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REVIEW PAPER

A Review on the Effect of Silica to Alumina Ratio, Alkaline Solution to Binder Ratio, Calcium Oxide + Ferric Oxide, Molar Concentration of Sodium Hydroxide and Sodium Silicate to Sodium Hydroxide Ratio on the Compressive Strength of Geopolymer Concrete

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Abstract

Recently, geopolymer concrete (GPC) has gained substantial consideration and commercial interest in the construction industry owing to the superior mechanical and chemical properties in comparison with the ordinary Portland cement (OPC) that it brings through the use of waste material and reduction in the CO_2 emission. Previous research Studies revealed that different ratios of chemical oxide combination of the raw material (fly ash, rice husk ash, meta kaolin, sugarcane bagasse ash, GGBS etc.) strongly affect the mechanical and durability properties of GPC. Nevertheless, findings concerning different ratios of Si/Al, alkaline solution to binder, NaOH to Na_2SiO_3, combined percentage of Fe_2O_3 + CaO and molar concentration of NaOH are controversial regarding the compressive strength of GPC. Therefore, in the light of literature, this study presents the investigation of the compressive strength behavior against the different ratios of oxides and alkaline solution (i.e. Si/Al, alkaline solution/binder, NaOH/Na_2SiO_3, Fe_2O_3 + CaO and NaOH molar concentration) present in the raw material used for the production of GPC. An extensive data from previous research publications has been collected and trend of compressive strength for 7 and 28 days was developed against different ratios of Si/Al, alkaline solution/binder, NaOH/Na_2SiO_3, in order to conclude a typical range for the above mention parameters. It was concluded that compressive strength of GPC greatly depends on the variation in ratios of Si/Al, alkaline solution/binder, NaOH/Na_2SiO_3, Fe_2O_3 + CaO and NaOH molar concentration. It was also concluded that the compressive strength of GPC has been primarily affected by the ratio of Si/Al, alkaline solution/binder, NaOH/Na_2SiO_3 and molar concentration of NaOH. Besides, the oxides like CaO and Fe_2O_3 although smaller in quantity in comparison with the alumina and silicate oxides, have indicated a distinct influence on the compressive strength development.

Keywords Compressive strength · Geopolymer concrete · Alkaline activators · Oxide composition of source material · Environmental degradation

1 Introduction

Concrete is comprehensively used construction material across the globe and during the production of ordinary Portland cement (OPC), a significant amount of energy is consumed and simultaneously the emission of huge amount of CO_2 into the atmosphere occurs. The $CaCO_3$ calcination process discharges about 0.53 tons of CO_2 to the atmosphere for the production 1 ton of OPC and if carbon fuel is utilized as an energy source for the production of OPC, the additional 0.45 tons of CO_2 might be produced [1]. Consequently, for the production of 1 ton of OPC, around 1 ton of CO_2 is released into the atmosphere. Currently, 4.0 billion tons of cement is produced annually by different countries across the globe with a growth rate of 4% [2]. However, the utilization of OPC in the construction industry cannot be avoided completely due to the beneficial properties that it brings to the structures in

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comparison with other relative construction materials. The alternative materials may also be useful to replace some part of the OPC. A possible replacement could be the use of alkali-activated binders which may be acquired from industrial waste material rich in alumina-silicate oxides [3–5]. In this regard, geo-polymer concrete (GPC) holds better chemical and mechanical properties [6, 7] and may not only reduce the CO_2 production but also helps in consuming industrial and agricultural wastes like fly ash, rice husk ash, bagasse ash, slag, red mud, etc. In this manner, the degradation concerns of the environment might be minimizes that occurs due to the dumping processes of industrial wastes [8–10]. In 1979, Joseph Davidovits started studying the GPC; however, his study didn't get proper attention in the early two decades but later on substantial research investigations have been carried out in this area and GPC has shown remarkable advantages due to its better performance than the conventional concrete. Besides, GPC is proved to be significant in reducing the CO_2 emission, thus provided a solution to the researchers for increasing emphasis on energy conservation and global warming [11, 12].

GPC is also termed as a green concrete that is produced by alkaline activation of source material rich in alumina and silicates. Alkaline activation is a chemical process, in which material rich in alumina and silicate of natural or industrial source might be converted into compacted cementitious structure after mixing with a highly alkaline solution like KOH or NaOH and solvable silicates i.e. sodium silicate or potassium silicate in gel, under suitable curing environments [12–18]. A large quantity of agricultural waste, industrial by-product and natural raw materials such as rice husk ash [19, 20], fly ash [19–21], palm oil fuel ash [22, 23], slag [24, 25], red mud [26, 27], sugarcane bagasse ash [28], hematite, barite and copper [29, 30], metakaolin [31, 32], silica fume [33] and other such material that are rich in alumina and silicates may be employed as source materials for GPC production. The source material employed for GPC passes through geo-polymerization process in the presence of alkaline activators and forms an amorphous to semi-crystalline structure with chemical and mechanical properties similar to conventional concrete or superior than conventional concrete.

In geopolymerization procedure, the Si and Al oxides present in source material goes through a quick chemical reaction in the presence of favorable alkaline conditions that yields an amorphous to semi-crystalline polymers chain reaction and a ring structure comprise of Si-O-Si and Si-O-Al bondings [34]. Primarily, the geopolymerization reaction is dependent upon the capability of the aluminum ions that occurs either in four-fold or six-fold coordination in inducing crystal structure and chemical changes in silica backbone [35].

By using GPC, CO_2 emissions might be decreased and the usage of OPC in the construction industry might be completely avoided. Besides, the utilization of waste materials from industrial sector and agricultural sector along with the minimization of CO_2 is very essential to solve the problems regarding waste disposal and environmental degradation. On the other hand, investigation of the mechanical properties of the final product is necessary as these properties are the main parameters in any type of concrete for deciding its superiority and suitability over others.

Up till now, several investigations have been carried out on the factors affecting the compressive strength of the GPC. Previous research studies revealed that the compressive strength properties of GPC is influenced by ratio and nature of alkaline activator [24, 36], molar concentration of alkaline activator [37, 38], curing time and temperature (ambient, elevated) [20, 33, 39, 40], type of source material and their corresponding chemical compositions [41], Si to Al ratio in the mix proportion of geo-polymer matrix [31], mass ratio of alkaline solution to binder material [42], mass ratio of sodium silicate to sodium hydroxide [43], ratio of water to geo-polymer solids [44, 45], state of sodium silicate (i.e. liquid or solid) [46], SiO_2 to Na_2O ratio in the geo-polymer matrix [47, 48], time of mixing and rest period before curing [44], molar ratio of water to Na_2O in the geo-polymer matrix [49], cumulative percentage of CaO and Fe_2O_3 [50] etc.

A large number of studies have been performed on the enhancement of compressive strength of GPC. Studies regarding the influence of Si to Al ratio, alkaline solution to binder ratio, CaO + Fe_2O_3, molar concentration of NaOH and Na_2SiO_3 to NaOH ratio on the compressive strength of GPC remains the core interest. Still many of the research studies are controversial regarding the effect of different oxide ratios, molar concentration and Na_2SiO_3 to NaOH ratio on the compressive strength of GPC. The other parameters like curing temperature, methods and mixing time etc. are manageable in the laboratory but the percentages of oxides present in the source material along with their ratios are uncontrollable in GPC matrix, therefore, it is important to conclude different oxide ratios, molar concentration and Na_2SiO_3 to NaOH ratio for the production of GPC in a scientific manner. This review study is carried out to discuss the literature results based on the findings related to Si to Al ratio, alkaline solution to binder ratio, CaO + Fe_2O_3, molar concentration of NaOH and Na_2SiO_3 to NaOH ratio on the compressive strength of GPC. Besides, from the literature, various oxides and alkaline solution ratios for the selection of an individual or combination of different material are also concluded.

2 Methodology

Before describing and evaluating the effect of silica to alumina ratio, alkaline solution to binder ratio, calcium oxide + ferric oxide, molar concentration of sodium hydroxide and sodium silicate to sodium hydroxide ratio on the compressive strength of geopolymer concrete, a detailed bibliographic search of related topics has been carried out and the data have been collected from various databases including Elsevier, Springer, Scopus and ScienceDirect etc. After collection of data from the past research studies, the data have been evaluated through discussions, tables and graphs. Finally, concluding remarks have been provided; the detailed methodology of the review paper is shown in the Fig. 1.

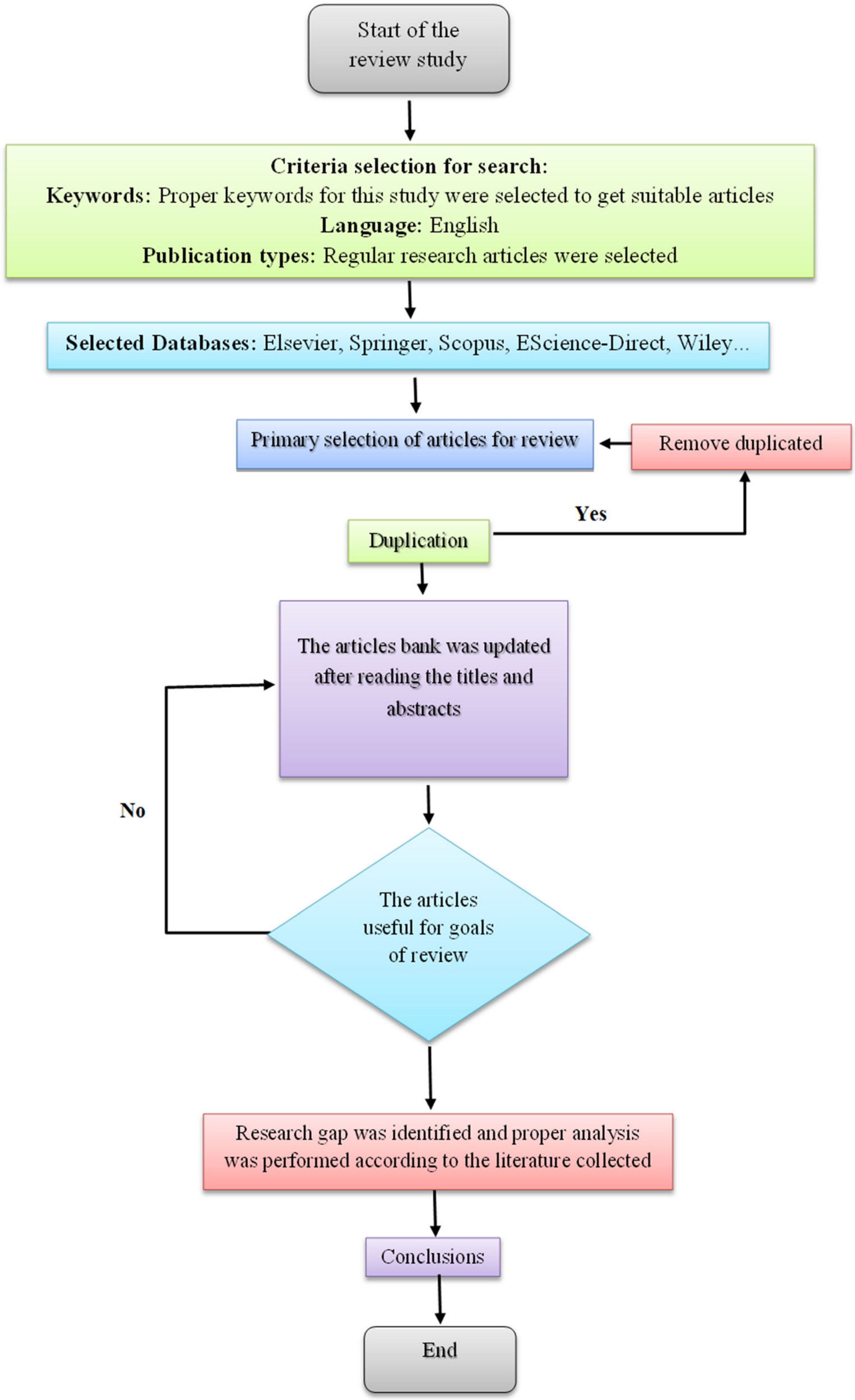

Fig. 1 Flowchart of the methodology used for the review

3 Basis for Data Points

Extensive data from the past studies regarding the compressive strength of GPC was collected in the current study. Primary importance was given to the influence of Si/Al ratio, alkaline solution to binder ratio, molar concentration of NaOH, $NaOH/Na_2SiO_3$ and cumulative percentage of $CaO + Fe_2O_3$ on the compressive strength of class-F fly ash-based GPC. Later on, the literature study is comprehended to compare the results of GPC through the use of various source materials i.e. fly ash, ground granulated blast furnace slag (GGBS), metakaolin, red mud in addition to the combination of these source material.

3.1 Silica to Alumina Ratio

Davidovits [51] defined three different polysialates monomers i.e. PS (polysialate), PSS (Poly-sialatesiloxo) and PSDS (poly-sialate-disiloxo) which can be formed during the reaction process of geopolymer concrete. The chemical formulae of the monomers are as follows:

PS: -Si-O-Al-O-
PSS: -Si-O-Al-O-Si-O-
PSDS: -Si-O-Al-O-Si-O-Si-O-

The formation of monomers in GPC matrix is entirely reliant upon the ratio of Si to Al present in the source material. The total Si to Al ratio should be in the range of 1.6–2.3, for the formation of stable geopolymer gel [52, 53]. The amorphous geopolymer structure was primarily proposed as PS (Si to Al = 1), PSS (Si to Al = 2) and PSDS (Si to Al = 3), respectively [54, 55]. Low ratio (Si to Al ≤ 3) might yield brittle and stiff GPC similar to cement and ceramics that may have 3-dimensional cross-linked rigid network. On the other hand, higher ratio (Si to Al >3) may yields adhesive GPC that may have 2-dimensional network having a polymeric structure of linear linkages [56]. This provides an indication about the importance of SiO_2 and Al_2O_3 composition, their ratios in the source material and its impact on the mechanical strength achieved in the final product of GPC. The Si to Al ratio can be changed up to some level by changing the ratio of NaOH and Na_2SiO_3 however, the chemical composition of Si and Al ratio primarily depend on the source material utilized for GPC, which indicates that the final strength of GPC is governed by SiO_2 and Al_2O_3 compositions and their corresponding ratios present in the source material. The type of formation of chemical structure depends entirely on the percentage of Al_2O_3 present in the source material [57]. Recently, GPC has been proposed as a feasible technology by utilizing by-product of waste material for tailings of mine, oil, and sand [35]. These are mostly unpredictable sources of alumina and silicate minerals, covering a significant range of Si and Al ratios. Therefore, to obtain optimum compressive strength of GPC, an attempt has been made in the current study for determining the optimum percentage level of SiO_2 and Al_2O_3 in the source materials and their corresponding ratios.

3.2 Alkaline Solution to Binder Ratio

Alkaline solution to binder ratio is a significant parameter of GPC which considerably affects the compressive strength of the GPC matrix. To develop GPC, a combination of NaOH, Na_2SiO_3 or KOH and K_2SiO_3 are extensively utilized as an alkaline activator with the incorporation of source material [19, 50]. The alkaline activation of source material (AASM) is a chemical process by which the source material (fly ash, rice husk ash, metakaolin, GGBS, etc.) rich in alumina and silicates is mixed with a certain amount of highly alkaline solutions and then the mixture is cured under a suitable temperature to make solid materials (geopolymer concrete). The glassy components of the source materials are transformed into well-compacted cement [13, 15, 58–62]. From the last two decades, significant development has been observed in GPC due to its eco-friendly nature, excellent mechanical properties, resistance against aggressive environment and durability [63–65]. When sodium is used as an activator, a three-dimensional reaction product gel ($Na_2O–Al_2O_3–SiO_2–H_2O$) is produced, adopting the OPC nomenclature. The product of this gel is essentially dependable for the mechanical strength and durability while secondary products are developed in the form of crystalline zeolites [66–69]. Alkaline solution to binder ratio is a significant parameter of GPC which affects the compressive strength in same manner as w/c ratio effects the strength of OPC [70, 71]. Moreover, increasing the addition of alkaline solution in the geopolymer matrix not only increases the alkaline solution to binder ratio, it also increases the water content, OH^- ions and the quantity of alkaline cations present in the geopolymer system. Ultimately, the increasing quantity of alkaline cations and OH^- amount would significantly influenced the type and nature of geopolymerization gel (N-A-S-H) and the zeolites developed through alkaline activation process [72]. Various researchers reported that low alkaline solution to binder ratios may develop densified microstructure of GPC which would ultimately results in the improved mechanical properties [73]. However, some researchers have indicated that high alkaline solution to binder ratio has encouraging influence upon the mechanical strength [74]. Thus, an attempt has been made in this study to determine the specific range of the alkaline solution to binder ratio for the production of GPC having superior mechanical and chemical properties.

3.3 Cumulative Percentage of Calcium Oxide and Ferric Oxide

Several research studies stated that the material having least CaO percentage is ideal for GPC as compared to the source material having high CaO percentage. The presence of high percentage of CaO could affect the geopolymerization reaction and can change the microstructure of the geopolymer matrix [75–77]. On the other hand, some research studies reported that material having a high percentage of CaO has favorable impact on the compressive strength of the final product (geopolymer matrix) [78, 79]. Furthermore, it is demonstrated that the source material having CaO more than 20% could exhibit a very quick setting of geopolymer matrix which is not recommendable for GPC [80]. The presence of CaO in material used for GPC either in low or high percentage can affect the geopolymerization reaction in addition to the compressive strength and microstructure of the geopolymer matrix [76]. Another main constituent of the oxide composition present in the source material is Fe_2O_3 that is used for the production of GPC. Studies regarding GPC are generally based on traditional source materials like metakaolin, fly ash, rice husk ash and GGBS having less than 10% of Fe_2O_3. However, recent research work revealed that source material with Fe_2O_3 percentage more than usually found in traditional source materials might be activated in a suitable alkaline environment [81–83]. However, due to the restrictions of NMR spectroscopy (method for microstructural analysis of geopolymer matrix), there is still insufficient knowledge regarding the role of Fe_2O_3 in GPC [84]. The current study intends to examine the range of the cumulative percentages of CaO and Fe_2O_3 present in the source material for achieving better performance of GPC.

3.4 Molar Concentration of Sodium Hydroxide

Molar concentration of sodium hydroxide (NaOH) plays a significant role in the synthesis of geopolymerization gel in GPC [85]. Geopolymerization gel is formed by the combined reaction of Na_2O, Al_2O_3, SiO_2 and H_2O (N-A-S-H). In the geopolymerization reaction, the Na^+ ions are used for balancing the charges to form alumina and silicate networks in the mixture [43, 86]. By increasing the molar concentration of NaOH, the solubility of alumina and silicate present in the geopolymer mix also increases [87]. This ultimately results in the higher compressive strength of the final product of GPC [88]. A study [89] was performed on fly ash-based geopolymer mortar in which the authors concluded that the compressive strength of geopolymer mortar is dependent upon the molar concentration NaOH i.e. the higher molar concentration may lead to higher compressive strength. Another study [14] was conducted on metakaolinite based GPC and the authors stated that higher molar concentration of NaOH solution delivers an improved dissolving capability to metakaolinite and develop even reactive bond for the monomer that subsequently increases the intermolecular bond strength of the GPC. It was also demonstrated that the mechanical behavior of metakaolinite-based GPC activated with a combined NaOH and sodium silicate (Na_2SiO_3) solution may be significantly influenced by the NaOH molar concentration. Increasing the molar concentration of NaOH, the apparent density and mechanical properties of GPC were increased.

3.5 Sodium Silicate to Sodium Hydroxide Ratio

The environmental concerns in regards with the manufacturing process of OPC are fully recognized [90, 91], the major concern being the CO_2 emission to the environment. The GPC was introduced by Davidovits that offers an alternate solution in avoiding the environmental concerns [92, 93]. The manufacturing of GPC is same as that of conventional concrete. The production of GPC needs 75% to 80% by mass of aggregate which are bounded together by geopolymer paste. The paste is formed by the reaction of the alumina and silicates present in the source material and the alkaline solution formed by the combination of KOH and K_2SiO_3 or NaOH and Na_2SiO_3. A mixture of Na_2SiO_3 or K_2SiO_3 and NaOH or KOH has been widely utilized as a source of activation material for the fabrication of GPC [90, 94, 95]. The ratio of Na_2SiO_3/NaOH is another significant factor in GPC which has a vital role in the development of compressive strength of geopolymer matrix. According to the data collected from past studies (Table 1), the GPC produced purely from fly ash as a source material has achieved the peak compressive strength of 66.1 MPa while using Na_2SiO_3 to NaOH ratio of 5.05 [96]. On the other hand, it was reported [97, 98] that while using Na_2SiO_3 to NaOH ratio of 1.0, yielded highest compressive strength of 70.2 MPa and 54.40 MPa respectively, whereas Na_2SiO_3 to NaOH ratio of 2.5 yielded in lower compressive strength of 26.10 MPa [99]. In addition, the Na_2SiO_3 to NaOH ratio of 5.0 has given a compressive strength of 26.70 MPa [96]. Based upon the above discussion, different research studies suggests different ratios of Na_2SiO_3/NaOH based on their findings and this disagreement is acceptable because of the different source material and different environmental conditions. The current study intends to examine the range of the Na_2SiO_3/NaOH ratios in the manufacturing of GPC having enhanced mechanical properties.

4 Combination of Different Materials

The most utilized waste material in the manufacturing of GPC is coal fly ash that is attributed due to the presence of high amorphous alumina and silica content. The availability of fly ash worldwide and the key role in the geopolymerization reaction gives a significant importance. The over-all fly ash production throughout the globe is around 480 million tons per annum while the entire quantity of OPC production is around 4 billion tons [2, 100]. Based on these statistics, there is a huge gap within the production of coal fly ash and OPC which would lead to the efficiency of GPC in replacement of OPC. Hence, some new source materials are required other than fly ash to reduce the gap and to replace OPC in the future. In this regard, researchers developed GPC by the combination of different source material i.e. fly ash + granulated lead smelter slag [101], fly ash + RHA [102], fly ash + silica fume [103], fly ash + metakaoline [104] and so on, for the purpose of overcoming the present gap between the production of OPC and fly ash and to solve the environmental problems related to CO_2 emission and waste material disposal.

Recently, the researchers have examined the utilization of different waste material in the production of GPC combining with the fly ash, aiming to enhance the durability and mechanical properties of GPC and at the same time, minimizing the CO_2 emission for sustainable infrastructural development [105]. Patel et al., [106] developed GPC while replacing fly ash by rice husk ash and concluded that up to 15% replacement of fly ash by RHA may increase the compressive strength behavior. Another research was carried out by Kusbiantoro et al., [107] and demonstrated that the replacement of fly ash up to 7% by RHA provides an appropriate condition of fast dissolution for the formation of silicate monomer, which supports the development of aluminosilicate solution in GPC matrix and make a denser geopolymer paste that ultimately results in higher compressive strength. Moreover, from the literature it is revealed that by using different source material in combination with fly ash, their basic parameter (Si/Al, alkaline solution/binder, $CaO + Fe_2O_3$, molar concentration of NaOH and Na_2SiO_3/NaOH ratio) value may remain in the typical range similar to fly ash-based GPC [26, 99].

5 Discussion

With the aim of determining the influence of Si/Al ratio, alkaline solution/binder ratio, Na_2SiO_3/NaOH ratio, molar concentration of NaOH, and the influence of combined percentage of CaO and Fe_2O_3 on the compressive strength of GPC, the data has been collected from the literature which is graphically shown in Figs. 2, 3, 4, 5 and 6 and tabulated in Table 1.

Several researchers developed GPC by considering the different ratios of Si/Al ratio, alkaline solution/binder ratio, Na_2SiO_3/NaOH ratio, molar concentration of NaOH, the effect of combined percentage of CaO and Fe_2O_3 for the purpose of studying the mechanical and chemical properties of GPC [72–75, 96–99, 106–123]. The ratio of Si to Al is an important factor of GPC which affect its compressive strength [124, 125]. Figure 2a and b represent the influence of Si to Al ratio on the 7 and 28-days compressive strength of GPC. Various Si to Al ratios have been defined and used for the manufacturing of GPC having higher durability and enhanced compressive strength. Pham (2020). [116] reported a high compressive strength at Si to Al ratio of 2.5 from basalt-based GPC. Nevertheless, Bignozzi et al. [96] reported high compressive strength at Si to Al ratio of 4 from fly ash-based GPC. This controversy is appropriate because different researchers have used different synthesizing conditions such as type of alkaline solution, binding material, temperature and curing time, etc. Moreover, in literature, the reactionary attribute of silicate precursor on the development of N–A–S–H gel and mechanical behavior of geopolymers is not uniform. Several researchers have demonstrated that with the addition of silicates, the structural stability of geopolymers was

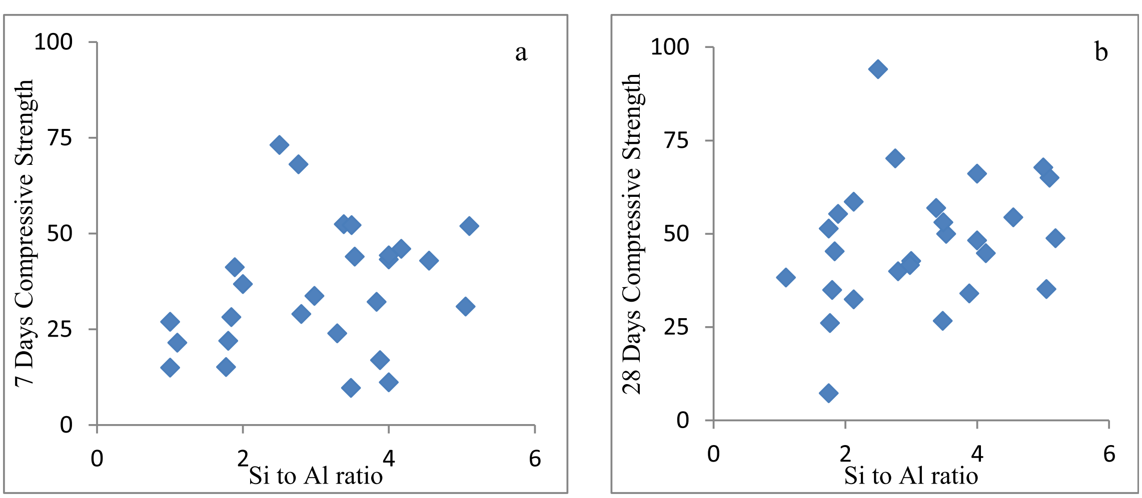

Fig. 2 **a** Influence of Si/Al ratio on 7 days compressive strength, **b** Influence of Si/Al ratio on 28 days compressive strength

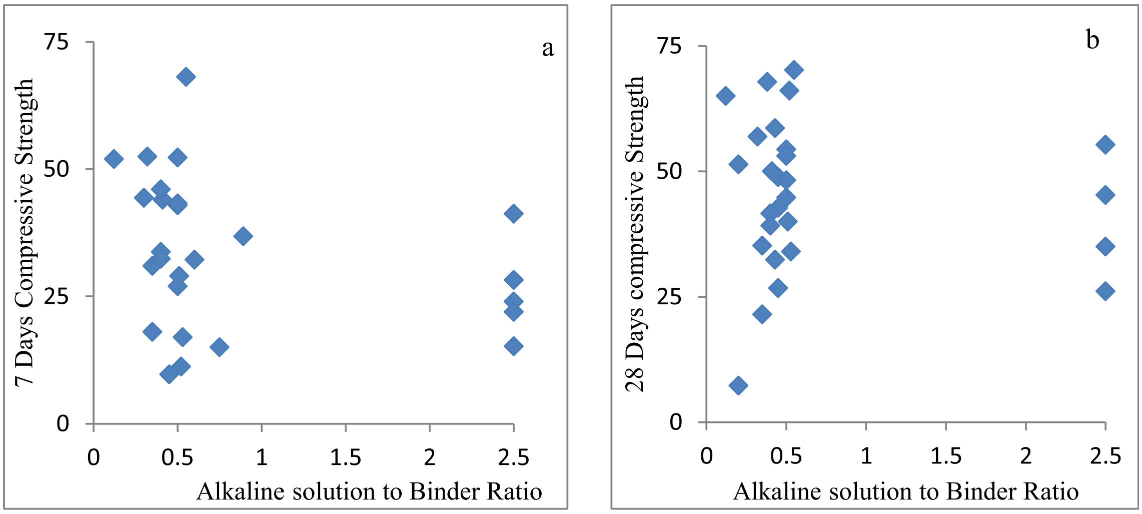

Fig. 3 **a** Influence of alkaline solution to binder ratio on 7 days compressive strength, **b** Influence of alkaline solution to binder ratio on 28 days compressive strength

improved because of the development of Al–O–Si complexes and long chained silicate oligomers within the geopolymers [126, 127].

The results of different alkaline solution to binder ratio and Na_2SiO_3 to NaOH ratios regarding the 7 and 28-days compressive strength are shown in Figs. 3a, b and 6a, b respectively. The figures have no evident and defined trend; however, the peak compressive strength of 66.1 MPa was reported at Na_2SiO_3 to NaOH ratio of 5.05 and an alkaline solution to binder ratio of 0.52, at the age of 28 days [96]. One of the studies [128] reported that by increasing the dosages of fly ash and activator solution concentration, the compressive strength enhances. This is owing to the increase in the amount of NaOH that is commonly obligatory in the reaction of geopolymerization. Moreover, compressive strength of 94.1 MPa was reported by keeping the ratio of Na_2SiO_3 to NaOH as 1 using basalt fiber-based GPC [116]. A similar trend in the result was reported by Chindaprasirt et al., [129]. In his study, the author concluded that for optimum compressive strength, the Na_2SiO_3 to NaOH ratio should be in the range of 0.67 to 1.00, which is quite different from the literature related to GPC. This could be owed to the variability of the Na_2SiO_3 to NaOH ratio that interrupts the pH condition of material and thus would have an influence upon the development of compressive strength of GPC.

Figure 4a and b represent the effect of $Fe_2O_3 + CaO$ on the 7 and 28-days compressive strength of GPC. From figures, it can be determined that the GPC compressive strength increases as the cumulative percentage of $Fe_2O_3 + CaO$ increases as reported by Chindaprasirt et al., [129]. It can be observed that a small increase in the cumulative percentage of $Fe_2O_3 + CaO$ can significantly affect the compressive strength. Moreover, it can be concluded from Figures that GPC made by source material having $Fe_2O_3 + CaO$

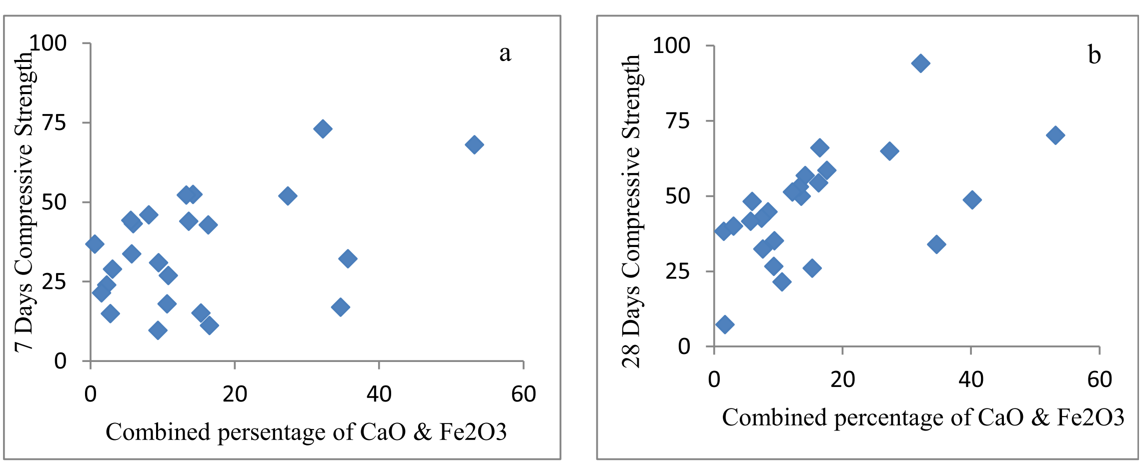

Fig. 4 **a** Influence of combined percentage of CaO and Fe_2O_3 on 7 days compressive strength, **b** Influence of combined percentage of CaO and Fe_2O_3 on 28 days compressive strength

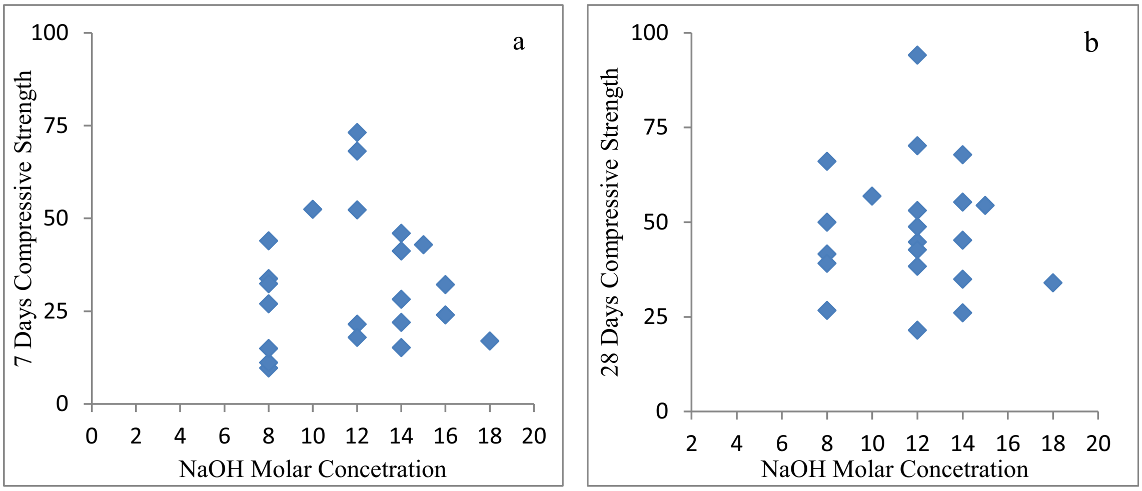

Fig. 5 **a** Influence of NaOH molar concentration on 7 days compressive strength, **b** Influence of NaOH molar concentration on 28 days compressive strength

percentages in the range of 8% to 20% yields better compressive strength as compared to the source material having more than 20% of Fe_2O_3 + CaO.

Figure 5a and b represent the impact of NaOH concentration on the 7 and 28-days compressive strength of GPC. By using 12-M NaOH solution, the compressive strength of 94.12 MPa was attained [116]. This is because of increasing the Na^+ ions in the geopolymer matrix which has a vital role in the geopolymerization reaction. The Na^+ ions are utilized for stability of charges in the geopolymer mixture to form alumina and silicate networks [43]. By increasing the NaOH solution beyond the 12-M, the compressive strength was reduced and the compressive strength of 34 MPa was attained for 18-M concentration [108]. Similar result was reported by Palomo et al., [61], that 12-M NaOH solution gives better strength as compared to 18-M NaOH solution.

Moreover, from the Figs. 2a and 3a, it has been realized that different compressive strengths were achieved for the same molar ratios. For instance, at Si/Al ratio of 4 and alkaline solution to binder ratio of 0.5, the resulting compressive strengths for 7 days decreases dramatically from as high as 43.26 MPa to as low as 11.2 MPa [96, 120]. In addition, it has been noticed from the literature study that the main oxide composition present in source material used for GPC are SiO_2, Al_2O_3, CaO and Fe_2O_3 and their percentages may vary in different source material. However, when GPC is produced by the combination of fly ash + GGBS and fly ash + RHA etc., the parametric ratios (Si/Al, alkaline solution/binder, CaO + Fe_2O_3, molar concentration of NaOH and Na_2SiO_3/NaOH) will remain in the typical range of ratio similar to fly ash-based GPC [112].

6 Conclusions

This study considers different oxide and alkaline solution ratios of source materials utilized for GPC production and their

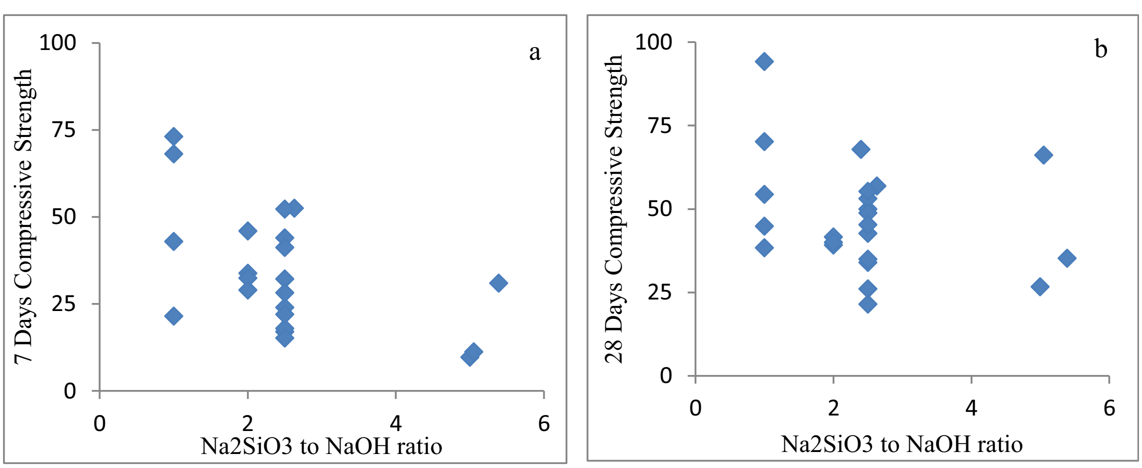

Fig. 6 **a** Influence of Na_2SiO_3 to NaOH ratio on 7 days compressive strength, **b** Influence of Na_2SiO_3 to NaOH ratio on 28 days compressive strength

Table 1 Effect of Si/Al ratio, alkaline solution/binder ratio, CaO + Fe_2O_3, molar concentration of NaOH and Na_2SiO_3/NaOH ratio on the compressive strength of GPC

Material	Oxide composition (%)	Compressive strength		SiO_2/ Al_2O_3	Alkaline solution/ binder ratio	Fe_2O_3 + CaO	NaOH	Na_2SiO_3/ NaOH	Ref.
		7 d	28 d						
Class F-FA	SiO_2: 51.8 Al_2O_3: 27.8 Fe_2O_3: 6.2 CaO: 4.6	27	NDA	1	0.50	10.77	8	NDA	When the system contains excess amount of alkaline activator, the polysialte reaction products tend to be produced which is irrespective of the starting composition [72]
Dehydroxylated white clay	SiO_2: 58.8 Al_2O_3: 32.8 Fe_2O_3: 1.7 CaO: 1.04	15	NDA	1	0.75	2.74	8	NDA	
Class F-FA	SiO_2: 49.7 Al_2O_3: 24.6 Fe_2O_3: 12.7 CaO: 4.9	NDA	58.6	2.13	0.43	17.6	NDA	NDA	The fresh and hardened properties are greatly affected by morphology and origin of the fly and as well as particle size, alkaline metal content, calcium content and amorphous content [73]
	SiO_2: 59.9 Al_2O_3: 21.6 Fe_2O_3: 4.7 CaO: 2.9	NDA	32.4	2.13	0.43	7.6	NDA	NDA	
	SiO_2: 50.1 Al_2O_3: 28.3 Fe_2O_3: 4.0 CaO: 8.2	NDA	51.4	1.75	0.20	12.2	NDA	NDA	
	SiO_2: 61.4 Al_2O_3: 33.0 Fe_2O_3: 1.1 CaO: 0.6	NDA	7.3	1.75	0.20	1.7	NDA	NDA	
Class F-FA	SiO_2: 60.02 Al_2O_3: 34.25 Fe_2O_3: 1.2 CaO: 1.05	24	NDA	3.29	2.50	2.24	16	2.5	The compressive strength is a function of alkaline solution to binder ratio, Na_2SiO_3 to NaOH ratio and molar concentration of NaOH [74]
Class F-FA	SiO_2: 49.4 Al_2O_3: 29.23 Fe_2O_3: 2.7 CaO: 6.6	9.7	26.7	3.48	0.45	9.34	8	5	The fresh and hardened properties are effected by fineness and mineralogical properties rather than by increasing the sodium silicate solution [96]
	SiO_2: 48.2 Al_2O_3: 25.01 Fe_2O_3: 1.3 CaO: 15.2	11.2	66.1	4	0.52	16.5	8	5.05	
Class C-FA	SiO2: 25.9 Al2O3:12.3 Fe2O3:32.3 CaO:20.9	68.1	70.2	2.76	0.55	53.2	12	1	Na_2SiO_3/NaOH ratio highly effect the mechanical strength of GPC [97]
Class F-FA	SiO_2: 45.23 Al_2O_3: 19.95 Fe_2O_3: 13.15 CaO: 15.51	42.92	54.40	4.55	0.5	16.31	15	1	With the usage of higher NaOH concentration, the compressive strength and modulus of elasticity are improved [98]
Class F-FA	SiO_2: 50 Al_2O_3: 28.25 Fe_2O_3: 13.5 CaO: 1.79	15.18	26.10	1.77	2.5	15.29	14	2.5	The addition FA in GGBFS may improve the setting time and compressive strength of the GPC [99]
FA+10%,20% ,30% of GGBFS	SiO_2: 50 Al_2O_3: 28.25 Fe_2O_3: 13.5 CaO: 1.79 + SiO_2: 32.46 Al_2O_3: 14.3 Fe_2O_3: 0.61 CaO: 43.1	21.98 28.20 41.25	34.98 45.28 55.30	1.80 1.84 1.89	2.5 2.5 2.5	NA NA NA	14 14 14	2.5 2.5 2.5	
Class F-FA	SiO_2: 51.75 Al_2O_3: 34.75	NDA	42.7	3	0.45	7.4	12	2.5	The optimal replacement level of RHA with GGBFS is 5%

Table 1 (continued)

Material	Oxide composition (%)	Compressive strength		SiO_2/Al_2O_3	Alkaline solution/ binder ratio	Fe_2O_3 + CaO	NaOH	Na_2SiO_3/ NaOH	Ref.
		7 d	28 d						
	Fe_2O_3: 6 CaO: 1.4								at ambient curing and 15% at a curing temperature of 70 °C [106]
GGBS	SiO_2: 34 Al_2O_3: 14.3 Fe_2O_3: 0.5 CaO: 39.7	NDA	48.8	5.19	0.45	40.2	12	2.5	
Class F-FA	SiO_2: 51.7 Al_2O_3: 29.1 Fe_2O_3: 4.76 CaO: 8.84	44	50	3.53	0.41	13.6	8	2.5	The high temperature provides an appropriate condition for fast dissolution of the monomers of silicate and oligomer from RHA surfaces that encourages the development of aluminosilicate solution in geopolymer matrix [107]
Class F-FA	SiO_2: 36.02 Al_2O_3: 20.58 Fe_2O_3: 15.91 CaO: 18.75	17	34	3.88	0.53	34.66	18	2.5	At SiO_2/Al_2O_3 ratio of 15.9, highest compressive strength was achieved. Fly ash was more reactive than RHBA [108]
Class F-FA	SiO_2: 49.45 Al_2O_3: 29.61 Fe_2O_3: 10.72 CaO: 3.47	52.5	56.9	3.38	0.32	14.19	10	2.63	The compressive strength is significantly increased by increasing the MS from 0.75 to 1.0 and 1.25 owing to the increment in the dissolution of FA and rate of reaction [109]
Class F-FA	SiO_2: 55.3 Al_2O_3: 25.8 Fe_2O_3: 5.5 CaO: 2.9	42.9	44.8	4.13	0.5	8.4	12	1	The higher molarity of alkaline activators has considerable effect on the early strength [110]
Class F-FA	SiO_2: 51.3 Al_2O_3: 30.1 Fe_2O_3: 4.57 CaO: 8.73	52.26	53.08	3.49	0.5	13.3	12	2.5	Compressive strength and workability increases with the increase in the dosage of superplasticizer [111].
Class F-FA	SiO_2: 53 Al_2O_3: 33 Fe_2O_3: 4.2 CaO: 1.5	33.77	41.62	2.98	0.4	5.7	8	2	Replacement of FA with RHA in different percentages has not shown any positive sign regarding the mechanical properties [112]
Class F-FA +10% RHA	SiO_2: 53 Al_2O_3: 33 Fe_2O_3: 4.2 CaO: 1.5 + SiO_2: 82.7 Al_2O_3: 0.15 Fe_2O_3: 0.16 CaO: 0.55	32.4	39.16	NA	0.4	NA	8	2	
Class F-FA	SiO_2: 57.30 Al_2O_3: 27.13 Fe_2O_3: 8.06 CaO: 0.03	46	NDA	4.17	0.4	8.09	14	2	The Compressive strength of GPC increases while increasing the curing temperature, curing time, rest time, concentration of NaOH solution. Whereas, it reduces while increasing the water to geopolymer ratio and admixture dosage [113]
Class C-FA	SiO_2: 32.10 Al_2O_3: 19.90 Fe_2O_3: 16.91 CaO: 18.75	32.2	NDA	3.83	0.6	35.66	16	2.5	Corrosion and chloride penetration of embedded steel decreases with the increase in NaOH concentration [114]
Class F-FA	SiO_2: 56.48	31	35.2	5.05	0.35	9.43	NDA	5.39	

Table 1 (continued)

Material	Oxide composition (%)	Compressive strength		SiO_2/ Al_2O_3	Alkaline solution/ binder ratio	Fe_2O_3 + CaO	NaOH	Na_2SiO_3/ NaOH	Ref.
		7 d	28 d						
	Al_2O_3: 20.34 Fe_2O_3: 6.61 CaO: 2.82								Alkaline solution to binder ratio of 0.35, GPC possesses better durability and mechanical properties as compared to other various ratios [115]
Rice husk ash	SiO_2: 90 Al_2O_3: 0.46 Fe_2O_3: 0.43 CaO: 1.10	21.50	38.33	1.1	NDA	1.53	12	1	Basalt fibers had a positive influence on fiber-matrix transition zone as a result compressive strength, flexural strength, initial setting time, final setting time and bulk density increases [116]
Basalt Fiber	SiO_2:46.5 Al_2O_3:13.4 Fe_2O_3:0.79 CaO:31.4	73.12	94.12	2.5	NDA	32.19	12	1	
Sugar cane bagasse ash	SiO_2: 66.7 Al_2O_3: 9.24 Fe_2O_3: 1.53 CaO: 10.07	18	21.5	NDA	0.35	11.58	12	2.5	The combination of SBA and PP composite can provide alternative ways to achieve sustainable GPC [117]
Metakaolin	SiO_2: 52.8 Al_2O_3: 43.7 Fe_2O_3: 0.6 CaO: –	36.8	NDA	2	0.89	0.6	NDA	NDA	The compressive strength of GPC at different Si to Al ratios depends upon the development of N-A-S-H gel, instead of the silicate derivatives or zeolitic nuclei [118]
Class F-FA	SiO_2: 43.7 Al_2O_3: 21.0 Fe_2O_3: 22.5 CaO: 4.85	52	65	5.1	0.12	27.35	NDA	NDA	Significant change has been observed in compressive strength by changing SiO_2/Al_2O_3 from 4.0 to 6.0 [119]
Class F-FA	SiO_2: 56.01 Al_2O_3: 29.8 Fe_2O_3: 3.58 CaO: 2.36	43.26	48.2	4	0.50	5.94	NDA	NDA	SEM and XRD results shows formation of a new amorphous alumina-silicate phase i.e. hydroxysodalite and herschelite which may affect the development of compressive strength [120]
Class F-FA	SiO_2: 55.15 Al_2O_3: 30.85 Fe_2O_3: 3.15 CaO: 2.45	44.36	NDA	4	0.3	5.6	12	NDA	The compressive strength and microstructure of GPC is dependent on alkaline content, silica content and water to binder ratio [121]
kaolin clay	SiO_2: 52.3 Al_2O_3: 39.8 Fe_2O_3: 1.29 CaO: 1.75	29	40	2.8	0.51	3.04	NDA	2	The kaolin based geopolymer concrete will be competitive to the cement concrete [122]
Class F-FA+Copper Slag + Crusher dust	SiO_2: 50.47 Al_2O_3: 28.76 Fe_2O_3: 4.3 CaO: 0.81 + SiO_2: 10.98 Al_2O_3: 2.35 Fe_2O_3: 37.41 CaO: 0.67	NDA	67.8	5.004	0.38	NA	14	2.4	Investigation on inclusion of copper slag to fly ash based geopolymer and their design parameters [123]

Where, *NDA*, no data available; *FA*, fly ash; *GPC*, geopolymer concrete; *RHA*, rice husk ash; *SBA*, sugar can baggas ash; *PP*, polypropylene; *GGBFS*, ground granulate blast furnace slag; *NA*, not applicable

corresponding influence on the compressive strength. From the past studies, it was found that different ratios of Si to Al, alkaline solution to binder, Na_2SiO_3 to NaOH, molar concentration of NaOH and combined percentages of CaO and Fe_2O_3

used in GPC has a significant impact on the compressive strength. Thus, special attention is required while selecting the above-mentioned ratios to be used for the production of GPC. Besides, while achieving higher compressive strength, it is very essential to find out the optimum level of each ratio. The ratio of Si to Al, alkaline solution to binder, Na_2SiO_3 to NaOH, the molar concentration of NaOH, used in geopolymer concrete should be in the range of 1–5.2, 0.2–2.5, 1–5.4, 8–18 and combined percentage of CaO and Fe_2O_3 should not be more than 10 to 25%. As SiO_2 and Al_2O_3 are the two main oxides of source material and their ratios predominantly govern the formation of geopolymerization gel which ultimately affects the compressive strength. Thus, knowledge of typical ranges of oxide compositions in the source material employed for GPC is of prime importance. It can be concluded from the literature studies that SiO_2 and Al_2O_3 in the ranges of 40 to 65% and 20 to 35% respectively, would result in higher compressive strength in case of fly ash-based GPC but for other material it may varies. The typical range of various parameter and oxides ratio is extremely important in choosing the correct source materials to be used for GPC when different source materials are available. The authors encourage further studies regarding, the mix design of GPC, based on the oxide ratios and alkaline solution ratios in order to know a fixed range of these parameters for a fixed value of compressive strength just like in ordinary concrete mix design.

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Authors Contributions All authors whose names appear on the submission made substantial contributions to the conception, analysis, interpretation of data and writing/revision of the article.

Data Availability The data used to support the findings of this study are included within the article.

Declarations

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare that there is no conflict of interest.

References

1. Lawrence CD (2003) The production of low-energy cements. Lea's Chemistry of Cement and Concrete:421–470
2. U.S. Geological Survey (2014). Mineral commodity summaries 2014. Mineral Commodity Summaries. https://doi.org/10.3133/70100414
3. Gjorv OE (1989) Alkali activation of a Norwegian granulated blast furnace slag. In: Proc. third international conference on FA, silica fume, slag, and natural Pozzolans in concrete, Trondheim, Norway, pp. 1501–1518
4. Philleo RE (1989). Slag or other supplementary materials? In: Proceedings of the third international conference on FA, silica fume, slag, and natural Pozzolans in concrete, Trondheim, Norway, pp. 1197–1208
5. Amran YHM, Alyousef R, Alabduljabbar H, El-Zeadani M (2020) Clean production and properties of geopolymer concrete; a review. J Clean Prod 251:119679. https://doi.org/10.1016/j.jclepro.2019.119679
6. Razak S, Zainal FF, Shamsudin SR (2020) Effect of porosity and water absorption on compressive strength of Fly ash based Geopolymer and OPC paste. IOP Conference Series: Materials Science and Engineering 957:012035. https://doi.org/10.1088/1757-899x/957/1/012035
7. Bellum RR, Muniraj K, Madduru SRC (2020) Exploration of mechanical and durability characteristics of fly ash-GGBFS based green geopolymer concrete. SN Applied Sciences 2(5). https://doi.org/10.1007/s42452-020-2720-5
8. Verma M, Dev N (2020) Sodium hydroxide effect on the mechanical properties of flyash-slag based geopolymer concrete. Struct Concr 22. https://doi.org/10.1002/suco.202000068
9. Madani H, Ramezanianpour AA, Shahbazinia M, Ahmadi E (2020) Geopolymer bricks made from less active waste materials. Constr Build Mater 247:118441. https://doi.org/10.1016/j.conbuildmat.2020.118441
10. Silva G, Kim S, Bertolotti B, Nakamatsu J, Aguilar R (2020) Optimization of a reinforced geopolymer composite using natural fibers and construction wastes. Constr Build Mater 258:119697. https://doi.org/10.1016/j.conbuildmat.2020.119697
11. Sandanayake M, Gunasekara C, Law D, Zhang G, Setunge S, Wanijuru D (2020) Sustainable criterion selection framework for green building materials – an optimisation based study of fly-ash Geopolymer concrete. Sustain Mater Technol 25:e00178. https://doi.org/10.1016/j.susmat.2020.e00178
12. Silva PD, Sagoe-Crenstil K, Sirivivatnanon V (2007) Kinetics of geopolymerization: role of Al2O3 and SiO2. Cem Concr Res 37(4):512–518. https://doi.org/10.1016/j.cemconres.2007.01.003
13. Duxson P, Fernández-Jiménez A, Provis JL, Lukey GC, Palomo A, van Deventer JSJ (2006) Geopolymer technology: the current state of the art. J Mater Sci 42(9):2917–2933. https://doi.org/10.1007/s10853-006-0637-z
14. Wang H, Li H, Yan F (2005) Synthesis and mechanical properties of metakaolinite-based geopolymer. Colloids Surf A Physicochem Eng Asp 268(1–3):1–6. https://doi.org/10.1016/j.colsurfa.2005.01.016
15. Xu H, Van Deventer JSJ (2002) Geopolymerisation of multiple minerals. Miner Eng 15(12):1131–1139. https://doi.org/10.1016/s0892-6875(02)00255-8
16. Buchwald A, Hohmann M, Posern K, Brendler E (2009) The suitability of thermally activated illite/smectite clay as raw material for geopolymer binders. Appl Clay Sci 46(3):300–304. https://doi.org/10.1016/j.clay.2009.08.026
17. Krivenko PV, Kovalchuk GY (2007) Directed synthesis of alkaline aluminosilicate minerals in a geocement matrix. J Mater Sci 42(9):2944–2952. https://doi.org/10.1007/s10853-006-0528-3
18. Bajpai R, Choudhary K, Srivastava A, Sangwan KS, Singh M (2020) Environmental impact assessment of fly ash and silica fume based geopolymer concrete. J Clean Prod 254:120147. https://doi.org/10.1016/j.jclepro.2020.120147

19. Pacheco-Torgal F, Castro-Gomes J, Jalali S (2008) Alkali-activated binders: a review. Part 2. About materials and binders manufacture. Constr Build Mater 22(7):1315–1322. https://doi.org/10.1016/j.conbuildmat.2007.03.019
20. Nazari A, Bagheri A, Riahi S (2011) Properties of geopolymer with seeded fly ash and rice husk bark ash. Mater Sci Eng A 528(24):7395–7401. https://doi.org/10.1016/j.msea.2011.06.027
21. Hajjaji, W., Andrejkovičová, S., Zanelli, C., Alshaaer, M., Dondi, M., Labrincha, J. A., & Rocha, F. (2013). Composition and technological properties of geopolymers based on metakaolin and red mud. Mater Des (1980-2015), 52, 648–654. doi:https://doi.org/10.1016/j.matdes.2013.05.058
22. Giasuddin HM, Sanjayan JG, Ranjith PG (2013) Strength of geopolymer cured in saline water in ambient conditions. Fuel 107:34–39. https://doi.org/10.1016/j.fuel.2013.01.035
23. Yusuf MO, Megat Johari MA, Ahmad ZA, Maslehuddin M (2014) Strength and microstructure of alkali-activated binary blended binder containing palm oil fuel ash and ground blast-furnace slag. Constr Build Mater 52:504–510. https://doi.org/10.1016/j.conbuildmat.2013.11.012
24. Oh JE, Monteiro PJM, Jun SS, Choi S, Clark SM (2010) The evolution of strength and crystalline phases for alkali-activated ground blast furnace slag and fly ash-based geopolymers. Cem Concr Res 40(2):189–196. https://doi.org/10.1016/j.cemconres.2009.10.010
25. Aydın S, Baradan B (2012) Mechanical and microstructural properties of heat cured alkali-activated slag mortars. Mater Des 35: 374–383. https://doi.org/10.1016/j.matdes.2011.10.005
26. He J, Jie Y, Zhang J, Yu Y, Zhang G (2013) Synthesis and characterization of red mud and rice husk ash-based geopolymer composites. Cem Concr Compos 37:108–118. https://doi.org/10.1016/j.cemconcomp.2012.11.010
27. Boskovic I, Vukcevic M, Zejak R (2015). The influence of the amorphous SiO2 content on the characteristics of red mud based geopolymers. Third International Conference on Advances in Bio-Informatics and Environmental Engineering - ICABEE 2015. https://doi.org/10.15224/978-1-63248-078-1-89
28. Rehman SKU, Imtiaz L, Aslam F, Khan MK, Haseeb M, Javed MF, Alabduljabbar H (2020) Experimental investigation of NaOH and KOH mixture in SCBA-based Geopolymer cement composite. Materials 13(15):3437. https://doi.org/10.3390/ma13153437
29. Chen Y, Zhang Y, Chen T, Zhao Y, Bao S (2011) Preparation of eco-friendly construction bricks from hematite tailings. Constr Build Mater 25(4):2107–2111. https://doi.org/10.1016/j.conbuildmat.2010.11.025
30. Ahmari S, Zhang L (2012) Production of eco-friendly bricks from copper mine tailings through geopolymerization. Constr Build Mater 29:323–331. https://doi.org/10.1016/j.conbuildmat.2011.10.048
31. Duxson P, Mallicoat SW, Lukey GC, Kriven WM, van Deventer JSJ (2007) The effect of alkali and Si/Al ratio on the development of mechanical properties of metakaolin-based geopolymers. Colloids Surf A Physicochem Eng Asp 292(1):8–20. https://doi.org/10.1016/j.colsurfa.2006.05.044
32. Pelisser F, Guerrino EL, Menger M, Michel MD, Labrincha JA (2013) Micromechanical characterization of metakaolin-based geopolymers. Constr Build Mater 49:547–553. https://doi.org/10.1016/j.conbuildmat.2013.08.081
33. Liu Y, Shi C, Zhang Z, Li N, Shi D (2020) Mechanical and fracture properties of ultra-high performance geopolymer concrete: effects of steel fiber and silica fume. Cem Concr Compos 112: 103665. https://doi.org/10.1016/j.cemconcomp.2020.103665
34. Dimas D, Giannopoulou I, Panias D (2009) Polymerization in sodium silicate solutions: a fundamental process in geopolymerization technology. J Mater Sci 44(14):3719–3730. https://doi.org/10.1007/s10853-009-3497-5
35. Davidovits J (2014) Geopolymer Chemistry and Applications, Geopolymer Institute, Third ed 8
36. Komljenović M, Baščarević Z, Bradić V (2010) Mechanical and microstructural properties of alkali-activated fly ash geopolymers. J Hazard Mater 181(1–3):35–42. https://doi.org/10.1016/j.jhazmat.2010.04.064
37. Reddy DV, Edouard JB, Sobhan K, Rajpathak SS (2011) Proceeding of 36th conference on 11 OUR WORLD IN CONCR. & STRUCT., Singapore
38. Xie Z, Xi Y (2001) Hardening mechanisms of an alkaline-activated class F fly ash. Cem Concr Res 31(9):1245–1249. https://doi.org/10.1016/s0008-8846(01)00571-3
39. Ridtirud C, Chindaprasirt P, Pimraksa K (2011) Factors affecting the shrinkage of fly ash geopolymers. Int J Miner Metall Mater 18(1):100–104. https://doi.org/10.1007/s12613-011-0407-z
40. Yahya Z, Abdullah M, Hussin K, Ismail K, Razak R, Sandu A (2015) Effect of solids-to-liquids, Na2SiO3-to-NaOH and curing temperature on the palm oil boiler ash (Si + Ca) Geopolymerisation system. Materials 8(5):2227–2242. https://doi.org/10.3390/ma8052227
41. Gunasekara MPCM, Law DW (2014) 23rd Australasian Conf. on the Mechanics of Struct. And Mater., Byron Bay, Australia, 113-118
42. Sukmak P, Horpibulsuk S, Shen SL (2013) Strength development in clay–fly ash geopolymer. Constr Build Mater 40:566–574. https://doi.org/10.1016/j.conbuildmat.2012.11.015
43. Sathonsaowaphak A, Chindaprasirt P, Pimraksa K (2009) Workability and strength of lignite bottom ash geopolymer mortar. J Hazard Mater 168(1):44–50. https://doi.org/10.1016/j.jhazmat.2009.01.120
44. Matthew SJ, Mary UC (2015). World of coal ash conference www.worldofcoalash.org
45. Hardjito, D., & Rangan, B.V. (2005). Development and properties of low-calcium Fly ash-based Geopolymer Concr. Res. Report GC
46. Kong DLY, Sanjayan JG (2008) Damage behavior of geopolymer composites exposed to elevated temperatures. Cem Concr Compos 30(10):986–991. https://doi.org/10.1016/j.cemconcomp.2008.08.001
47. Gao K, Lin KL, Wang D, Hwang CL, Shiu HS, Chang YM, Cheng TW (2014) Effects SiO2/Na2O molar ratio on mechanical properties and the microstructure of nano-SiO2 metakaolin-based geopolymers. Constr Build Mater 53:503–510. https://doi.org/10.1016/j.conbuildmat.2013.12.003
48. Ghanbari M, Hadian AM, Nourbakhsh AA (2015) Effect of processing parameters on compressive strength of Metakaolinite based Geopolymers: using DOE approach. Procedia Mater Sci 11:711–716. https://doi.org/10.1016/j.mspro.2015.11.047
49. Khale D, Chaudhary R (2007) Mechanism of geopolymerization and factors influencing its development: a review. J Mater Sci 42(3):729–746. https://doi.org/10.1007/s10853-006-0401-4
50. Xu H, Van Deventer JSJ (2000) The geopolymerisation of alumino-silicate minerals. Int J Miner Process 59(3):247–266. https://doi.org/10.1016/s0301-7516(99)00074-5
51. Davidovits J (1991) Geopolymers. J Therm Anal 37(8):1633–1656. https://doi.org/10.1007/bf01912193
52. Palomo A, Glasser F (1992) Chemically-bonded cementitious materials based on metakaolin, British ceramic. Transp J 91(4):107–112
53. Van Jaarsveld JGS, Van Deventer JSJ, Lorenzen L (1997) The potential use of geopolymeric materials to immobilise toxic metals: part I. theory and applications. Miner Eng 10(7):659–669. https://doi.org/10.1016/s0892-6875(97)00046-0
54. Davidovits, J. (1982). The need to create a new technical language for the transfer of basic scientific information. Transfer and Exploitation of Scientific and Technical Information

Luxembrourg, Commission of the European Communities, 7716, 42 (2007) 729–746
55. Liu X, Wu Y, Li M, Jiang J, Guo L, Wang W, Duan P (2020) Effects of graphene oxide on microstructure and mechanical properties of graphene oxide-geopolymer composites. Constr Build Mater 247:118544. https://doi.org/10.1016/j.conbuildmat.2020.118544
56. Reddy MS, Dinakar P, Rao BH (2016) A review of the influence of source material's oxide composition on the compressive strength of geopolymer concrete. Microporous Mesoporous Mater 234:12–23. https://doi.org/10.1016/j.micromeso.2016.07.005
57. Rao F, Liu Q (2015) Geopolymerization and its potential application in mine tailings consolidation: a review. Miner Process Extr Metall Rev 36(6):399–409. https://doi.org/10.1080/08827508.2015.1055625
58. Fernández-Jiménez A, Palomo A (2005) Composition and microstructure of alkali activated fly ash binder: effect of the activator. Cem Concr Res 35(10):1984–1992. https://doi.org/10.1016/j.cemconres.2005.03.003
59. Zhang F, Zhang L, Liu M, Mu C, Liang YN, Hu X (2017) Role of alkali cation in compressive strength of metakaolin based geopolymers. Ceram Int 43(4):3811–3817. https://doi.org/10.1016/j.ceramint.2016.12.034
60. Xie J, Wang J, Rao R, Wang C, Fang C (2019) Effects of combined usage of GGBS and fly ash on workability and mechanical properties of alkali activated geopolymer concrete with recycled aggregate. Compos Part B 164:179–190. https://doi.org/10.1016/j.compositesb.2018.11.067
61. Palomo A, Grutzeck MW, Blanco MT (1999) Alkali-activated fly ashes. Cem Concr Res 29(8):1323–1329. https://doi.org/10.1016/s0008-8846(98)00243-9
62. Shi C, Jiménez AF, Palomo A (2011) New cements for the 21st century: the pursuit of an alternative to Portland cement. Cem Concr Res 41(7):750–763. https://doi.org/10.1016/j.cemconres.2011.03.016
63. Fernandez-Jimenez A, García-Lodeiro I, Palomo A (2006) Durability of alkali-activated fly ash cementitious materials. J Mater Sci 42(9):3055–3065. https://doi.org/10.1007/s10853-006-0584-8
64. Palomo A, Blanco-Varela MT, Granizo ML, Puertas F, Vazquez T, Grutzeck MW (1999) Chemical stability of cementitious materials based on metakaolin. Cem Concr Res 29(7):997–1004. https://doi.org/10.1016/s0008-8846(99)00074-5
65. Fernández-Jiménez A, Monzó M, Vicent M, Barba A, Palomo A (2008) Alkaline activation of metakaolin–fly ash mixtures: obtain of Zeoceramics and Zeocements. Microporous Mesoporous Mater 108(1–3):41–49. https://doi.org/10.1016/j.micromeso.2007.03.024
66. Provis JL, Lukey GC, van Deventer JSJ (2005) Do Geopolymers actually contain Nanocrystalline zeolites? A reexamination of existing results. Chem Mater 17(12):3075–3085. https://doi.org/10.1021/cm050230i
67. Villaquirán-Caicedo MA (2019) Studying different silica sources for preparation of alternative waterglass used in preparation of binary geopolymer binders from metakaolin/boiler slag. Constr Build Mater 227:116621. https://doi.org/10.1016/j.conbuildmat.2019.08.002
68. Barbosa VF, MacKenzie KJ, Thaumaturgo C (2000) Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: sodium polysialate polymers. Int J Inorg Mater 2(4):309–317. https://doi.org/10.1016/s1466-6049(00)00041-6
69. Fernández-Jiménez A, Palomo A (2003) Characterisation of fly ashes. Potential reactivity as alkaline cements☆. Fuel 82(18):2259–2265. https://doi.org/10.1016/s0016-2361(03)00194-7
70. Provis JL, Yong CZ, Duxson P, van Deventer JSJ (2009) Correlating mechanical and thermal properties of sodium silicate-fly ash geopolymers. Colloids Surf A Physicochem Eng Asp 336(1–3):57–63. https://doi.org/10.1016/j.colsurfa.2008.11.019
71. ZUHUA Z, XIAO Y, HUAJUN Z, YUE C (2009) Role of water in the synthesis of calcined kaolin-based geopolymer. Appl Clay Sci 43(2):218–223. https://doi.org/10.1016/j.clay.2008.09.003
72. Ruiz-Santaquiteria C, Skibsted J, Fernández-Jiménez A, Palomo A (2012) Alkaline solution/binder ratio as a determining factor in the alkaline activation of aluminosilicates. Cem Concr Res 42(9):1242–1251. https://doi.org/10.1016/j.cemconres.2012.05.019
73. Van Jaarsveld JGS, van Deventer JSJ, Lukey GC (2003) The characterisation of source materials in fly ash-based geopolymers. Mater Lett 57(7):1272–1280. https://doi.org/10.1016/s0167-577x(02)00971-0
74. Joshi, S.V., & Kadu, M.S. (2012). Role of alkaline activator in development of eco-friendly fly ash based geo polymer concrete. International Journal of Environmental Science and Development, 417–421. https://doi.org/10.7763/ijesd.2012.v3.258
75. Lloyd N, Rangan B (2010) 2nd Int. Conf. on Sustainable Constr. Mater. & Technol, Ancona, Italy
76. Vaidya S, Diaz E, Allouche E (2011) World of coal ash (WOCA) Denver USA
77. Puligilla S, Mondal P (2013) Role of slag in microstructural development and hardening of fly ash-slag geopolymer. Cem Concr Res 43:70–80. https://doi.org/10.1016/j.cemconres.2012.10.004
78. Chindaprasirt P, De Silva P, Sagoe-Crentsil K, Hanjitsuwan S (2012) Effect of SiO2 and Al2O3 on the setting and hardening of high calcium fly ash-based geopolymer systems. J Mater Sci 47(12):4876–4883. https://doi.org/10.1007/s10853-012-6353-y
79. Wongpa J, Kiattikomol K, Jaturapitakkul C, Chindaprasirt P (2010) Compressive strength, modulus of elasticity, and water permeability of inorganic polymer concrete. Mater Des 31(10):4748–4754. https://doi.org/10.1016/j.matdes.2010.05.012
80. Diaz EI, Allouche EN, Eklund S (2010) Factors affecting the suitability of fly ash as source material for geopolymers. Fuel 89(5):992–996. https://doi.org/10.1016/j.fuel.2009.09.012
81. Gomes KC, Torres SM, de Barros S, Barbosa NP (2008) ETDCM8- 8th seminar on experimental techniques and Design in Composite Materials
82. Gomes KC, Torres SM, de Barros S, Barbosa NP (2009). in: Solid Mechanics in Brazil 09 edited by H. S. C. Mattos, M. Alves, Associação Brasileira de Engenharia e Ciências Mecânicas. 2
83. Komnitsas K, Zaharaki D (2009) in: Structure, processing, properties and industrial applications PART II: Manufacture and properties of geopolymers, edited by J. Provis and Jannie S.J. van Deventer, CRC Press, Woodhead Publishing Ltd, Oxford 343
84. Gomes KC, Lima GST, Torres SM, de Barros SR, Vasconcelos IF, Barbosa NP (2010) Iron distribution in Geopolymer with ferromagnetic rich precursor. Mater Sci Forum 643:131–138. https://doi.org/10.4028/www.scientific.net/msf.643.131
85. Puertas F, Martínez-Ramírez S, Alonso S, Vázquez T (2000) Alkali-activated fly ash/slag cements. Cem Concr Res, 30(10), 1625–1632. https://doi.org/10.1016/s0008-8846(00)00298-2
86. Wang Y, Liu X, Zhang W, Li Z, Zhang Y, Li Y, Ren Y (2020) Effects of Si/Al ratio on the efflorescence and properties of fly ash based geopolymer. J Clean Prod 244:118852. https://doi.org/10.1016/j.jclepro.2019.118852
87. Gasteiger HA, Frederick WJ, Streisel RC (1992) Solubility of aluminosilicates in alkaline solutions and a thermodynamic equilibrium model. Ind Eng Chem Res 31(4):1183–1190. https://doi.org/10.1021/ie00004a031
88. Safari Z, Kurda R, Al-Hadad B, Mahmood F, Tapan M (2020) Mechanical characteristics of pumice-based geopolymer paste.

Resour Conserv Recycl 162:105055. https://doi.org/10.1016/j.resconrec.2020.105055

89. Hardjito D, Cheak CC, Lee Ing CH (2008) Strength and setting times of low calcium Fly ash-based Geopolymer mortar. Mod Appl Sci 2(4). https://doi.org/10.5539/mas.v2n4p3
90. Hardjito D, Wallah SE, Sumajouw DMJ, Rangan BV (2005) Fly ash-based Geopolymer concrete. Aust J Struct Eng 6(1):77–86. https://doi.org/10.1080/13287982.2005.11464946
91. Shah SP, Wang K (2009) Development of 'green' cement for sustainable concrete using cement kiln dust and Fly ash, International Workshop on Sustainable Development and Concrete Technology, 15–23
92. Davidovits J (1999) Chemistry of Geopolymeric systems, terminology in: proceedings of 99 international conference. eds. Joseph Davidovits, R. Davidovits & C. James, France
93. Davidovits J (1994, October) Properties of geopolymer cements. In First international conference on alkaline cements and concretes (Vol. 1, pp. 131-149). Kiev State Technical University, Ukraine: Scientific Research Institute on Binders and Materials
94. Rangan BV (2008) in: Low-calcium, fly-ash-based geopolymer concrete, concrete construction engineering handbook, Taylor and Francis Group, LLC, 1–19
95. Bondar D, Lynsdale CJ, Milestone NB, Hassani N, Ramezanianpour AA (2011) Effect of type, form, and dosage of activators on strength of alkali-activated natural pozzolans. Cem Concr Compos 33(2):251–260. https://doi.org/10.1016/j.cemconcomp.2010.10.021
96. Bignozzi MC, Manzi S, Natali ME, Rickard WDA, van Riessen A (2014) Room temperature alkali activation of fly ash: the effect of Na 2 O/SiO 2 ratio. Constr Build Mater 69:262–270. https://doi.org/10.1016/j.conbuildmat.2014.07.062
97. Malkawi AB, Nuruddin MF, Fauzi A, Almattarneh H, Mohammed BS (2016) Effects of alkaline solution on properties of the HCFA Geopolymer mortars. Procedia Engineering 148:710–717. https://doi.org/10.1016/j.proeng.2016.06.581
98. Rattanasak U, Chindaprasirt P (2009) Influence of NaOH solution on the synthesis of fly ash geopolymer. Miner Eng 22(12):1073–1078. https://doi.org/10.1016/j.mineng.2009.03.022
99. Nath P, Sarker PK (2014) Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Constr Build Mater 66:163–171. https://doi.org/10.1016/j.conbuildmat.2014.05.080
100. Feuerborn HJ (2005, November). Coal ash utilisation over the world and in Europe. In Workshop on environmental and health aspects of coal ash utilization (Vol. 5)
101. Albitar M, Mohamed Ali MS, Visintin P, Drechsler M (2015) Effect of granulated lead smelter slag on strength of fly ash-based geopolymer concrete. Constr Build Mater 83:128–135. https://doi.org/10.1016/j.conbuildmat.2015.03.009
102. Nuaklong P, Jongvivatsakul P, Pothisiri T, Sata V, Chindaprasirt P (2020) Influence of rice husk ash on mechanical properties and fire resistance of recycled aggregate high-calcium fly ash geopolymer concrete. J Clean Prod 252:119797. https://doi.org/10.1016/j.jclepro.2019.119797
103. Okoye FN, Durgaprasad J, Singh NB (2016) Effect of silica fume on the mechanical properties of fly ash based-geopolymer concrete. Ceram Int 42(2):3000–3006. https://doi.org/10.1016/j.ceramint.2015.10.084
104. Wang YS, Alrefaei Y, Dai JG (2020) Influence of coal fly ash on the early performance enhancement and formation mechanisms of silico-aluminophosphate geopolymer. Cem Concr Res 127:105932. https://doi.org/10.1016/j.cemconres.2019.105932
105. Fairbairn EMR, Americano BB, Cordeiro GC, Paula TP, Toledo Filho RD, Silvoso MM (2010) Cement replacement by sugar cane bagasse ash: CO2 emissions reduction and potential for carbon credits. J Environ Manag 91(9):1864–1871. https://doi.org/10.1016/j.jenvman.2010.04.008
106. Patel YJ, Shah N (2018) Development of self-compacting geopolymer concrete as a sustainable construction material. Sustainable Environment Research 28(6):412–421. https://doi.org/10.1016/j.serj.2018.08.004
107. Kusbiantoro A, Nuruddin MF, Shafiq N, Qazi SA (2012) The effect of microwave incinerated rice husk ash on the compressive and bond strength of fly ash based geopolymer concrete. Constr Build Mater 36:695–703. https://doi.org/10.1016/j.conbuildmat.2012.06.064
108. Songpiriyakij S, Kubprasit T, Jaturapitakkul C, Chindaprasirt P (2010) Compressive strength and degree of reaction of biomass- and fly ash-based geopolymer. Constr Build Mater 24(3):236–240. https://doi.org/10.1016/j.conbuildmat.2009.09.002
109. Law DW, Adam AA, Molyneaux TK, Patnaikuni I, Wardhono A (2014) Long term durability properties of class F fly ash geopolymer concrete. Mater Struct 48(3):721–731. https://doi.org/10.1617/s11527-014-0268-9
110. Ryu GS, Lee YB, Koh KT, Chung YS (2013) The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Constr Build Mater 47:409–418. https://doi.org/10.1016/j.conbuildmat.2013.05.0
111. Nuruddin F, Demie S, Memon FA, Shafiq N (2011) Effect of superplasticizer and NaOH molarity on workability, compressive strength and microstructure properties of self-compacting geopolymer concrete. World Acad Sci Eng Technol 75
112. Parthiban D, Vijayan DS, Sanjay Kumar R, Santhu AP, Abraham Cherian G, Ashiq M (2020) Performance evaluation of Fly ash based GPC with partial replacement of RHA as a cementitious material. Materials today: proceedings, 33, 550–558 33:550–558. https://doi.org/10.1016/j.matpr.2020.05.244
113. Vora PR, Dave UV (2013) Parametric studies on compressive strength of Geopolymer concrete. Procedia Engineering 51:210–219. https://doi.org/10.1016/j.proeng.2013.01.030
114. Chindaprasirt P, Chalee W (2014) Effect of sodium hydroxide concentration on chloride penetration and steel corrosion of fly ash-based geopolymer concrete under marine site. Constr Build Mater 63:303–310. https://doi.org/10.1016/j.conbuildmat.2014.04.010
115. Chi M (2017) Effects of the alkaline solution/binder ratio and curing condition on the mechanical properties of alkali-activated fly ash mortars. Sci Eng Compos Mater 24(5):773–782. https://doi.org/10.1515/secm-2015-0305
116. Pham TM (2020) Enhanced properties of high-silica rice husk ash-based geopolymer paste by incorporating basalt fibers. Constr Build Mater 245:118422
117. Akbar A, Farooq F, Shafique M, Aslam F, Alyousef R, Alabduljabbar H (2021) Sugarcane bagasse ash-based engineered geopolymer mortar incorporating propylene fibers. Journal of Building Engineering 33:101492. https://doi.org/10.1016/j.jobe.2020.101492
118. Wan Q, Rao F, Song S, García RE, Estrella RM, Patiño CL, Zhang Y (2017) Geopolymerization reaction, microstructure and simulation of metakaolin-based geopolymers at extended Si/Al ratios. Cem Concr Compos 79:45–52. https://doi.org/10.1016/j.cemconcomp.2017.01.014
119. Atmaja L, Fansuri H, Maharani A (2011) Crystalline phase reactivity in the synthesis of fly ash-based geopolymer. Indian J Chem 11(1):90–95. https://doi.org/10.22146/ijc.21426
120. Thakur RN, Ghosh S (2009) Effect of mix composition on compressive strength and microstructure of fly ash based geopolymer composites. ARPN Journal of Engineering and Applied Sciences 4(4):68–74

121. Ghosh K, Ghosh P (2012) Effect of synthesizing parameters on compressive strength of flyash based geopolymer paste. Int J Struct Civ Eng 1(8):1–11
122. Abbas R, Khereby MA, Ghorab HY, Elkhoshkhany N (2020) Preparation of geopolymer concrete using Egyptian kaolin clay and the study of its environmental effects and economic cost. Clean Techn Environ Policy 22(3):669–687. https://doi.org/10.1007/s10098-020-01811-4
123. Khan KA, Raut A, Chandrudu CR, Sashidhar C (2021) Design and development of sustainable geopolymer using industrial copper byproduct. J Clean Prod 278:123565. https://doi.org/10.1016/j.jclepro.2020.123565
124. Bondar D (2013, August) Geo-polymer concrete as a new type of sustainable construction materials. In Proceedings of the Third International Conference on Sustainable Construction Materials and Technologies (ICSCMT) (pp. 18–21)
125. Nath SK, Kumar S (2020) Role of particle fineness on engineering properties and microstructure of fly ash derived geopolymer. Constr Build Mater 233:117294. https://doi.org/10.1016/j.conbuildmat.2019.117294
126. McCormick AV, Bell AT, Radke CJ (1989) Multinuclear NMR investigation of the formation of aluminosilicate anions. J Phys Chem 93(5):1741–1744. https://doi.org/10.1021/j100342a015
127. Lee WKW, van Deventer JSJ (2002) Structural reorganisation of class F fly ash in alkaline silicate solutions. Colloids Surf A Physicochem Eng Asp 211(1):49–66. https://doi.org/10.1016/s0927-7757(02)00237-6
128. Sathia, R., Babu, K.G., & Santhanam, M. (2008, November). Durability study of low calcium fly ash geopolymer concrete. In The 3rd ACF international conference-ACF/VCA (Vol. 2008). Indian Institute of Technology Madras Chennai, India
129. Chindaprasirt P, Chareerat T, Sirivivatnanon V (2007) Workability and strength of coarse high calcium fly ash geopolymer. Cem Concr Compos 29(3):224–229. https://doi.org/10.1016/j.cemconcomp.2006.11.002