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Research paper

Alkali Activated Concrete with Steel Slag Aggregate for Concrete Pavements

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Abstract

In the present study, an attempt is made to investigate the usability of steel slag, which is a byproduct from the iron and steel industry, as coarse aggregates in alkali activated slag/ fly ash concrete mixes. The mix design for alkali activated slag/ fly ash concrete mixes was optimized and further steel slag coarse aggregates were incorporated in the optimized alkali activated slag/ fly ash concrete mixes mix by replacing natural coarse aggregates at different replacement levels (0%, 25%, 50%, 75% and 100% by volume). The mechanical properties were studied in detail. The flexural fatigue behavior of concrete mixes were investigated The experimental results showed that alkali activated slag/ fly ash concrete mixes with steel slag aggregates display slightly lower mechanical strength as compared to natural aggregates. The fatigue life of alkali activated slag/ fly ash concrete mixes was found to decrease with the inclusion of steel slag aggregates. The performance of steel slag aggregates in alkali activated slag/ fly ash concrete mixes was found satisfactory for use in pavement quality concrete.

Keywords: Alkali activated slag/flyash concrete; Steel slag; Mechanical properties; Flexural fatigue behaviour; Sustainable concrete, pavement quality concrete.

1. Introduction

Production of Ordinary Portland Cement (OPC) is associated with emission of large quantities of CO_2 gas into the atmosphere. Huge amount of CO_2 is generated during calcinations of carbonate in the kilns and through combustion of fuel during the production of Portland cement [1]. The primary approach towards the reduction of CO_2 emissions aimed at the reduction of production of Portland cement with the introduction of new variety of binders such as alkali activated binders which utilize industrial wastes such as Ground Granulated Blast Furnace Slag (GGBFS), Fly Ash (FA) etc. Alkali activated concretes are cement less binders which include an clinker-free binder matrix such as Alkali Activated Slag (AAS), Geopolymers, Alkali activated Slag/FA(AASF) etc. AAS can be identified as a new generation binder which is manufactured by mixing GGBFS with a strong alkaline activator. The alkali activation of the precursor materials can be done using a variety of alkaline activators such sodium/potassium silicate, sodium / potassium hydroxide or combination of both etc. However a blend of liquid sodium silicate and sodium hydroxide are believed to deliver the best strength properties in AAS. The main reaction component produced in AAS is Calcium-Silicate-Hydrate (C-S-H), with low Ca/Si ratio than that which is formed in OPC. Studies conducted in the past on AAS concrete have reported AAS concrete to have displayed superior properties as compared to conventional OPC concrete in terms of strength development, durability in chemical environments, lower heat of hydration etc. The addition of FA in AAS has proved to have reduced the strength properties of AAS concrete. However at lower levels of replacement of GGBFS with FA (Upto 25% by weight of binder), the strength variation was found to be insignificant. The problems associated with the production and disposal of FA is more prominent than that associated with GGBFS. The utilisation of FA in AAS concrete upto 25% (by weight of binder) will provide a partial solution to the disposal related problems associated with FA without compromising the strength properties of concrete [2,3].

Steel slag, which is generally considered as waste product from the iron and steel industry, can be viewed as a potential replacement for natural aggregates. Steel slag may be available in two forms depending upon the manufacture technique namely Basic Oxygen Furnace (BOF) slag and Electric Arc Furnace (EAF) slag. The EAF slag may be different in its chemical composition from BOF slag. Problems such as volume deformation and high density are associated with steel slag aggregates which limit its use in construction industry. The volume deformation occurs with the free lime or magnesia available in steel slag aggregates combines with water. However the problem of volume deformation can be countered by subjecting the steel slag aggregates to weathering for time period of three to six months, to allow the free lime or magnesia content to bring with permissible limits [4]. Experimental investigations have revealed that OPC concrete incorporating steel slag aggregates display better mechanical properties as compared to concretes containing traditional aggregates [5]. However, few researchers have reported the performance of steel slag aggregates in conventional concrete to be similar or slightly lower than natural aggregates [6].

The purpose of the present study is to investigate the performance of air cured alkali activated slag/fly ash (AASF) blended mixes incorporating steel slag as coarse aggregates for Pavement Quality Concrete (PQC). The mix design for AASFC with Slag:Fly ash ratio of 75:25 was optimized and compared with control OPC based concrete mix. The natural coarse aggregates were replaced by steel slag coarse aggregates in AASFC at different levels of replacement (25%, 50%, 75% and 100% by volume). Various engineering properties such as workability, density, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity were assessed. The flexural fatigue behavior of the concrete mixes was also studied in detail.

2. Experimental Investigation

2.1 Materials

In the present investigation, OPC 43 grade in compliance with the IS 8112-2013 [7] was used. The GGBFS conforming to IS: 12089-1987 [8]was obtained from JSW Iron and Steel Plant, Bellary India, while Class C Fly Ash in accordance to IS: 3812-2003 [9] was procured from Raichur Thermal Power Station (RTPS), India. A combination of liquid sodium silicate (14.7% Na_2O + 32.8% SiO_2 + 52.5% H_2O by mass, and density = 1570 kg/m^3) and commercial grade sodium hydroxide flakes (97% purity, density = 2110 kg/m^3) were used along with potable water for the preparation of alkaline activators. The tap water available in the institution was utilised for the preparation of alkaline activators as well as for curing of OPCC specimen. Fine aggregates used were locally available river sand conforming to the requirements of IS: 383-1970 [10] while crushed granite aggregates with maximum size of 20mm (20mm to 4.75mm) were used as natural coarse aggregates. All aggregates used in present study were tested for different properties as per relevant Indian standard code and the results are presented in Table 1.

2.2 Steel Slag Aggregates

The steel slag aggregates (BOF slag) used in the present study was procured from JSW Iron and Steel Plant, Bellary India. The steel slag is black in colour, angular shape, and stone like appearance and having porous texture surface. The slag was subjected to weathering process by allowing it in outdoor conditions and spraying water regularly for 360 days to bring the free lime and free magnesia content within permissible limits. It was observed that a thin film or coating of calcium carbonate (calcite) appeared on the aggregate surface after being subjected to weathering process. Washing of weathered aggregates was done to check if the coat of calcite could be removed; however it was found that the bond between the aggregate and the coating layer was strong enough to be washed away. The free lime present in steel slag undergoes reaction with water to form calcium hydroxide, which further reacts with the atmospheric carbon dioxide to form calcium carbonate ($CaCO_3$) [11]. The images of steel slag aggregates before and after undergoing the weathering process are depicted in Figure.1. Steel slag of Maximum Aggregate Size (MAS) of 20 mm is considered in the present study. Physical properties of steel slag are presented in Table 1.

Table I.: Physical characteristics of aggregates

Sl. No	Test	Crushed granite	Steel Slag	Fine aggregate	Method of Test, reference
1	Specific Gravity	2.69	3.35	2.64	IS 2386 (P-III) -1963
2	Bulk Density a) Dry loose	1495 kg/m^3	1726 kg/m^3	1475 kg/m^3	
	Bulk Density b) Dry compact	1653 kg/m^3	1935 kg/m^3	1548 kg/m^3	
3	Aggregate Crushing Value	24%	21%	-	IS 2386 (PIV)-1963
4	Los Angeles Abrasion value	20%	18%	-	
5	Aggregate Impact value	21%	16%	-	

(a) **Steel slag aggregates before weathering process**

(b**) Formation of thin film of calcite on slag aggreagtes after undergoing weathering process**

Fig.1:. Image showing steel slag aggregates before and after weathering process.

2.3 Mix Proportion and Specimen Details

The OPC concrete was designed based on the guidelines suggested by IS: 10262-2009 [12] as the reference concrete. A total binder content of 425 kg/m^3, with water/binder ratio of 0.40 and ratio of coarse aggregate: fine aggregate of 0.64:0.36 was selected. The mix design was aimed to achieve of slump value of 25-50 mm. In order to arrive at the designated slump, a super plasticizer dosage of 0.40% (by weight of binder content) was added to the mix.

The AASFC mixes were designed with same binder content (425 kg/m^3) as that considered for OPCC with water/binder (w/b) ratio of 0.40. However, a blend of GGBFS: FA in the ratio 75:25 (weight ratio) was selected as the binder for AASFC mixes. The alkaline activator were formulated to provide a sodium oxide dosage of 4% (by weight of binder), having an activator modulus (Ms) of 1.25 (weight ratio of SiO_2/Na_2O) and with total water/binder ratio of 0.40. The total water content in the alkaline activator solution for AASFC mixes was adjusted by considering the water readily present in liquid sodium silicate along with the extra added water, to achieve the required water/binder ratio (i.e. 0.40). No super-plasticizers were used for AASFC mixes as they achieved the required workability without adding super-plasticizers. AAFSC mixes incorporating steel slag coarse aggregates were prepared by replacing the normal aggregates at 25%, 50%, 75% and 100% (by volume) maintaining the volume of total coarse aggregates constant. The details of mix proportions for OPCC and AASFC are tabulated in Table 2. All ingredients were properly mixed in the mixer and the fresh concrete was poured into steel moulds for the preparation of specimen for evaluating hardened properties. Cube specimens of dimensions (100x100x100) mm were cast for evaluating compressive strength, prism specimens of size (100x100x500) mm were cast for determining flexure strength and fatigue strength, cylinder specimens of size 100mm dia x 200 mm height for split tensile strength and cylinder specimens of size 150mm dia x 300 mm height for testing modulus of elasticity; were cast. After 24 hours of casting the specimens were demoulded and were allowed for curing. The OPCC specimens were cured in water and the AASFC specimens were exposed to curing at relative humidity of 80±10 and room temperature of 27±3°C.Three specimens were tested for each test and their average was recorded.

Table II:. Details of Mix proportions of concrete mixes (all quantities are in kg/m3)

Mix ID	OPC	GGBFS	FA	Sand	CA	Steel slag	Sodium silicate	NaOH	Added water
OPCC	425		-	660	1195	-	-	-	170
AASFC-0	-	319	106	636	1152	-	64.78	9.64	136
AASFC-25	-	319	106	636	864	359	64.78	9.64	136
AASFC-50	-	319	106	636	576	717	64.78	9.64	136
AASFC-75	-	319	106	636	288	1076	64.78	9.64	136
AASFC-100	-	319	106	636	-	1434	64.78	9.64	136

Note: OPCC - represents Portland cement based control mix; **AASFC-0** - represents AASFC mix with natural aggregates; **AASFC-X** represents AASFC mixes with X (% by volume) of normal aggregates replaced with steel slag aggregates.

2.4 Flexural Fatigue Behaviour of Concrete Mixes

The flexural fatigue tests were performed on prism specimen of size (100x100x500) mm using a MTS servo-controlled hydraulic repeated load testing machine with capacity up to 5 tonnes (Figure.2). The fatigue tests were performed on OPCC; and for AASFC samples with 0%, 50% and 100% replacement of normal aggregates with steel slag aggregates. Before beginning the fatigue test, the static flexural strength at 90 days was recorded and the results are presented in Table 4. The prism specimen for fatigue test was at a span of 400 mm similar to static flexural tests. The prism specimen was loaded using constant amplitude half sinusoidal wave form at a frequency of 4 Hz without any rest period. The maximum load was adjusted based on the required stress ratio (ratio of applied stress to the modulus of rupture of concrete) while minimum load is maintained as zero. The fatigue tests were performed at various stress ratios i.e. 0.85, 0.80, 0.75 and 0.70 in order to obtain a relationship between stress ratios (S) and the number of cycles to failure (N). In order to eliminate the errors occurring due to progressive strength development of concrete mixes with age after 28 days of curing, the fatigue test was performed after 90 days of curing. The Fatigue life (N) i.e. the number of cycles up to failure of the sample was recorded for each specimen. The tests were conducted on 80 prism specimens, with set of five samples for each mix. One set of fatigue lives of the various concrete mixes are presented in Table 5 while the complete data of fatigue lives are represented using S-N curves. The experimental set up of fatigue testing machine is presented in Figure.2.

Fig. 2:. Repeated load testing set up.

4. Results and Discussions

4.1 Workability and Unit Weight

The slump test for various concrete mixes was performed and the results of slump test and unit weights for different mixes are presented in Table 3. However, the workability of AASFC mixes with steel slag aggregates slightly decreased with the increasing content of steel slag in the mixes. This can be clearly noticed in the mixes AASFC- 0 and AASFC-100. The angular shape of the steel slag aggregates tends to reduce the mobility of the matrix thus causing reduction in the workability [13]. The incorporation of steel slag in concrete mixes will lead to the requirement of a slightly higher water/binder ratio to achieve a designated slump as compared to that achieved by traditional aggregates. However, the mix AASFC-25 achieved similar workability as that of AASFC-0. The unit weights of OPCC and AASFC-0 were found to be similar however, the incorporation of steel slag in AASFC mixes resulted in increase in the unit weights of AASFC mixes. The unit weights of AASFC mixes increased with higher amounts of steel slag aggregates which may be attributed to higher density of steel slag as compared to conventional aggregates.

Table III:. Compressive strength of concrete mixes at different ages

Mix ID	Slump	Compressive strength (MPa)				Density
	(mm)	*3 days*	*7 days*	*28 days*	*90 days*	*(kN/m^3)*
OPCC	35	23.1	40.4	56.9	62.8	24.8
AASFC-0	60	36.3	43.6	55.6	62.4	24.5
AASFC-25	55	36.1	42.9	54.2	60.2	25.2
AASFC-50	45	34.2	40.8	52.9	57.6	25.7
AASFC-75	40	33.1	38.4	50.8	54.1	26.2
AASFC-100	30	30.4	36.7	48.9	51.7	27.2

4.2 Compressive Strength of Concrete Mixes

The OPCC and AASFC mixes were tested for compressive strength as per IS: 516-1959 [14] at 3, 7, 28 and 90 days of curing and the results are presented in Table 3. It can be observed that all the concrete mixes undergo progressive strength development upto 90 days of curing. The AASFC with normal aggregates attain similar compressive strength as that of OPCC at the 28 and 90 days of curing. However the inclusion of steel slag aggregates resulted in the reduction of the compressive strength in the AASFC mixes. AASFC with 100% steel slag displays compressive strength 12% lower than AASFC with natural aggregates. This may be accounted to the formation of weak interfacial transition interface between steel slag aggregates and the paste due to the presence of thin coating of calcite on the surface of steel slag aggregates. Incidents of de-bonding of steel slag aggregates from the paste were observed after visual inspection of the failed samples. The bond between the paste and the aggregates has significant influence on the strength and durability of concrete. The presence of coating or film on the aggregate surface leads to the reduction in mechanical and durability properties of concrete mixes; especially if the bond between the paste and coating layer is stronger than the bond between the coating and aggregate surface, due to the formation of a weak coating aggregate interface [15]. The strength variation between samples tested for the same mix was greater for AASFC mixes higher amounts of steel slag which may be due to the higher heterogeneity of steel slag aggregates, however the strength variation was found to be within normal range of variability. The strength reduction of AASFC mixes with steel slag at lower levels of replacement of natural aggregates (upto 25%) was found to be insignificant. It was noticed that the AASFC mixes displayed high early strength i.e. compressive strength at 3 and 7 days of curing, as compared to conventional concrete, which may be due to the physical and structural characteristics of the binders. The GGBFS in AASFC undergoes quicker dissolution and precipitation in the presence of high alkaline environment, which makes the hydration process of AASFC faster than that occurring in Portland cement leading to high early strength [16]. The strength development after 7 days slowed down and the OPCC and AASFC-0 displayed similar 28 and 90 days strength. The high early strength of AASFC is advantageous for pavement quality concrete, as it would allow the early opening of vehicular traffic to newly constructed pavements. All the mixes satisfied the minimum strength requirements for application in pavement quality concrete.

4.3 Tensile Properties and Modulus Of Elasticity

The test for the flexural strength and split tensile strength for all concrete specimens were performed according to IS 516:1959 [14] and IS 5816:1999 [17] respectively. The flexural strength of concrete specimens is evaluated at 7, 28 and 90 days of curing and the results are depicted in Table 4. From Table 4, it can be observed that AASFC with steel slag aggregates display lower flexural strength as compared to AASFC with natural aggregates. The flexural strength of AASFC decreases progressively with increasing contents of steel slag. This may be attributed to the weak paste and aggregate interface due to the presence of coating of calcite, as observed in compressive strength. The mix AASFC-0 exhibits higher flexural strength than OPCC at all ages. The AASFC-0 display higher flexural strength than OPCC at all ages despite of having similar strength which may be attributed to the distinct microstructure and presence of dense interfacial transition zone between the paste and aggregates as compared to cement concrete [18,19]. The 28-day split tensile strength values of concrete mixes are tabulated in Table 4. AASFC mix with normal aggregates exhibit higher split tensile strength than OPCC. The split tensile strength of AASFC reduced with the increasing steel slag content. The test for modulus of elasticity was performed as per IS 516:1959[14]. The results of static modulus of elasticity for OPCC and AASC mixes at 28 days of curing are tabulated in Table 4. It can be noticed that the AASFC-0 exhibits slightly lower modulus of elasticity as compared to OPCC despite of similar compressive strength. The relationship of properties such as tensile strength, modulus of elasticity with 28-day compressive strength of concrete mixes may differ as a function of the binder type and binder chemistry. Alkali activated binders display different strength development rate, and differences in the microstructure which may lead to variation in the tensile and elastic properties [20]. The replacement of natural aggregates with steel slag resulted in decrease the modulus of elasticity in AASFC mixes. However, the variation in modulus of elasticity is marginal at lower levels (upto 25%) of replacement by steel slag.

Table IV: Tensile properties and modulus of elasticity of concrete mixes

Mix ID	**Flexural Strength (MPa)**			**Split tensile strength (MPa)**	**Modulus of Elasticity (GPa)**
	7 days	***28 days***	***90 days***	***28 days***	***28 days***
OPCC	4.62	6.01	6.39	3.90	34.9
AASFC -0	5.46	6.40	6.81	4.12	33.5
AASFC-25	5.36	6.26	6.67	3.99	32.8
AASFC-50	5.07	6.09	6.32	3.91	31.4
AASFC-75	4.82	5.77	6.20	3.78	30.9
AASFC-100	4.67	5.65	5.94	3.61	30.2

4.4 Flexural Fatigue Behaviour of Concrete Mixes

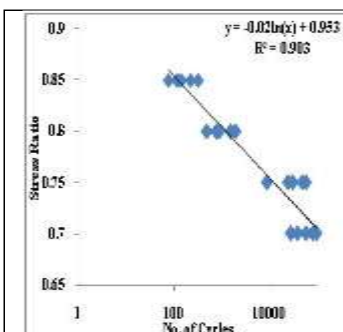
The results for fatigue life i.e. the number of cycles up to failure for OPCC and AASFC mixes with/without steel slag are tabulated in Table 5. Representation of fatigue data of concrete specimen using S-N curves or Wohler curve is the most basic method in the analysis of fatigue data. The S-N curve in which 'S' denotes the stress amplitude and 'N' denotes the number of cycles to complete failure, represents the progressive deterioration of the structure and breaking of the bonds. The S-N curves for OPCC and AASFC with and without steel slag are obtained by plotting graph of stress level v/s number of cycles up to failure, and the results are presented in Figure.3. The estimation of fatigue cycle at any stress level can be done using the equations obtained from the S-N curves. The equations generated from S-N curves for different concrete mixes are tabulated in Table 6.

Table V:. Fatigue life (N) of OPCC and AASFC specimens

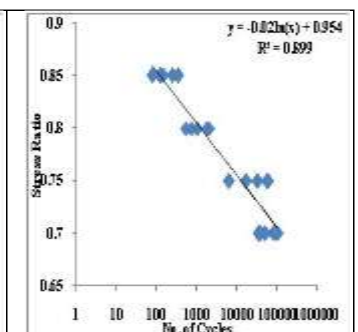
Stress Ratio (SR)	**Number of cycles (N)**			
	OPCC	***AASFC-0***	***AASFC-50***	***AASFC - 100***
0.85	317	340	321	346
0.80	1986	2018	1576	1374
0.75	57835	59146	63545	44696
0.70	97587	102592	82456	89621

Table VI:. Relationship between fatigue cycle (N) and stress ratio (SR)

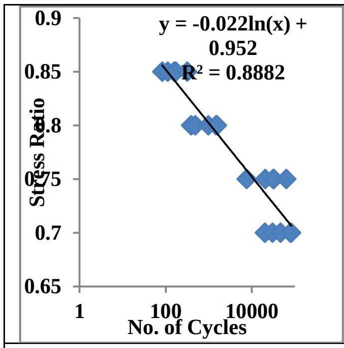
Mix ID	**Equations**	$\mathbf{R^2}$
OPCC	ln(N)=0.953-SR/0.02	0.903
AASFC-0	ln(N) = 0.954-SR/0.02	0.899
AASFC-50	ln(N) = 0.952-SR/0.02	0.888
AASFC-100	ln(N) = 0.944-SR/0.02	0.855



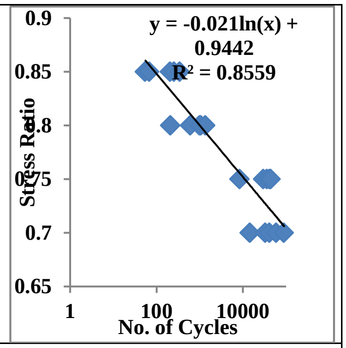
S-N curve for OPCC



S-N curve for AASFC-0



(c) S-N curve for AASFC-50



(d) S-N curve for AASFC-100

Fig.3. S-N curves for various concrete mixes

The variation of fatigue life cycles at various stress levels for different concrete mixes is presented in Table 5. It can be observed that AAFSC-0 exhibit better fatigue life as compared to OPCC and other AASFC mixes at all stress levels. The higher fatigue life of AASFC-0 may be attributed to the denser interfacial transition zone in AASFC-0 than that in OPCC [20] which restricts the early formation and propagation crack under repeated application of load. The incorporation of steel slag aggregates lead to the reduction of fatigue life of AASFC mixes. The weak interfacial transition zone between the steel slag and paste in AASFC-50 and AASFC-100 may have lead to formation and propagation of cracks leading to early fatigue failure. It can be observed that the S-N curves for AASFC-100 show greater scatter as compared to other mixes at all stress levels. It can be noticed that the fatigue life of concrete specimens increase with the decrease in stress level from 0.85 to 0.70. The visual examination of failed specimen revealed the failure to be within the middle one third spans. From Table 6 it can be noticed that statistical correlation coefficients obtained from the S-N curves for concrete mixes at different stress levels are in the range 0.85 to 0.91, thus indicating the fatigue data to be statistically significant. From Figure.3, it can be seen that the variation of fatigue life cycles at different stress levels is found to exhibit similar behavior. The equation presented in Table 6 may be utilized to predict the number of failure cycles any particular concrete mix undergo when subjected to different values of stress ratios.

5. Conclusions

The major conclusions drawn from present investigation can be summarized as follows:

1. The incorporation of steel slag aggregates decreased the workability of AASFC mixes with corresponding increase in the unit weight.

2. AASFC-0 attain high early strength as compared to conventional OPCC mixes, however the ultimate strengths were similar. The replacement of natural aggregates with steel slag led to the decrease in mechanical strengths of AASFC mixes due to the presence of thin coating of calcite on the steel slag surface.

3. The inclusion of steels slag aggregates in AASFC mixes slightly reduced the fatigue life of AASFC. The statistical correlation coefficients obtained from the S-N curves for concrete mixes at different stress levels are in the range 0.85 to 0.91, thus indicating the fatigue data to be statistically significant.

4. The performance of steel slag aggregates is found to be satisfactory for application in pavement quality concrete. The utilization of steel slag aggregates will lead to the reduction in environmental hazards occurring from its disposal, along with protecting the natural aggregates.

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