Alkali-Activated Slag/ Fly Ash Concrete: Mechanism, Properties, Hydration Product and Curing Temperature

Sonal Banchhor, Meena Murmu, Shirish V. Deo

*Abstract***:** *Alkali-activated concrete (AAC) is mounting as a feasible alternative to OPC assimilated to reduce greenhouse gas emanated during the production of OPC. Use of pozzolana results in gel over-strengthening and fabricate less quantity of Ca(OH)$_2$ which provide confrontation to concrete against hostile environment. (AAC) is potential due to inheriting the property of disbursing CO$_2$ instantly from the composition. Contrastingly an option to ordinary Portland cement (OPC), keeping this fact in mind the goal to evacuate CO$_2$ emits and beneficiate industrial by-products into building material have been taken into consideration. Production of alkali-activated cement emanates CO$_2$ nearly 50-80% less than OPC. This paper is the general assessment of current report on the fresh and hardened properties of alkali-activated fly ash (AAF), alkali-activated slag (AAS), and alkali activated slag and fly ash (AASF) concrete. In the recent epoch, there has been a progression to blend slag with fly ash to fabricate ambient cured alkali-activated concrete. Along with that the factors like environmental friendliness, advanced studies and investigation are also mandatorily required on the alkali activated slag and fly ash concrete. In this way, the slag to fly ash proportion impacts the essential properties and practical design of AAC. This discusses and reports the issue in an intensive manner in the following sections. This will entail providing a good considerate of the following virtues like workability, compressive strength, tensile strength, durability issues, ambient and elevated-temperature curing of AAC which will improve further investigation to elaborate the correct test methods and to commercialize it.*

Keywords: Fly ash, Slag, Alkali activator, Workability, Strength, Durability, Hydration Product, Curing temperature.

I. INTRODUCTION

The plunking of pozzolana is an environmental problem. Slag and Fly Ash (FA) are conventionally utilized binder to augment the workability, strength and durability properties. These industrial by-products FA, Slag with the partial replacement of OPC

has been extensively utilized and resulted not merely in enhanced sustainability and environmental friendliness additionally improved the mechanical properties, durability and rheology. The auxiliary ratio is 15 to 25% for FA to total cementitious material and the replacement ratio for Slag is 50–70% [1, 2]. AAC utilizes industrial by-products as binders comprising silica and alumina, alkali activators for activating the binders and fine and coarse aggregates, later cured under apposite conditions [3]. Production of alkali-activated cement emanates CO$_2$ nearly 50-80% less than OPC [4]. Class F (low calcium) and Class C (high calcium) FA system are two major subclasses [5].

Researches on AAC illustrates that workability depends on fineness, the composition of raw material, alkaline concentration and activator modulus. It is investigated that durability properties like permeability, water sorption, carbonation of AAC can be enhanced by proper mix design [6]. The key features of AAF are low shrinkage, high acid and heat resistance [7] whereas those of AAS are rapid setting, high strength and fire resistance [8].

In AAC, the chemical and physical properties depend fundamentally on curing conditions and raw material. The AAC appraise in this article are composed of FA, Slag, and blend of FA and Slag, providing an assessment of research on the properties of AAC. Subsequent properties are discussed: workability, compressive strength, tensile strength, durability properties, ambient and elevated-temperature curing.

This comprehensive survey will entail providing a good considerate of the following virtues like workability, compressive strength, tensile strength, durability issues, ambient and elevated-temperature curing of AAC which will improve further investigation to elaborate the correct test methods and to commercialize it.

II. MATERIALS

A unanimous term applied to the reaction between solid aluminosilicate and activator, to fabricate a solidified binder based on hydrous alkali-aluminosilicate is Alkali activation (termed as 'precursor'). These definitions ensue to include Slag, FA and alkali activator [9].

A Fly Ash: It is a by-product of coal-fired electric generating plants. Its particles are spherical and steadily finer than OPC, its diameter ranges from 1μm – 150μm and its size is exaggerated by the type of dust collection system [10]. The strength and additional properties depend upon the chemical composition and fineness of source material in AAC [11].

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204

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The mass ratio of SiO_2 and Al_2O_3 in class F fly ash is in the range of 1.7-4.0 while the amorphous content is generally more than 50 % [12]. (Class F) FA has a cleaner surface in contrast to (class C) FA due to the absence of alkalis and sulphates ions [13].

B Slag: It is a by-product of blast furnaces utilized for crafting iron. The slag reactivity depends upon the fineness, dissemination of particle size and specific surface area [14]. The strength intensified whereas the setting time is diminish on increasing the fineness of Slag. The fineness of Slag for AAS should be in between 400-550 m^2/kg (Blaine) [15]. Table 1&2 illustrates the physical and chemical characteristic of (class F) FA, Slag and OPC.

Table 1 Physical characteristic of Fly Ash, Slag, OPC [10, 14]

Property	FA	Slag	OPC
Specific gravity	1.3 – 4.8	2.85-2.9	3.15
Bulk density (kg/m^3)	540-860	1200	1450
Physical appearance	Grey powder	Off white powder	Grey powder
Median particle size (lm)	12.3	12.4	-

Table 2 Chemical characteristic of Fly Ash, Slag, OPC [15, 16]

Component	Slag	Fly Ash	OPC
SiO_2	32.40-36.9	62.2-70.3	17-25
Al_2O_3	14.96-14.2	23.1-27.5	3-8
Fe_2O_3	0.3-0.83	1.4- 3.92	0.5-6
CaO	36.0- 40.70	0.2- 2.27	60-67
MgO	5.1- 5.99	0.6- 1.05	0.5-4
K_2O	0.1-0.29	0.9- 1.24	0.3-1.2
Na_2O	0- 0.42	0.4- 0.52	0.3-1.2
TiO_2	0.6- 0.84	0.16-2.6	-
P_2O_5	0.38-0.4	0.2-0.30	-
Mn_2O_3	0.4-0.40	0- 0.09	-
SO_3	2.74-6.1	0-0.2	2.0-3.5
LOI	0-0.3	0-2.0	-

C Alkali Activator: The ratio of Na_2O to the binder mass (fly ash for AAF and slag for AAS), alkali activator is characterizing as activator dosages (in terms of %Na_2O) while the ratio of SiO_2 to Na_2O is delegate as activator modulus (Ms) in the alkaline activator as follows [16]

%Na_2O = %Na_2O in Na_2SiO_3 and NaOH / binder mass

Ms = SiO_2 (activator) / Na_2O

NaOH and Na_2SiO_3 have steadily used activators in AAC. Investigation of employing sole activators such as NaOH or Na_2SiO_3 is detailed [17]. In polymerization, alkaline liquid plays a vital role. The rate of reaction is eminent when alkaline liquid consists of either potassium or sodium silicate. The reaction takes place at an eminent rate when the activator consists of both NaOH and Na_2SiO_3. Addition of Na_2SiO_3 to NaOH solution enhanced the reaction rate between binder and solution. The heat generation and NaOH concentration have a linear relationship and time at which maximum heat of hydration takes place and NaOH concentration has the inverse relationship. The mechanical properties enhanced on adding Na_2SiO_3 to NaOH, beyond the capacity of NaOH alone. Prior studies and researches notify that the Na_2SiO_3/NaOH proportion plays an imperative role in the mechanical properties of AAC. The accelerate mass ratio of Na_2SiO_3 to NaOH liquid illustrates the high compressive strength of AAC [18]. The SiO_2/Na_2O ratio is the key parameter in AAC design. The variations in SiO_2/Na_2O proportion modify the polymerization rate of species dissipate in Al/Si solution [19]. Moreover, it is noted that a high SiO_2/Na_2O (1.6 and 2.0) was utilized to fabricate an AAC, the strength was much higher whilst more alkali activated precursors formed at the maximal strength [20]. Higher rates of dissolvable silica in Alkali-activated systems obstruct dissolution of the ash material because of expanded saturation of ionic silica species and enhance the precipitation of bigger molecular species, resulted in strong gel and upgraded density [21].

The activator comprising both Na_2SiO_3 and NaOH cannot reflect the impact of concentration of Na_+ ion in the binder. Hence it is proposed that use of the activator in terms of the mass proportion of total Na_2O to FA as the main indicator of Na concentration in an activator solution [22]. A comparative methodology was also adopted utilizing an activator in terms of the mass proportion of Na to FA. In activator solution, the mass proportion of Na_2O to FA for the Na_2SiO_3 based activator is further appropriate. Grade of Na_2SiO_3 solution is indicated by SiO_2 to Na_2O making the blend calculation easier [23]. The activator modulus and dosage of Na_2O have a considerable effect on the strength enhancement of AAS mortar [24]. No significant increase in strength takes place above a certain value of Na_2O. However, in mixed NaOH and Na_2SiO_3, there is a contending influence of the activator modulus and Na_2O dosage resulted in optimum value for both the activator modulus (Ms) and Na_2O dosage. It is reported that the optimum dosage of Na_2O ought to be 3.0% – 5.5% Na_2O by slag weight to stop negative effect such as brittleness and efflorescence because of the presence of alkali at a high dose. It is investigated that, the optimum dosage of Na_2O depends on the obligation for high early strength design under the normal curing [25]. Optimum limits for the activator modulus is recommended. Variation in optimum value depends upon the slag type, i.e. for acid slag = 0.75 – 1.25, for neutral slag = 0.90 – 1.30, and for basic slag = 1.00 – 1.50. Comparative conclusions drawn from previous research is that the activator modulus between 0.60 – 1.50 is having high ultimate strength as compared to traditional [26].

III. MECHANISM

Alkali activation is a geosynthesis process integration of minerals through a chemical reaction.
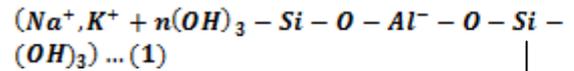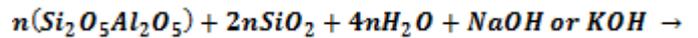
The exposure of aluminosilicate materials to high alkaline conditions develop the Alkali activation process, outlined by 2 to 3-dimensional Si-O-Al structure [27]. These cementitious products offer ceramic and zeolitic properties generally omitted in traditional cement material.

These are wrought from initial pozzolanic activation to final microstructure through diverse miscellaneous reaction process. The assistance of utilizing pozzolana for agglomeration is that these have an affinity to be environmental-friendly, economical, more absorbent of liquids and extremely durable product [28]. The significant procedure embrace a breakdown of aluminosilicate species in an extremely alkaline nature, polymerization of dispersing minerals into a short structural gel, precipitation of produced reaction products resembling natural zeolites and solidify the matrix by surplus water prohibition and development of crystalline structures.

The former phase is breaking of covalent bonds Si–O–Si and Al–O–Si, takes place as pH raise in an alkaline solution, and distorted in the colloidal phase. The next phase is the accumulation of destroyed products, which proceed mutually to fabricate a coagulated structure, and the third phase is the instigation of a compact structure [29]. The first approach of alkali activation is the AAS that is (Si + Ca) utilizing mild alkaline solution, CSH is the hydration products [29]. The second system is the AAF that is (Si + Al), with normal to elevated alkaline solutions. The activation of FA gives rise to the formation of amorphous polymer like a zeolite.
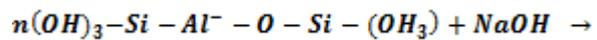
It is an exothermic procedure, in which the breaking of covalent bonds Si–O–Si and Al–O–Al takes place. The products generated by the FA demolition begin to accumulate and finally a condensation of the formed structure in a roughly ordered structure with excessive mechanical strength. It is embedded that the nucleation mechanism includes the ordering of the water molecules by the alkali cations [30]. The higher dimension cations are less suitable than lower dimension cations. However, higher condensation levels have been observed in less ordered systems, it can be the case with a high percentage of water and fewer cations to order it, resulting in a higher condensation structure. Heat evolution analysis are done using NaOH alkali-activated fly ash (AAF), several phase peaks are identified. The first peak is because of the FA dissolution, which is followed by an induction period with a low heat release and, finally, a third exothermic peak interrelated to the final structure formation and influenced by the alkaline activator concentration [31]. Analysis of heat release in AAS is analyzed and observed that the process of hydration was affected by the silica modulus (Ms) and sodium content. The higher sodium content and silica modulus were related to higher hydration levels. The process begins with a destruction of the slag bonds Ca–O, Mg–O, Si–O–Si, Al–O–Al and Al–O–Si, connected to the early peaks, and the second peaks occur due to the formation of the layer Si–Al all over the surface of slag grains and, finally the hydration product is formed [32]. The principal difference between the OPC binders and the alkali-activated binder (AAB) is that it utilizes water with an underlying neutral pH that gradually turns alkaline as the hydration process endure a series of non-hydrated particles and several kinds of crystalline CSH gel. In the previous case, strong alkali solutions are required to initiate the disintegration process. In order to attain good chemical and physical properties in the final product, it is essential to add soluble

silica (Na_2SiO_3) but, as the initial pH is high, that hinder the coagulation and polymerization of the silicate. If the pH turns out to be under 14 due to the disintegration of the prime materials, condensation occurs rapidly. Then a set of reactions of polysialatization, coagulation, colloid developed and solidifying occurs in a final product of undissolved aluminosilicate species in an amorphous aluminosilicate structure [33]. Chemical reactions of schematic formation of AAC is specified in equaion1&2 below.
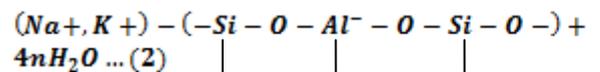
$$n(Si_2O_5Al_2O_5) + 2nSiO_2 + 4nH_2O + NaOH \ or \ KOH \ \rightarrow$$

$$(Na^+, K^+ + n(OH)_3 - Si - O - Al^- - O - Si - (OH)_3) \dots (1)$$

$$(OH)_2$$

Alkali-activated Precursor

$$n(OH)_3 - Si - Al^- - O - Si - (OH_3) + NaOH \ \rightarrow$$

$$(OH)_2$$

$$(Na+, K+) - (-Si - O - Al^- - O - Si - O -) + 4nH_2O \dots (2)$$

$$O \qquad O \qquad O$$

Backbone of alkali activator

Schematic formation of Alkali activated concrete [32]

The geopolymerization is a three-phase technique: formation of a gel by the dissolution of kaolin and feldspar, condensation of gel with the polymerization of Al and Si in three-dimensional structures. The water acts as a reagent during the process of geopolymerization and also as a reaction process. The dissolution phase of Al-Si uses water, but the polymerization releases water [34]. A dissolution procedure of Si and Al emerge when fly ash and alkaline solution are blended mutually. It is observed that on expanding SiO_2/Al_2O_3 proportion diminishes the underlying rate of reaction [35].

IV. FRESH AND HARDENED PROPERTIES OF ALKALI ACTIVATED CONCRETE.

A Workability

The workability of AAC is categorized based on the condition of compaction. The workability of AAC is lesser than OPC concrete because the presence of Na_2SiO_3 in AAC emit a sticky characteristic. AAC can be compacted well on the vibrating table for relatively low slump value. AAC achieving a slump value of 90 mm and more, it is deemed as enormous workable concrete. AAC achieving a slump values between 50 mm and 89 mm is classified as medium workability,

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206

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while AAC achieving a slump value below 50mm is considered as low workability due to the considerable vibration of compaction. [12, 14, 25] The AAF concrete gives good workability. The degree of workability diminished as the replacement of FA and slag increased. The Na_2SiO_3 powder is used to activate either Fly Ash or GGBS, the W/b ratio of 0.5 is used. It is investigated that AAS concrete had lower workability than AAF concrete.

It is reported that on elevating the slag content the flow value diminish. When replacement of slag increased from 10% to 30% the flow value decreased from 137.5% to 123.5%, which indicates that on enhancing the slag content of the mixture would increase the degree of viscosity of AASF pastes and thus the workability is diminished. When 120% of flow value and over is conquer, the AASF pastes can compact well on a vibrating table. Thus, all the pastes of AASF can be considered as highly workable and can fulfil the requirement of workability. [36]

B Compressive Strength

In most structural applications, concrete is utilized fundamentally to endure compressive stresses. Therefore, concrete making properties of a diverse component of the blend are typically measured in terms of the compressive strength. Strength is additionally utilized as a qualitative estimate for different hardened properties of concrete. It is the most essential property of AAC which is effected by fineness and the source materials, activator type and its dose, the Alkaline liquid to binder proportion, the type of curing either ambient curing or elevated temperature curing etc. [14,23-27, 35].

Alkali-activated slag concrete

AAC always indicates comparatively rapid high strength development more than 100MPa. It can accomplish 60MPa of compressive strength in one year [25]. The AAS concrete has high early strength due to the high rate of the hydration reactions at raised pH, which provide early high strength. It also exhibits a homogenous and dense interface transition zone. The interface transition zone and binders have negligible strength difference. [26]. Rapid high strength is developed by heat cured alkali-activated slag concrete (i.e., l day strength) as compared to the ambient curing temperature of AAS concrete [27]. The later compressive strength of elevated temperature-cured concrete was reduced, which interrelated with the inhomogeneity in the microstructure of the matrix because the reaction rate was faster than dispersion. In AAS concrete the compressive strength was kept on increasing until 400 days, which is subjected to bath curing and the sealed AAS concrete gained a small amount of strength after 91 days [28]. The AAS concrete with ambient curing exhibited the strength retrogression because of the micro cracks in the matrix. The impact of an activator has not been deliberately examined on the compressive strength of AAS concrete. The strength increased on expanding the dosage of NA_2O of AAS concrete [29]. On comparing the experiment outcome, liquid Na_2SiO_3 gives higher early strength than powdered Na_2SiO_3 [30, 31].
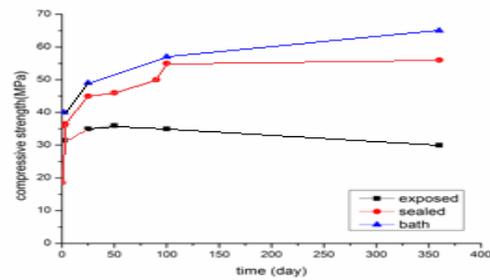

Fig.1. Effect of Curing Condition on Compressive Strength of Alkali Activated Slag Concrete [28]
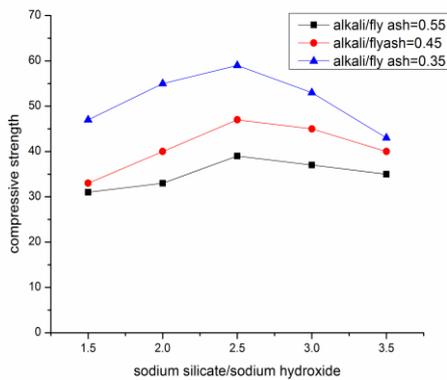
Alkali-activated fly ash concrete

AAF concrete entail high temperature curing to enhance its early strength [32]. Since FA has elevated activation energy. As revealed in Fig (2a), research has found that if the mass proportion of liquid/binder is intensified, the strength of AAF concrete is diminished [33, 34]. The water included is the water in $Na_2SiO_3$and NaOH solutions and the solids are the totals of FA, solid in Na_2SiO_3 and NaOH. The result was identical to the impact of W/C proportion on strength of Ordinary Portland Cement Concrete, these binders have a discrete chemical reaction. It is depicted in Fig (5c) that strength increased on increasing the temperature of curing from 30^0C to 90^0C [35]. On increasing the temperature of curing from 75^0C to 90^0C the strength gain became insignificant. The increase in compressive strength is significant up to 100^0C [36]. Longer curing period results in advanced compressive strength when the curing period is exceeded to 48 hrs the compressive strength became less significant [37], as depicted in Fig. (2b), high molarity of NaOH exhibit higher strength [38] because the high pH causes an increase in breaking of the glassy chain at the fly ash surface of fly ash and upgrade Si and Al reaction to form a gel which gives structural strength. The ideal concentration of NaOH solution, as depicted in Fig.(2b), after 10M (ideal concentration) the compressive strength decreased because the surplus OH- in the matrix obstruct the condensation of silicate species [38]. From Fig.(2a) it can be noticed that strength increased with the mass ratio of Na_2SiO_3 to NaOH solution until the ratio reached 2.5, and then it reduces. When the mass proportion increased from 0.4 to 2.5 the strength increased [39].
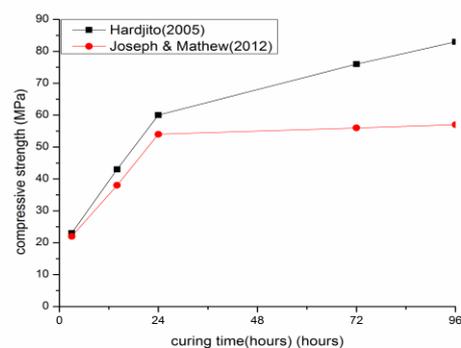
a Mass ratio of Na_2SiO_3 to NaOH solution [33, 34]
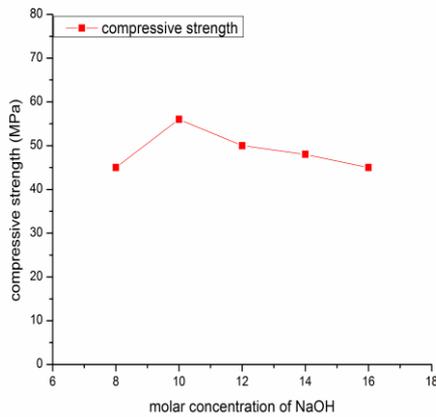
b Molar concentration of NaOH [38]

3a) Replacement ratio of slag [41]

c. Curing Period [35]

Fig.2 Various Parametric impacts on compressive strength of alkali-activated fly ash concrete

3b) W/S ratio [43]

Fig. 3 Parametric effect on compressive strength of alkali-activated slag and fly ash concrete

Alkali-activated slag and fly ash concrete

The blend of high-calcium with low calcium, mix of FA and Slag, can be cured at ambient temperature and augment the early strength. These investigations revealed that on expanding the extent of slag in AASF concrete compressive strength is increased [40].
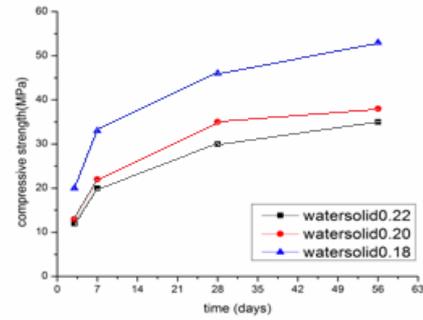
When the replacement ratio of slag for fly ash is extended from 10% to 15% the 28 days strength is enhanced from 15.5 MPa to 23 MPa as revealed in fig.(3a) [41].

With the addition of slag, the strength is increased into the matrix which develop the phases of C-S-H gel, subsequently the water/solid proportion had a considerable impact on the strength of AASF concrete [42].
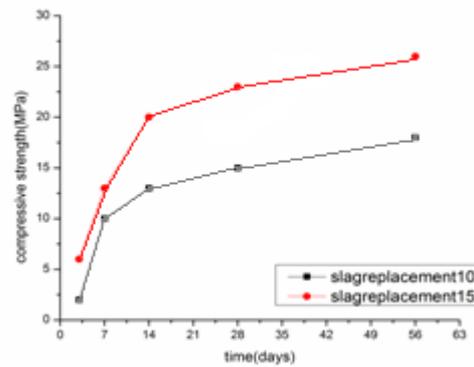
As depicted in fig (3b) the strength of the concrete is diminished on enhancing the proportion of water/solid from 0.18 to 0.22[43]. In AASF concrete the strength is developed steadily when subjected to room temperature curing.

The specimen with high-temperature curing attain early high strength but irrelevant strength gain with time [44].

Specimen prepared using 50/50 fly ash/slag blends gained 45 MPa in 28 days while reaching 65 MPa in 90 days. It is reported that 28-day compressive strength of around 51 MPa for alkali-activated systems with 80/20 FA/Slag at ambient curing. [45].

C Tensile Strength

It is only a part of its compressive strength and the tension failure of concrete is fragile. The tensile strength of OPCC has been commonly investigated and can be appropriately calculated by performing the tensile strength test or the compressive strength test, by using an equation (iii) and (iv) [45].

$$fct = 0.56\sqrt{f'c}………………………(iii)$$

$$fct = (1/3)\ (fc)\ 2/3\ fc < 50MPa………………. (iv)$$

Where fct is the tensile strength, f'c is specified compressive strength and f'c is the average compressive strength.

Alkali-activated slag concrete

The splitting tensile strength of AAS concrete is examined using Na_2SiO_3 and NaOH, it is initiate that splitting tensile strength fit well with ACI building code 318 anticipation [46] In addition, the splitting tensile strength assess with $Ca(OH)_2$ as an activator and diverse Al/bi proportion and detailed that AAS concrete has superior splitting tensile strength than those anticipated by the Eurocode 2, concurred well with ACI building code 318 [47].

Alkali-activated fly ash concrete

A number of experiments executed for splitting tensile strength and their outcome fit well with assessment of Eurocode2.

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208

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The tensile strength obtained by Sarker [48] was superior than achieved by Ryu et al. [49]. The conditions of curing were similar (60^0C, 24 h). Different Alkaline/binder proportion and alkali concentration adopted in these two studies were attributed to the variation in splitting tensile strength. In Sarker's study, the liquid/binder proportion was 0.56, though Ryu et al. used a proportion of less than 0.30. The lower alkali/binder proportion resulted in higher splitting tensile strength because of the less porous matrix, which made it denser and progressively homogenous. Sarker utilized NaOH of 9 M and Ryu et al. utilized NaOH of 14 M.

Alkali-activated slag-fly ash concrete

It is reported that most of the splitting tensile strength of AASF concrete measured were lower than anticipated by ACI building code 318 Sofi et al. [50]. Similarly, it was reported that splitting tensile strength had a linear relationship with the square root of the compressive strength in AASF concrete [51]. The tensile strength of the AAFS concrete using 100% FA and 0% Slag was particularly very low because of low reactivity of FA at ambient temperature. On increasing the amount of slag the tensile strength increased due to C-A-S-H gel formation in AAFS concrete [52]. The tensile strength development of AAFS concrete is associated with FA/slag proportion, concentration of Na_2O, and activator modulus proportion [53].

D Durability properties

Concrete may breakdown when depicted in an aggressive environment. Decays may be classified as physical, resulting from exposure to extreme environmental changes for instance freeze/thaw or fire; chemical, being caused by acid or sulfate attack, water, or the alkali-aggregate reaction; biological, including the presence of bacteria; or structural, i.e., live loads or load cycles. Relevant results published during the past decade on the latest trends on the durability of alkali-activated FA and/or slag focused on their resistance to sulfate attack, CO_2 penetration and drying shrinkage are evaluated in this work. Table 3 is depicted in various recent researches on durability properties.

i. Drying shrinkage

Shrinkage of concrete is the drying of concrete or chemical reformation of the structure. Shrinkage results in internal tensile stresses of concrete which causes cracking and shrinkage warping [68]. Inappropriate curing of AAC can result in high drying shrinkage, because of introduction to drying environment in early stage and high water content [68]. AAC has more resistance to chloride penetration and sulfate attack. Autogenous and drying shrinkage is much higher in AAC [69]. Shrinkage is caused due to the activator type, curing condition and the concentration of alkali and can be reduced by adding fibres and by using shrinkage reducing admixtures [70]

Alkali-activated slag concrete

It is reported that AAS has 10% less shrinkage compared to OPC concrete. Furthermore, it is stated that high water to binder ratio results in high shrinkage of concrete. Use of Na_2SiO_3 solutions at varying SiO_2 and Na_2O composition is investigated and it is concluded that an increase of Na_2SiO_3 in the binder results in higher shrinkage [71]. Furthermore, the same authors stated that autogenous shrinkage is higher in AAS mortar compared to the drying shrinkage. It is observed that on increasing the activator content drying shrinkage increase in slag based concrete [72]. On increasing the activator C-S-H volume is increased which decrease the porosity at later stages. The shrinkage of AAS is higher than OPC [73].

Alkali-activated slag and fly ash concrete

Shrinkage of AASF binder was studied. AAC is prepared using Na_2SiO_3 and 60/40 FA/Slag blend and reported 6000μstrain drying shrinkage after 6 months, it is reported that on increasing the water content the drying shrinkage is increased. Above observation is in line with another study which is mainly caused by an increase of porosity [74]. Drying shrinkage depends on alkali activator type used in the binder. The shrinkage values observed in the above studies were higher than OPC concrete. Addition of a high amount of calcium content results in a significant increase of shrinkage and cracking which ultimately leads to a weaker structure [75]. The drying shrinkage of AAC can change slightly as per the activator and precursor material used. It is reported that increasing the quantity of slag in AASF concrete and mortar the drying shrinkage is increased [76].

ii. Sulphate Resistance

The reaction of sulfate ions, acting as a destructive material, with the aluminate constituent of hardening cement paste is sulphate attack. Water or aggregates contaminated with sulphate causes sulphate attack in concrete. Reactions of such substances, alumina-bearing hydration products, or unhydrated tricalcium aluminate with calcium hydroxide produce compounds like gypsum, ettringite and thaumasite, between cement reaction products and the sulphate ions and causes an expansion in OPC concrete, resulting in an irregular crack pattern. Further penetration of sulfates due to these cracking becomes easier and up to complete disintegration the process is continued. [77]

Author	Activator	Material	Properties Studied
Palacios and Puertas [54]	NaOH and Na_2SiO_3	GGBS	Carbonation
Al-Otaibi [55]	$Ca(OH)_2$ and Na_2SiO_3	GGBS	Chloride penetration resistance, porosity, carbonation
Bernal et al. [56]	NaOH and Na_2SiO_3	GGBS and FA	Carbonation
Shaikh [57]	NaOH and Na_2SiO_3	FA	Chloride penetration, sorptivity and corrosion resistance
Wallah [58]	NaOH and Na_2SiO_3	FA	Drying shrinkage
El-Sayed et al. [59]	NaOH and Na_2SiO_3	GGBS	Sulphate resistance
Allahverdi et al. [60]	NaOH and Na_2SiO_3	GGBS	Drying shrinkage
Kushal and Partha [61]	NaOH and Na_2SiO_3	FA	Porosity, water absorption and sorptivity
Yang et al. [62]	$Ca(OH)_2$ and Na_2SiO_3	GGBS	Shrinkage strain
Miranda et al. [63]	NaOH and Na_2SiO_3	FA	Corrosion resistance
Fernandez-Jimenez et al. [64]	NaOH and Na_2SiO_3	FA	Acid attack and sulphate resistance
Chaparro et al. [65]	NaOH and Na_2SiO_3	GBGS	Corrosion resistance
Thokchom et al. [66]	NaOH and Na_2SiO_3	FA	Acid attack
Beemamol et al. [67]	NaOH	FA	Chloride permeability and shrinkage

Table 3 Recent Researches on Durability properties

Alkali-activated slag concrete

Mechanisms of deterioration of OPC and slag cement paste are different in sulphate attack because of their distinctive phase and chemical composition. Obliteration of C-S-H is an imperative deterioration mechanism when attacked by $MgSO_4$ solution for cement with high slag. It was previously found that obliteration of C-S-H was a major outcome when attacked by $MgSO_4$ solution for sulfate-resistant Portland cement [78]. Gypsum, hydrous silica, brucite, and magnesium silicate hydrate were produced in this reaction [79]. The deterioration of $MgSO_4$ attack is more brutal than Na_2SO_4 attack. Two tests were performed to find the resistance of AAS concrete to sulfate attack, the first test involves the immersion of concrete specimen in 5% magnesium sulphate and the second test involve immersion in 5% sodium sulphate solutions. In the case of Na_2SO_4 solution the strength reduced up to 16% for AAS concrete and up to 26% reduced for OPC concrete. In the case of $MgSO_4$ solution, the strength decrease was 36% for OPC, and 22% for AAS. In sulfate attack, the products of degradation in OPC concrete are Gypsum and Ettringite and the main product of degradation in AAS concrete is gypsum [80]. AAS specimen was immersed in $MgSO_4$ and Na_2SO_4 separately. It is reported that the specimens immersed in MgSO4 have different in sulphate attack because of their distinctive phase and chemical composition. Obliteration of C-S-H is an imperative deterioration mechanism when attacked by $MgSO_4$ solution for cement with high slag. It was previously found that obliteration of C-S-H was a major outcome when attacked by $MgSO_4$ solution for sulfate-resistant Portland cement [78]. Gypsum, hydrous silica, brucite, and magnesium silicate hydrate were produced in this reaction [79]. The deterioration of $MgSO_4$ attack is more brutal than Na_2SO_4 attack. Two tests were performed to find the resistance of AAS concrete to sulfate attack, the first test involves the immersion of concrete specimen in 5% magnesium sulphate and the second test involve immersion in 5% sodium sulphate solutions. In the case of Na_2SO_4 solution the strength reduced up to 16% for AAS concrete and up to 26% reduced for OPC concrete.

In the case of $MgSO_4$ solution, the strength decrease was 36% for OPC, and 22% for AAS. In sulfate attack, the products of degradation in OPC concrete are Gypsum and Ettringite and the main product of degradation in AAS concrete is gypsum [80]. AAS specimen was immersed in $MgSO_4$ and Na_2SO_4separately. It is reported that the specimens immersed in MgSO4 have cracks and the specimens immersed in Na_2SO_4 solution did not have any visible cracks and hence found that AAC performed well compared to OPC concrete [81].

Alkali-activated fly ash concrete

AAF concrete is analyzed and found that it shows better sulphate resistance [82]. An experiment is carried out with (class F) FA and alkali activators exposed to sulfate environment. 3 tests were performed to conclude the resistance of AAM which involved immersion of Na_2SO_4 and $MgSO_4$ and a combined solution of 5% Na_2SO_4 and $MgSO_4$ solution for 5 months. Compressive Strength, change in weight and degradation was investigated. In the Na_2SO_4 solution, fluctuation of strength occurred with strength reduction 18% in the fly ash, Na_2SiO_3 and 65% in the materials prepared with a mixture of NaOH and KOH activators (8M) while 4% strength increase was measured in specimens activated by NaOH (8M). In the $MgSO_4$ solution, 12% and 35% strength increase was measured in FA and FAK specimens, respectively and 24% strength decline was measured in the FASS samples. The least changes in alkali-activated specimens were found in the solution of 5% Na_2SO_4 + 5% $MgSO_4$ [83]. Most significant fluctuations of strength and microstructural changes took place in 5% solution of Na_2SO_4 and $MgSO_4$. In the solution of Na_2SO_4, migration of alkalis from alkali activated specimens into the solution was observed. Diffusion of alkali ions into the solution caused significant stresses and the formation of deep vertical cracks in the specimens prepared a mixture of NaOH and KOH. The $MgSO_4$ solution, Specimens prepared with NaOH were more stable in sulphate solutions than specimens prepared using Na_2SiO_3 or mixture of NaOH and KOH solutions.

Alkali-activated slag and fly ash concrete

AASF concrete has better performance with respect to sulphate attack. It is also investigated that AASF blends have better resistance to sulphate attack [84]. The samples were immersed in the $MgSO_4$ and Na_2SO_4 solution for around three months. It is found that magnesium sulphate results in a more aggressive environment compared to Na_2SO_4. It is concluded that $MgSO_4$ can attack, phases like C-S-H, C-A-S-H and N-A-S-H and deteriorate the mechanical properties of binders.

iii. Carbonation

A chemical reaction between the hydration product of a matrix and the CO_2 from the atmosphere is carbonation. In AAC the pH is controlled by the pore solution and in OPC concrete pH is controlled by portlandite Ca(OH) $_2$. The carbonation is 2 phase system with these binders: the first phase is carbonation of the pore solution prompting a decrease on pH and precipitation of Na/rich carbonates then the decalcification of gel and deterioration of structure [85]. It is prohibited by reactivity and diffusivity of CO_2. The interconnectivity of the pore structure and the carbonation exposure conditions is Diffusivity while reactivity is allied to concentration, binder type, the gel development and pore solution chemistry [86]. CO_2 concentration plays a vital role

for both reactivity and diffusivity, influencing the rate of carbonation during material exposure.

Alkali Activated slag

The resistance for the carbonation in AAS based concrete and OPC binder is studied. AAS has less resistance to carbonation. The compressive strength of the concrete decays when exposed to carbonating environment. AAS has comparably lower Ca content (compare to OPC) and decomposition of $CaCO_3$ is lower leading to higher porosity resulting in high CO_2 dispersion into the binder. The carbonation depths in AAS concrete and mortars in comparison with OPC based specimens are studied [87]. At longer time of exposure to carbonation, the compressive strength increased in both the binders due to the precipitation of carbonates which resulted in the refined pore structure of specimens. In this study, the used relative humidity (90%) and CO_2 concentration (100%) are higher than normally used values which make it difficult to compare with other results or formulate any relationship. Exposure of AAS concrete specimen to the natural carbonation for 7 years was recently studied. It was observed that different activation conditions lead to different carbonation rates [88].

Alkali Activated fly ash

The effect of internal carbonates in fly ash based systems on network formation and mechanical properties are explored. Sodium bicarbonate is blended with the source materials. Faster reaction with $NaHCO_3$ was observed and stated that CO_2 formation due to the decomposition of sodium carbonate help leaching of Si and Al ions from precursor leading to higher reaction rate. However, the addition of $NaHCO_3$ more than 5% affects negatively decaying mechanical properties of alkali-activated binders [89]. FA based alkali-activated binders are used and the samples were exposed to 5% CO_2 environment. Higher reduction of pH in alkali-activated samples prepared using FA containing a significant level of CaO (12.9%) compared to others with lower CaO content. The researchers also measured splitting tensile strength in both carbonated samples and control samples. After 450 days of CO_2 exposure, alkali-activated samples with high CaO level reduced the strength by about 35% compared to 3% and 17% strength reduction observed in other low CaO based AAC. Moreover, they observed carbonated high calcium fly ash based geopolymer had total porosity about 28% and this value was double the value that obtained for low calcium fly ash based systems [90]. The performance of AAS concrete and OPC concrete with binder contents of 300, 400 and 500 kg/m^3 is compared and acquire that, regardless of the binder content, the activated slag concrete performed similar or better than the corresponding OPC concrete with respect to strength, water absorption, permeability and porosity. However, the carbonation resistance of the activated slag concrete was inferior to the OPC concrete [91]. The pore solution chemistry of alkali-activated binders is investigated and found distinct behaviors under normal carbonation and accelerated carbonation. It is found that under normal exposure to the atmosphere, the pore solution develops sodium carbonate, whereas under accelerated curing sodium bicarbonate is developed rapidly.

E Hydration Products

The reaction products of AAS and AAF are not similar. The reaction products of AASF are different but their synthesis conditions are the same [92]. As far as the final hydration products are concerned, Researchers have stated distinct hydration product for various prime materials.

Alkali Activated slag

Calcium Silicate Hydrate (C-S-H) is the hydration product of AAS, similar to OPC. The major component of hardened AAS pastes is hydrated calcium silicate (C-S-H). The C-S-H gel in AAS is the ratio Ca/Si is un-hydrated slag, lower than Ca/Si in OPC. CSH and xonotlite is formed in AAS [93]. The hydration product is CSH gel, lower C/S ratio is because of the high pH solutions, favouring lower Ca concentrations and higher Si concentrations. Formation of hydrotalcite is reported when the alkaline solution is composed of NaOH or in combination with Na_2SiO_3. Zeolite or the mica with alkali cations is omitted in AAS [94]. The sodium based hydrated compounds are not found (zeolites) but confirmed that sodium was inside the CSH gel, which can be confirmed by the low C/S ratio, replacement of the ion Na_+ by Ca_{2+} [95]. Many authors investigated that in CSH phase the amount of sodium increase with a reduction in C/S proportion [96]. NCSH is the hydration product when the extent of sodium is high. New crystalline phases are not found in fly ash. When Na_2SiO_3 and NaOH are used mutually as an activator the ratio Si/Al doubles and ratio Na/Al remains the same. The following molar ratios are reported for the hydration product Si/Al = 2.8 and Na/ Al = 0.46 for NaOH and Si/ Al = 5.2 and Na/Al = 0.46 for NaOH mixed with Na_2SiO_3 [97]. Activation of slag with red mud is investigated, in which CSH is the reaction products with Ca/Si (0.8–1.2). Zeolite and portlandite are not detected [98]. Activation of slag with NaOH is studied, presence of hydrotalcite, calcite and CSH is reported by XRD analysis [99]. The authors have noticed that activation of slag with NaOH, leads to the higher hydration products with the molar ratio Al/Si than the activator NaOH mixed with Na_2SiO_3. C-A-S-H gel is depicted in fig 7a.

Alkali Activated fly ash

The hydration product of low-calcium FA is N-A-S-H gel, with a 3-dimensional structure. Hydroxisodalite and herschlite are the hydration products in AAF [100]. In the XRD analysis, the crystalline phases are not distorted by the alkali activation reaction.

The zeolitic phases found in XRD analysis are hydroxysodalite and herschelite. In SEM analysis it is found that, prior to the activation the particles of fly ash are spheres of miscellaneous sizes with crystals of mullite and iron and after the activation, it showed some unreacted spheres and aluminosilicate gel with the molar proportion of Si/ Al: 1.6–1.8 and Na/Al: 0.46–0.68 for mortars activated with NaOH. The product formed is more compacted when NaOH and Na_2SiO_3 are used together, with molar ratios (Si/Al: 2.7) and (Na/Al: 1.5) [101].

The AAF utilizing NaOH and Na_2SiO_3, in XRD analysis only the characteristics peaks of the original fly ashes were identified and in the SEM analysis, a large number of crystals were identified due to unreacted Na_2SiO_3, which had crystallized [102]. AAF utilizing NaOH and Na_2SiO_3.

The formation of zeolites like analcime and hydroxysodalite with high molar proportion, SiO_2/Al_2O_3 (4.5– 5) is reported [103].

Alkali-activated slag and fly ash concrete

The hydration product of 50% FA and 50% Slag with 10M NaOH is hydrated calcium silicate of the CSH gel with high tetrahedrically coordinated Al amounts and interlayer Na ions in structure. Hydrated alkaline alumino-silicates were not formed with 3-dimensional structure characteristics of the alkaline activation of FA [104]. The hydration product of fly ash and slag is CSH gel. Formation of hydrotalcite, pirssonite and calcite is detected and alkaline aluminosilicate is not found.

F Curing Temperature

The production of AAC can be successfully attained by appropriate curing time and temperatures. The alkali activation reaction can be achieved by providing external heat curing to elevate the alkaline reactivity of source material. In AAC elevated curing temperature gives high strength [105]. The compressive strength is increased on increasing the curing time in alkali-activated systems, but due to the product densification and alkaline saturation, the gain occurred at a slow rate as the time increased [106]. Various investigations reported that the polymerization process is enhanced by long curing which results in higher compressive strength [107]. AAC has miscellaneous advantages, such as after curing at 60^0 -75^0C for 24 h, a higher mechanical strength of 62–66 MPa is achieved [108], good resistance to elevated temperature and chemical resistance to sulphates [109].

Alkali Activated fly ash

Reactivity of fly ash is lower at ambient temperature, therefore, it entail elevated temperature curing, above 60^0C to get elevated mechanical properties [110]. High temperature curing is a critical factor. Amend in compressive strength versus curing epoch at discrete temperatures is investigated and it is reported that when the curing temperature range between 50 to 80^0C, the strength is enhanced by 100% [111]. The research on strength of alkali-activated mortar cured at 80, 70 and 65^0C temperature for 24 h and accounted that on enhancing the temperature of curing the early age strength is enhanced. The outcome reveals that temperature for curing plays a vital role in the alkali activation process. However, high-temperature curing opposes the use of an alkali-activated binder, it expands more energy as compare to the ambient-temperature curing. The process of heat curing may diminish the scale of applicability in the industrial field. The understanding of ambient cured AAC is significant for several commercial utilization.

Alkali Activated slag and fly ash

Studies on expanding Slag to FA to develop the strength of AAC under ambient curing are considerate. Various properties of AASF cured under room temperature is studied and tested assessing the flow value, setting time, compressive strength, strength development with time, modulus of elasticity, splitting tensile strength and porosity and in what proportion the slag added to AASF concrete enhance the mechanical properties is also studied [112].

V. PRACTICAL APPLICATION

AAM has a significant ability for consumption not only in the building industry.

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212

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Alkali-Activated Slag/ Fly Ash Concrete: Mechanism, Properties, Hydration Product and Curing Temperature

Their pervasive utilization in building practice prohibits the need for considerable technological discipline.

During the alkaline activation process, the cessation of which ultimately leads to significant fluctuations in the values of monitored parameters. The broad application of AAC is also obstructed because of the absence of a standard for testing, using liquid activator and the moderate approach. Builders are anxious about utilizing these AAM. Because of the prerequisite of sustainable advancement and conservation of mineral resources. A growth of products in the market based on alkali-activated systems is expected slightly in a brief timeframe. In1999-2000, researchers in Ukraine inspected few structures developed using AAS cement, among which it is worth featuring diverse structure, for instance, silage pits, railway embankments, structures up to 15th floor etc. In such cases, AASC was effective and demolish the Portland cement concrete performance utilized in a similar region. Diverse applications were urbanized by Australian and Spanish scientists using AAF concrete: channeling pipes and railroad ties.

VI. RESULT & CONCLUSIONS

The paper presented the concept and facts in the above section tend to put before the vibrant issue of the exact mechanism and reactions of alkali-activated binders which are not completely achieved. However, most of the authors observe that alkali activation is mere a 3 step process - dissolution, orientation and hardening. The hydration product for a system (Si + Ca) is CSH gel and the reaction products for a system (Si + Al) are zeolite-like polymers.

The noticeable benefits of using AASF concrete are a worthy decline in the environmental impacts resulting from cement production and reduction in stockpiling of common wastes.

The degree of reaction is high for Na_2SiO_3 and NaOH both, in contrast to the utilization of only NaOH. Liquid Na_2SiO_3 imply high early strength as compare to powered Na_2SiO_3.

AAC has relegate workability than OPC since the persistence of Na_2SiO_3 brings a sticky characteristic, the workability essentially depending on the extent of slag added conversely. AAS has reduced workability than AAF. Auxiliary factors influencing the workability are the molarity of NaOH, reduced AL/B. On expanding the quantity of slag the flow value diminished in AAC. AAS has brisk and excessive early compressive strength development, whereas AAF concrete necessitates elevated temperature curing to gain early age strength. AASF concrete accomplishes prominent early age compressive strength at ambient curing temperature. The tensile strength of AASF concrete is notably advanced than OPC concrete with equivalent compressive strength. The splitting tensile strength of AAC is associated with subsequent compressive strength for Portland cement concrete by a power function of comparable form to those formerly anticipated for OPC concrete. AAF paste appearances elevated heat resistance as compared to OPC paste. The AAF paste exposed to these elevated heat the strength will increase if the early compressive strength is low. The strength performance of AAS concrete is equivalent to the OPC in a temperature range of 400 - 800^{0}C. The strength loss is mainly accredited to thermal incompatibility. A requisite to elaborate the mix design for AAC and associate it to properties by large variations in properties as a dispute in this manuscript. Sustainable development in concrete structures is needed. It is concluded that this environmentally friendly concrete could be an appropriate alternative for ordinary Portland cement concretes.

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