Slag–Fly Ash–Glass Powder-Based Alkali-Activated Concrete—A Critical Review

Shriram Marathe, I. R. Mithanthaya, and Siddhivinayaka Hegde

Abstract This paper presents some key research findings in the field of "alkali-activated concretes" (AAC) incorporating ingredients which are industrial by products like slag, fly-ash, etc., as a binding ingredient. The paper gives the brief outlook of the current development in the field alkali-activated materials for concrete applications starting from the historical developments. The literature review reveals that, the alkali-activated concretes proven to be feasible (sustainable) and satisfactory substitute for conventional Portland cement-based cementitious substances. In addition to the conventional ingredients, the use of powdered waste glass has shown an improved engineering performance in concrete production as per the research outputs from many potential researchers. The paper also presents the possibility of a wide scope for the research as a research gap in the field of AAC and their applications.

Keywords Alkali activation · Fly-ash · Glass powder · Slag · Na_2O dosage · Strength

1 Introduction

The environmental aspects involved in the manufacturing and use of "ordinary Portland cement" ("OPC") is a challenge and lot of research is going on in this regard. OPC has been a suitable binder for structural applications for more than 150 years, but not without drawbacks. Cement production consumes massive quantities of natural elements. Again it is energy intensive with high energy consumption at 100–150 kW per ton of cement produced. On the other hand, sulfur dioxide emission is also in a high rate, depending upon the kind of the fuel used for its manufacture. It is becoming increasingly capital intensive to erect new cement plants to meet a huge demands for housing and infrastructural needs. Finally, many structures of concrete have showed early distress and problems, which have an unfavorable consequence

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S. Marathe · I. R. Mithanthaya · S. Hegde (✉)
Department of Civil Engineering, NMAM Institute of Technology, Nitte, Karkala, India

I. R. Mithanthaya
e-mail: irmithanthaya@nitte.edu.in

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on the resource output of the industry. The call for the day is, hence “Sustainable Development” which demands the new concrete technology which uses minimum natural resource, energy and generates “carbon dioxide,” without compromising on strengths and robustness behaviors [1–3].

Alkali-activated cements are considered as new generation binders, which have a potential to give a sustainable replacement to OPC. There is an urge to limit the usage of the OPC in infrastructural development due to its adverse environmental issues and its structural limitations [4]. Because of low internal energy and low carbon dioxide emission associated with production of alkali-activated binder (AAB)-based mixtures compared to conventional Portland Cement Concretes, this novel material may be considered to be more eco-friendly [3, 5].

These AABs have been extensively addressed and encouraged as a constituent of the recent and forthcoming toolkit of “sustainable cementing binder systems.” “Alkali activation” is the process of reaction of a solid aluminosilicate (“precursor”) under alkaline conditions (induced by the “alkali activator”), to generate a toughened binder which is based on an amalgamation of “hydrous alkali–aluminosilicate” and/or “alkali–alkali-earth–aluminosilicate” phases [6].

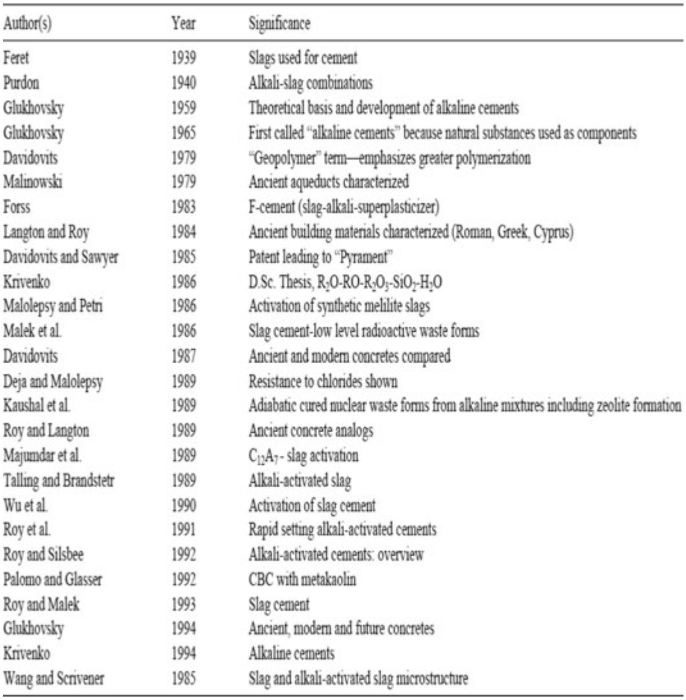
This chapter gives an overview of the various key literatures available in the field of alkali activation and geopolymerization techniques of concrete production. Also, few essential background studies for this research work—including few standard IS codal provisions, literatures related to paver and masonry blocks, IRC codal provisions, and also few key literatures on FE-based software utilized in the present research exploration.

2 Brief Historical Overview of Alkali-Activated Materials

The initial works in alkali-activated systems started from the year 1930. Way back in 1930, for the first time Kuhl has invented the hardening behavior of slag in the incidence of an alkali (caustic potash, i.e., potassium hydroxide). Then in 1937, Chassevent had measured the rate of reactivity of slag using “caustic potash and soda” solution. In 1940, Purdon carried out laboratory study on clinker-free cements which consisted slag as the binder and caustic alkalis formed by a base and an alkaline salt. In 1959, a researcher from Russia, Glukhovsky discovered a new group of binders which included both of low calcium or free from calcium, “aluminosilicate” and alkali metal solutions which were termed “soil cements” and the respective concretes termed as “soil silicates.” Further, Glukhovsky was the first author to investigate the cements used in prehistoric Egyptian and Roman constructions. He stated these structural creations were made of “aluminosilicate calcium hydrates,” which are alike to the constituents of “Portland cement” and also of “crystalline phases of analcite,” a rock which is natural that would elaborate the binders durability [4]. He (Glukhovsky) also divided the binders into two groups based on the mineral constituents of preliminary materials; the first group of binders were called as “alkaline binding systems” and the second group as “alkaline-earth–alkali binding systems.” The study by Glukhovsky was considered as a significant step stone for the further researches in the field of “alkali-activated cements,” following which the development of “alkali-activated concretes” [7]. In the year 1979, Davidovits developed an innovative faction of binders produced by combining sintering kaolinite products, “limestone” or “dolomite” as the “aluminosilicate” ingredients, and called those binders as “geopolymers.” The term “geopolymer” was given to such binders because of the presence of a polymeric structure. He proposed that any source, either from natural geological source or an industrial waste material such as rice husk ash and fly-ash, that are rich in alumina and silica can be effectively activated by means of highly alkaline liquid solutions [8]. The classification of alkali-activated binders based on their chemical configuration and characterization of hydration products was done by Krivenko in 1994 [7]. The “alkaline aluminosilicate systems,” “(R–A–S–H, where R=Na or K)” were called “geocements,” whose formation process is similar to process of natural zeolites and “alkaline–alkaline-earth systems” (R–C–A–S–H) in which the products of hydration included the formation of “calcium silicate hydrates,” i.e., “C–S–H” with low “Ca/Si” ratio. Further, it has been suggested by few researchers that the use of the term “geopolymer” in alkali-activated cementitious materials only if there is a presence of a zeolite-like phase with amorphous to semi-crystalline characteristics [9]. The chief historic developments of alkali-activated binders are abridged by Roy [10] as shown in Fig. 1. The field of “alkali-activated cements” was witnessed further contributions from many researchers [1, 2, 4, 11–13].

3 Source Materials, Alkaline Activator, and Mechanical Properties

The raw constituents used for the making of AABs may be classified as pozzolanic or latent hydraulic materials [7]. Pozzalans are the materials rich in silica and alumina, possess diminutive or no cementitious behavior by themselves, but in finely divided state and in the occurrence of moistness, experience chemical reaction with calcium hydroxides at ambient temperature to form composites having cementing behavior [14, 15]. Low calcium “(class F) fly-ash” and “silica fume” are the commonly used “pozzolanic materials.” Latent hydraulic materials are finely divided materials similar to pozzolans, which contain sufficient amount of calcium to form complexes with binding property after reacting with water. In general, the latent hydraulic materials cannot undergo direct setting and hardening after reacting with water in normal conditions [14]. The hardening energy is quiescent and requires an “activator” such as “calcium hydroxide” or other alkaline compound that is strong to release the cementitious properties. The “latent hydraulic materials” (LHM) when combined with OPC and water get activated under the influence of “calcium hydroxide” which is generated during the hydration reaction of cement. GGBS is one of the examples of LHM, which have a good potential to be used in cement manufacturing. Both the pozzolans and latent hydraulic materials may be naturally occurring in nature or may



Author(s)	Year	Significance
Feret	1939	Slags used for cement
Purdon	1940	Alkali-slag combinations
Glukhovsky	1959	Theoretical basis and development of alkaline cements
Glukhovsky	1965	First called "alkaline cements" because natural substances used as components
Davidovits	1979	"Geopolymer" term—emphasizes greater polymerization
Malinowski	1979	Ancient aqueducts characterized
Forss	1983	F-cement (slag-alkali-superplasticizer)
Langton and Roy	1984	Ancient building materials characterized (Roman, Greek, Cyprus)
Davidovits and Sawyer	1985	Patent leading to "Pyrament"
Krivenko	1986	D.Sc. Thesis, R_2O-RO-R_2O_3-SiO_2-H_2O
Malolepsy and Petri	1986	Activation of synthetic melilite slags
Malek et al.	1986	Slag cement-low level radioactive waste forms
Davidovits	1987	Ancient and modern concretes compared
Deja and Malolepsy	1989	Resistance to chlorides shown
Kaushal et al.	1989	Adiabatic cured nuclear waste forms from alkaline mixtures including zeolite formation
Roy and Langton	1989	Ancient concrete analogs
Majumdar et al.	1989	$C_{12}A_7$ - slag activation
Talling and Brandstetr	1989	Alkali-activated slag
Wu et al.	1990	Activation of slag cement
Roy et al.	1991	Rapid setting alkali-activated cements
Roy and Silsbee	1992	Alkali-activated cements: overview
Palomo and Glasser	1992	CBC with metakaolin
Roy and Malek	1993	Slag cement
Glukhovsky	1994	Ancient, modern and future concretes
Krivenko	1994	Alkaline cements
Wang and Scrivener	1985	Slag and alkali-activated slag microstructure

Fig. 1 Historical development of AAC systems and alkaline cements

be produced artificially from industrial processes. Davidovits discovered that during the production of geopolymeric binders, the addition of GGBS, which is a "latent hydraulic" cementitious end product, that quickens the setting time and improves compressive and flexural strengths [8].

Many researchers reported [16] the use of mineral admixtures in the GGBS-based alkali-activated concrete to obtain the enhanced concrete performance. The silica-rich materials such as powdered waste glass, silica fume, alumina-rich red mud, natural pozzolan, calcium-rich powdered lime were utilized to enhance the engineering performance. The study by Rostami and Behfarnia revealed the enhanced 90 days compressive strength by 32% by the use of 15% substitution of GGBS by silica fume. It also enhanced the resistance to chloride penetration, reduced voids, and reduced water captivation potential of the concrete [17].

Numerous researchers have used "fly-ash" as source substance in the making of "geopolymer" concrete. Since the fly-ash is available as an abundant waste material obtained mainly from coal based on the thermal power plants; it is considered as most used binding material in production of geopolymer concrete. The yearly production of "fly-ash" is assessed to be approximately 780 million tonnes. It mainly consists of amorphous alumina and silica along with a favorable particle size and shape which has proved to improve the workability property of geopolymer mix production [1, 18]. Many studies were also carried out by considering other waste materials which have pozzolanic properties in the production of geopolymer concrete. However, except GGBS and fly-ash, other industrial left-over materials such as "palm oil fuel ash," "rise husk ash (RHA)," "biomass ash," red mud (i.e., bauxite residue), heavy metal containing wastes were also used in geopolymer binder production in concrete applications [18].

The source materials for alkali-activated binders need to be activated using strong alkalis in order to form the resulting binding material. "caustic alkalis" or "alkaline salts" are the most widely used "alkaline activators." The alkaline activators generally consist of mixtures of silicates and hydroxides of alkali. "sodium silicate" (Na_2SiO_3), "sodium hydroxide" (NaOH), "sodium carbonate" (Na_2CO_3) or mixture of "sodium–potassium hydroxide" (NaOH, KOH) with "sodium silicate–potassium silicate," or any other combinations are the most widely used "alkaline activators." A combination of "sodium hydroxide" with liquid sodium silicate has been agreed to provide the best strength performance for activation of alkali-activated binders [19] The strength of "AABs" is governed by the alkaline activator type, activator modulus, and dosage of alkaline activator [20]. The "activator modulus" (Ms) is defined as the ratio of the mass ratio of "SiO_2" to "Na_2O" components present in the alkaline activator, while the dosage (usually referred as %Na_2O) is the total sum of the mass of "Na_2O" present in the alkaline activator (Mass of "Na_2O" present in liquid sodium silicate + mass of Na_2O equivalent in sodium hydroxide if mixture of "sodium silicate" and "sodium hydroxide" used as alkaline activator).

Wang et al. [21, 22] stated that mechanical strength and other properties of AAS mortars were influenced by the nature of the alkaline activators. The dosage and the activator modulus have significant effects on the properties of AABs. They provided a range of activator modulus within maximum compressive strength may be obtained based on the type of GGBS. Wang et al. suggested that, optimum "modulus of alkaline activator" solution is ranging from 0.75 to 1.25 for acid slag, 1.0 to 1.5 for basic slag, and 0.9 to 1.3 for neutral slag [22]. It was observed that, for all types of GGBS in AAS-based mixes of concrete, as the dosage of activator modulus increases, there is a rise in the compressive strength value up to certain optimum value of dosage and further increment of the modulus leads to an decrease of strength value.

Few researchers [23] studied the activation of GGBS using diverse activators such as "sodium carbonate," "sodium silicate," "sodium phosphate," "sodium hydroxide," and combinations of mentioned activators. They recommended that sodium silicate solution was the best giving higher value of compressive strength with 8% Na_2O dosage with an activator modulus of 1.25 for better results (shown in Fig. 2). They also observed that, at a higher modulus dosage, there is a significant decrease in setting time and a reduced early strength gain was seen. At a very higher dosage of modulus, there was a sign of high shrinkage in concrete—which further performed like a fast-setting cement (Fig. 3).

Fernandez-Jimenez et al. [20] reported that the strength of "AAS" mortars is mostly influenced by the type and nature of alkaline activator, dosage of alkaline activator (AA) and observed that the optimal dosage of "alkaline activator" varies

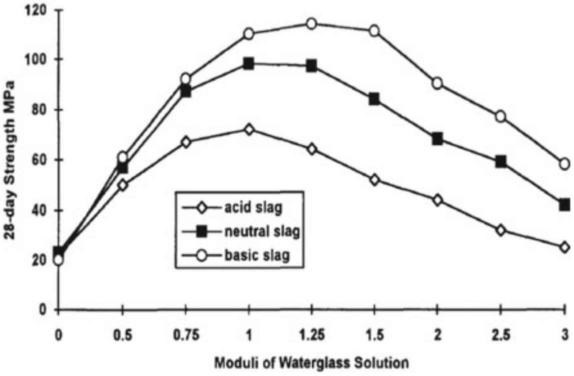


Fig. 2 Variation of "moduli of sodium silicate solution" with 28-day compressive strength value for different types of GGBS

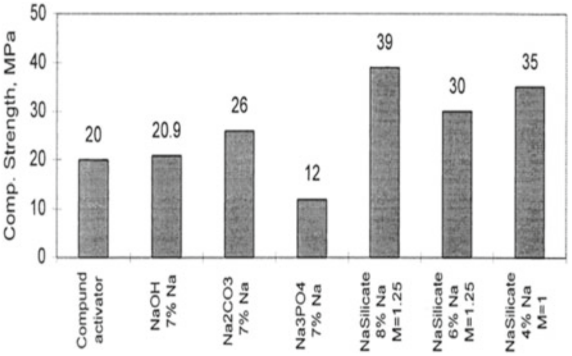


Fig. 3 Compressive strengths of slag-based alkali-activated cements

from 3 and 5.5% of "Na_2O" by the mass of GGBS. "Na_2O" dosage above this limit may cause efflorescence problems along with inefficient uneconomical mixtures.

Study by Krizan and Zivanovic [24] shown that an higher ultimate strength than OPC can be achieved with GGBS-based alkali-activated cements activated using sodium silicate with "activator modulus" ranging in between 0.6 and 1.5 with the suitable Na_2O dosage. They also shown from the study of hydration properties of AAC mixes that the liquid sodium silicate-activated GGBS displays two heat evolution peaks during preinduction period, and by increasing the modulus of liquid sodium silicate, there is a rise in the value of additional initial peak and lasting induction period. However, the rise in the dosage of activator leads to a decrease in the induction period.

Fernandez and Palomo [25] studied the activation of FA using different types of alkaline activators and by varying the Na_2O dosage between 5 and 15% (mass of binder). They reported that the activator modulus along with a "water/binder" ratio (w/b), affects the mechanical strength. Also observed that the Na_2O dosage of 5.5% (mass of fly-ash) led to very less pH, that affected the reaction development negatively, while the increase in Na_2O dosage led to higher strength with 14% Na_2O dosage (mass of FA) providing the maximum compression strength.

Wardhono et al. [26] studied the activation of AASFA mixes with different GGBS:FA mixes of 100:0, 90:10, 80:20, 70:30, 60:40, and 50:50 activated using sodium silicate and sodium hydroxide solutions. The “activator modulus” dosages were varied from 4.06 to 4.72. The results shown that the maximum compression strength of about 62 MPa was obtained for 50:50 mix for an alkaline activator modulus of 4.72.

Cengiz et al. examined the AAS mortars using different types of activators such as “sodium hydroxide,” “sodium carbonate,” and “sodium silicate,” with varying activator modulus and with Na_2O dosages in the range of 4–8% (mass of GGBS). It was detected that the compressive and tensile strengths of “AAS” mortars increased with Na_2O dosage of alkaline activators and also suggested that there exists an optimal alkaline modulus for which the highest compressive and tensile strengths can be obtained [27].

Palankar et al. deliberated the use of slag–fly-ash-based AAC for the application of concrete pavements. In this study, “alkali-activated slag concrete” (AASC) and “alkali-activated slag–fly-ash concrete” (AASFAC) were developed which was then related with OPC concrete of alike design grade. GGBS and fly-ash were used in the mix, in ratio 100:0, 75:25, 50:50, and 25:75 as the binder ingredient. The modulus of alkaline activator was varied from 0.75 to 1.75, and the dosage of Na_2O was varied from 4.0 to 5.5. All the AAC mixes were subjected to air curing in laboratory conditions. The results indicated that, all OPC, AASC, and AASFC mixes have obtained the target slump value. The density of AAFC was found to decrease as there is a rise in the dosage quantity of fly-ash. The compressive strength test for the mixes was carried out at 3, 7, 28, and 90 days curing; results indicated that the performance of alkali-activated mixes had shown better outcome than OPC-based mixes. Effect of activator modulus on compressive strength of AASC and AASFC is shown in Fig. 4.

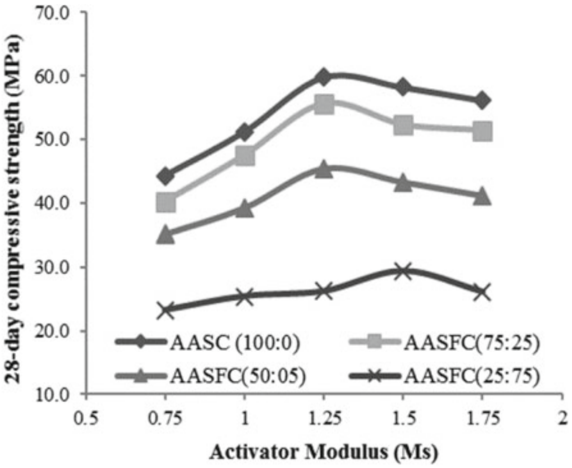


Fig. 4 Effect of “activator modulus” on strength of “alkali-activated mixes”

The early strength gain was also better in the mixes where the dosage of GGBS was more. However, the 28 days and 90 days strength of all mixes were similar. AASFAC displayed a max. compressive strength values of 67.4 MPa at 90 days for Ms 1.25 and for the mix of 75:25. The "flexural strength" and the "modulus of elasticity" were also investigated. "OPCC" and "AAC" mixes displayed similar "modulus of elasticity," but the flexural strength of AAC combinations were higher than OPCC. It was a peculiar observation that, as there is a rise in "fly-ash" content, the workability of the mix increased, but there was a little reduction in the strength and "modulus of elasticity" values. Absorption of water and total porosity tests were conducted on the concrete mixes according to "ASTM C 642–06" at curing of 28 days. The AASC displayed the less porosity and absorption of water, among all the concrete mixes. The AASFC with 25:75 displayed the maximum porosity and water absorption [28].

Karim et al. studied consequence of various alkaline activators, i.e., "NaOH," "KOH," and "$Ca(OH)_2$" on a concrete mix using triple blend of binders ("slag," "fly-ash," and "rice-husk ash") and comparing the results with conventional Portland-based concrete. They called the cement as zero-cement, which was abbreviated as Z-Cem. The alkaline activators were used in varied weights. They have stated that the setting time and consistency of the Z-Cem raised with the increase in the rice-husk ash dosage. The maximum compressive strength of about 42–44 N/mm^2 was achieved at 28 days of curing with 5% of NaOH dosage. They studied the microstructure and FTIR analysis which revealed that the development of the strength is due to the advancement of hydration products called silica-hydrates which are similar to the CSH gel in Portland-based concretes [29].

A extensive variety of "Si, Al, and Ca" wealthy sources of mineral has been explored as solo forerunners and as admixtures in dual and ternary alkali-activated concretes based on fly-ash, GGBS, MK, and powdered waste glass. Some studies have also shown that the usage of OPC as an admixture to produce alkali-activated cementitious systems. Aliabdo et al. reported the use of Portland cement in "fly-ash"-based alkali-activated concrete decreased the setting time of the concrete from 24 h to half an hour. This also leads to an improved mechanical performance of the hardened concrete (i.e., increased tensile and compressive strength, reduced porosity, and absorption of water) [30]. Assi et al. have deliberated the effect of addition of Portland cement (15% by weight) to the fly-ash and silica fume-based AAC, which lead to a very superior mechanical performance and the reduction in cost of construction. The study suggested that good mechanical performance is achieved without the use of external heat which makes this type of concrete mix more eco-friendly [31].

4 Durability and Flexural Fatigue Studies on AAC Mixes

The durability property of any material is one of the key parameters to use the material in practice. In the conventional OPC concrete, studies have exposed that the usage of pozzolanic "mineral admixtures" such as fly-ash, GGBS will enhance the durability performance [32], whereas in the case of AAC mixes, the durability is ruled by many factors such as type of mix, composition of binders, Na_2O dosage, “water/binder ratio” (w/b), and the modulus of activator [33, 34]. Several researchers have made the effort to study the performance of durability of various types of alkali-activated cementitious systems and several research outcomes reported that the alkali-activated concretes performed far well than that of the “OPC”-based concrete systems [7, 35–38]. The better durability performance of “alkali-activated slag and fly-ash”-based concrete mixes are mainly because of the nonexistence of calcium hydroxide (Portlandite) and little calcium content in the reaction products [39]. Few of the works were presented in this section.

Karim investigated the durability performance of two types of “slag–fly-ash–rice husk ash”-based “alkali-activated concrete” mixes. He studied the durability of these two types of mixes which gave the satisfactory performance (in strength) were done by testing it for porosity, absorption of water, sulfate resistance, chloride penetration, sulfate resistance, thermal resistance, and corrosion. Further, the durability results were related with the OPC mix. All the results shown that the alkali-activated binder-based concrete shown better performance in all the durability tests when compared it with the OPC-based concrete. He also developed the regression equations showing the connection between “porosity” and “compressive strength” of the AAC and “OPC”-based concrete mixes. To investigate the sulfate attack, the prepared mortar mixes were immersed in 5% $MgSO_4$ solution, and reduction in strength is tested at age of 30, 60, and 90 days [29].

Palankar et al. studied the long-term aging performances of GGBS–fly-ash-based alkali-activated cementitious systems by studying their long-term exposure to sulfate environment ($MgSO_4$), and acid environment (sulfuric acid) is carried out. Along with this, the absorption of water and their volume of permeable voids are also determined. In the study, the incorporation of “steel slag aggregates” is done. Results were compared with that of the Portland cement-based cementitious systems. The economical and ecological analysis was also performed on both type of mixes. For the acid and sulfate resistance test, the 100 mm cube specimens were immersed in the prepared solution after curing for 28 days (air curing for AAC and water curing for OPC were adopted), and testing at regular intervals till 360 days. The solution for sulfate attack test was the aqueous solution comprising 10% “$MgSO_4$” by maintaining a pH value of 6.5–7.5 using nitric acid. The solution for acid attack test was the aqueous solution containing 1% H_2SO_4 of pH of 1.0. The alkali-activated binder mixes have shown better performance than the OPC-based concrete mixes [40]. Similar results were reported by Mithun and Narasimhan where a type of AAC performed better than OPC-based concrete mixes subjected to sulfate attack and acid test [5].

El-Didamony et al. studied the durability of “alkali-activated slag” (AAS) concretes subjected to extreme saline exposure (sea water). The performance of the pastes developed by utilization of sea water and tap water was done by using two types of cements, i.e., GGBS-based alkali-activated cement and the sulfate-resistant cement (SRC) were compared. The study involved IR spectroscopy, thermogravimetric analysis, scanning electron microscopy, bulk density determination, and compressive strength determination. The studies on durability were carried out by immersing the concrete specimens which were cured, (both AAS and SRC) in sea water up to 12 months. The results show that the for SRC mixes, a drastic reduction in compressive strength were reported after 6 months of immersion, whereas for AAS mixes, there is no reduction strength were reported till 12 months; which was mainly due to the absence of chloro-aluminate and ettringite in the hydration product of AAS systems [37].

"Fatigue failure" is one of the vital forms of failure in concrete pavement structures which subjected to frequent application of loads. This type of failure in pavements arises under the manipulation of recurring loads or cyclic loads, whose ultimate values are considerably lesser than safe loads guesstimated through static tests. In the case of fatigue breakdown, the material fails by recurring application of traffic loading, which is not of a sufficient amount to cause failure due to single load application. In any concrete constructions, the failure due to fatigue causes localized, progressive, and permanent harm due to dynamic loads. Typically, these changes escort the development of cracks, further this leads to the growth of this crack which may lead to failure. This kind of failure is most common in the case of concrete pavements which will happen due to the cracks with progressive growth under the working of cyclic traffic loading, mostly when the stresses induced are greater than the strength of flexure of the concrete [41, 42].

Mithun et al. studied, the "flexural fatigue behavior" of AAS-based concrete mixes prepared at alkaline modulus of 1.25 by utilizing "copper slag" as fine aggregate, replacement to natural sand. Results were compared with OPC-based mixes designed for same target strength as that of alkali-activated concrete mixes. The studies were conducted on six types of concrete mixes, one being OPC mix by incorporating OPC as binder with the utilization of natural sand; other five are "AASC" mixes by varied dosage of copper slag with the replacement to the natural sand (replacement level varied from 0 to 100%, at an interval of 25%). The fatigue tests, done at different values of stress ratios varied from 0.70 to 0.85, and the fatigue life were determined. The fatigue lives of all the mixes were represented using "S–N curves." Further, the probabilistic analyses were carried out using Weibull distribution. The results indicate that both the static and fatigue flexural strength of the AAC mix was better than that of the OPC mix. This was due to the presence of dense and uniform ITZ in the case of AAC mixes when compared it with that of the OPC concrete mix [36, 43]. Comparable results were reported by Palankar et al., where a type of alkali-activated concrete developed using steel slag aggregate replaced in place of conventional granite aggregates performed better under flexural fatigue loading while compared with that of the similarly target designed conventional OPC-based concrete mixes [33, 38].

5 Usage of Glass Powder in Making Concrete

There is a continuous search for new supplementary materials which can be used as a complete or partial replacement as cementitious systems in place of conventional OPC-based concretes. Mineral concrete admixtures such as “GGBS, Silica fume, fly-ash, rice husk-ash” and limestone fines are few famous examples for such supplementary materials, use of which as a fractional standby in OPC/AAC-based concrete production is well known. Powdered glass is a new addition to such supplementary materials, and the several research has shown that the powdered glass which can be used as accompanying material in concrete production [44]. Another reason to test out the utilization of glass in some fruitful manner is to solve the disposal problems associated with waste glass. It is a renowned fact that there is a generation of more than million tonnes of waste glass yearly all over the world, and this will create lot of disposal problems as this waste material can be considered as a non-biodegradable waste. The reuse of waste glasses from customer utilization and industrialized progression pretense a major difficulty for metropolis worldwide [12]. Thus, making an attempt to utilize such a waste in producing sustainable concrete is really appreciable [45].

Zidol et al. have worked on the use of glass powder in producing OPC-based concrete. The studies were done by 0%, 20%, and 30% replacement of conventional cement with glass powder; and the result was compared with the 30% fly-ash + 70% OPC concrete mix and 30% GGBS + 70% OPC concrete mix. Four types of mixes were made with four different w/c ratios (i.e., 0.35, 0.40, 0.55, and 0.65) were investigated. The results show that the conventional control OPC mix have shown better performance in case of compressive strength and chloride ion permeability. They also reported that glass powder-based concrete behaved in a similar manner as that of the class F fly-ash-based concrete mixes. Use of GP reflects the slow and continuous pozzolanic behavior which may lead to better durability of glass powder-based concrete systems. Thus, from the results obtained, Zidol et al. [44] concluded that the performance of glass powder can be considered to be similar to those of other major supplementary materials (such as “fly-ash” and “GGBS”), hence where the conventional supplementary materials are not available, and where powdered glass is easily available, this can be effectively used.

Schwarz et al. deliberated, that the long-term compressive strength of 10% glass powder-based OPC mixes will obtain the strength which is just 5% different than that of the 10% fly-ash-based OPC mixes. They also experimentally established that there is a “potential” of glass powder which will help to minimize the expansion in concrete due to “alkali–silica” reaction. Further, 10% glass powder–10% fly-ash blended with 80% OPC mix have shown that there is a similarity between the mix prepared using 20% fly-ash with 80% OPC binder. The long-term performance with regard to the strength, sorptivity, and coefficient of moisture diffusion values indicates that the “glass powder-modified concretes” perform equal or better than concretes with improved fly-ash at beginning ages [46].

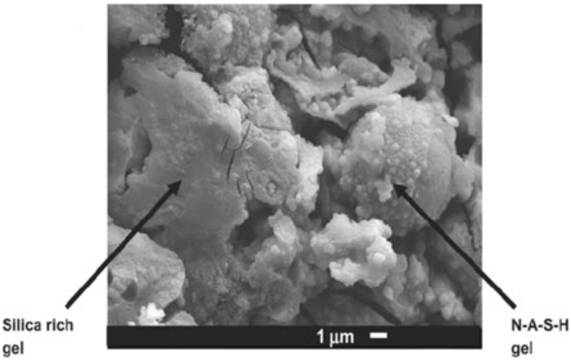
Many studies were also reported with the usage of glass powder in the manufacture of “alkali-activated cementitious systems.” The results reveal that there is a huge potential to use powdered waste glass in production of quality alkali-activated binder-based concretes. Some of the key results were presented in the following subsections.

Zhang and Yue stated that use of 14.57% of powdered glass had led to 28 day compressive strength and flexural strength of 66.4 MPa and 7.1 MPa with the optimum use of 8.31% Na_2O dosage. Further, this GGBS–glass powder-based AAC had shown a better resistance to sulfate attack; but the mix had limitation that it shown a higher shrinkage than the Portland cement-based concrete mix. From this research, it was revealed that the use of powdered “waste-glass” is a potential admixture for preparing “alkali-activated slag-based concrete” when the mixture of “sodium silicate” and “sodium hydroxide” were used as alkaline activators. Further, it was recommended that the optimization between glass powder content and Na_2O equivalent should be regarded when waste glass powder is used in alkali-activated cementitious systems [47].

Redden and Neithalath studied the strength, moisture stability, and “microstructure” of alkali-activated concretes formed using fly-ash and powdered glass as binders. The study revealed that a high value of compressive strength achieved with glass powder-activated mixes when compared with that of the “fly-ash”-activated mixes at lower heat curing temperatures. They found that the hydration product of glass powder-activated mixes was sodium silicate gel, whereas for “glass powder-fly-ash”-blended-activated mixes gave the combination of “sodium silicate and sodium aluminosilicate (N–A–S–H) gels form” as a hydration product. Further, they observed that there was a drastic loss in strength when the concrete mixes containing more % of glass powder, when it is bare to the moisture or vulnerability to an alkaline solution. To eradicate this problem, the use of aluminum containing mineral such as metakaolin or slag was suggested to be used in the alkali-activated mixes containing glass powder, which may lead to the development of moisture-stable hydration products of reaction. Also, the changes in structure upon the contact to moisture are explained using microstructural and “FTIR spectroscopical” observations. Micrograph showing the hydration reaction products of alkali-activated concrete mix upon heat curing for 48 h at 75 °C containing 50% powdered glass and 50% fly-ash blend activated using 8 M NaOH is shown in Fig. 5, where the structure of NASH and silica-rich gel can be seen [48].

Similar studies were conducted by Tashima et al. who investigated that strength and microstructure characteristics of “alkali-activated mortars” by using “glass fiber waste” product. The alkaline activator solutions used for the study are “NaOH and KOH” solution. The compressive strength of the mortar samples obtained was in the order of 77 N/mm^2 just after 3 days of heat curing done at 65 °C when “10 mol/L” sodium hydroxide solutions was used as activator. Whereas the similar mixes produced using KOH as activator have shown that the development of the strength around 70 N/mm^2. This was because of a higher degree of reaction when NaOH is used as activator when compared it with that of KOH activator-based mixes. This fact was proved even by the microstructure studies on the two types of mixes,

Fig. 5 SEM Image showing hydration products of fly-ash glass powder-blended AAC



where the NaOH-based mixes shown a dense and compact microstructure while compared with that of KOH-based systems [49].

Pascual et al. studied the combination of “powdered glass with metakaolin.” The use of metakaolin will lead to the induction of aluminum content and also to stabilize alkali ions in the glass powder-based alkali-activated systems. There was a rise in the compressive strength value of the mortars when the dosage of metakaolin was up to 8%. When the metakaolin content was less than 3%, there was decrease in the strength values were observed, which significantly shows that there must be aluminum content in the mix when glass powder is used to produce alkali-activated cementitious mixes, otherwise it will be adversely affect the performance [50].

Banjare et al. studied the use of an amalgamation of “calcined kaolin clay,” dross from “aluminum recycling,” and “lead–silica glass” from recycled fluorescent lamps to produce a bubbled “alkali-activated binder-based cementitious systems.” They could produce a very lightweight concrete weighing 460–560 kg/m^3 with around 82% porosity and a maximum compressive strength up to 2.3 N/mm^2 [51].

Puertas and Torres Carrasco explored the utilization of powdered waste glass for the potential activation of slag in producing alkali-activated concrete. The findings showed that the possibility of using waste glass in producing alkali-activated slag. Treating waste glass with “$NaOH/Na_2CO_3$” ($pH = 13.6$) favors the partial liberation of the reactive silica from the powdered glass. The resulting solution from the treatment of glass waste acts as “alkaline activators”, partially dissolving the “vitreous blast furnace slag.” The compressive strength was over 60 N/mm^2 at the age of 28 days when the “$NaOH/Na_2CO_3$” mixture and glass waste mixed solution were used as activators, indicating that the glass was potentially useful as an additional silica source in place of commercial silicate solutions. The strength, composition, and microstructure of the products of reaction recognized in conventional activator and activated powdered glass waste as activator were comparable.

6 Key Findings from Literature Review

From the comprehensive "literature review," it is noticed that the durability and strength of AAC mixes are influenced by several factors, namely the nature of binder, chemical characteristics of the binder, % of sodium oxide dosage (Na_2O), water content and water-to-binder ratio, nature of alkaline activator, activator modulus of the alkali, curing regime, etc. Properly designed AAC mixes have an ability to perform far better (with respect to the durability and strength) than that of the similarly designed conventional OPC-based concrete mixes. AAC mixes containing higher dosages of slag (i.e., GGBS dosage more than 50% by weight of binding ingredient) may arrive at adequate amount of strength even at room temperatures, i.e., when subjecting it to air curing, without need for any kind of heat curing or other methods. The addition of higher quantities of fly-ash in AAC mixes may lead to a reduction in the strength performance, but this will lead to a rise in workability of the concrete mixes. Further, the "activation energy" required for AAC mixes containing massive proportions of fly-ash is higher (i.e., in the mixes where fly-ash dosage greater than 50% by weight of binding ingredient); thus, the replacement of GGBS with FA ahead of 50% in AAC mixes requires a higher amount of dosage of the "alkaline activator" solution; also these mixes may require heat curing for attaining the required target strength. Among many alkaline activators, the incorporation of NaOH flakes and sodium silicate (Na_2SO_3) solution will provide the most excellent activation solution in producing alkali-activated concretes. The strength durability performances of AAC mixes are appreciably influenced by the modulus of activation (Ms) of alkaline activators and the dosage of sodium oxide (Na_2O). It is essential to find the "Na_2O" dosage and the "optimal activator modulus" (Ms) for which the target strength of AAC can be conquered. The optimal value of Na_2O dosage for any AAC mixes may differ somewhere between 3 and 6% by weight of binder; whereas higher dosages might lead to uneconomical concrete assortment and efflorescence problems. Whereas, the optimal modulus of activation (Ms) for the AAC mixes may fluctuate between 0.50 and 2.0. The Na_2O dosage, Ms Value of alkaline activator, water-to-binder ratio, etc., required to be controlled in order to acquire mixes of the required workability and desired strength. Waste glass is an industrial end product and can be looked upon as a potential substitution for traditional ingredients in concrete production. A satisfactory and an improved engineering performance of this powdered glass in concrete production have been reported by many researchers which were used in producing both conventional OPC and AAC-based concrete as a cementing ingredient. However, there is limited research available on strength, durability, and fatigue performance of AAC mixes incorporating powdered waste glass as binding ingredient along with conventional slag and fly-ash. The further research works can be focused to investigate the properties of sustainable air-cured AAC mixes with powdered waste glass as binding ingredient with an object of conserving environment by utilizing waste product.

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