Performance of Alkali Activated Slag and Alkali Activated Slag + Fly Ash with various Alkali Activators

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Abstract— **The production of OPC is responsible for about 7% of the world's CO_2 emissions, lead to the search for more environmentally variable alternative to cement. Some of those alternative materials are alkali-activated slag (AAS) and fly ash (FA), where alkali-activated slag and fly ash are used not as a partial replacement to cement but as a sole binder's in the production of concrete. The durability performance of alkali-activated slag (AAS) concrete with Sodium Silicate, Sodium Hydroxide and Sodium Carbonate with addition hydrated lime, Potassium Hydroxide with hydrated lime as activators are studied and The durability performance of alkali-activated slag (60%) + fly ash (40%) (AASF) mixes with Sodium Hydroxide and Potassium Hydroxide with hydrated lime as activators are studied. All the activators are used at 4% Na_2O or 4% K_2O (by weight of slag) and 4% of hydrated lime by total weight of solid binder content if used as a retarder. The main aim of the work is to overcome the production of OPC which is responsible for about 7% of the world's CO_2 emissions, a major contributor to the green house effect which is implicated in global warming and climate change. We can also increase the ductility property of Alkali activated concrete (AAS) mix and alkali activated slag + fly ash (AASF) mix when compared to Ordinary Portland cement concrete mix. The need to meet a sustainable development is now an important challenge to the cement industry. The overall aim of the study was lead to the search for more environmentally viable alternative to cement. Among AAS mix Sodium Hydroxide (SH_4) was best; Potassium Hydroxide (KH_4) was second; Sodium Carbonate (SC_4) was third and Sodium Silicate (SS_4) was last in terms of compressive, in terms of split tensile strength Sodium Silicate (SS_4) was best; Sodium Carbonate (SC_4) was second; Potassium Hydroxide (KH_4) was third and Sodium Hydroxide (SH_4) was last in terms of flexure strength Potassium Hydroxide (KH_4) was best; Sodium Hydroxide (SH_4) was second; Sodium Carbonate (SC_4) was third; sodium silicate (SS_4) was last. Among AASF mix Sodium Hydroxide (SF_4) was best; Potassium Hydroxide (KF_4) was second in terms of compressive, in terms of split tensile strength Potassium Hydroxide (KF_4) was best; Sodium Hydroxide (SF_4) was second and in terms of flexure strength.**

Potassium Hydroxide (KF_4) was best; Sodium Hydroxide (SF_4) was second. Hence form our investigation Potassium Hydroxide is the best activator among other activators for both AAS and AASF mixes.

Index Terms— **Alkali-activated slag, fly ash, Sodium Silicate, Sodium Hydroxide, Sodium Carbonate, Potassium Hydroxide.**

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I. Introduction

Portland cement clinker is made from calcinations of limestone and siliceous material where de-carbonation occurs according to reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

The total emission of CO_2 per kg of cement clinker produced is 0.53 kg from the decarbonisation of calcite, plus 0.33 kg from the burning process plus 0.12kg from the generation of electrical power required, making a total of 0.98kg. Therefore, for every ton of cement clinker produced, an approximately equal amount of carbondioxide is released into atmosphere. The world cement industry contributes some 7% to the total man made CO_2 emission. This leads to the search for more environmentally viable alternatives to Portland cement. Some of these alternative materials are alkali-activated slag (AAS) fly ash (FA), in which alkali-activated slag and fly ash are used not as a partial replacement for cement but as a sole binder itself in the production of concrete. This will produce an environmentally friendly concrete. The use of slag and fly ash has advantages due to its excellent cementations properties over Ordinary Portland cement (OPC). Various studies had investigated ways to enhance the reactivity of the slag and fly ash. One of the economic ways of activation is alkali activation. The alkalis that are going to be used in this dissertation are Sodium Silicate (Na_2SiO_3), Sodium Carbonate (Na_2CO_3), Sodium Hydroxide (NaOH) and Potassium Hydroxide (KOH). There are many slag like granulated blast-furnace slag, electro thermal furnace phosphorous slag and steel slag but GGBS is generally used. Slag has latent hydraulic properties. If GGBS is placed in water alone, it dissolves to a small extent but a protective film deficient in Ca^{2+} is quickly formed, which inhibits further reaction. The reaction continues if the P^H is kept sufficiently high. The pore solution of a Portland cement, which is essentially one of alkali hydroxides, is a suitable medium. The supply of K+ and Na+ ions is limited, but these ions are only partially taken up by the hydration products, and the presence of calcium hydroxide ensures that the supply of OH^- ions is maintained.

The slag can be similarly activated by OH^- ions supplied in other ways such as addition of sodium hydroxide or silicate. Alkali activated slag is not widely known and used as construction material. Most of the research has been done at the material development stage dealing with paste and mortar specimens to study the material chemistry and microstructure. The scope of the work covers a normal strength OPC control mix, AAS mixes, AASF mixes with the same binder content and the same w/c ratio. The AAS concrete comprise four mixes with 100% slag as the sole binder activated with four alkalis Sodium Silicate, Sodium Carbonate, Sodium Hydroxide and Potassium Hydroxide with a dosage of 4% Na_2O or 4% K_2O (by weight of slag) and AASF concrete comprise two mixes with 60% slag+ 40% fly ash as the sole binder activated with two alkalis Sodium Hydroxide and Potassium Hydroxide with a dosage of 4% Na_2O or 4% K_2O (by weight of slag). The normal water curing was used.

II. Materials

Cement: Ordinary Portland cement conforming to IS 12269 – 2002 was used for the concrete mix and Specific gravity was found to be 3.5

Fine Aggregate: The fine aggregate used in the work was obtained from a nearby river course. The fine aggregate that falls in zone –II was used. The specific gravity was found to be 2.60.

Coarse aggregate: Crushed coarse aggregate of 4.75mm size passing and 10mm retained proportion and 10 mm passing-20mm retained proportion was used in the mix. Uniform properties were to be adopted for all the prisms for entire work. Specific Gravity of coarse aggregate is 2.78.

Admixtures:

Slag: The ground granulated blast-furnace slag (GGBS) used was obtained from the Toshali cements pvt. Ltd., it complied with BS: 6699-1992.

Fly ash: The most widely used supplementary cementations material in concrete is a byproduct of the combustion of pulverized coal in electric power generating plants. Upon ignition in the furnace, most of the volatile matter and carbon in the coal are burned off. During combustion, the coal's mineral impurities (such as clay, feldspar, quartz, and shale) fuse in suspension and are carried away from the combustion chamber by the exhaust gases. In the process, the fused material cools and solidifies into spherical glassy particles called Fly ash.

Sodium Silicate Powder: Powder form of sodium silicate was used in the investigation. It has a molecular ratio SiO_2: Na_2O (Ms) =3.21 with 29.2% of SiO_2 and 9.1% of Na_2O by weight.

Sodium Hydroxide Pellets: Sodium hydroxide pellets. It is 97 % pure. The pellets are used to make solution of required dosage in water.

Sodium Carbonate: Sodium carbonate powder. It is almost 99.5 % pure. The powder is used to make solution of required dosage in water.

Potassium Hydroxide Pellets: Potassium Hydroxide pellets. It is 97 % pure. The pellets are used to make solution of required dosage in water.

Water: Potable water supplied by our colleges was used in the work.

Moulds: Specially made wooden specimens are used for casting prisms. Standard cast iron cube and cylinder were used for casting of cubes, cylinders.

Vibrator: To compact the concrete, a plate vibrator and as well as needle vibrator was used and for compacting the Test specimens, cubes, cylinders and prisms.

Casting: The moulds were tightly fitted and all the joints were sealed by plaster of Paris in order to prevent leakage of cement slurry through the joints. The inner side of the moulds was thoroughly oiled before going for concreting. The mix proportions were put in miller and thoroughly mixed. The prepared concrete was placed in the moulds and is compacted using needle & plate vibrators. The same process is adopted for all specimens. After specimens were compacted the top surface is leveled with a trowel.

Curing: The NSC specimens were removed from the moulds after 24 hours of casting and HSC specimens were removed after 48hours of casting, the specimens were placed in water for curing.

III. Mix Design Procedure

The proportioning of a concrete mixture is based on determining the quantities of the ingredients which, when mixed together and cured properly will produce reasonably workable concrete that has a good finish and achieves the desired strength when hardened. This involves different variables in terms of water to cement ratio, the desired workability measured by slump, cement content and aggregate proportions. The mix is M30 Grade. Mix design is done according to Indian standard recommended method of concrete mix design IS 10262-2009.The details of different mixes are presented in Table 1.

The notation for the mixes is as follows:

CM: OPC control mix with w/c=0.43.

SH_4: Sodium hydroxide-activated slag concrete mixture with Na_2O content of 4% by weight of slag with w/c=0.43.

SS_4: Sodium Silicate powder-activated slag concrete mixture with Na_2O content of 4% by weight of slag with w/c=0.43.

SC_4: Sodium Carbonate-activated slag concrete mixture with Na_2O content of 4% by weight of slag and with w/c=0.43.

KH_4: Potassium Hydroxide-activated slag concrete mixture with K_2O content of 4% by weight of slag and with w/c=0.43.

SF_4: Sodium Hydroxide activated fly ash- slag concrete with 4% N_2O by weight of fly ash- slag and w/c=0.43 with 60%AAS+40% Fly ash.

KF_4: Potassium Hydroxide-activated fly ash- slag concrete with 4% K_2O by weight of slag and with w/c=0.43 with 60%AAS+40% Fly ash.

Fig 1: Mix

Table 1: Details of Mix Proportions

Mix No	Type of Binding Material	Binding Material (kg/m^3)	Type of Activator	Activator (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Lime 4% by weight of slag	W/C Ratio
CM	OPC	420			562.8	1209.6		0.43
SS_4	Slag	420	Na_2SiO_3	16.8	562.8	1209.6	16.8	0.43
SH_4	Slag	420	NaOH	21.67	562.8	1209.6	16.8	0.43
SC_4	Slag	420	Na_2CO_3	28.72	562.8	1209.6	16.8	0.43
KH_4	Slag	420	KOH	19.95	562.8	1209.6	16.8	0.43
SF_4	Slag+ fly ash	420	NaOH	21.67	562.8	1209.6	16.8	0.43
KF_4	Slag+ fly ash	420	KOH	19.95	562.8	1209.6	16.8	0.43

IV. WORKABILITY

The workability of concrete describes the homogeneity and the case of mixing, handling, placing, compacting and finishing of the concrete. Workability or rheology of fresh concrete is the term traditionally been used in concrete technology to embrace all the necessary qualities. The test used in our investigation is slump cone test.

Table 2: Slump at 5 Minutes

Activator	Slump(mm)
CM	135
SS_4	145
SH_4	136
SC_4	139
KH_4	142
SF_4	137
KF_4	140

Results and Discussion: The results from above Table show acceptably workable concrete with the CM, having the lower slump than AAS and AASF concrete which has same w/c ratio. From the results displayed in above Table it can be concluded that the workability of AAS and AASF concrete has more workability when compared to normal OPC.

V. ENGINEERING PROPERTIES

The Engineering properties of concrete including the Compressive Strength, Split Tensile Strength, and Flexural Strength of different concrete mixes OPC, four AAS mixes and two AASF mixes with different activators. First the four AAS mixes Compressive Strength are compared with OPC Compressive Strength and the highest Compressive Strength giving activators (2 activators) are selected and with those activators the AASF mixes are prepared and they are compared with AAS mixes. The influence of curing conditions at different ages is presented.

Results for Engineering properties for OPC mix and four **AAS** mixes.

A. Compressive Test

Compressive Strength is an important criterion used to evaluate the quality of concrete. The Compressive Strength is done as determined in IS 456: 2005 and three samples were tested at 3, 7 and 28 days and the average results are reported.

Table 3: Compressive Strength for Different Ages

Cement or Slag Mix	3-Day (Mpa)	7-Day (Mpa)	28-Day (Mpa)
CM	15.35	25.32	38.63
SH_4	11.71	24.91	30.92
SC_4	10.62	20.18	29.36
SS_4	12.31	23.62	27.24
KH_4	10.78	23.83	30.35

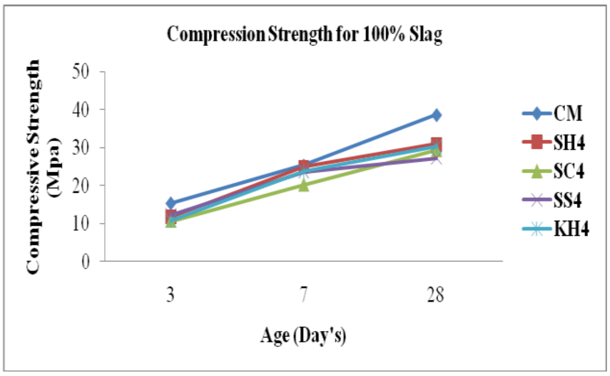

Fig. 2 Compressive Strength (100% Slag) Result in Graphical Representation

Result for Compressive Strength: The result from the above Fig.1 shows that among AAS concrete mixes NaOH (SH_4) with a dosage of 4% Na_2O by weight of slag achieved higher compressive strength (30.92 MPa at 28 days respectively in water curing) in comparison with all the other mixes. KOH (KH_4) activated concrete exhibited second highest compressive strength (30.35 MPa at 28 days) among alkali-activated concrete mixes. Na_2CO_3 (SC_4) activated concrete exhibited third highest compressive strength (29.36 MPa at 28 days) among alkali-activated concrete mixes. Na_2SiO_3 (SS_4) activated slag concrete mix has compressive strength (27.32 Mpa at 28 days).

B. Split Tensile Test

Concrete in general is known to be weak in tension leading to the use of steel reinforcement in structural concrete. Although concretes and mortars are not generally designed to resist tension, the knowledge of the tensile strength is significant to estimate the load under which the sample will crack. There are three types of test for the tensile strength: direct tension test, flexure test and splitting tensile test. The splitting tensile test is a simple test to perform and it is believed that it leads to a close value of direct tensile strength. However, it is stated that the splitting tensile test yields a low result for mortars. The test was performed as described in IS 5816: 1999 and three samples were tested at the ages 3, 7, 28 days for water curing and average values are reported.

Table 4: Split Tensile Strength for Different Ages

Cement or Slag Mix	3-Day (Mpa)	7-Day (Mpa)	28-Day (Mpa)
CM	0.895	2.313	2.863
SH_4	0.595	1.595	2.169
SC_4	0.623	1.836	2.472
SS_4	0.609	1.874	2.598
KH_4	0.583	1.675	2.458

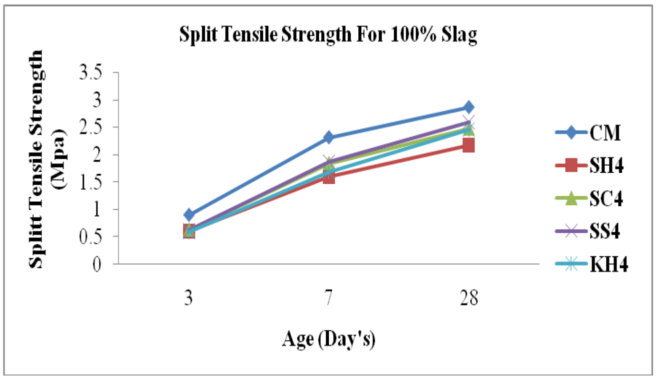

Fig. 3 Split Tensile Strength (100% Slag) Result in Graphical Representation

Result for Splitting Tensile Test: The result from the above Fig.2 shows that among AAS concrete mixes, SS_4 showed the highest value of tensile strength around 2.598 MPa at 28 days, followed by SC_4 (2.47 MPa), followed by KH_4 (2.458 Mpa), SH_4 showed the lowest value (2.16 Mpa).

C. Flexural Test

The Flexural Strength of concrete mixes was measured according to I.S.9399:1983. Samples of 150x150x700 mm were cast in order to perform the Flexural Strength Test and three samples were tested for curing at the age of 12 days and average are reported.

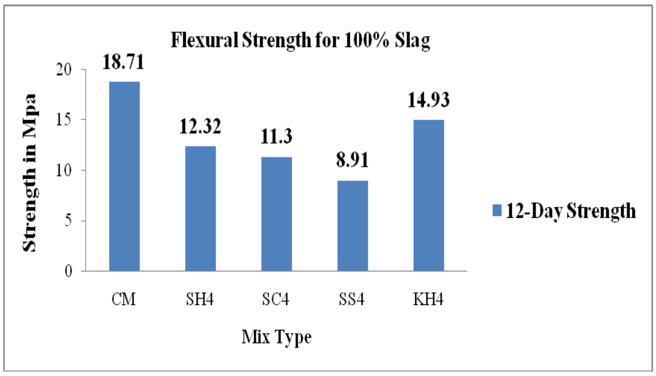

Fig.4 Strength (100% Slag) Result in Graphical Representation

Result for Flexural Strength: From the above Fig.4 we can observe effect of curing on all different mixes. The highest flexural strength is shown by concrete mix where as the lowest flexural strength is shown by Na_2SiO_3 activated concrete mix (SS_4). Almost all AAS concrete shows comparable values of flexural strength with concrete mixes. Among AAS concrete KOH (KH_4) shows higher flexural strength followed by NaOH activated slag mix (SH_4) followed by Na_2CO_3 activated slag mix (SC_4) and then finally the least flexural strength is given by $NaSiO_3$ (SS_4).

Hence from the above Compressive Test results, **Sodium Hydroxide (NaOH)** and **Potassium Hydroxide (KOH)** were selected and with those activators the performance of AASF mixes were investigated.

The Results for engineering properties for two **AAS** and two **AASF** mixes.

Selection of ratio of Slag and Fly Ash: For the selection of slag and fly ash ratio compressive test is done for 7 days for the ratio of 90% slag + 10% fly ash, 80% slag + 20% fly ash, 70% slag + 30% fly ash, 60% slag + 40% fly ash, 50% slag + 50% fly ash with Sodium Hydroxide (NaOH) as activator. Compressive Strength obtained for 100% slag with NaOH activator in 7 days value is nearer to 60% Slag & 40% Fly ash 7 days value with NaOH activator. So we have selected 60% slag & 40% fly ash.

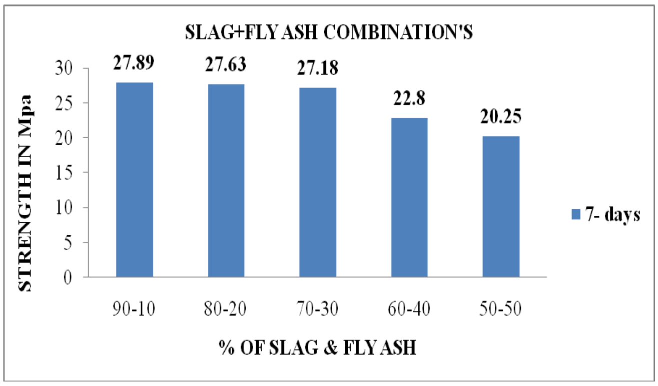

Fig. 5 Slag + Fly Ash Combinations in Graphical Representation

D. Compressive Test

Compressive Strength is an important criterion used to evaluate the quality of concrete. The Compressive Strength is done as determined in IS 456: 2005 and three samples were tested at 3, 7 and 28 days and the average results are reported.

Table 5: Compressive Strength for Different Ages

Cement or Slag Mix	3-Day (Mpa)	7-Day (Mpa)	28-Day (Mpa)
SH_4	11.71	24.9	30.92
SF_4	12.03	22.8	32.64
KH_4	10.78	23.83	30.35
KF_4	10.27	22.57	31.9

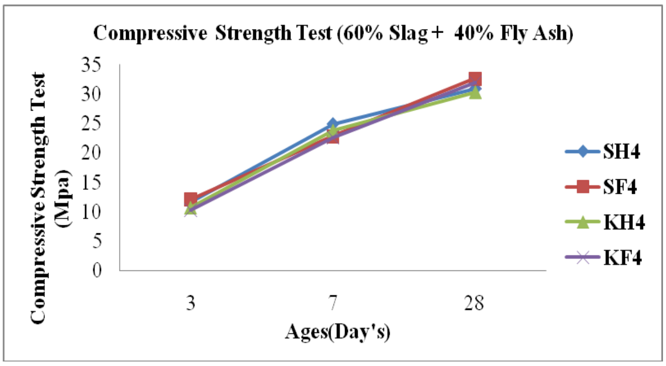

Fig. 6 Compressive Strength (60% ASS + 40% FA) Result in Graphical Representation

Result for Compressive Strength: The result from the above Fig.6 shows that among AAS and AASF concrete mixes NaOH (SF_4) with a dosage of 4% Na_2O by weight of slag + fly ash achieved higher compressive strength (32.64 MPa at 28 days respectively in water curing) in comparison with all the other mixes. KOH (KF_4) activated (slag + fly ash) concrete exhibited second highest compressive strength (31.9 MPa at 28 days) among alkali-activated concrete mixes. NaOH (SH_4) activated (slag) concrete exhibited third highest compressive strength (30.92 MPa at 28 days) among alkali-activated concrete mixes. KOH (KH_4) activated (slag) concrete mix has compressive strength (30.35 Mpa at 28 days).

E. Split Tensile Test

The Splitting Tensile Test is a simple test to perform and it is believed that it leads to a close value of direct tensile strength. The test was performed as described in IS 5816: 1999 and three samples were tested at the ages 3, 7, 28 days for water curing and average values are reported. The splitting tensile strength of all mixes was measured using 100 mm Φ X 300 mm long cylinders.

Table 6: Split Tensile Strength for Different Ages

Cement or Slag Mix	3-Day (Mpa)	7-Day (Mpa)	28-Day (Mpa)
SH_4	0.595	1.595	2.169
SF_4	0.447	0.952	1.95
KH_4	0.583	1.675	2.458
KF_4	0.526	1.235	2.086

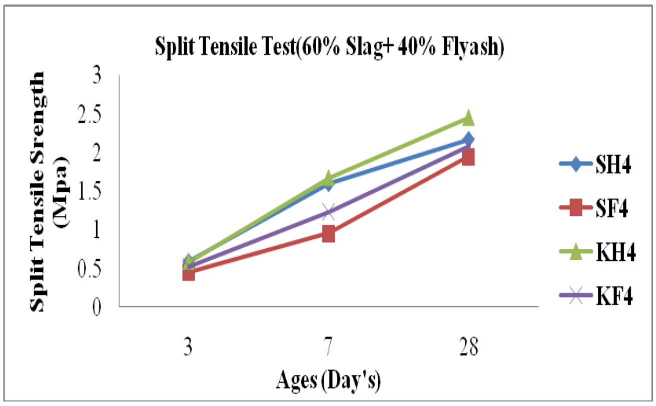

Fig. 7 Split Tensile Strength (60%ASS+ 40% FA) Result in Graphical Representation

Result for Splitting Tensile Test: The results from the above Fig. 7 shows that among AAS and AASF concrete mixes, KH_4 showed the highest value of tensile strength around (2.458 MPa at 28 days) followed by SH_4 (2.169 MPa at 28 days) followed by KF_4 (2.086 MPa at 28 days). SF_4 showed the lowest value (1.95 Mpa at 28 days).

F. Flexural Test

The Flexural Strength of concrete mixes was measured according to I.S.9399:1983. Samples of 150x150x700 mm were cast in order to perform the Flexural Test and three samples were tested for curing at the age of 12 day and average are reported.

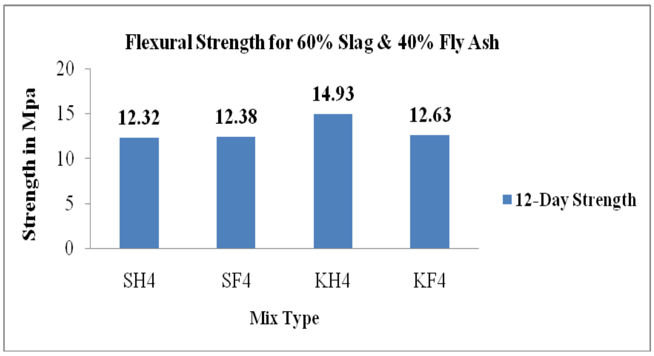

Fig. 8 Flexural Strength (60%ASS+ 40%FA) Result in Graphical Representation

Result for Flexural Strength: All AAS, AASF concrete shows comparable values of flexural strength with concrete mixes. Among AAS, AASF concrete KOH (KH_4) shows higher flexural strength followed by KOH activated slag + fly ash mix (KF_4) followed by NaOH activated slag + fly ash mix (SF_4) and then finally the least flexural strength is given by NaOH (SH_4).

VI. CONCLUSION

Overall it can be concluded that AAS and AASF concretes has a great potential and presents a viable alternative to OPC to help in decreasing the effect on the environment in terms of energy conservation and less CO_2 emissions. AAS and AASF concrete shows good ductility than traditional concrete. So AAS and AASF concretes are good to use where ductile designs are needed i.e., in seismic prone areas. Curing is a very important factor in the engineering properties of concrete in general, but AAS and AASF concretes are much more sensitive to curing where if there is no addition of retarder hydrated lime to the mix. In case lime is added then effect of curing in strength loss in case of AAS is comparable or even less than normal OPC concrete. Strength of concrete of dry cured samples is lower than that of concrete that is water cured samples for all types of concrete. AASF concrete can achieve high strength in comparison with AAS and OPC concretes. Among AAS concrete Sodium Hydroxide activated concrete showed high strength followed by Potassium Hydroxide, Sodium carbonate**,** Sodium Silicate in Compression Test. In terms of Split Tensile Test Sodium Silicate activated concrete showed high strength, followed by Sodium carbonate, Potassium Hydroxide, Sodium Hydroxide. In terms of Flexural Strength Test Potassium Hydroxide activated concrete showed high strength, followed by Sodium Hydroxide, Sodium carbonate, Sodium Silicate. Among AASF concrete Sodium Hydroxide activated concrete showed high strength in Compression Test, followed by Potassium Hydroxide. In terms of Split Tensile Test Potassium Hydroxide activated concrete showed high strength, followed by Sodium Hydroxide. In terms of Flexural Strength Test Potassium Hydroxide activated concrete showed high strength, followed by Sodium Hydroxide. The AASF concrete is more efficient than AAS concrete only in terms of Compressive Test but in terms of Split Tensile and Flexural Strength Tests AAS concrete is efficient than AASF concrete. In both the AAS and AASF concrete Potassium Hydroxide activated concrete showed best strength results when compared to other alkali activators in all the three tests conducted. The addition of hydrated lime does not show a marked effect on strength at early ages (3 and 7 day) but slightly improves strength at 28 day in case of AAS and AASF concretes.

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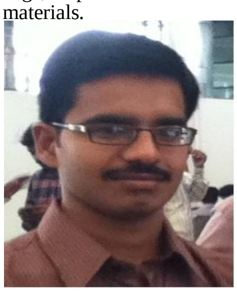

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