50:50 and 25:75 by weight were adopted and are represented with the symbols A, B, C and D respectively. The liquid sodium silicate solution had activator modulus (weight ratio of SiO_2/Na_2O) of 2.23 when procured from the industry. The activator modulus of the sodium silicate solution was modified by mixing sodium hydroxide flakes to it, to achieve the desired activator modulus. The alkali solution was formulated to provide activator modulus of 0.75, 1, 1.25, 1.5 and 1.75 for the activation of various AASC and AASFC mixes. Sodium oxide (Na_2O) dosages of 3%, 4% and 5% expressed as percentage of weight of binder material were adopted. The details of mix proportioned for 3%, 4% and 5% are presented in Tables III, IV and V respectively. After thorough mixing of the ingredients, cube specimen of size (100x100x100) mm for compression, prisms of size (100x100x500) mm for flexure and cylinders of size 100 mm dia x 200mm height for split tensile strength were cast. The slump values of the concrete mixes were recorded according to IS: 1199-1959[25]. The specimens were demoulded after 24h and were subjected to curing in the atmosphere at 80-90% relative humidity and room temperature (27±3^{o}C). The compressive strengths of the specimen were determined at 3, 7 and 28 days of curing as per IS: 516-1959[26]. The flexural strength and split tensile strength were determined in accordance with IS: 516:1959[26] and IS: 5816-1999[27] respectively for optimal mixes at 7 days and 28 days of curing.

The mix ID "3-A-0.75" in Table III represents AASC mix with 3% Na_2O dosage with an activator modulus of 0.75. Similarly all other concrete mixes are designated. The AASC mixes i.e. GGBFS: FA ratio of 100:0 is represented with the alphabet A while AASFC mixes with GGBFS: FA ratios of 75:25, 50:50 and 25:75 are represented with the alphabet B, C and D respectively.

Table III: *Mix Proportions of concrete for 3% Na_2O dosage (all quantities in kg/m^3)*

Mix ID	**GGBFS**	**Fly Ash**	**Coarse Aggregates**	**Sand**	**NaOH**	**Na_2Si0_3**	**Added Water**	**Slump measured (mm)**
3-A-0.75	425	-	1215	633	10.9	29.2	154.7	100
3-A-1.0			1211	630	9.1	38.9	149.6	80
3-A-1.25			1189	646	7.2	48.6	144.5	60
3-A-1.50			1185	644	5.4	58.3	139.4	50
3-A-1.75			1181	642	3.5	68.0	134.3	35
3-B-0.75	319	106	1195	622	10.9	29.2	154.7	120
3-B-1.0			1191	620	9.1	38.9	149.6	105
3-B-1.25			1169	635	7.2	48.6	144.5	85
3-B-1.50			1165	633	5.4	58.3	139.4	70
3-B-1.75			1161	631	3.5	68.0	134.3	55
3-C-0.75	212.5	212.5	1175	611	10.9	29.2	154.7	130
3-C-1.0			1171	609	9.1	38.9	149.6	120
3-C-1.25			1149	625	7.2	48.6	144.5	95
3-C-1.50			1145	622	5.4	58.3	139.4	90
3-C-1.75			1141	620	3.5	68.0	134.3	75
3-D-0.75	106	319	1154	601	10.9	29.2	154.7	160
3-D-1.0			1150	599	9.1	38.9	149.6	140
3-D-1.25			1129	614	7.2	48.6	144.5	105
3-D-1.50			1125	612	5.4	58.3	139.4	105
3-D-1.75			1121	609	3.5	68.0	134.3	90

Table IV: *Mix Proportions of concrete for 4% Na_2O dosage (all quantities in kg/m^3)*

Mix ID	**GGBFS**	**Fly Ash**	**Coarse Aggregates**	**Sand**	**NaOH**	**Na_2Si0_3**	**Added Water**	**Slump measured (mm)**
4-A-0.75	425	-	1204	626	14.6	38.9	149.6	90
4-A-1.0			1198	624	12.1	51.8	142.8	70
4-A-1.25			1175	639	9.6	64.8	136.0	50
4-A-1.50			1170	636	7.2	77.7	129.2	45
4-A-1.75			1164	633	4.7	90.7	122.4	30
4-B-0.75	319	106	1183	616	14.6	38.9	149.6	100
4-B-1.0			1178	613	12.1	51.8	142.8	85
4-B-1.25			1155	628	9.6	64.8	136.0	70
4-B-1.50			1150	625	7.2	77.7	129.2	60
4-B-1.75			1144	622	4.7	90.7	122.4	50

4-C-0.75	212.5	212.5	1163	605	14.6	38.9	149.6	120
4-C-1.0			1158	602	12.1	51.8	142.8	100
4-C-1.25			1135	617	9.6	64.8	136.0	85
4-C-1.50			1129	614	7.2	77.7	129.2	80
4-C-1.75			1124	611	4.7	90.7	122.4	70
4-D-0.75	106	319	1142	595	14.6	38.9	149.6	145
4-D-1.0			1137	592	12.1	51.8	142.8	125
4-D-1.25			1114	606	9.6	64.8	136.0	110
4-D-1.50			1109	603	7.2	77.7	129.2	100
4-D-1.75			1104	600	4.7	90.7	122.4	95

***Table V**: Mix Proportions of concrete for 5% Na_2O dosage (all quantities in kg/m^3)*

Mix ID	GGBFS	Fly Ash	Coarse Aggregates	Sand	NaOH	Na_2Si0_3	Added Water	Slump measured (mm)
5-A-0.75	425	-	1192	620	18.2	48.6	144.5	85
5-A-1.0			1185	617	15.1	64.8	136.0	65
5-A-1.25			1161	631	12.1	81.0	127.5	45
5-A-1.50			1154	627	9.0	97.2	119.0	30
5-A-1.75			1148	624	5.9	113.4	110.5	20
5-B-0.75	319	106	1172	610	18.2	48.6	144.5	95
5-B-1.0			1165	606	15.1	64.8	136.0	80
5-B-1.25			1141	620	12.1	81.0	127.5	60
5-B-1.50			1134	617	9.0	97.2	119.0	45
5-B-1.75			1128	613	5.9	113.4	110.5	35
5-C-0.75	212.5	212.5	1152	599	18.2	48.6	144.5	115
5-C-1.0			1145	596	15.1	64.8	136.0	100
5-C-1.25			1121	609	12.1	81.0	127.5	80
5-C-1.50			1115	606	9.0	97.2	119.0	70
5-C-1.75			1108	602	5.9	113.4	110.5	60
5-D-0.75	106	319	1131	588	18.2	48.6	144.5	130
5-D-1.0			1124	585	15.1	64.8	136.0	120
5-D-1.25			1100	598	12.1	81.0	127.5	95
5-D-1.50			1094	595	9.0	97.2	119.0	90
5-D-1.75			1087	591	5.9	113.4	110.5	75

Results and Discussions:

Workability: The workability in terms of slump test is presented in Tables III, IV and V for concrete mixes with 3%, 4% and 5% Na2O dosage respectively. It can be noticed that AASC and AASFC exhibit reduced workability with the increase of activator modulus. This may be due to the increase in the quantity of sodium silicate at higher activator modulus which makes the concrete mix sticky [20]. The workability of the mixes reduced slightly with increase in the Na_2O dosage in the alkaline activator. This may be due to the increase in the viscosity of the solution with the increase in sodium oxide dosage. The AASFC mixes exhibit higher workability as compared to AASC mixes. The workability increased with increasing FA content in the AASFC mixes. The inclusion of FA in the AASC results in the increase in the workability [14]. The spherical shape of FA particles when combined with activator solution increases the lubricating effect thus increasing the workability. AASC mixes showed rapid setting with increasing activator modulus and dosage. However, no rapid setting was observed in case of AASFC mixes. No signs of segregation or bleeding were noticed in any of the concrete mixes.

Compressive strength: The compressive strength results for 100:0, 75:25, 50:50 and 25:75 mixes for various dosages and at different ages are depicted in Figures 1, 2, 3 and 4 respectively. From the results, it can be noticed that the modulus of activator solution has significant influence on the compressive strength of AASC and AASC mixes. All the mixes follow a similar and definite trend line. The compressive strength increase with the increase in the activator modulus until an optimal point is reached and later decrease with further increase in the modulus. From the figures it can be noticed that the optimal modulus at 28-days of curing for 100:0, 75:25 and 50:50 mixes is 1.25 for all the Na_2O dosages. However, for mix 25:75, the optimal modulus at 28 days of curing is 1.50.

The strength of AASC mixes (100:0) is higher than AASFC mixes (75:25, 50:50 and 25:75) at all dosages. AASC mix at an activator modulus of 1.25 exhibits highest strength at 5% Na_2O dosage. The AASC mixes display moderate compressive strength even at lower i.e. 3% Na_2O dosage. The AASC mixes show high early strength when compared to AASFC mixes. The compressive strengths of the mixes reduced with the incorporation of FA for a constant Na_2O dosage. This may be due to the lower reactivity to FA as compared to GGBFS. However the reduction in the strength is not significant at lower level of replacement (i.e. 75:25). Replacement of GGBFS beyond 50% with FA resulted in crucial reduction in the compressive strength. The AASFC mixes with high amount of FA (i.e. 25:75) display low strength at lower dosages (3% Na_2O). The AASFC mix with 75% FA at 3% Na_2O dosage developed very low early strength thus posing problem of demoulding even after 24 hours of casting. The AASFC mix (25:75) developed reasonable strengths at the end of 28 days. However, at higher dosages (i.e. 4% and 5%) the AASFC mixes (25:75) developed adequate strength after 28 days of curing.

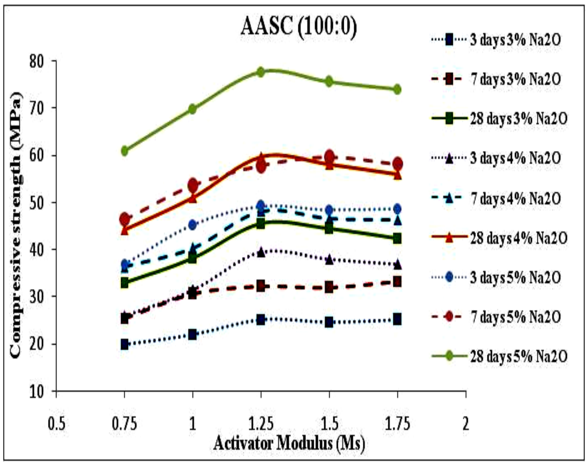

Fig. 1 *Strength of AASC (100:0) mixes for different activator modulus at various Na_2O dosages*

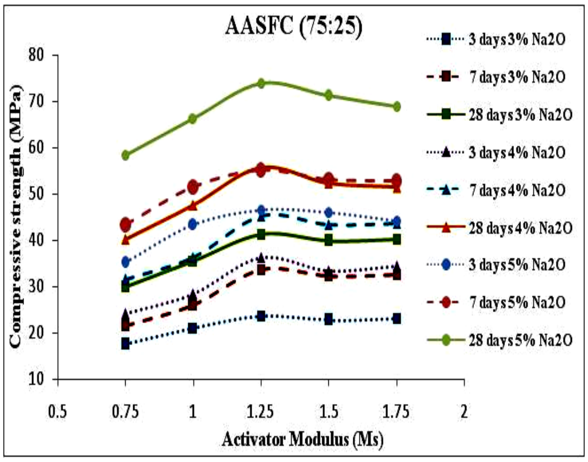

Fig. 2 *Strength of AASFC (75:25) mixes for different activator modulus at various Na_2O dosages*

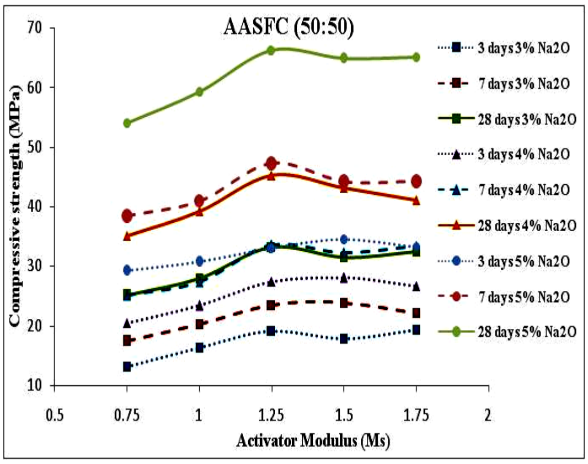

Fig. 3 *Strength of AASFC (50:50) mixes for different activator modulus at various Na_2O dosages*

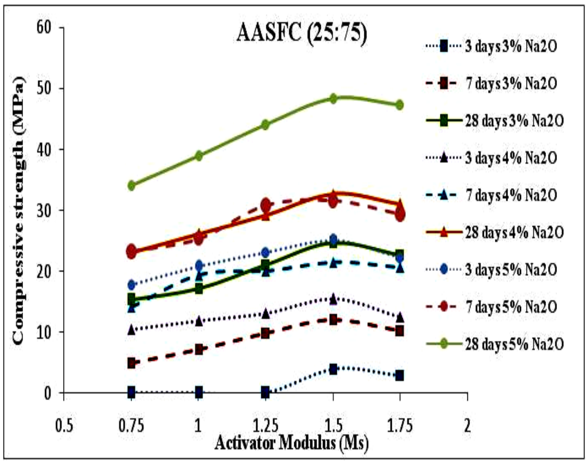

Fig. 4 *Strength of AASFC (25:75) mixes for different activator modulus at various Na_2O dosages*

Flexural strength and split tensile strength: The flexural strength and split tensile strength results for AASC and AASFC mixes (only for optimal activator modulus) at 28 days for different Na_2O dosages are depicted in Figures 5 and 6 respectively. It can be observed that AASC at 5% Na_2O dosage exhibit the highest flexural strength and the split tensile strength.

The AASC display the high flexural and split tensile strength as compared to AASFC mixes at all sodium oxide dosages. This may be due to the high compressive strength of the AASC mixes when compared to AASFC. The tensile properties of AASC and AASFC are influenced by the compressive strength which depends on the sodium oxide dosage and GGBFS to FA ratio and hence the tensile strength increase with increasing Na_2O dosage.

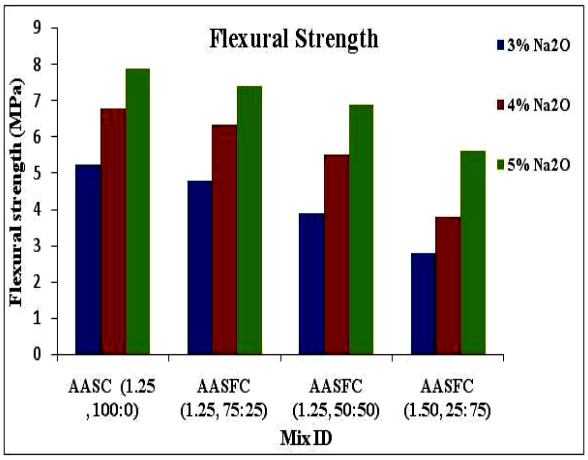

Fig. 5 *Flexural strength of mixes for different activator modulus at various Na_2O dosages*

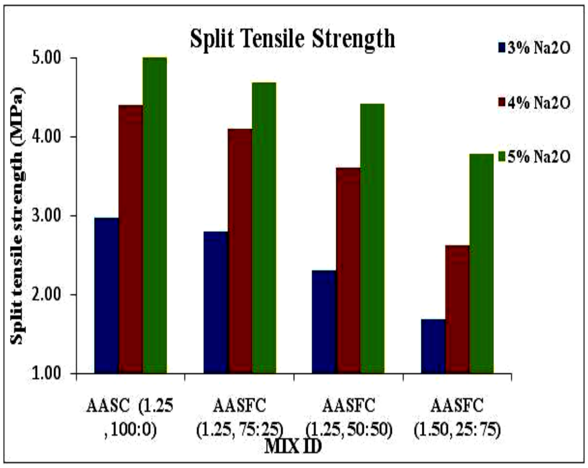

Fig. 6 *Split tensile strength of mixes for different activator modulus at various Na_2O dosages*

Conclusions:

1. The workability of the AASC and AASFC mixes decrease with the increase in activator modulus of the alkaline solution. The incorporation of FA increases the workability in the AASC mixes
2. The strength properties of AASC and AASFC are influenced widely by the activator modulus and the sodium oxide dosage of the alkaline solutions. The use of activator modulus of 1.25 in the alkaline activator provided the highest compressive strength for AASC and AASFC mixes (for 100:0, 75:25 and 50:50). For AASFC mix 25:75, the highest strength was attained at an activator modulus of 1.5.
3. The strength of the AASC and AASFC depend on the sodium oxide of the alkaline activators. Higher the sodium oxide dosage, higher the strength achieved.
4. The strength of the AASC and AASFC mixes decreased with the increased FA content.
5. AASC and AASFC develop satisfactory strength under air-curing conditions and thus leading to saving of water.

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