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Air-Cured Alkali Activated Binders for Concrete Pavements

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Abstract: The present study focuses on the possibility of use of alkali activated binders for use in concrete pavements. Alkali Activated Slag Concrete (AASC) and Alkali Activated Slag Fly ash Concrete (AASFC) are prepared and the properties are compared with Ordinary Portland Cement Concrete (OPCC). The Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash (FA) are blended in the ratios 100:0, 75:25, 50:50 and 25:75 as binder and activated using strong alkaline solution. Trial mixes are carried out to identify the optimal Activator Modulus (Ms) for each combination of GGBFS and FA. The mix design for the optimal activator modulus is optimised to achieve sufficient strength for Pavement Quality Concrete (PQC) and the fresh and mechanical properties are studied in detail. The results indicate the properties of AASC and AASFC are similar or slightly better than conventional OPCC and satisfy the minimum strength requirements for concrete pavements. The application of alkali activated binders will minimise the environmental hazards occurring from augmented OPC production, along with effective utilisation of industrial waste materials and conservation of natural resources.

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***Key words**: Alkali activated binders; Concrete pavements; Mechanical properties; Sustainable concrete.*

Introduction

The highways and road network in India are considered to be the backbone of Indian infrastructure with the total length of roads exceeding about 3.3 million kilometres. Quality concrete roads and efficient pavement design are the necessary for sustainable highway infrastructure in the country. The utilisation of industrial by-products such as Ground Granulated Blast Furnace Slag (GGBFS), Fly Ash (FA) etc. in concrete pavements is now necessary not just to reduce the initial investment for rigid pavements but also to enhance the mechanical properties of concrete for pavements. Increased emission of CO_2, high consumption of energy and faster depletion of natural resources has posed threats to the environment in future. With the opportunity of addressing these issues, alkali activated binder concrete can be looked upon as new class of concrete which utilise the industrial by-products such as GGBFS, FA as binders. The alkali activated binders are synthesised from the reaction of silica, calcium and alumina rich materials with strong alkaline activator solution. Alkali Activated Slag Concrete (AASC), which accommodate 100% GGBFS as sole binder and Alkali Activated Slag Fly Ash Concrete (AASFC) in which a combination of GGBFS and FA in different proportions; may be considered as examples for alkali activated binders. The reaction products of AASC are similar to that obtained in Ordinary Portland Cement Concrete (OPCC) i.e. C-S-H (Calcium Silicate Hydrate) [1-3]. However, the reaction products of AASFC may comprise of C-S-H along with A-S-H (Alumina Silicate Hydrate) depending upon the GGBFS:FA ratio [4]. The AASC and AASFC possess excellent mechanical and durability properties as compared to conventional cement concrete [5-8]. The strength and durability of AASC and AASFC are governed by several factors such as type, concentration, sodium dosage and activator modulus (ratio of SiO_2/Na_2O) of alkaline activator, curing regime, composition of binders, water to binder ratio etc [9, 10]. Liquid sodium silicate combined with sodium hydroxide is found to provide the best performance for AASC and AASFC [11]. The addition of FA in AASC reduces the strength of AASC, while increases the workability and hence the ratio of GGBFS: FA affects plays an important role in determining the properties of AASFC [11, 12]. The AASC and AASFC develop sufficient strength under ambient curing conditions [13].

The present study focuses on the usability of alkali activated concrete as an alternative for OPCC for concrete pavements. The alkali activated binders are produced by mixing GGBFS and FA in different ratio i.e. 100:0, 75:25, 50:50 and 25:75 using strong alkaline activator. The mechanical properties of AASC and AASFC mixes such workability, density, compressive strength, flexural strength, modulus of elasticity, water absorption and total porosity are studied and compared with OPCC.

Experimental Investigation

Materials

In the present investigation, OPC 43 grade (in accordance with IS 8112–2011 [14]) having a specific gravity of 3.14 was used. GGBFS(meeting the requirements of IS 12089 – 1987 [15]) and FA (in accordance with IS: 3812-2003 [16]) were procured from Iron and Steel Plant, Bellary, India and Raichur Thermal Power Station (RTPS), Karnataka, India respectively. The chemical composition and physical properties of GGBFS and FA are presented in Table 1. 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) in combination with potable tap water was used as alkaline activator. The liquid sodium silicate had an activator modulus (Ms = SiO_2/Na_2O) ratio of 2.23 when procured from the supplier. Crushed granite aggregates

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Table 1. Chemical Composition and Physical Properties of GGBFS and FA [(%) by Weight]

Constituents	GGBFS	FA
CaO	34.77	0.79
Al_2O_3	16.7	32.17
Fe_2O_3	1.20	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	2.90	2.20
Blaine Fineness (m^2/kg)	370	350

with maximum size of 20mm were used as coarse aggregates (20 mm to 4.75 mm), while locally available river sand was used as fine aggregates in the present investigation. The aggregates used were conforming to requirements of IS: 383–1970 [17] and were tested as per relevant Indian standard codes [18]. The physical properties of aggregates are presented in Table 2. Sulfonated naphthalene formaldehyde (SNF) polymer admixture (“Conplast SP 430”) supplied by FOSROC, Chemicals (India) Pvt. Ltd was used as super plasticizers.

Preliminary Investigation on Effect of Activator Modulus (Ms) on Compressive Strength

Preliminary mix design was carried out for AASC and AASFC mixes in order to determine optimal activator modulus to achieve the desired strength. The AASC and AASFC were prepared using binder content of 425 kg/m^3 by mixing GGBFS: FA in the ratios 100:0, 75:25, 50:50 and 25:75 with water to binder ratio (w/b) of 0.4. The alkaline activator solution was prepared by dissolving the sodium hydroxide flakes in sodium silicate solution, in proper proportion in order to achieve the desired activator modulus (Ms = SiO_2/Na_2O) and desired sodium oxide dosage. The solution was stirred properly and laboratory water was added in order to bring the solution to contain total water content equivalent to water/binder (w/c) 0.2 of total binder content. The solution was stored in tight plastic container at least one day prior to mixing. The solution was brought to the desired total water/binder ratio (0.4) by mixing extra water during the time of casting of specimen. The mixes were activated at sodium oxide dosages of 4% (by weight of binder) and the activator modulus (Ms) was varied between 0.75 and 1.75. The activator modulus for which the mix attained the maximum strength on 100x100x100 mm cube at 28 days of curing was considered for further optimisation. The results of the preliminary investigation are presented in Fig. 1.

The compressive strength results for 100:0, 75:25, 50:50 and 25:75 mixes at 4% and for different activator modulus is depicted in Fig. 1. From the Figure, it can be observed that the compressive strength of mixes is significantly influenced by the activator modulus of the alkaline solution. With the increase in ratio of activator modulus, the compressive strength increases until an optimal value of activator modulus; however the compressive strength decreases with further increase in ratio of activator modulus. The increase in activator modulus implies the increase in the concentration of the anions of sodium silicate in the activator solution which help in the dissolution process of the binder materials contributing higher strength to the mix [19]. The variation of compressive strength of AASC and AASFC mixes with activator modulus display a similar and definite trend line.

Table 2. Physical Properties of Aggregates Used in the Present Study.

Sl. No	Test	Crushed Granite	River Sand	Method of Test, Reference to
1	Specific Gravity	2.69	2.64	
2	Bulk Density a) Dry Loose	1494 kg/m^3	1478 kg/m^3	IS 2386 (P-III) -1963
	b) Dry Compact	1655 kg/m^3	1550 kg/m^3	
3	Aggregate Crushing Value	24%	-	
4	Los Angeles Abrasion	20%	-	IS 2386 (PIV)-1963
5	Aggregate Impact Value	21%	-	
6	Water Absorption	0.50%	0.80%	

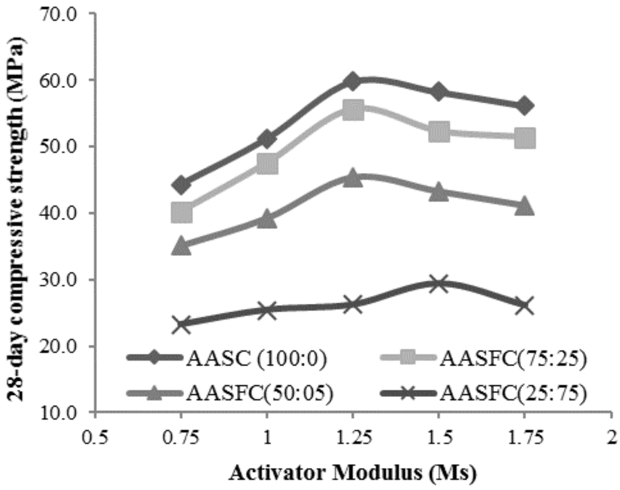

Fig. 1. Effect of Activator Modulus on Compressive Strength of AASC and AASFC.

It may be observed that the AASC (100:0) and AASFC mixes (75:25, 50:50) attained the highest compressive strength at an activator modulus of 1.25; the AASFC (25:75) achieved the highest compressive strength at an activator modulus of 1.50. The mix AASC (100:0) attained the highest compressive strength as compared to other mixes at constant water/binder ratio (w/b) and sodium oxide dosage. The strength of AASC and AASFC mixes reduced with replacement of GGBFS with higher contents of FA. This is mainly due to the lower reactivity of FA as compared to GGBFS under a similar activation condition. AASFC (75:25) with lower content of FA did not display significant reduction in the compressive strength, however the replacement of GGBFS beyond 50 wt.% with FA resulted in crucial reduction in the compressive strength. This indicates that under the activation conditions used, the inclusion of 50 wt.% FA in the binder affects the kinetics of reaction at early times of curing. This is believed to be due to alkalinity supplied by alkaline activator solution not being sufficient to promote the extensive reaction of the FA at early age. AASFC mixes containing higher amounts of FA would require higher concentration of activator solution i.e., lower water/binder (w/b) ratio and higher sodium oxide dosage [12]. However, AASFC (25:75) still achieved a compressive strength up to 30 MPa at an activator modulus of 1.5.

It was noticed that the slump values tested using slump cone test were 40 mm, 55 mm, 70 mm and 85 mm for the mixes 100:0, 75:25, 50:50 and 25:75, respectively. However, according to the Indian standard code IRC: 58:2008, PQC should have a minimum compressive strength of M40 and a slump value in the range 25-50 mm. From the preliminary investigation, it can be noticed that the mixes AASC (100:0) and AASFC (75:25) satisfy both strength and workability. However, the mixes AASFC (50:50) and AASFC (25:75) achieve greater slump than the required slump but do not satisfy the compressive strength requirements. Therefore revision of sodium oxide dosages for AASFC (50:50) and AASFC (25:75) was done with simultaneous reduction in the water/ binder ratio for the optimal activator modulus. Based on trials, sodium oxide dosage of 4.5% with 0.38 w/b ratio and 5.5% with 0.37 w/c ratios was adopted for AASFC (50:50) and AASFC (25:75) respectively. The revised dosages were selected such that the compressive strength of all mixes fall in the similar range. The Table 3 presents the sodium oxide dosages and activator modulus adopted for various AASC and AASFC mixes for which the other properties were studied.

Mix Proportion and Details of Specimens

The OPC concrete was designed based on guidelines provided by IS: 10262-2009 [20]. The mix design constituted total binder content of 425 kg/m^3 with coarse aggregate: fine aggregate ratio of 0.64:0.36 and water to binder ratio of 0.4. Super plasticizer dosage of 0.4% (by weight of binder) is added to the mix to arrive slump value of 25-50mm. The AASC mixes were prepared with 100% GGBFS as binder (425 kg/m^3) while AASFC (with binder content of 425 kg/m^3) mixes were prepared by combining GGBFS and FA in the ratios 75:25, 50:50 and 25:75. The details of activator modulus (Ms) and sodium oxide dosages adopted for the mixes are tabulated in Table 3. The alkaline activator solution was prepared by considering total water content readily available in liquid sodium silicate was estimated and then extra water required to arrive at required water to binder ratio was added. No super-plasticizers are added for AASC and AASFC mixes. The details of the mix proportions of concrete mixes are provided in Table 4.

The ingredients were mixed thoroughly in the concrete mixer and then poured in different moulds to test the hardened state properties.

Table 3. Sodium Oxide Dosages and Activator Modulus for AASC and AASFC.

Mix ID	Sodium Oxide Dosage (%)	Water/ Binder	Modulus Activator
AASC (1.25, 100:0)	4	0.4	1.25
AASFC (1.25, 75:25)	4	0.4	1.25
AASFC (1.25, 50:50)	4.5	0.38	1.25
AASFC (1.50, 25:75)	5.5	0.37	1.5

Cubes of size 100x100x100 mm, prisms of size 100x100x500 mm and cylinders of size 150 mm dia x 300 mm height were prepared to determine compressive strength, flexural strength and modulus of elasticity respectively. The water absorption and total porosity were tested on cubes of size 100x100x100 mm. All specimens were demoulded after 24 hrs of casting. The OPCC specimens were cured in water tank while the AASC and AASFC specimens were subjected to curing at relative humidity of 80-90% and room temperature of (27±3°C). An average value of three specimens is recorded for all the tests.

Results and Discussions

Workability and Density of Concrete Mixes.

The slump test was performed according to the procedure suggested in IS 1199:1959 [21]. The slump values and unit weights obtained for different mixes are presented in Table 5. The OPCC, AASC and AASFC mixes attained the target slump values for which they were designed. During the preliminary investigation it was observed that the slump increases with the inclusion of higher FA content in AASC mixes. The inclusion of FA required less water to achieve desirable workability due to the particle size and morphology of this precursor [22], thus facilitating a lower water to binder ratio with equivalent workability. Hence the water to binder ratios for AASFC (50:50, 25:75) were reduced in order to achieve a slump in the range 25-50 mm. From Table 5, it can be noticed that all the mixes have density more or less same density as that of conventional concrete. The density of AASFC was found to decrease with the increase in FA content which may be attributed to the lower specific gravity of FA as compared to GGBFS. However, the unit weights of AASC and OPCC are in the same range

Compressive Strength of Concrete Mixes

The tests for compressive strength of concrete mixes at 3, 7, 28 and 90 days of curing were conducted as per IS: 516-1959 [23] and the results are tabulated in Table 5. From the Table 5, it can be noticed the strength of concrete mixes increases progressively with age. It

Table 4. Details of Mix Proportions of Concrete (All Quantities are in kg/m^3)

Mix ID	OPC	GGBFS	FA	CA	Sand	NaOH	Na_2Si0_3	Water
OPCC	425	-	-	1195	660	-	-	170
AASC (1.25, 100:0)	-	425	-	1172	647	9.64	64.8	136
AASFC (1.25, 75:25)		319	106	1152	636	9.64	64.8	136
AASFC (1.25, 50:50)		212.5	212.5	1127	628	10.52	72.8	123
AASFC (1.50, 25:75)		106	319	1121	583	9.88	106.9	101

Table 5. Properties of Various Concrete Mixes.

Mix ID	Compressive Strength (MPa)				Slump	Density
	3 days	7 days	28 days	90 days	(mm)	(kg/m^3)
OPCC	23.1	37.4	56.6	62.8	35	2480
AASC (1.25, 100:0)	39.6	48.2	59.8	67.4	40	2470
AASFC (1.25, 75:25)	36.2	43.6	55.6	62.6	60	2455
AASFC (1.25, 50:50)	32.6	45.3	58.4	65.1	55	2420
AASFC (1.50, 25:75)	33.5	44.6	56.8	63.5	50	2385

may be noticed that the alkali activated binders display high early strength (3-day and 7-day) as compared to that of conventional OPC concrete. This may be attributed to the structural and physical characteristics of the alkali activated binders. The high early strength is mainly due to the presence of GGBFS in the alkali activated binders which undergoes a faster reaction in the presence of high alkaline activator. The rate of hydration reactions in alkali activated binder is faster than of OPC concrete, hence delivering high early strength [24, 25]. However, the OPCC, AASC and AASFC achieve similar 28-days strength. The AASC achieve the highest strength of 67.4 MPa at 90 days of curing as compared to other mixes. The AASFC specimens with FA up to 75% (25:75) exhibit comparable mechanical strengths as that of AASC independent of content of FA included in the binder. The lower water/binder ratios and higher sodium oxide dosage used at higher FA content were able to counteract the decrease in strength which would otherwise have been induced by the incorporation of higher contents of FA. This indicates that the water/binder ratio and sodium oxide dosage can be controlled to achieve the desired strength in alkali-activated concretes formulated with high FA content. All concrete mixes attained sufficient strength at 28 days of curing necessary for application in PQC. The high early strength of AASC and AASFC mixes is of great benefit for PQC as it would allow the early opening of the constructed pavements to the traffic movement.

Flexural Strength and Modulus of Elasticity of Concrete Mixes

The static flexural strengths and modulus of elasticity for all concrete specimens were determined according to IS 516:1959 [23]. Table 6 presents 7, 28 and 90 days results of flexural strength and 28-day modulus of elasticity for concrete mixes. The mix AASC (100:0) achieved the highest flexural strength of 6.93 MPa while the mix AASFC (25:75) attained the lowest flexural strength of 6.26 MPa amongst the alkali activated concretes when tested at 28 days. AASC and AASFC mixes display higher flexural strength than OPCC concrete at all ages. This is believed to be due to development of distinct microstructure and existence of strong aggregate-paste interface on account of presence of dense interfacial transition zone in alkali activated binders as compared to cement concrete [26]. From Table 6, it may be noticed that the OPCC attained a modulus of elasticity of 34.9 GPa while AASC achieved a similar modulus of elasticity of 34.2 GPa at 28 days of curing. The modulus of elasticity slightly decreased with the increase in FA content in the AASFC mixes. The static modulus of elasticity of OPCC mixes is higher than that of AASC and AASFC mixes although the OPCC, AASC and AASFC display similar 28-day

Table 6. Flexural Strength and Modulus of Elasticity of Mixes.

Mix ID	Flexural Strength (MPa)			Modulus of Elasticity (GPa)
	7 Days	28 Days	90 Days	28 Days
OPCC	4.62	6.01	6.39	34.9
AASC (1.25, 100:0)	6.08	6.93	7.46	34.2
AASFC (1.25, 75:25)	5.46	6.40	6.81	33.5
AASFC (1.25, 50:50)	5.62	6.51	7.01	33.1
AASFC (1.50, 25:75)	5.27	6.26	6.42	31.2

compressive strength. The results obtained are in agreement with the literature [12]. This may be attributed to the differences in the binder chemistry due to which the relationship of properties such as modulus of elasticity, flexural strength, porosity etc., with 28-day compressive strength is altered [26-28]. AASC and AASFC, both being subsets of the general class of alkali activated materials display differences in the microstructure and rate of strength development up to 28 days which lead to variation in elastic and flexural properties [29]. The AASC and other AASFC mixes satisfy the minimum strength requirements for rigid pavements i.e. compressive strength of M40 grade, flexural strength of 4.5 MPa and modulus of elasticity of 30 GPa.

Water Absorption and Total Porosity

The water absorption and total porosity were evaluated according to ASTM C 642-06 [30]. A set of three cubes of 100x100x100 mm size were tested for each mix. The water absorption and total porosity of different mixes at 28 days are presented in Fig. 2. The AASC displayed the lowest water absorption 3.28% and porosity of 8.05% as compared to other mixes. The AASFC (25:75) mix exhibited the highest water absorption 4.49% with corresponding porosity of 11.12%. AASC and AASFC (75:25) mixes having same binder content and water-binder ratio as OPCC show reduced water absorption and total porosity values as compared to OPCC at 28 days of curing. This may be probably due to the presence of very refined closed pore structure in the AASC samples [31, 32] which restrict the water from penetrating into the structure. The inclusion of FA in AASC shows significantly higher porosity. The water absorption and total porosity values increased with FA replacements in AASFC mixes even though when the water to binder (w/b) ratios of AASFC (50:50) and AASFC (25:75) were lower than AASC (100:0). The higher porosity with higher contents of FA may be attributed to nature of the gel type forming in the binder. The formation of C-S-H binding gel is more dominant in the microstructure in AASFC containing upto 50% of GGBFS.

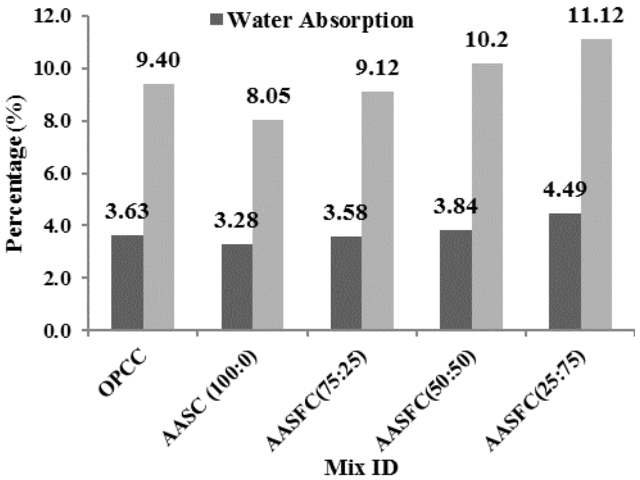

Fig. 2. Water Absorption and Total Porosity of Concrete Mixes.

However, at higher FA contents greater than 50%, the A-S-H type gel dominates the microstructure which is less dense than the C-S-H type gel [33]. The pore structure promoted by each binding gel type is different and hence different porosities [31].

Conclusions

AASC and AASFC are eco-friendly sustainable concrete which utilises industrial wastes for its production thus providing solutions for the problems associated to dumping of such wastes. 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. The water/binder ratio and sodium oxide dosage can be controlled to achieve the desired strength in alkali-activated concretes formulated with high FA content. The AASC and AASFC mixes attained a compressive strength in the range 50- 60 MPa with flexural strength in the range 6-7 MPa at 28 days of curing. All concrete mixes attained sufficient strength at 28 days of curing necessary for application in PQC. The high early strength of AASC and AASFC mixes is of great benefit for PQC as it would allow the early opening of newly constructed pavements to the traffic movement. AASC and AASFC being air curing lead to the saving of water required for curing which otherwise is a key issue in rigid pavements. Such type of concrete is of utmost benefit at places having acute shortage of water such as deserts and arid regions.

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