Review of Low to High Strength Alkali-Activated and Geopolymer Concrete

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Abstract Popular building material has always been improving in the lines of material science developments. In this paper, the no use of Ordinary Portland Cement concrete studied, viz., fly ash-, slag- and meta-kaolin-based concrete, etc., from low to high strengths has been presented. Presently, all researchers and construction industries are working on using waste and energy-efficient material to develop sustainable concrete. This article presents the effects of various variables on the slump properties and mechanical properties, specifically to compressive strength. Recent study results indicated the alkali-activated and geopolymer binders have strong potential to replace conventional binders to a greater extent. Application of this environmentally friendly concrete may be an appropriate alternative to traditional concrete.

Keywords Cement · Alkali-activated · Geopolymer

1 Introduction

Cement is the primary binding material used for concrete making. With the growth in infrastructure, the demand and use of cement are ever increasing. Cement industry causes environmental pollution by emitting CO_2 that is a significant contributor to the carbon footprint around the globe [1]. Ordinary Portland Cement has been the most popular cementitious material for making concrete. OPC performs well and maintains its integrity, chemical stability when it is subjected to extreme conditions from low to high temperatures, various environmental conditions, radiation.

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Environmental issues made the researchers work toward the development of new generation binders, that are eco-friendly and also, cater to the need for special concrete such as high strength concrete, self-compacting concrete [9]. The new generation energy-efficient and sustainable binders, which can produce green concrete is the need of the hour.

Waste disposal is yet another problem faced by mankind. Industrial wastes if not utilized effectively will be dumped in the landfill. To reduce the load on landfill, researchers have been working on zero waste technologies [19]. Alkali-activated cementitious binders utilize industrial waste such as fly ash, GGBS so forth that possess pozzolana properties in significant quantities. The binders activated by using the alkaline solution, which contains sodium hydroxide and sodium silicates.

First research published related to alkaline or alkali-activated cement is a 1908 patent right by the German chemist and engineer Kühl [13]. The process described contains an essential combination of an alkali source, which is rich alumina-silica (pozzolanic) contained solid precursor with combination of alkaline liquid resulting into alkali-activated concrete. Alkali-activated cement seems to have superior performance and durability than the Portland cement.

There have been several studies of alkali-activated binders since the 1940s. Purdon [20] published the study of the interaction of 30 different types of GGBS with various activators in two steps. In the first step, blast furnace slag activated with sodium hydroxide solutions. The second step involves combining calcium hydroxide and different sodium salts. The performance of the resulting paste was found to be comparable to OPC in terms of rate of strength development and ultimate strength [20].

The alkali-activated slag is associated with low water permeability and low heat. Despite excellent mechanical and durability performance, Purdon did mention some issues as potential problems to achieve the desired strength. High activator concentrations are often necessary, and these can lead to prohibitively short setting times. Due to the accelerating effect of highly alkaline activators, it depends on the viscosity of the activating solution as well as the amount of water added [21]. However, all those issues are remedied by understanding the problem at hand.

The alkali-activated binders have been studied in Western Europe by researchers of the former Soviet Union and China. Later by the year of 1957 after several experiences, Victor Glukhovsky a Soviet Union scientist, was the first scientist to discover alkali-carbonate activation of metallurgical slag at the institute in Kiev Ukraine [10].

Subsequently, the effort of Purdon, alkali activation research in the Western world was quite limited until the 1980s, as reviewed by Roy [25]. By the 1980s, Joseph Davidovits from France reinvigorated the area, brought a fresh and scientifically sophisticated way, which was a significant positive step forward from the work of the Glukhovsky. An era that has been developing slowly and on making geopolymer binders Joseph called them "geopolymer" because their microstructure is on polymers [6].

This paper aims to review the hardened properties of alkali-activated and geopolymer concrete. This article presents the silica-alumina abundant particles, sodium hydroxide, sodium silicate, hardening mechanisms, and effects of various variables on the slump properties and mechanical properties, specifically to compressive strength. An overview of alkali-activated and geopolymer contains various variation of binders, viz., fly ash, GGBS, metakaolin, microsilica, and nanosilica.

2 Prime Material

2.1 Fly Ash

Fly ash is the by-product of the thermal power plant. The flaming of solid, older anthracite coal typically produces low calcium fly ash. Globally, more than 65% of the fly-ash particles are waste product of thermal power stations deposited in ash ponds and landfills. The recycling of fly ash is the major concern to use in geopolymer concrete, which can reduce the consumption of OPC. Generally, fly ash is classified into two grades, i.e., Class C, which contains over 20% lime (Cao) and Class F, which contains under 7% lime (Cao) [16, 29, 30].

2.2 Ground-Granulated Blast-Furnace Slag (GGFS)

Ground-granulated blast-furnace slag (GGFS) is the waste by-product of steel production. GGFS produced by knock downing the molten iron slag with rapid cooling which is then dried and broken down into the glassy and granular particles. GGFS has been found to have a huge potential of being used as a supplementary binder. Typically, it has SiO_2, CaO and Al_2O_3 contain high percentage, which exhibits higher pozzolanic compared with fly ash [3].

2.3 Metakaolin (MK)

Metakaolin is the mineral clay, which is derived from kaolin in the form of the anhydrous compound. The Clay kaolin is calcined at the 600–700 degree Celsius. The metakaolin is finer than the OPC, but not fine as microsilica. The effective use of metakaolin clay tends us to less energy consumption comparing to traditional cement. It majorly consists of SiO_2 and Al_2O_3 above 90% approximately, which is geopolymeric [26].

3 Compressive Strength

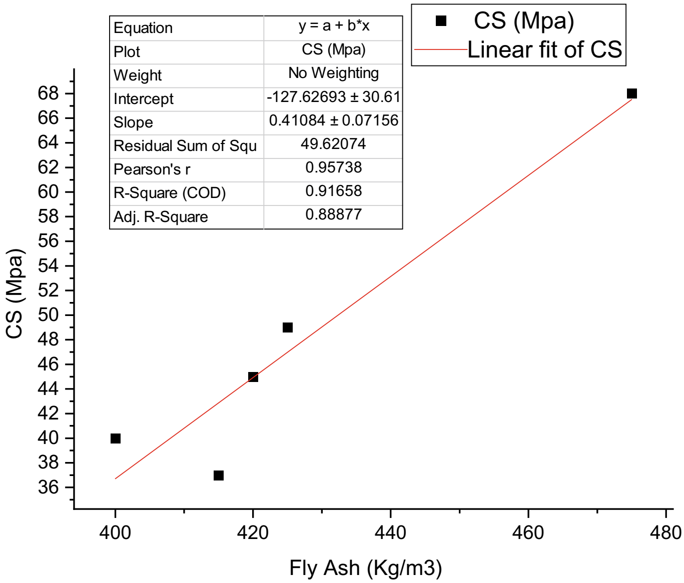
3.1 Fly Ash-Based Concrete

Assi Lateef et al. (2018) have elucidated the result of particle size distribution and source on the strength and microstructural properties of pozzolana-based geopolymer concrete. The two pozzolana sources and three different sizes of pozzolana particles, i.e., 38.8, 17.9 and 4.78 μm were studied. Strength (compressive) was found to improve when the distribution of finer particle size used and a different source. Water absorption and the permeable voids proportion after immersion ratio decreased as a fly ash size reduced to the range of 4.78 μm [2]. Gunasekara Chamila et al. (2016) have investigated the durability aspects of various fly ash geopolymer concrete. Fly ash was collected from four different sources, i.e., Collie, Pt. August, Gladstone, and Tarong. Except for the concrete samples prepared from Collie, other all fly ash geopolymer concrete achieved the compressive strength 30 N/mm^2 in 3 days comparable to OPC concrete, 37 N/mm^2 in 90 days and 45 N/mm^2 in 1 year, which shows geopolymerization, which continued after 90 days [10]. Ferdous Wahid et al. (2015) proposed the mix design of geopolymer concrete. Stepwise mix design proposed was evaluated. In this paper, a detailed mix design considered in this experiment is specific gravity, air volume, slump, and lastly density concrete. Geopolymer concrete achieved the compressive strength 40 N/mm^2 in 28 days, modulus of elasticity 190 Gpa and ultimate strain 0.3% [7].

Khoa Tan Nguyen et al. [16] have investigated the properties of marine sand as fine aggregate based on geopolymer concrete and the deterioration of embedded steel reinforcement. The maximum strength (compressive) obtained was 37 N/mm^2 in 28 days when liquid–alkaline to fly ash ratio increased from 0.35 to 0.4 using marine sand as fine aggregate. Then when liquid–alkaline to fly ash ratio increased from 0.4 to 0.65, the compressive strength decreased from 37 to 21 N/mm^2, refer Graph 3. If the Si/Al ratio is increased from 1.16 to 1.67 that resulted in an enhancement of strength (compressive) [16]. Vasquez Alexander et al. (2016) carried out the study on the geopolymer using concrete demolition waste (CDW). In this experiment, OPC was partially replaced with fly ash and metakaolin up to 30% using CDW. Geopolymer concrete based on CDW, fly ash replaced with of 30% OPC and with of 10% metakaolin achieved the highest value of compressive strength of 25 N/mm^2, 33 N/mm^2 and 46.4 N/mm^2 at 28 days with Si to Al ratio of 10.5 without heat curing [28]. From the literature, Graph 1 is plotted between compressive strength (28th day) and fly ash, which showing good fitting value of R^2 equal to 91.5%.

3.2 GGBS-Based Concrete

Rafeet Ali et al. (2017) have compared the aspects of slag-based alkali-activated-concrete (SAAC) and fly ash geopolymer concrete (FGPC) with boron as



Graph 1 Linear fit of compressive strength (CS) and fly ash

environment-friendly material. The presence of boron results in the improvement of strength (compressive) in both FGPC and SAAC. The enhancement in the quantity of CaO in the binder system produced as a result of reaction compound formed due to product of fly ash and GGFS with the alkaline liquid. The difference between with fly ash-based and GGFS-based concrete is the high content of calcium oxide (almost 45%). In GGFS binder which may direct in forming a calcium–silicate–hydrate paste in the matrix of GGBS concrete. These C–S–H bonds carry a considerable portion in the hardening of the SAAS [22].

Thomas Robert et al. (2015) have investigated on the modulus of elasticity, tensile strength, and the stress–strain correlation of alkali activated-concrete (AAC) with fly ash and slag. The strength (mechanical) of AAC fly ash-based concrete with room temperature curing (28 days @ 22°) which found to have less strength compared with heat curing (48 h @ 50°). There is no difference in AAC slag-based concrete consistently. The strength (tensile) of AAC slag/fly ash both which established to have strength slightly more than OPC-based geopolymer concrete. The Poisson ratio for AAC slag/fly ash is consistently about two-thirds of OPC concrete. The stress–strain relationship showed similar behavior of all AAC concrete [26]. Reddy et al. [23] developed the mix-design for slag/fly ash-based geopolymer concrete under room temperature curing. In this paper, a rational and simple mix design has been explained for developing the slag/fly ash-based geopolymer concrete. One of the main verdicts of the study is that for the development of a well-performing GPC, ACI strength versus the W/B ratio. Alkali activator particle (AAP) to binder particle

(BP) ratio is the parameters to be controlled. Further, the study has found that the medium–high strength is in the range of 32–66 N/mm^2 [23].

4 Metakaolin-Based Concrete

Hadi Muhammad et al. (2017) designed the slag-based geopolymer concrete at room temperature curing by Taguchi approach. In this paper, blend of binder particle-like fly ash, steel slag, metakaolin (MK) and microsilica (MS) to achieve the relative amount of Al to a binder ratio (A/B), SS to SH (SS/SH) with variation SH concentration from 10 to 14 M were studied. Geopolymer concrete with a binder content of 450 kg/m^3, A/B fraction of 0.35, SS/SH fraction of 2.5 and concentration SH of 14 M achieved the maximum strength (compressive) of 60 N/mm^2 in 7 days with normal curing. The combination of fly ash and steel slag found to have increased the setting time under the room curing condition but showed superior compared to a blend of MK and MS [11]. Pouhet et al. [18] developed metakaolin-based geopolymer mortar and concrete. The slump of metakaolin-based geopolymer concrete revealed that with nonporous siliceous aggregate is capable of replacing the conventional cement. The compressive strength of 60 N/mm^2 obtained in 7 days for geopolymer concrete. Geopolymer concrete has shown the refinement of pores compared with normal concrete regardless of pore size [18]. Peem Nuaklong et al. (2018) studied the engineering properties of metakaolin and high-calcium fly ash (Class C) geopolymer concrete incorporating recycled aggregate. The metakaolin replaced 0–30% with Class C fly ash to produce the geopolymer concrete. The partial replacement of metakaolin was found to have improvement of acid attack resistance, transport properties, abrasion and engineering properties. The metakaolin is finer that fly ash refined the pore structure and geopolymerization. 30% metakaolin significantly enhanced the strength (compressive), porosity and absorption (water) with subsequent values of 134%,69% and 89% of geopolymer recycled aggregate concrete compared with concrete without meta-kaolin [17].

5 OPC Based

Yi Fang Cao et al. [4] have investigated the effect of CAC (Calcium–Aluminates–Cement) on geopolymer concrete cured at moist curing. CAC was replaced within the range of 5–20% and NaOH concentration in the range of 10–14 M, while the activator ratio between 35 and 45%. The addition of CAC in the geopolymer concrete found to have strong development at moist curing. The best mix design of geopolymer concrete, which contains 10 M alkali solution, 5% CAC replacement and 45% activator proportion. Again, with the best mix design which found to have the compressive strength of 57 N/mm^2 in 28 days with 14 M alkali solution, 10% CAC and 35% activator [4]. Ankur Mehta et al. (2017) studied the fly ash geopolymer concrete with various variables on absorption and strength properties. OPC 20% replaced with fly ash with an addition of 15 M solution NaOH cured at 70 degrees for 24 h which found to have the strength (compressive) of 64.39 N/mm^2 in 7 days [14]. Askarian Mahya et al. (2018) have investigated the engineering properties of room temperature cured one-part-hybrid OPC–geopolymer concrete. The one-part geopolymer concrete, which found to have the maximum workability of 120 mm and with 60% OPC, which obtained the lowest workability of 30 mm [1]. Farhan Nabeel et al. (2019) analyzed and compared the OPC concrete with low to high strength fly ash geopolymer concrete (FGPC) and alkali-activated slag concrete (AAC). The direct-tensile strength, flexural strength and indirect-tensile strength of low strength (35 N/mm^2) and high strength (65 N/mm^2) FGPC and AAC concrete were superior to, compared to, OPC concrete [6].

6 Conclusion

On reviewing the available literature on alkali-activated binders and geopolymer binders. Most of the published research attempted to develop the geopolymer concrete as a base binder with fly ash, GGBS, meta-kaolin and so on in conjunction with various curing regimes such as moist curing, steam curing and high-temperature curing. The base binder then activated using alkaline solution with various ratios. Efficient utilization of waste product and alternative binder system to produce green concrete may restrict the consumption of OPC.

In comparison with fly ash based, GGBS-based and metakaolin-based alkali-activated and geopolymer concrete. The early compressive strength development was achieved within 7 days by metakaolin-based concrete. At the same time, GGBS-based alkali-activated concrete highest compressive strength was achieved within 28 days, which is significant compared with OPC concrete.

The present study results indicate that the alkali-activated and geopolymer concrete has exhibited significant feasibility. Application prospect to use as a green building material, which may be an appropriate replacement for the traditional concrete in the future. Studies on long-term performance on alkali-activated and geopolymer for various environmental conditions is not well documented.

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