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REVIEW PAPER

Fly Ash Based Geopolymer Concrete: a Comprehensive Review

Avinash Ojha[1] · **Praveen Aggarwal**[2]

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Abstract

Manufacturing of ordinary Portland cement is an energy intensive process that emits harmful greenhouse gases in the atmosphere which pollutes the environment. With the surge in infrastructural activities across the world consumption of the concrete is also expected to increase thereby increasing the OPC production. On the other hand, under-utilization of fly ash from thermal power plants compare to its generation has created environmental and disposal problem. Utilization of fly ash based geopolymer concrete in place of Portland cement concrete presents a suitable remedy to the environmental and land disposal problems. Also, geopolymer concrete have less carbon footprint compared to Portland cement concrete. This paper presents a comprehensive review of composition, mix design methods, production process, curing regimes, benefits, limitation, and applications of fly ash based geopolymer concrete. It reports most notable research findings on properties of fresh and hardened state geopolymer concrete over past decade. Lastly, it determines key factors to be considered for selecting appropriate curing regime for achieving required performance of concrete. Compilation of such extensive volume of information may provide a valuable insight for future research.

Keywords Geopolymer concrete · Alkali activated binders · Fly ash · Sustainable construction material · Supplementary cementitious material

1 Introduction

Concrete is the world's second most consumed material after water [1]. Ordinary Portland cement (OPC) is conventionally utilized as binding material for producing cement concrete. Manufacturing of OPC is an energy-intensive process that emits harmful greenhouse gases (such as carbon dioxide) in the atmosphere thereby polluting the environment. According to literature, cement manufacturing plants are responsible for approximately 7 % of the world's carbon dioxide emissions [1, 2]. With the surge in infrastructural activities around the world, cement demand is likely to increase and so its production. On the other side fly ash is a traditionally waste material obtained from coal-based thermal power plants. According to the survey in 2016, the worldwide production of coal combustion products (CCP) or coal ash was about 1.2 billion tons [3]. In India, fly ash production was about 226.13 million tons in the year 2019-20 and it is predicted to be around 300–400 million tons by the year 2025 [4–7]. Problems associated with fly ash include menace to the environment and requirement of huge land for its disposal. So, to decrease the negative impact of greenhouse gas emission out of OPC and resolve troublesome fly ash disposal issues it is imperative to find a suitable green alternative in terms of Geopolymer concrete (GPC). Geopolymer concrete or alkali-activated concrete has shown the potential to be an appropriate alternative to the cement concrete as it partially or fully utilizes fly ash (in place of cement) as binder material along with alkaline activator solution and aggregates for its production [8–10]. GPC not only addresses the environmental pollution from the cement manufacturing process but also utilizes fly ash a waste product obtained from coal-based thermal power plants [11–13]. This paper aims to carry out a comprehensive review of the development of geopolymer concrete. It covers the composition, mix design, production process, curing regimes, properties, benefits, limitations, and applications of geopolymer concrete. It reports notable research findings on properties of

✉ Avinash Ojha
ojhaavinash87@gmail.com

Praveen Aggarwal
praveen@nitkkr.ac.in

[1] Sir Padampat Singhania University, Udaipur, Rajasthan 313601, India

[2] National Institute of Technology, Kurukshetra, Haryana 136119, India

geopolymer concrete of past decade and key factors that are to be considered for selecting appropriate curing regime based on the performance requirement. It also suggests future research directions.

2 Geopolymer Concrete Composition

GPC primarily consists of binder paste, aggregates (both fine and coarse), and admixtures as shown in Fig. 1. For fly ash-based, GPC binder paste is made from fly ash and alkaline activators [14–16]. Fly ash is a waste product obtained from coal-based power plants. It is collected in electrostatic precipitators and transferred to silos [17]. As per American Society for Testing and Materials, ASTM C 618, fly ash is classified as Class 'C' and Class 'F' depending upon sum of total silicon, aluminum, and iron ($Sio_2 + Al_2O_3 + Fe_2O_3$) content in the ash. The sum lies between 50 and 70 % in Class 'C' fly ash whereas for Class 'F' types fly ash it is more than 70 %. Class 'C' fly ash is recommended for use in soil stabilizations and circumstances where early strength is required because of high calcium content i.e. more than 15 %. Class 'F' is mostly utilized in places where higher early strength is required and also recommended in situations where the concrete requires high acid resistance [18, 19]. Alkaline activators are the chemical solutions that are used along with fly ash to generate binder paste. Generally, in geopolymer concrete, sodium-based solutions such as sodium silicate (SS) and sodium hydroxide (SH) are utilized in place of potassium-based solutions owing to its less price and easy availability in the market (in liquid and pellets form) [20]. The optimum alkaline activator ratio i.e., sodium silicate (SS) to sodium hydroxide (SH) ratio may be kept between 2 and 2.5 at constant molarity of SH to obtain maximum compressive strength of concrete as per past literature. With the increase in the molarity of SH, strength of the concrete increases [21, 22]. In geopolymer concrete, aggregates occupy 70–80 % of volume like Portland cement concrete [23]. Careful selection of aggregate type and total aggregate to fine aggregate ratio may enhance strength, elasticity modulus, and Poisson's ratio. Overall, optimal surface area and interfacial bonding between geopolymer concrete constituents provide higher strength concrete [23–25]. Admixtures are materials (Chemical) which are added in fresh concrete to improve its characteristics like durability, early setting, workability, strength etc. [26]. As per literature, addition of superplasticizer typically in the range of 0.6–2.0 % by weight of binder enhances workability of concrete without affecting its strength characteristics. Addition of superplasticizer, beyond 2 % may lead to strength degradation of geopolymer concrete. However, the influence of superplasticizer on strength of GPC depends on the type of superplasticizer and activator. For instance, in case of fly ash-based GPC polycarboxylates type superplasticizers are preferred which helps in improving workability without affecting compressive strength [27, 28].

3 Mix Design

It's a process of determining relative proportions of ingredients to produce concrete of desired strength economically. Composition of GPC have a notable influence on its numerous aspects such as strength, durability, workability etc. GPC consists of one or more industrial waste materials (such as ground granulated blast furnace slag (GGBS), fly ash, etc.), alkaline activators (such as sodium hydroxide (SH), and sodium silicates (SS)), aggregates and chemical admixtures. Many variables such as raw materials (inconsistent), alkali activators, curing regimes employed in GPC production, results in intricate mix design [29–32]. Therefore, properties of materials should be taken into account before designing concrete mixture.

3.1 Mix Design Parameters

Several researchers have taken design parameters very similar to plain cement concrete (PCC) owing to their similarity. In some conditions GPC mix design is considered as sub section

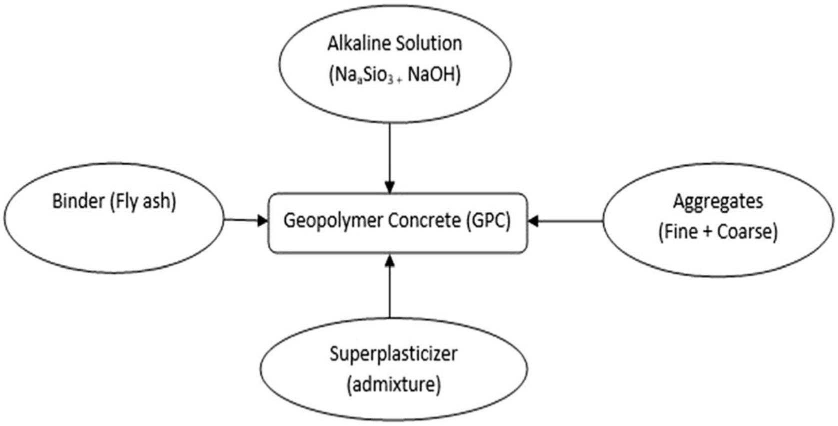


Fig. 1 Composition of geopolymer concrete (GPC)

of plain cement concrete mix design [32, 33]. For PCC the compressive strength is governed by water-binder (cement) ratio which can be measure by compression testing machine, workability by water content which can be determined by slump test also the gradation of aggregates i.e. fine to total aggregate ratio has significant impact on workability. Though, PCC mix design methods accepted and employed worldwide cannot be smoothly replicated in GPC. The important parameters influencing GPC properties are water to solid ratio, alkaline liquid - binder ratio, quantity of alkalis, curing regime and molar ratio of Sio_2 to Na_2O in sodium silicate [2, 34–39]. The contribution of these parameters towards the strength of GPC is not completely known. However, it is widely recognized that increase in water to solids ratio negatively affects the GPC strength and increase workability, high molar ratio of Sio_2 to Na_2O in sodium silicate enhances the strength but at the same time increases the cost of production and increase in curing temperature and period improves the GPC strength [35, 40]. It is a very challenging task to develop the comprehensive mix design for GPC because of many variables involved. The above parameters (but not limited to) can be considered for GPC mixture proportioning. Due to wide variations in raw materials and activators (alkaline) the identical mix design may result in different workability and strength [40, 41].

3.2 Mix Design Methods

Ukraine published the first mix design standard (RSN 336 − 84) slag based GPC in 1984 [42]. Mix design methods in the starting were mostly based on trial and error. Since then more literature has been reported in the past decade on mix design methods. Rangan devised a mix design method for fly ash based GPC. In this method the density of the fresh concrete mix was assumed 2400 kg/m^3. While assuming the density the author didn't considered air content and effect of specific gravity of different ingredients. The presence of different materials with varying specific gravity may have significant influence on the GPC density [43]. Anuradha et al. suggested a design procedure for fly ash based GPC in accordance with Indian standard. As per the target strength, fly ash (binder) and alkaline solution to binder ratio (AS/B) were determined at the same time fine aggregate to total aggregate (FA/TA) ratio was fixed as per sand gradation [44]. Ferdous et al. further enhanced the design method for fly ash based GPC considering air content, specific gravity of materials, workability, and required strength. The main concern in this design was the alkaline to binder ratio [45, 46]. Pavithra et al. developed the mix design by fixing the activator content and provided much needed flexibility in design mixtures on the required activator content and strength. The method also considered the specific gravities of ingredients and aggregate content was investigated by combined grading curve [47]. Li et al. suggested the guideline for mix design of slag based GPC for 40 MPa, 60 MPa and 80 MPa strength, recommending appropriate setting time and workability. The authors employed mix design method based on the approach of high performance concrete and the concept of Taguchi methods, excess paste thickness theory and close packing [48]. Bondar et al. adopted a performance based method for GPC mix proportioning rather than normal water-binder based mix proportioning method. For determining the suitability of the concrete the authors exposed the concrete to the chlorides for ascertaining chloride diffusion, examined the influence of water-binder (W/B) ratio and binder content on the slump and strength [49]. Bellum et al. developed the mix design where the authors followed the standard method of mixture proportioning. In this method the density of fresh slag based GPC mix was assumed 2400 kg/m^3 and corrected unit weight of coarse and fine aggregate were utilized [50]. Recently, Rao et al. successfully developed ANN prediction models (statistical model method) for 20 MPa, 40 MPa and 60 MPa grade of geopolymer and conventional concrete with varying proportion of recycled aggregates and effectively correlated it with experimental results with minimum errors [51]. Longos et al. employed RSM technique to obtain optimal proportions of nickel laterite mine waste (50.1 %), activator to precursor ratio (0.428) and sodium hydroxide (SH) to sodium silicate (SS) ratio (0.52) to produce goepolymeric material of desired compressive strength [52]. In addition to these, some mix (modified) design methods based on prevailing methods were reported. So according to the literature the mix design methods can broadly be categorized in three groups: target strength based method, performance based method and statistical (factorial) model method. A summary of different mixture design methods with observations is presented in Table 1.

3.2.1 Target Strength Method

The main targets in this method of mixture proportioning are strength and workability. Content determination of different ingredients such as raw materials or binder, activators, aggregates and water are based on these targets. In plain cement concrete mix design method workability and compressive strength can be regulated by binder content and water cement ratio [49, 53, 64]. On the other hand, in GPC type, amount and concentration of alkaline activator can be considered. The target strength method includes following steps: (1) alkaline to binder ratio selection as per required compressive strength, (2) determine binder content as per requirement, (3) determine quantities of total aggregates, (4) determine fine aggregates to total aggregates ratio as per workability requirement, (5) add admixture (chemical) as per workability requirement, (6) to meet the required performance adjust mixture proportion.

Table 1 Summary of GPC mix design methods

Author	Year	Mix Design Method	Observation
Rangan [43]	2008	Target Strength Method	While assuming densities, air content and specific gravities of various constituents were not considered.
Anuradha et al. [44]	2012		In accordance with Indian standard (IS 10,262−2009) with some minor modification to accommodate different grades of GPC.
Ferdous et al. [46]	2015		Enhanced the design method for GPC by considering specific gravities of ingredients with focus on alkaline to binder ratio.
Pavithra et al. [47]	2016		Devised mix design method by fixing activator content with respect to target strength.
Li et al. [29]	2018		Employed concept of Taguchi method, excess paste thickness theory and close packing of aggregates to obtain required strength.
Bondar et al. [49]	2019		Proposed mix design method based on packing fraction of fine and coarse aggregates with different paste contents.
Bellum et al. [50]	2019		Considered corrected specific gravities of coarse and fine aggregate in mix design.
Bondar et al. [53]	2018	Performance Method	In a bid to produce performance based GPC, author considered chloride ion diffusion and water binder ratio in mix design.
Turkmen et al. [54]	2008	Taguchi Method	Determined optimum conditions (parameters i.e., 10% Silica Fume, 5% Blast furnace slag, 0.3 water binder ratio and 120 days curing period in lime water) to obtain most durable concrete mixture.
Hadi et al. [55]	2017		Optimum parameters were obtained as Binder content – 450 kg/m^3, 0.35 AS/B ratio, 2.5 SS to SH ratio and 14 M sodium hydroxide concentration for GPC mix and attained maximum compressive strength of 60.4 MPa, at 7 Day.
Mehta et al. [56]	2017		Optimum parameters were obtained as OPC content – 20%, 15 M sodium hydroxide concentration and 70^{o}C curing temperature for GPC mix and attained maximum compressive strength of 64.4 MPa at 7 day.
Li et al. [48]	2018		Optimum parameters were obtained as Na_2O/Binder ratio – 6%, water/binder ratio – 0.45 for GPC mix and attained maximum compressive strength of 60 MPa at 28 day.
Zain and Abd [57]	2009	Multivariate regression model	A statistical relationship between different variables (Cement, Water, Silica fume, fly ash, coarse aggregate, and fine aggregate) of GPC mixture was developed to attain compressive strength of high performance concrete.
Lokuge et al. [58]	2018		A statistical relationship between different variables (SH concentration, water-binder ratio, AS/B ratio, and SS to SH ratio) of GPC mixture was developed to attain compressive strength using multivariable adaptive regression analysis.
Hadi et al. [59]	2019		A statistical relationship between different variables (water-binder ratio, AS/B ratio, SS to SH ratio, and sodium silicate content) of GPC mixture was developed to attain compressive strength using multivariable polynomial regression model.
Dao et al. [60]	2019	Artificial Intelligence Approaches	An ANN model was developed for prediction of compressive strength of geopolymer concrete with sodium silicate solution, sodium hydroxide, fly ash and water as input parameters and compressive strength as output.
Ling et al. [61]	2019		An ANN model was established based on the set of mix design parameters data for predicting key properties (geopolymerization heat, compressive strength and setting time) of high calcium fly ash based geopolymer concrete. The ANN modelling method found to be suitable for analyzing impact of different design parameters on key properties of fly ash based geopolymer.
Rao et al. [51]	2020		ANN prediction models for 20 MPa, 40 MPa and 60 MPa grade of geopolymer and conventional concrete with varying proportion of recycled aggregates (10%, 20%, 30%, 40% and 50%) was

Table 1 (continued)

Author	Year	Mix Design Method	Observation
			developed and prediction were effectively correlated with experimental results with minimum errors.
Gao et al. [62]	2016	Response Surface Method	RSM technique used in optimizing liquid to solid ratio and amount of alkali activator for achieving early compressive strength of alkali activated slag-based concrete.
Zahid et al. [63]	2018		RSM technique used for obtaining optimal proportions of NaOH molarity concentration, ratio of NaOH and Na_2Sio_3 ratio and curing temperature for getting expected responses (flexural strength, flexural toughness, elastic modulus, compressive strength, setting time, first crack strength and ductility index) for engineered geopolymer composite.
Longos et al. [52]	2020		Employed RSM technique to get optimal proportions of nickel-laterite mine waste activator to precursor ratio and sodium hydroxide to sodium silicate ratio to produce goepolymeric material of desired compressive strength.

3.2.2 Performance Based Method

A performance based method was proposed to achieve great precision in producing GPC rather than following the traditional approach of mix design accepted by market. Bondar et al. investigated chloride ion diffusion of slag-based GPC. The authors observed that molar ratio of Na_2O and Sio_2 and Na_2O% affected the chloride diffusion coefficients. Also, molar ratio of Na_2O and Sio_2 and water binder ratio are important parameters for mix design of GPC [53].

3.2.3 Statistical Model Method

The statistical model method is based on the correlation between different critical parameters such as amount of binder (or precursors), alkaline concentration and amount, water to binder (W/B) ratio, fine aggregate to total aggregate ratio (FA/TA) etc. affecting the properties of fresh and hardened GPC. Suitable values for individual parameter are obtained to determine appropriate mix proportion.

3.2.4 Taguchi Method

Taguchi methods uses a set of orthogonal arrays to investigate several variables with as less experiments as possible which renders it more effective than traditional methods [54]. Hadi et al. employed Taguchi method and obtained optimum binder content (450 kg/m$^{3)}$, alkaline to binder ratio (0.35), SS to SH ratio (2.5) and SH concentration (14 M) for maximum compressive strength (at 7 days) of 60.4 MPa at ambient curing conditions [55]. Mehta et al. used Taguchi method to obtain optimum values of ordinary Portland cement content (20 %), sodium hydroxide concentration (15 M) and curing temperature (70°C) and achieved maximum compressive strength of 64.4 MPa (at 7 days) with lowest water absorption of 3.04 % [56]. Taguchi methods has many advantages such as saving of time and cost, performance of fewer experiments and good results. However, the limitation of this method is that it does not provide results beyond the mentioned factors and levels. Therefore, Li et al. carried out additional experiments to obtain relationship between important parameters and performance of GPC beyond chosen levels [48].

3.2.5 Multivariate Regression Model Method

Multivariate regression model has been used in many studies to predict the properties of Portland cement concrete [65, 57]. Hadi et al. suggested multivariable polynomial regression model to speculate the workability, initial setting time, and compressive strength of GPC based on limited number of experiments. The model studied four factors i.e., alkaline solution to binder (AS/B) ratio, slag content, SS to SH ratio and water-binder (W/B) ratio [59]. Lokuge et al. suggested a mixture proportioning method for fly ash based GPC utilizing multivariable adaptive regression splines model. Extensive data were collected from past literature and examined to obtain optimum value of AS/B ratio, SS to SH ratio, water-binder (W/B) ratio and sodium hydroxide concentration. After obtaining the optimum values a concrete was prepared which provided compressive strength of 30–55 MPa [58]. Multivariate regression models provide time efficiency for the fly ash GPC based concrete with necessary compressive strength.

3.2.6 Artificial Intelligence (AI) Approach

Artificial intelligence (AI) approach (for e.g., artificial neural networks) for the mix design of concrete has been used by researchers in the past and over the time became popular because of its prediction ability (of mechanical properties of concrete) [60]. Many researchers in the past decade utilized same approach for predicting mechanical strength of GPC. For instance, Ling et al. established artificial neural networks (ANN) models based on set of mix design parameters data for predicting key properties of high calcium fly ash based geopolymer concrete. The authors were successfully able to establish strong correlation between experimental measurements and ANN model predictions based on test results of 72, 273 and 36 geopolymer mixes for geopolymerization heat, compressive strength and setting time, respectively. The ANN modelling method found to be suitable for analyzing impact of different design parameters on key properties of fly ash based geopolymer [61]. Rao et al. developed ANN prediction models for different grades (20 MPa, 40 MPa and 60 MPa) of geopolymer and conventional concrete with varying proportions (10 %, 20 %, 30 %, 40 % and 50 %) of recycled aggregates. The authors conducted experimental analysis on different grades of geopolymer and conventional concrete. The results gathered from experimental analysis then taken as training data for generating prediction data by employing ANN prediction model. The prediction data showed good results with minimum error. The results are in conformance with previous reported literature [51]. Overall, ANN modeling method has been successful in providing desired predictions for fly ash based geopolymer concrete. This method requires substantial amount of data for good prediction.

3.2.7 Response Surface Method

Response surface method (RSM) is widely accepted technique for designing and analyzing of experiments in a systematic manner. RSM is used for modeling and optimizing experimental outputs for Portland cement-based concrete. The technique helps in decreasing the design time and improves the reliability and performance of existing process and product [66]. Cihan et al. successfully utilized RSM to establish a model (statistical) taking six distinct variables as input and strength (compressive) as output [67]. Aldahdooh et al. successfully used RSM technique to optimize utilization of silica fume and Portland cement to produce ultra-high performance fiber reinforced concrete [68]. Mohammed et al. utilized RSM technique to model and optimize a particular type of self-compacting polyvinyl alcohol (PVA) fiber reinforced composite. The authors investigated the effect of fiber volume fraction and nano silica on the elastic modulus, compressive strength and energy absorption of concrete and suggested optimal quantity [69]. Overall, RSM technique has been successfully employed in the modeling and optimization of Portland cement concrete, however, its use in field of geopolymer concrete is still new. Gao et al. employed RSM technique in optimizing liquid to solid ratio and amount of alkali activator for achieving early compressive strength of alkali activated slag-based concrete [62]. Zahid et al. utilized RSM technique to obtain optimal proportions of NaOH molarity concentration, ratio of NaOH and Na_2Sio_3 ratio and curing temperature for getting expected responses (flexural strength, flexural toughness, elastic modulus, compressive strength, setting time, first crack strength and ductility index) for engineered geopolymer composite. The authors successfully obtained the optimal proportions with desirability close to 1 and validated the proportions with experimental results [63]. Longos et al. employed RSM technique to obtain optimal proportions of nickle laterite mine waste (50.1 %), activator to precursor ratio (0.428) and Sodium hydroxide to sodium silicate ratio (0.52) to produce goepolymeric material. The authors successfully obtained the desired compressive strength (36.3 MPa) of geopolymeric material [52]. Overall, the RSM technique is useful in optimizing the input parameters for obtaining desired responses for fly ash based geopolymer concrete.

Statistical modelling methods are able to ascertain the effect of important parameters on GPC. However, the demonstrating the relationship between key factors or parameters and concrete properties requires substantial database.

4 Production Process

To get a fine mix, alkaline solutions must be prepared one day in advance before casting. Diffusion of sodium hydroxide (NaOH) in water triggers an exothermic reaction which generates huge amount of heat which overall helps in polymerization process [70, 71]. Majority of researchers have adopted conventional mixing technique (of plain cement concrete) for GPC production as shown in Fig. 2. First of all, raw material or binder along with aggregates are dry mixed to get uniform color for about 3 to 5 min. Thereafter, alkaline solution along with admixture is added to the dry mixture and mixing continued for another 3 to 5 min until uniform mix slurry is obtained [24]. However, large scale production of GPC depends upon the binder material, mixture condition (speed of rotation) and setting time of the mixture. Class ‘F’ fly ash takes more time to set as compared to Class ‘C’ fly ash. Therefore, mixing time is not uniform for all batches and type of GPC. Lastly, the obtained mix is casted in the desired shape.

5 Curing Regimes

There are broadly three methods which are utilized in curing of GPC i.e. Oven (heat) curing, Steam Curing and Ambient curing.

5.1 Oven (heat) Curing

In oven curing regime the GPC is cured at desired temperature and period in order to gain strength. Vijai et al. reported that heat curing helps GPC develop early strength. The authors achieved greater strength of GPC cured at 60°C for 24 h [72]. Adam and Horianto suggested that curing period and temperature plays very important role in hardening of GPC [73]. Patil et al. cured GPC samples at ambient curing conditions and oven (heat) curing conditions. The authors observed that oven (heat) cured samples showed better compressive strength over ambient cured samples [74]. Venkateswar Rao et al. made fly ash based GPC and cured it in oven. The authors observed rapid strength development in early stage but no significant increase in strength after 28 days [75].

5.2 Steam Curing

Limited number of studies has been conducted in this domain, Karunanithi and Anandan employed steam and hot air curing regimes for curing GPC samples. The authors reported that steam cured samples showed better compressive strength over hot air cured samples [76]. Srinivasan and Sivakumar endorsed steam curing and low binder-aggregate ratio for creating GPC. The authors observed surge in mechanical properties of GPC [77]. Yewale et al. obtained optimum value of steam curing which is 80°C. The authors also concluded that elevated temperature helps in developing early strength in GPC [78]. Azarsa and Gupta created GPC by mixing equal proportion of fly ash and bottom ash and subjected it to steam curing (accelerated, 24 h) at 30°C, 60°C, and 80°C. The authors achieved highest compressive strength at 80°C after 28 days [79].

5.3 Ambient Curing

Ambient curing means the concrete sample cured at ambient conditions. Vijai et al. noticed that rate of setting of geopolymer paste is slow at ambient temperature. The authors also reported that after 28 days of ambient temperature curing and heat curing, GPC samples achieved lesser compressive strength at ambient condition compared to heat curing i.e. about 20 MPa and 33 MPa respectively [72]. Kumaravel S produced 40 MPa grade of GPC cured at ambient environment. The author reported better strength (compressive) as compared to the cement concrete of similar grade [80]. Rao and Venu made GPC composite (20 % GGBS and 80 % Fly ash) and employed ambient curing method. The authors reported low strength development in early phase up to 7 days, in-between 7 and 28 days the strength development was notable which kept on increasing up to 90 days. Rao and Venu developed GPC of desired strength with the help of ambient curing regime [81].

5.4 Microwave Radiation Curing

Microwave technique of curing provide fast and uniform heating which helps in promoting dissolution and polycondensation of the precursor and resulting in development of early strength in the concrete. Chindaprasit et al. produced fly ash based geopolymer mortar and subjected it to different curing methods combination such as, oven heat curing (for 24 h at 65°C), oven heat curing (for 24 h at 65°C) + microwave curing (for 5 min at 90 W), microwave curing (for 5 min at 90 W) then oven heat curing (for 12 h at 65°C) and room temperature curing). The authors observed higher compressive strength (42.5 MPa) with microwave curing (for 5 min at 90 W) then oven heat curing (for 12 h at 65°C) combination out of all curing methods combinations [82]. Hong and Kim developed coal bottom ash based geopolymer concrete which was first pre-cured at 75°C for 24 h and then cured at different microwave irradiation power (200, 400, 600, 800, and 1000 watts) and time (in ranging from 1 min to 20 min). The authors observed increase (3 times approximately) in compressive strength of geopolymer concrete compared to control concrete (cured at 75°C for 24 h) with increase in microwave irradiation until samples reach their critical moisture content (4–6 %), after that compressive strength of concrete decreases. The increase in compressive strength attributed to evaporation of redundant free water from concrete matrix and the decrease

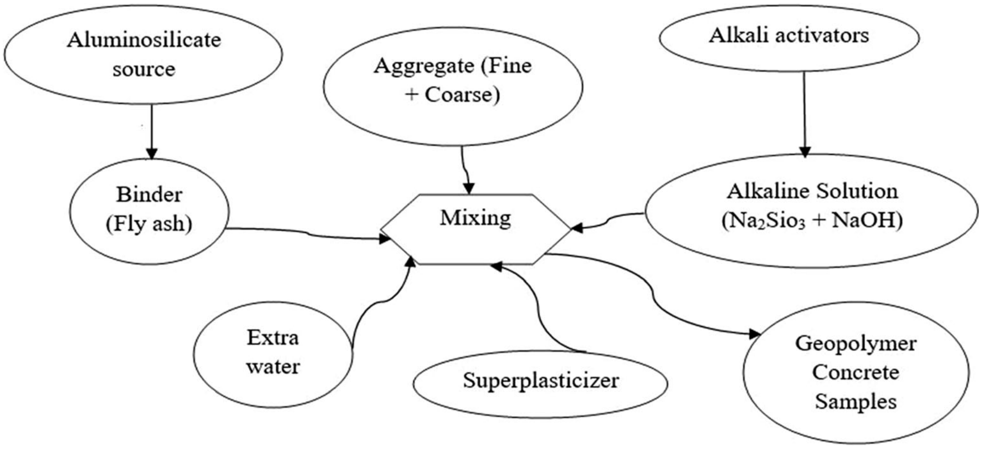


Fig. 2 Production of geopolymer concrete (GPC)

in the strength is attributed to the thermal stress induced from over-evaporation of water from concrete matrix [83]. Kastiukas et al. developed fly ash (both regulated and unregulated) and GGBS based geopolymer concrete and subjected them to oven heat curing (60, 80 and 120 degrees) for 7- and 24-hours durations and microwave curing (with 350, 540 and 750 Watts) for 5 min duration. The authors observed early strength gain in case of microwave oven curing method compared to oven heat curing method (on all durations) for both fly ash and GGBS based geopolymer concrete. The reason for attaining early strength is attributed to uniform and fast heating process enabling faster production of binder gel [84]. Optimization of power and time is crucial in achieving better results in microwave curing method compared to other curing methods (oven heat and steam) which is also mentioned in previous reported literature [82–84].

Overall oven (heat) curing, steam curing and microwave curing methods are employed where early strength gain is required i.e., precast application whereas, ambient curing method is mostly employed where there is no requirement of early strength and where heat/steam curing is not feasible. A summary of the different curing regimes for GPC has been presented in Table 2.

6 Properties of GPC

Properties of GPC concrete in wet and dry state are compared in this section as observed by various researchers.

6.1 Fresh Concrete

6.1.1 Workability

Workability is the ease with which a freshly produced concrete can be transported, placed and compacted to a dense mass. The freshly produced GPC possess stiff consistency and glossy appearance. Hardijito et al. reported that the workability of GPC can be enhanced by adding 2 % of naphthalene based superplasticizer by weight of binder [85]. Addition of naphthalene sulphonated based superplasticizer (up to 4 % by weight of binder) enhanced the workability of GPC. However, slight reduction in compressive strength is observed at higher doses beyond 2 % [86]. Memon et al. prepared self-compacting GPC and observed increase in workability with increase in superplasticizer dosage as shown in Fig. 3a. As per EFNARC (2002), “Specification and Guidelines for Self-Compacting Concrete” the maximum and minimum workability of self-compacting concrete should be 650 mm and 800 mm [87]. The consistency of the GPC depends up on the sodium hydroxide and sodium silicate ratio by mass and maximum flow value can be acquired in the rage of 95-145mm [9]. Memon et al. observed increase in workability with increase in extra water content (by weight of binder). Further, Sanni and Khadiranaikar concluded that increase in concentration (Molarity) of sodium hydroxide in GPC increases strength but decreases workability due to reduction in water and water to geopolymer solids (W/GS) ratio [88]. Joseph and Mathew reported that for a given alkali solution to the binder (fly ash) ratio if W/GS ratio increases workability increases which can be observed from Fig. 3b. Further, increase in AS/B ratio results in increase in workability [23]. Nath and Sarker reported increase in workability by increasing alkaline liquid (without adding extra water) from 35 to 45 % and decrease in workability with increase in SS to SH ratio for a given AS/B ratio in the GPC mixture. The authors obtained 200mm of slump value [89]. Deb et al. reported decrease in workability with increase in ground granulated blast furnace slag (GGBFS) percentage and decrease in AS/B ratio [90]. Yasir and Iftekar concluded that workability increases with the increase in alkaline solution to fly ash ratio and observed stiffness if the ratio (alkaline to fly ash) falls below 0.3 as shown in Fig. 4a. which are in line with the studies conducted by Joseph and Mathew and Nath and Sarker [91]. Singhal et al. studied workability of fly ash based GPC with alccofines and observed that for a given AS/B ratio and SS to SH ratio workability decreases with increase in SH concentration (in molarity) which can be observed from Fig. 4b. which in agreement with Sanni and Khadiranaikar [92]. Gomaa et al. utilized class C fly ash with varying calcium content (21–37 %) calcium for making GPC and obtained highest workability (slump value = 200mm) at 0.34 water to fly ash ratio. Further, the authors reported that fineness of fly ash also plays important role in the workability of GPC (refer Fig. 5.) which was also reported in past studies [93, 94]. Overall, superplasticizers (SP), water to geopolymer solids ratio (W/GS), sodium silicate to sodium hydroxide (SS to SH) ratio, alkaline solution/liquid to binder (AS/B) ratio, sodium hydroxide (NaOH) concentration (in molarity, M) are important parameters which affects the workability of freshly prepared fly ash based GPC. For instance, surge in consistency is observed with addition of optimum quantity of superplasticizers, increasing water content (water to binder ratio), and increase in alkaline activator solution, whereas increase in NaOH concentration (in molarity), decrease in alkaline to binder ratio (from optimum value), and increase in Sodium Silicate to Sodium hydroxide ratio for a given AS/B ratio results in loss of consistency in GPC [85–92]. The freshly prepared GPC is stiffer compared to PCC. However, the higher slump value (230–270 mm) of the GPC is quite attainable with the help of selection of optimum values of parameters.

6.1.2 Density

Density is an estimation of mass (of matter) occupied in the volume or space. Hardjito and Rangan noted that density of

GPC with granite coarse aggregates lies in the range of 2330 to 2430 kg/m^3 [95]. Olivia and Nikraz obtained the density of GPC in the range of 2248–2294 kg/m^3 [96]. Shetty et al. obtained wet and dry GPC densities of about 2350 kg/m^3 and 2270 kg/m^3 respectively [97]. Nath and Sarker reported density of GPC mix about 2420 kg/m^3 [89]. Abdullah et al. produced lightweight fly ash based GPC using foaming agent and obtained average density of 1650 kg/m^3 (cured in ambient conditions) and 1667 kg/m^3 (heat cured). The authors attributed higher density of GPC (cured at elevated conditions) to lower water absorption and porosity [98]. Omar et al. produced lightweight aggregate geopolymer concrete using river sand as fine aggregates and expanded clay as coarse aggregates and obtained density of 1438.7 kg/m3 [99]. Khalil et al. manufactured light weight GPC by replacing natural sand with artificial light weight sand in varying proportions (25,

Table 2 Summary of different curing regimes for GPC

Author	Year	Type of Curing Regime	Curing Temperature and Time (°C and hours)	Compressive Strength (MPa)	Observation
Chindaprasirt et al. [82]	2013	Heat	65 and 24	32.7	The authors observed higher compressive strength in microwave curing followed by oven heat curing combination over other curing/ curing combinations regimes.
		Heat+Microwave	(65 and 24) + (90 W for 5 min)	32.4	
		Microwave+Heat	(90 W for 5 min) + (65 and 12)	42.5	
Kumaravel [80]	2014	Heat	60 and 24	24.50 (at 12 days)	Highest compressive strength of fly ash based GPC (M20 grade) is observed in heat curing regime.
		Steam	60 and 24	19.34 (at 12 days)	
		Ambient	30-40°C	18.25 (at 12 days)	
Vijai et al. [72]	2010	Heat	60 and 24	33.22 (at 28 days)	Higher compressive strength in heat curing regime is obtained. In this study authors have taken 5 days of rest period.
		Ambient	25-30°C	17.69 (at 28 days)	
Karunanithi and Anandan [76]	2014	Heat	100 and 6	29.2 (at 28 days)	Higher compressive strength in steam curing regime as compared to heat curing regime is obtained.
		Steam	75 and 6	29.3 (at 28 days)	
Yewale et al. [78]	2016	Heat	80 and 24	40 (at 7 day)	The authors achieved target strength through heat curing regime as compared to steam and ambient. The authors also observed increase in strength increases rate of strength development in GPC.
		Steam	80 and 18	25 (at 7 day)	
		Ambient	25-35°C	10 (at 7 day)	
Hong and Kim [83]	2019	Microwave	At 200 (Watts) for 12–15 min	70	Greater compressive strength in microwave curing method is observed compared to heat and ambient curing methods.
Azarsa and Gupta [79]	2020	Heat	80 and 24	23 (at 28 days)	Higher compressive strength in steam curing regime as compared to heat curing regime at 30, 45, 60 and 80°C is obtained.
		Steam	80 and 24	35 (at 28 days)	
Kastiukas et al. [84]	2020	Heat	60 and 24	35	The authors obtained better compressive strength with microwave curing method compared to oven heat curing method for GGBS based geopolymer concrete.
			80 and 24	35.5	
			120 and 24	37	
		Microwave	350 (Watts) for 5 min	42	
			540 (Watts) for 5 min	28	
			750 (Watts) for 5 min	38	

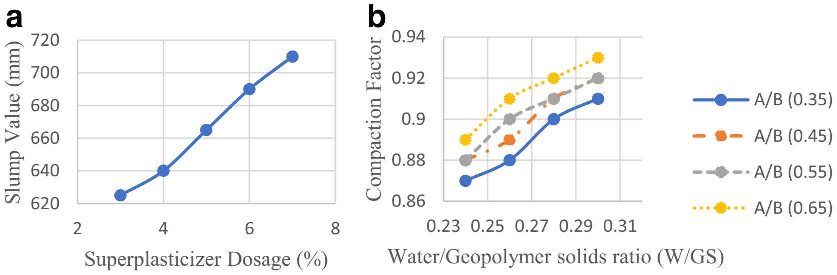
50, 75 and 100 %). The authors obtained density (fresh concrete) in the range of 1860 kg/m^3 and 1725 kg/m^3 and dry density (after heat curing) in the range of 1780 kg/m^3 to 1640 kg/m^3 [100]. Top et al. manufactured light weight GPC with expanded perlite and acidic pumice as coarse aggregates. The authors obtained density in the range of 1250 kg/m^3 and 1700 kg/m^3 [101].

6.2 Hardened Concrete

6.2.1 Compressive Strength

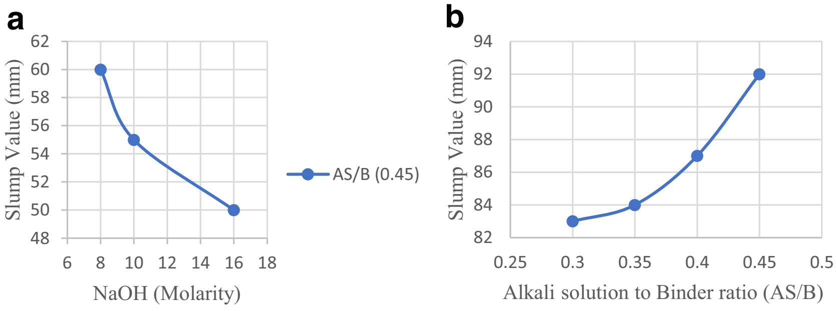
Compressive strength is the ability of a material to resist compression forces. Hardijito et al. concluded that curing temperature, curing period, SS to SH ratio and water content were the important parameters which influence the compressive strength of GPC. The authors achieved the target strength at 60°C after 24 h of curing. Further, compressive strength increased with the surge in curing temperature and curing period up to 48 h beyond which the gain in strength was insignificant. Heat cured GPC gain compressive strength faster than ambient cured GPC because of faster rate of geopolymeric reactions which produces more binder gel [85]. Leung and Pheerapha concluded that heat curing led to the elimination of water from freshly prepared GPC which resulted in dense microstructure [102]. Palomo et al. noticed that the prolonged curing at higher temperature may lead to the collapse of structure (granular) resulting in excessive loss of moisture from concrete and shrinkage [103]. Ahmed et al. observed that at constant temperature compressive strength increased with increase in curing period up to 48 h beyond which the gain was not significant (as shown in Fig. 6.) this is in line with the previous studies [104]. Joseph and Mathew reported that increase in curing temperature yields higher compressive strength up to 100°C thereafter it starts decreasing as shown in Fig. 7. Also, by selecting appropriate curing period and temperature early compressive strength of the GPC can be attained i.e., 96.4 % of 28-day strength can be attained in 7 days with 100°C curing for 24 h. Increase in the alkali solution to fly ash ratio up to 0.55 and SS to SH ratio up to 2.5 results in surge in compressive strength thereafter it slumps. The surge can be due to increase in SS content and decrease may be due to unavailability of SS at higher ratios. Further, increase in total percentage of aggregate (TA) (by volume) results in increase in compressive strength and fine aggregate to total aggregate ratio (FA/TA) plays an instrumental role in development of compressive strength in GPC (as depicted in Fig. 8a, b). GPC made with alkali solution to fly ash ratio 0.55, 10 M SH solution, SS to SH ratio 2.5, fine to total aggregate ratio 0.35, 70 % of total volume occupied by aggregates and cured at 100°C attained compressive strength of 52 MPa after 28 days. As the molarity of SH increases compressive strength increases and loss in compressive strength occurs when for a given alkaline solution to fly ash ratio temperature exceeds from 100°C which can be observed from Fig. 7 [23, 103]. Shetty et al. obtained 46 MPa of strength from G40 grade of GPC after 28 days of open air curing compare to control mix (PCC) which showed 53 MPa [97]. Duxson et al. and Sagoe-Crentsil and Weng reported that sodium hydroxide solution concentration has constructive influence on condensation, hydrolysis and dissolution reactions during geopolymerization. However, increase in the concentration above the optimum value discourage the condensation of silicates. Optimum ratio of SS and SH is proposed to be 2.5 below or beyond which strength gets affected this is in conformity with previous studies [91, 105–107]. It is also observed that rest period up to 5 days before the heat curing, increased SH molarity, increased SS to SH ratio enhanced compressive strength. GPC strength gets negatively affected with the increase in W/GS ratio (by mass) which is consistent with studies previously reported. Fly ash based GPC possess better resistance to acid, sulphate, creep, and drying shrinkage. Hou et al. reported that increase in modulus of sodium silicate up 1.4 increases the compressive strength beyond which compressive strength drops because of decrease in sodium silicate breakdown. Further, the authors obtained maximum compressive strength at 32 % sodium silicate concentration beyond this concentration the compressive strength decreases [108]. Hardijito and Rangan observed surge in modulus of elasticity with the surge in compressive strength fly ash based GPC and Poisson ratio to be in the range of 0.12–0.16. Also, the behaviour and failure mode of the fly ash based GPC was quite similar to PCC and failure strain (maximum) remain in the range of 0.0024–0.0026 [95]. Water content plays similar role in GPC and PCC, increase in water content of GPC results in increase in workability and decrease in compressive strength. Further, the aggregate shape and grading has quite similar impact on the compressive strength of GPC just like PCC which is in agreement with studies conducted by Joseph and Mathew [96]. Panias et al. observed that reduction in water content in GPC system leads to increase alkaline activators which accelerates the geopolmeric reactions and which results in quick gain of strength. When aggregate to solids ratio raised from 3.5 to 4.7 the compressive strength slumped from 48.06 to 25.44 MPa [109]. Fernandez-Jimenez and Palomo noticed that the optimum amount of aggregate, fly ash and reduction of water content were the important factors which helps in enhancing the compressive strength [110]. Jaydeep and Chakravarthy reported that GPC sample with heat curing shows higher strength than sunlight curing. Also, appropriate selection of FA/TA content and TA content for GPC may provide equivalent or better modulus of elasticity and Poisson ratio than PCC which is in agreement with Joseph and Mathew studies [111]. Chindaprasit et al. investigated compressive strength and setting time of high calcium fly ash based GP mortar under ambient cured condition by

Fig. 3 **a** Slump value with superplasticizer. **b** Compaction factor with water to geopolymer solids ratio (W/GS)



incorporating three different calcium rich materials (calcium hydroxide ordinary Portland cement and calcium oxide). The authors reported increase in compressive when calcium hydroxide and ordinary Portland cement were added and decrease in compressive strength when calcium oxide is added. It was concluded that 5–15 % calcium hydroxide and 15 % Portland cement were suitable for repair material [112]. Nath and Sarker produced GPC by adding Portland cement, GGBFS and hydrated lime and cured in ambient curing conditions. The authors reported that flexural strength of the prepared GPC samples improved compared to control mix made with ordinary Portland cement. However, the modulus of elasticity of the samples found to be lower than the control mix samples. The authors observed that compressive strength of GPC reduced beyond the 14 M of SH solution because of variation in phase composition at interface (aggregates and bulk matrix). Also, the compressive strength increases significantly with age [89, 90]. Vijai et al. reported that age of GPC has significant effect on the compressive strength of GPC this is in conformity with the previous reported literature. The authors reported significant increase in compressive strength (for both ambient and heat curing methods) between 7 days to 28 days. As depicted in Fig. 9 [72]., Patil et al. reported that compressive strength increases with increase in age of GPC which is consistent with previous reported literature [33, 73, 95]. Nagalia et al. investigated impact of curing environment, fly ash types and concentration of alkali hydroxide on microstructure and strength of GPC. The authors reported that greater concentration of calcium oxide in fly ash (utilized for GPC production) yields higher GPC strength. Also, out of different alkali hydroxides (sodium, potassium, barium and lithium) utilized for GPC production sodium hydroxide was the only one resulted in higher compressive strength. Also, greater calcium content, longer curing period, higher temperature results in higher compressive strength [113]. Deb et al. produced GPC (80 % Fly ash and 20 % GGBFS) with 0.4 alkaline to binder ratio and cured conditions at 20^{o}C, obtained compressive strength (maximum) of 51 MPa. The authors observed increase in compressive strength with age upto 28 days then the increase was insignificant which is consistent with previous studies [90]. Singhal et al. studied compressive strength of Fly ash based GPC with alccofines (10 %) and reported increase in compressive strength (obtained 37.5 MPa at 28 days, 12 M NaOH) with increase in fly ash content and molarity of sodium hydroxide [92]. Van and Trinh investigated fly ash based GPC with replacement of natural coarse and fine aggregates with slag aggregates. The authors obtained compressive strength in the rage of 34.8 to 44.85 MPa [114]. Hardjasaputra et al. reported maximum compressive strength of ambient cured fly ash based GPC as 61 MPa after 28 days. The authors observed increase in SH concentration as driving factor for gain in strength [115]. Gomaa et al. used class C fly ash with varying calcium content (21–37 %) for making GPC and obtained highest compressive strength (41.2 MPa, at 21 % calcium content) at 28 days. The authors observed faster gain in compressive strength with heat curing at constant alkali concentration [94]. Overall, it shows that age, concentration of alkali (in Molarity), curing temperature, curing period, sodium silicate to sodium hydroxide (SS to SH) ratio influence the compressive strength of the GPC. Optimum values of above parameters must be selected to obtain maximum compressive strength.

Fig. 4 **a** Slump value with sodium hydroxide concentration (NaOH, Molarity). **b** Slump value with alkaline solution to binder ratio (AS/B)



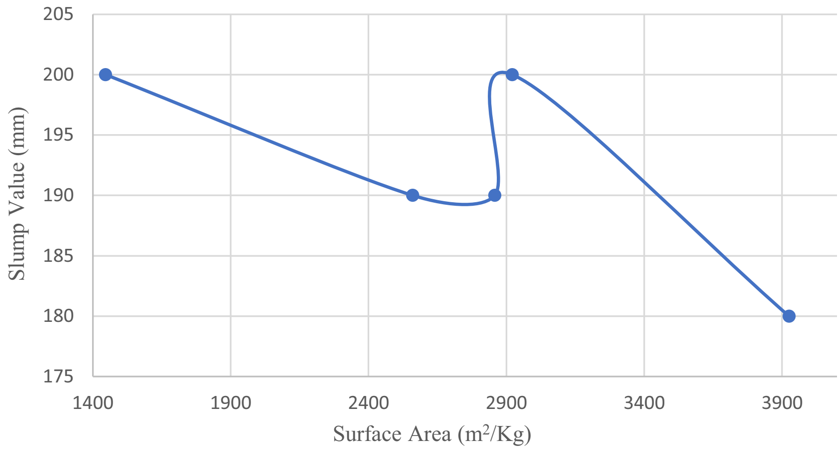


Fig. 5 Variation in slump value with varying fineness of fly ash

6.2.2 Splitting Tensile Strength

Splitting tensile strength is a method of determining tensile strength of hardened concrete. Joseph and Mathew obtained 3.45 MPa strength after 28 days and concluded that splitting tensile strength increases with increase in total aggregate in percentage by volume (TA) at constant fine aggregate to total aggregate in percentage by mass (FA/TA) ratio content in GPC mix which can be seen in Fig. 10a [23]. Shetty et al. obtained 2.97 MPa of strength from G40 grade of GPC after 28 days of open air curing compare to control mix which showed 2.79 MPa [97]. Yasir and Iftekar reported 2.56 MPa strength after 28 days for G20 grade of GPC [91]. Singhal et al. studied splitting tensile strength of Fly ash based GPC with alccofines (10 %) and reported increase in splitting tensile strength (obtained 3.5 MPa at 28 days, 12 M NaOH) with increase in fly ash content and molarity of sodium hydroxide [92]. Ganesh and Muthukannan studied the impact of adding glass & polypropylene fibers (various proportions i.e., 0&1, 0.25&0.75, 0.5&0.5, 0.75&0.25, and 1&0) on mechanical properties of GGBS based geopolymer concrete. The authors observed increase in splitting tensile strength (achieved maximum of 5.5 MPa at 100 % glass & 0 % polypropylene fiber) with increase in glass fiber proportion [116]. Moradikhou et al. used polypropylene, 2-part hybrid polypropylene and 4-part polyolefin fibers in various volume content (0.15, 0.2 and 0.25 %) to produce metakaolin based geopolymer concrete. The authors reported highest splitting tensile strength (2.1 MPa for polypropylene, 2.3 MPa for 2-part hybrid polypropylene and 2.4 MPa for 4-part polyolefin) for all three types of fibers at 0.2 % fiber content. At the same time addition of 4-part polyolefin fiber produced greatest splitting tensile strength among all three fibers [117]. Gomaa et al. utilized class C fly ash with varying calcium content (21–37 %) for making GPC and obtained highest splitting tensile strength (3.1 MPa, at 21 % calcium content) at 28 days [94]. In general, sodium hydroxide concentration, total aggregate (in % by volume), curing temperature, curing period, SS to SH ratio, alkaline solution to binder ratio, addition of fibers etc. influence the splitting tensile strength. Figure 10b. shows splitting tensile strength achieved in different studies.

6.2.3 Flexural Strength

Flexural strength of a material is its ability to resist distortion under load. Joseph and Mathew obtained 4.74 MPa strength after 28 days and concluded that flexural strength increases with increase in total aggregate content in GPC mix as shown in Fig. 11a [23]. Shetty et al. obtained 3.97 MPa of strength from G40 grade of GPC after 28 days of open air curing

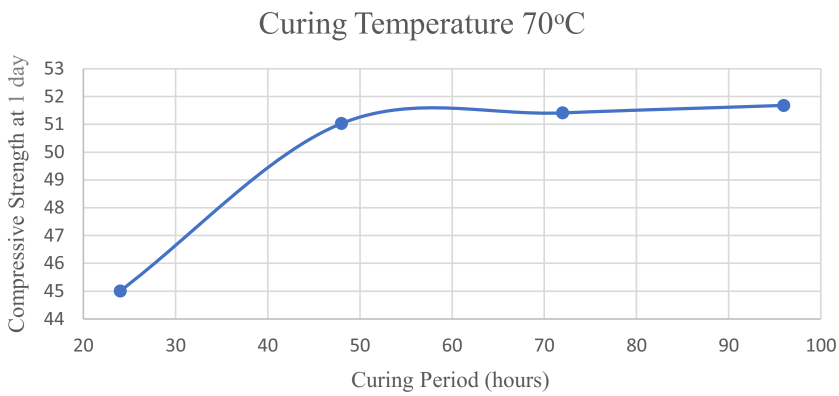


Fig. 6 Compressive strength with curing period

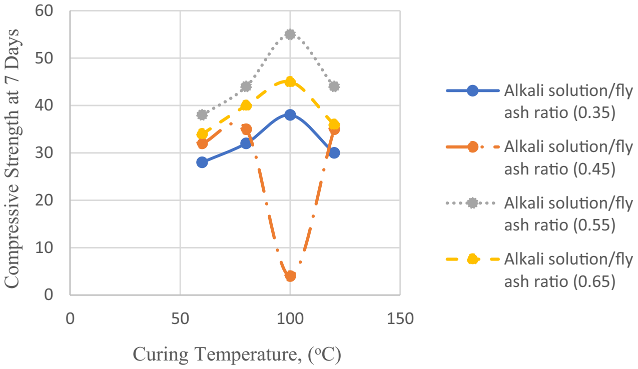


Fig. 7 Compressive strength with curing temperature

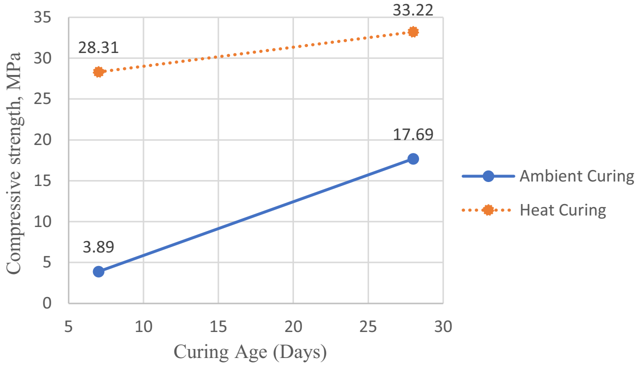
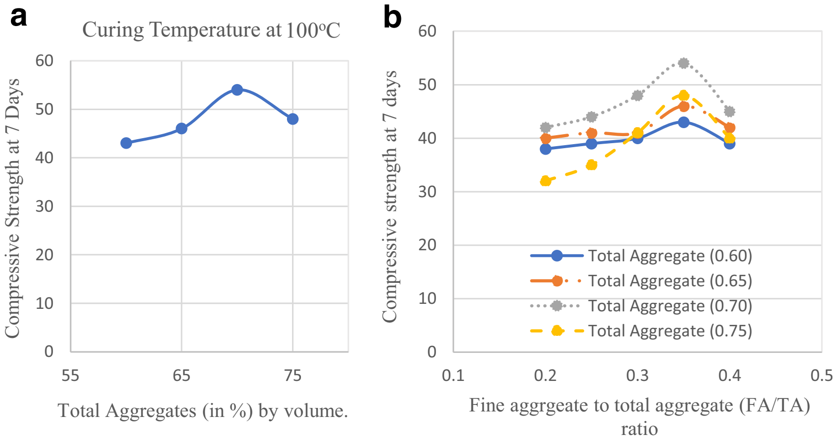


Fig. 9 Compressive strength with curing age

compare to control mix which showed 5.59 MPa [97]. Singhal et al. studied flexural strength of Fly ash based GPC with alccofines (10 %) and reported increase in flexural strength (obtained 4 MPa at 28 days, 12 M NaOH) with increase in fly ash content and molarity of sodium hydroxide. Further, Stress-Strain behavior found to be like PCC [92]. Van and Trinh investigated fly ash based GPC with slag aggregates instead of natural coarse and fine aggregates. The authors obtained flexural strength in the range of 4.5 to 5.9 MPa [114]. Nematollahi et al. utilized glass fiber (by volume of concrete) in varying proportions (0.5 %, 0.75 %, 1 % and 1.25 %) in fly ash based GPC and observed 12 %, 18 %, 10 % and 34 % increase (compare to GPC without glass fibers) in flexural strength at 0.5 %, 0.75 %, 1 % and 1.25 % glass fibers content (by volume of concrete). The authors achieved highest flexural strength of 9.1 MPa at 1.25 % of glass fiber content [118]. Hardjasaputra et al. reported maximum flexural strength of ambient cured fly ash based GPC to be 8.2 MPa after 28 days [115]. Ganesh and Muthukannan studied the impact of adding glass & polypropylene fibers (various proportions i.e., 0&1, 0.25&0.75, 0.5& 0.5, 0.75&0.25, and 1&0) on mechanical properties of GGBS based geopolymer concrete. The authors observed increase in flexural strength (achieved maximum of 7.5 MPa at 100 % glass & 0 % polyproplene fiber) with increase in glass fiber proportion [116]. Lach et al. used carbon fiber (1 m long and 5mm width) in geopolymer composite and obtained flexural strength of 8.3 MPa which was 15.1 % higher than control geopolymer composite (without fiber) [119]. Moradikhou et al. used polypropylene, 2-part hybrid polypropylene and 4-part polyolefin fibers in various volume content (0.15, 0.2 and 0.25 %) to produce metakaolin based geopolymer concrete. The authors reported highest flexural strength (4.1 MPa for polypropylene, 5.6 MPa for 2-part hybrid polypropylene and 5.8 MPa for 4-part polyolefin) for polypropylene fibers at 0.2 % fiber content (by volume) and for2-part hybrid polypropylene and 4-part polyolefin at 0.15 % fiber content. At the same time addition of 4-part polyolefin fiber (by volume) produced greatest flexural strength among all three fibers [117]. Gomaa et al. utilized class C fly ash with varying calcium content (21–37 %) for making GPC and obtained highest flexural strength (4.4 MPa, at 21 % calcium content) at 28 days [94]. Overall, it has been widely reported in the literature that majority of factors that affects compressive strength also influence flexural strength. It has been also reported that addition of fiber enhances the flexural strength of GPC compared to GPC without fibers. Figure 11b. shows flexural strength achieved in different studies.

Fig. 8 **a** Compressive strength with total aggregate (TA). **b** Compressive strength with fine aggregate to total aggregate (FA/TA) ratio



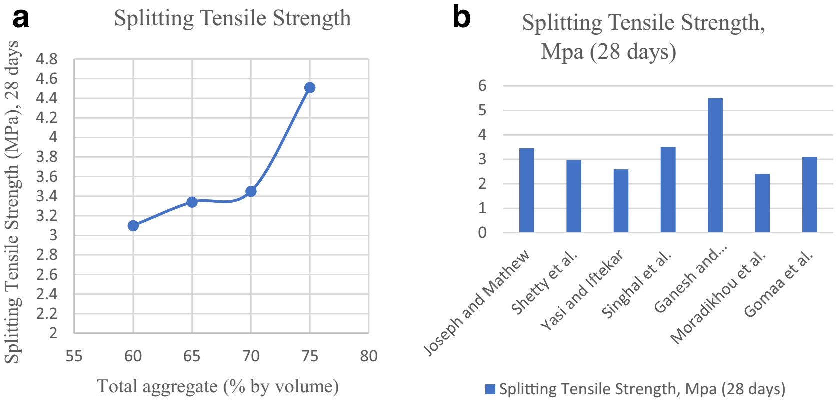


Fig. 10 **a** Splitting tensile strength with total aggregate. **b** Splitting tensile strength, MPa

6.2.4 Durability

Durability is the ability of the material to remain serviceable during the useful life without deterioration and unforeseen maintenance. Sanni and Khadiranaikar reported no changes in the shape and no visible cracks on the GPC samples when immersed in 10 % sulphuric acid solution for over 45 days. However, in the beginning white powder deposition was observed later it hardened. Further, reduction in splitting tensile strength of about 8–45 %, compressive strength of about 7–23 % and slight weight loss was noticed for all the grades of concrete as shown in Fig. 12a and b. The authors also immersed samples in magnesium sulphate solution for a period of 45 days and observed loss in compressive strength (3–12 %) and weight (7–30 %) and no major visible changes except minute amount of white deposit as shown in Fig. 13a and b [88]. Sukmak et al. investigated sulphate resistance of silt clay-fly ash based GPC by immersing samples in 5 % magnesium sulphate and 5 % sodium sulphate solutions by weight for 240 days. The authors observed 21.6 % and 10.8 % loss in compressive strength (as shown in Fig. 14.) due to immersion in magnesium sulphate and sodium sulphate respectively after 30 days, smooth surfaces and no visible cracks [120]. Yasir and Iftekar observed depletion in compressive strength (20.2 MPa to 12.96 MPa) when high alkaline liquid to fly ash ratio geopolymer concrete samples immersed in 10 % sulphuric acid. GPC have better resistance to acid attack compared to PCC because of low amount of calcium [91]. Nguyen et al. investigated the effect of rest period, curing time and curing temperature on the acid resistance and compressive strength of the GPC with varying molarities (1, 2, 4 M) of hydrochloric acid at 80^{o}C for 10 h. The authors observed GPC's better acid resistance capability compared to PCC owing to the sluggish endosmosis [121]. Wallah and Rangan studied the behaviour of low calcium fly ash based GPC (cured at 60^{o}C for 24 h) subject to varying sulphuric acid concentration (0.5, 1, 2 %) for a year. The authors reported 3 % loss in mass compared to OPC [122]. Olivia and Nikraz investigated the void content and water permeability of GPC and found them to be in the range of 8.2–13 % and 2.46×10^{-11} to 4.67×10^{-11} m/s. GPC considered of average quality when permeability is in the range of 10^{-11} to 10^{-12} m/s [96, 123]. Bhutta et al. produced GPC with waste fuel ash along with control mix with ordinary Portland cement (OPC) and subjected it to 5 % sodium sulphate solution for 1.5 years. The authors concluded that GPC samples incurred 4 % loss of mass compared to 20 % in case of OPC samples. Further, GPC resistance to sulphate attack and water absorption is better than OPC [124]. Overall, the deterioration of the concrete depends upon the concentration of acid and its exposure period. Deterioration in compressive strength of GPC is observed when it is subjected to acid attack but was significantly less compared to OPC.

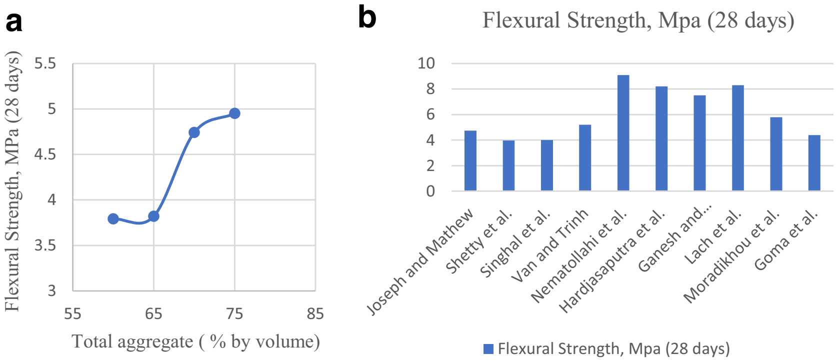


Fig. 11 **a** Flexural strength with total aggregate. **b** Flexural strength, MPa

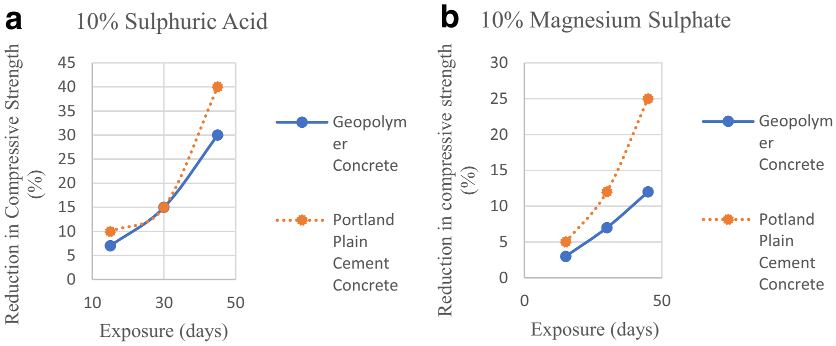


Fig. 12 **a** Reduction in compressive strength with sulphuric acid exposure. **b** Reduction in compressive strength with magnesium sulphate exposure

6.2.5 Drying Shrinkage

Shrinkage is the reduction in the volume of concrete with passing of time. It is different from creep as it is not dependent on the external loads. Wallah observed very low drying shrinkage strain in low calcium fly ash based GPC. The value of micro strains at one year measurement is about 100 compared to 500–800 micro strain in OPC. Further, micro strain values of all test series of samples showed no noteworthy difference [125]. Shetty et al. concluded during initial 30 days GPC showed slightly higher drying shrinkage compared to same grade of OPC [97]. Davidovits and Hardjito and Rangan reported that the presence of water in the micro pores of hardened GPC is very less and evaporates under heat curing. Hence, GPC exhibits low drying shrinkage under heat curing regime [95, 126].

7 Benefits

GPC is an innovative and appropriate sustainable construction material. GPC has gathered attention of engineers and researchers because of its low carbon footprint and ecofriendly production process. In addition to this GPC has many other noteworthy benefits with regard to mechanical property and economy compared to conventional cement concrete [26]. Benefits of GPC include:

a) GPC requires low maintenance cost due to better durability [26].
b) GPC production results up to 90 % cutting in carbon dioxide emission as compared to OPC [127, 128].
c) GPC can be utilized as lightweight concrete [17, 129].
d) GPC possess higher freeze and thaw resistance [129].
e) GPC shows low drying shrinkage property and is better corrosion resistant against sulphide and sulphate [130, 131].
f) Provides better compressive strength over OPC [132–134].

8 Limitations

Apart from the benefits there are some limitations of GPC which include:

a) Despite low priced fly ash compared to Portland cement the overall cost of the GPC is more than the Portland cement concrete. This is mainly due to costly alkaline solution which amounts to approximately 60 % of total GPC cost [135, 136]. However, in large scale production the cost of GPC may be comparable to OPC.
b) GPC is brittle and cracks at peak load similar to conventional concrete. Addition of fibers can prevent the rapid propagation of cracks and improve tensile strength along with ductility [137, 138].
c) GPC develops early strength at elevated temperature curing and at ambient temperature it takes time to gain strength. This limits its application to precast structures

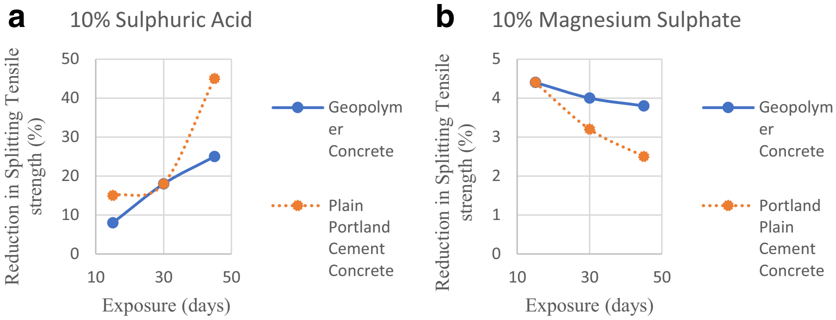


Fig. 13 **a** Reduction in splitting tensile strength with sulphuric acid exposure. **b** Reduction in splitting tensile strength with magnesium sulphate exposure

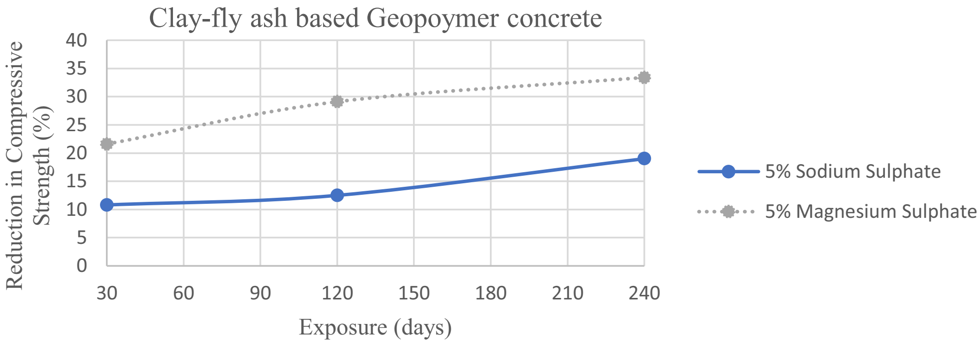


Fig. 14 Compressive strength with sodium sulphate and magnesium sulphate exposure

only where elevated temperature curing is possible [26]. However, there is limited number of studies which concluded that ambient cured GPC also develop strength comparable to OPC [139].

d) Due to wide variations in raw materials and activators (alkaline) the same mix design may result in different workability and strength which may have a negative impact on the quality of the GPC mix [31, 40].

9 Applications

GPC can be utilized from small scale to large scale constructions projects. The application of GPC can be in both reinforced concrete construction and Plain concrete construction. VicRoads or Roads Coorperation of Victoria, Victoria, Australia utilized GPC first time in 2009 for an in-situ construction of landscape retaining wall at a bridge site. Thereafter GPC was used to build bicycle path, kerb and channel. VicRoads also constructed GPC based reinforced retaining wall at M80 Western ring road and underground storm water drains where they have used steel reinforced GPC pipes [138]. GPC exhibit exceptional durability properties such as high resistance to acid attack, alkali-silica reaction, fire, limited sulphate attack, and low carbonation. GPC are most suitable for precast concrete elements such as girders, beams, wall panels, railways sleepers etc. as elevated temperature curing in GPC provide early strength gain compared to the ambient curing.

10 Conclusions

With the boom in infrastructural development activities around the globe the consumption of concrete has increased, which further rocketed the cement production. This has led to more carbon dioxide emission into the atmosphere. At the same time thermal power plants have been producing enormous amount of fly ash which is not fully utilized. So, in present scenario development of geopolymer concrete as an alternative to plain cement concrete can give us a sustainable remedy. This can reduce the requirement of cement thereby reducing the carbon dioxide emission and at the same time increase the utilization of fly ash. Geopolymer concrete (GPC) as an alternative sustainable material to Portland cement concrete has significant benefits in terms of environment, mechanical strength properties, resistance to aggressive environment, low maintenance cost etc. However, it does have some limitations such as costly compared to Portland cement concrete, intricate mix design, variation in results due to inconsistent quality of raw materials and ambiguity in application of type of curing regime. The limitations can be overcome by bringing down the cost through mass production, by developing and adopting consistent mix design guidelines, utilizing uniform quality of raw materials and adopting type of curing appropriate to the work undertaken. Also, based on observation and analysis of comprehensive literature review following conclusion may be drawn.

- Composition of fly ash based geopolymer concrete differs from Portland cement concrete except aggregates and admixtures. In GPC, binder paste is made from fly ash and alkaline activators solution whereas, in PCC binder paste is made from cement and water.
- There are no globally accepted uniform guidelines for mixture design of GPC compare to PCC. This may be due to involvement of many variables such as raw materials, alkali activators, different curing regimes in GPC production, which make mix design process intricate.
- Type of curing regime, concentration and quantity of alkaline solution, rest period, period of heat curing, and water content impacts the performance of fly ash based geopolymer concrete.
- Compressive strength of fly ash based geopolymer concrete increases with increase in curing temperature, sodium silicate to sodium hydroxide solution ratio (up to 2.5 only) and alkaline solution concentration but decreases with increase inn water-geopolymer solids ratio, alkaline

solution to fly ash ratio and superplasticizer beyond 2 % by weight of binder content. Further, increase in rest period duration during heat curing regime results in enhanced strength of GPC. Heat curing primarily employed when early strength is required.

- Workability of fresh geopolymer concrete found to be less compared to Portland cement concrete. However, the workability can be increased by the addition of superplasticizers. For instance, polycarboxylates based superplasticizer, naphthalene-based superplasticizers etc.
- It has been observed that geopolymer concrete possess better resistance against drying shrinkage and acids such as sulphuric acid, magnesium, and sodium sulphate.

11 Future Scope for Research

Extensive research has been conducted in the field of fly ash based geopolymer concrete in the past decade. Yet, there is lack of uniform guidelines on mixture design of GPC, which may be due to utilization of variety of inconsistent materials in production of GPC. Hence, for industry acceptance of geopolymer concrete development of uniform guidelines (specially in India) may be undertaken. Investigations on structural behaviour and durability studies of fly ash based geopolymer concrete are limited. Hence, more studies may be undertaken in this direction.

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Data availability Not applicable.

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Declarations

Conflicts of competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to participate The author(s) declare that no humans or participants are involved in this study.

Consent for publication The author(s) declare that the figures and tables used in this paper are original and are not published anywhere.

References

1. Malhotra VM (2002) Introduction: sustainable development and concrete technology. ACI Concr Int 24:22
2. Hardjito D, Wallah SE, Sumajouw DM, Rangan BV (2004) On the development of fly ash-based geopolymer concrete. Mater J 101:467–472
3. Harris D, Heidrich C, Feuerborn J (2019) Global aspects on coal combustion products. In: World of Coal Ash Conference, Conference Paper
4. Haque ME (2013) Indian fly-ash: production and consumption scenario. Int J Waste Resour 3:22–25
5. Surabhi S (2017) Fly ash in India: generation vis-à-vis utilization and Global perspective. Int J Appl Chem 13:29–52
6. Report on fly ash generation at coal/Lignite based thermal power stations and its utilization in the country for year 2019-20 (Nov 2020) Central Electricity Authority, New Delhi. http://www.cea.nic.in/reports/others/thermal/tcd/flyash_2019-20.pdf. Accessed 02 Feb 2021
7. Rastogi A, Paul VK (2020) A critical review of the potential for fly ash utilisation in construction-specific applications in India. Env Res Eng Manag 76:65–75
8. Davidovits J (1989) Geopolymers and geopolymeric materials. J Therm Anal 35:429–441
9. Meesala CR, Verma NK, Kumar S (2020) Critical review on fly-ash based geopolymer concrete. Struct Concr 21:1013–1028
10. Agrawal US, Wanjari SP, Naresh DN (2019) Impact of replacement of natural river sand with geopolymer fly ash sand on hardened properties of concrete. Const Build Mater 209:499–507
11. Malhotra VM (1999) In: Parameswaran VS (eds) International Conference on Fibre Composites, High-Performance Concrete and Smart Materials, Chennai, India
12. McCaffrey R (2002) Climate change and the cement industry. GCL: Envir Sp Issu 8:15–19. https://thegreencaiman.files.wordpress.com/2016/03/climate_change_and_the_cement_industry.pdf
13. Agrawal US, Wanjari SP, Naresh DN (2017) Characteristic study of geopolymer fly ash sand as a replacement to natural river sand. Const Build Mater 150:681–688
14. Mathew BJ, Sudhakar M, Natarajan C (2013) Strength, economic and sustainability characteristics of coal ash–GGBS based geopolymer concrete. Int J Comput Eng Res 3:207–212
15. Risdanareni P, Ekaputri JJ, Abdullah Al Bakri MM (2015) Effect of alkaline activator ratio to mechanical properties of geopolymer concrete with trass as filler. Appl Mech Mater 754:406–412
16. Temuujin J, Van Riessen A, MacKenzie KJD (2010) Preparation and characterisation of fly ash based geopolymer mortars. Const Build Mater 24:1906–1910
17. Headwaters Resources (2005) Fly ash types& benefits. Utah, USA. http://www.flyash.com/data/upimages/press/TB.1%20Fly%20Ash%20-%20Types%20&%20Benefits.pdf
18. Thomas M (2007) Optimizing the use of fly ash in concrete. Portland Cement Association, Skokie, vol 5420, p 24
19. Ekaputri JJ, Bahrul UM, Bayuaji R, Eddy ST, Mustafa M, Bakri A, Ash F (2015) A comprehensive characterization and determination of fly ashes in indonesia using different methods. Appl Mech Mater 754:320–325
20. Das SK, Mohapatra AK, Rath AK (2014) Geo-polymer concrete – Green concrete for the future — A review. Int J Civ Eng Res 5:21–28
21. Al Bakri MM, Mohammed H, Kamarudin H, Niza IK, Zarina Y (2011) Review on fly ash-based geopolymer concrete without portland cement. J Eng Technol Res 3(1):1–4

22. Ryu GS, Lee YB, Koh KT, Chung YS (2013) The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Const Build Mater 47:409–418
23. Joseph B, Mathew G (2012) Influence of aggregate content on the behavior of fly ash based geopolymer concrete. Scientia Iranica 19:1188–1194
24. Isabella C, Xu H, Luckey GC, Van Deventer JSJ (2003) In: Mistry V, Azizinamini A, Hooks JM (eds). The effect of aggregate particle size on formation of geopolymeric gel. In: Advanced Materials Proceedings, Davos, Switzerland. https://dc.engconfintl.org/advanced_materials/9/
25. Ma CK, Awang AZ, Omar W (2018) Structural and material performance of geopolymer concrete: A review. Const Build Mater 186:90–102
26. Zerfu K, Ekaputri JJ (2016) Review on alkali-activated fly ash based geopolymer concrete. Mater Sci For 841:162–169
27. Shah MV, Kammula R, Nannapaneni P, Raijiwala PDB (2014) Alkali activated flyash based geopolymer concrete. J Artic 3:159–166
28. Nematollahi B, Sanjayan J (2014) Effect of different superplasticizers and activator combinations on workability and strength of fly ash based geopolymer. Mater Des 57:667–672
29. Li N, Zhang Z, Shi C, Zhang J (2018) In: Alengram UJ, Hung MK, Jumaat MZ, Sulong NHR, Raman SN (eds) Some progresses in the challenges for geopolymer. IOP Conference Series: Material Science and Engineering, Malaysia
30. Montes C, Gomez SA, Khadka N, Allouche EN (2013) Statistical software to improve the accuracy of geopolymer concrete mix design and proportioning. Proceedings of 2013 world of coal ash conference, Lexington, Kentucky, USA, 22–25 April 2013. American Coal Ash Association, Farmington Hills, Michigan, USA. http://www.flyash.info/2013/123-Montes-2013.pdf
31. Li N, Shi C, Zhang Z, Wang H, Liu Y (2019) A review on mixture design methods for geopolymer concrete. Compos Part B Eng 178:107490
32. Xie T, Visintin P, Zhao X, Gravina R (2020) Mix design and mechanical properties of geopolymer and alkali activated concrete: Review of the state-of-the-art and the development of a new unified approach. Constr Build Mater 256:119380
33. Rangan B (2007) Concrete construction engineering handbook. CRC Press, Boca Raton
34. Diaz-Loya EI, Allouche EN, Vaidya S (2011) Mechanical properties of fly-ash-based geopolymer concrete. ACI Mater J 108:300
35. Diaz EI, Allouche EN, Eklund S (2010) Factors affecting the suitability of fly ash as source material for geopolymers. Fuel 89:992–996
36. Junaid MT, Narong T, Pichai N (2006) Reducing bleeding in mix for bored pile application without affecting other fresh concrete properties: methodology and procedure. In: Proceedings of the tenth East Asia-Pacific conference on structural engineering and construction. Bangkok, Thailand
37. Nawy EG (2008) Concrete construction engineering handbook. CRC Press, Boca Raton
38. Lloyd N, Rangan V (2010) In: Zachar J, Claisse P, Naik TR, Ganjian E (eds) Geopolymer concrete with fly ash. ASCE, Italy
39. Kong DL, Sanjayan JG (2008) Damage behavior of geopolymer composites exposed to elevated temperatures. Cem Conc Comp 30:986–991
40. Li N, Shi C, Wang Q, Zhang Z, Ou Z (2017) Composition design and performance of alkali-activated cements. Mater Struct 50:178
41. Aughenbaugh KL, Williamson T, Juenger MCG (2015) Critical evaluation of strength prediction methods for alkali-activated fly ash. Mater Struc 48:607–620
42. RSN 336-84 (1984) Republican building norms for production and use of slag alkaline binders, concretes and structures. The National Committee Ukrainian Republic of the USSR for construction, Kiev, USSR
43. Rangan BV (2008) Design and manufacture of flyash-based geopolymer concrete. Conc Aust 34:37–43
44. Anuradha R, Sreevidya V, Venkatasubramani R, Rangan BV (2012) Modified guidelines for geopolymer concrete mix design using Indian standard. Asian J Civ Eng (Build Hous) 13:353–364
45. Ferdous MW, Kayali O, Khennane A (2013) A detailed procedure of mix design for fly ash based geopolymer concrete. In: Proceedings of the fourth Asia-Pacific conference on FRP in structures. Melbourne, Australia https://researchbank.swinburne.edu.au/file/552b44c9-7cb9-4509-8229-ec0f1f9bba0c/1/PDF%20%28Published%20version%29.pdf
46. Ferdous W, Manalo A, Khennane A, Kayali O (2015) Geopolymer concrete-filled pultruded composite beams–concrete mix design and application. Cem Conc Comp 58:1–13
47. Pavithra PE, Reddy MS, Dinakar P, Rao BH, Satpathy BK, Mohanty AN (2016) A mix design procedure for geopolymer concrete with fly ash. J Clean Prod 133:117–125
48. Li N, Shi C, Zhang Z, Zhu D, Hwang HJ, Zhu Y, Sun T (2018) A mixture proportioning method for the development of performance-based alkali-activated slag-based concrete. Cem Conc Comp 93:163–174
49. Bondar D, Nanukuttan S, Provis JL, Soutsos M (2019) Efficient mix design of alkali activated slag concretes based on packing fraction of ingredients and paste thickness. J Clean Prod 218:438–449
50. Bellum RR, Nerella R, Madduru SRC, Indukuri CSR (2019) Mix design and mechanical properties of fly ash and GGBFS-synthesized Alkali-Activated Concrete (AAC). Infrastructures 4:20
51. Rao GM, Kumar KS, Poloju KK, Srinivasu K (2020) In: Kumar SV, Jena SP, Vardhan MV (eds) An emphasis of geopolymer concrete with single activator and conventional concrete with recycled aggregate and data analyzing using artificial neural network. IOP Conference Series: Materials Science and Engineering, India
52. Longos A, Tigue AA, Dollente IJ, Malenab RA, Bernardo-Arugay I, Hinode H, Kurniawan W, Promentilla MA (2020) Optimization of the mix formulation of geopolymer using nickel-laterite mine waste and coal fly ash. Mine 10:1144
53. Bondar D, Ma Q, Soutsos M, Basheer M, Provis JL, Nanukuttan S (2018) Alkali activated slag concretes designed for a desired slump, strength and chloride diffusivity. Const Build Mater 190:191–199
54. Türkmen İ, Gül R, Çelik C (2008) A Taguchi approach for investigation of some physical properties of concrete produced from mineral admixtures. Build Env 43:1127–1137
55. Hadi MN, Farhan NA, Sheikh MN (2017) Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method. Const Build Mater 140:424–431
56. Mehta A, Siddique R, Singh BP, Aggoun S, Łagód G, Barnat-Hunek D (2017) Influence of various parameters on strength and absorption properties of fly ash based geopolymer concrete designed by Taguchi method. Const Build Mater 150:817–824
57. Zain MFM, Abd SM (2009) Multiple regression model for compressive strength prediction of high performance concrete. J App Sci 9:155–160
58. Lokuge W, Wilson A, Gunasekara C, Law DW, Setunge S (2018) Design of fly ash geopolymer concrete mix proportions using Multivariate Adaptive Regression Spline model. Const Build Mater 166:472–481
59. Hadi MN, Zhang H, Parkinson S (2019) Optimum mix design of geopolymer pastes and concretes cured in ambient condition based on compressive strength, setting time and workability. J Build Eng 23:301–313

60. Dao DV, Ly HB, Trinh SH, Le TT, Pham BT (2019) Artificial intelligence approaches for prediction of compressive strength of geopolymer concrete. Mater 12:983
61. Ling Y, Wang K, Wang X, Li W (2019) Prediction of engineering properties of fly ash-based geopolymer using artificial neural networks. Neur Comp Appl 3:1–21
62. Gao Y, Xu J, Luo X, Zhu J, Nie L (2016) Experiment research on mix design and early mechanical performance of alkali-activated slag using response surface methodology (RSM). Ceram Int 42: 11666–11673
63. Zahid M, Shafiq N, Isa MH, Gil L (2018) Statistical modeling and mix design optimization of fly ash based engineered geopolymer composite using response surface methodology. J Clean Prod 194: 483–498
64. CEN/TR PD (2013) Principles of the equivalent durability procedure. CEN, Brussels, p 16563
65. El-Hassan H, Ismail N (2018) Effect of process parameters on the performance of fly ash/GGBS blended geopolymer composites. J Sustain Cem Based Mater 7:122–140
66. Khayat KH, Ghezal A, Hadriche MS (2000) Utility of statistical models in proportioning self-consolidating concrete. Mater Str 33: 338–344
67. Cihan MT, Güner A, Yüzer N (2013) Response surfaces for compressive strength of concrete. Constr Build Mater 40:763–774
68. Aldahdooh MAA, Bunnori NM, Johari MM (2013) Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method. Mater Des 52:957–965
69. Mohammed BS, Achara BE, Nuruddin MF, Yaw M, Zulkefli MZ (2017) Properties of nano-silica-modified self-compacting engineered cementitious composites. J Clean Prod 162:1225–1238
70. Joshi SV, Kadu MS (2012) Role of alkaline activator in development of eco-friendly fly ash based geo polymer concrete. Int J Environ Sci Dev 3:417
71. Motorwala A, Shah V, Kammula R, Nannapaneni P, Raijiwala DB (2013) Alkali activated fly-ash based geopolymer concrete. Int J Emerg Technol Adv Eng 3:159–166
72. Vijai K, Kumutha R, Vishnuram BG (2010) Effect of types of curing on strength of geopolymer concrete. Int J Phys Sci 5: 1419–1423
73. Adam AA, Horianto (2014) The effect of temperature and duration of curing on the strength of fly ash based geopolymer mortar. Proc Eng 95:410–414
74. Patil AA, Chore HS, Dode PA (2014) Effect of curing condition on strength of geopolymer concrete. Adv Conc Const 2:029
75. Venkateswara Rao J, Srinivasa Rao K, Rambabu K (2019) Performance of heat and ambient cured geopolymer concrete exposed to acid attack. Proc Inst Civ Eng Const Mater 172:192–200
76. Karunanithi S, Anandan S (2014) Flexural toughness properties of reinforced steel fibre incorporated alkali activated slag concrete. Adv Civ Eng 4(3):1–12
77. Srinivasan K, Sivakumar A (2015) Chemical activation and curing regime of geopolymer concretes. Proc Inst Civ Eng Const Mater 168:24–34
78. Yewale VV, Shirsath MN, Hake SL (2016) Evaluation of efficient type of curing for geopolymer concrete. Int J New Technol Sci Eng 3:10–14
79. Azarsa P, Gupta R (2020) Comparative study involving effect of curing regime on elastic modulus of geopolymer concrete. Buildings 10:101
80. Kumaravel S (2014) Development of various curing effect of nominal strength Geopolymer concrete. J Eng Sci Technol Rev 7:116–119
81. Rao GM, Venu M (2020). In: Sunramaniam KVL, Khan AM (eds) Mix design methodology for fly ash and GGBS-based geopolymer concrete. Springer, Singapore
82. Chindaprasirt P, Rattanasak U, Taebuanhuad S (2013) Role of microwave radiation in curing the fly ash geopolymer. Adv Powder Technol 24:703–707
83. Hong S, Kim H (2019) Effects of microwave energy on fast compressive strength development of coal bottom ash-based geopolymers. Sci Rep 9:1–17
84. Kastiukas G, Ruan S, Liang S, Zhou X (2020) Development of precast geopolymer concrete via oven and microwave radiation curing with an environmental assessment. J Clean Prod 255: 120290
85. Hardjito D, Wallah SE, Sumajouw DM, Rangan BV (2004) Factors influencing the compressive strength of fly ash-based geopolymer concrete. Civ Eng Dimens 6:88–93
86. Rangan BV, Wallah S, Sumajouw D, Hardjito D (2006) Heat-cured, low-calcium, fly ash-based geopolymer concrete. Ind Conc J 80:47–52
87. Memon FA, Nuruddin MF, Demie S, Shafiq N (2012) Effect of superplasticizer and extra water on workability and compressive strength of self-compacting geopolymer concrete. Res J Appl Sci Eng Technol 4:407–414
88. Sanni SH, Khadiranaikar RB (2012) Performance of geopolymer concrete under severe environmental conditions. Int J Civ Struct Eng 3:396–407
89. Nath P, Sarker PK (2015) Use of OPC to improve setting and early strength properties of low calcium fly ash geopolymer concrete cured at room temperature. Cem Conc Comp 55:205–214
90. Deb PS, Nath P, Sarker PK (2014) The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. Mater Des 62:32–39
91. Yasir S, Iftekar G (2015) Study of properties of Fly ash based geopolymer concrete. Inter J of Eng Res 3(3):74–79 http://www.ijoer.in/3.1.15/Yasir%2074-79.pdf
92. Singhal D, Junaid MT, Jindal BB, Mehta A (2018) Mechanical and microstructural properties of fly ash based geopolymer concrete incorporating alccofine at ambient curing. Const Build Mater 180:298–307
93. Jamkar SS, Ghugal YM, Patankar SV (2013) Effect of fly ash fineness on workability and compressive strength of geopolymer concrete. The Ind Conc J 87:57–62
94. Gomaa E, Sargon S, Kashosi C, Gheni A, El Gawady MA (2020) Mechanical properties of high early strength class C fly ash-based alkali activated concrete. Trans Res Rec J Transp Res Board 2674: 430–443
95. Hardjito D, Rangan BV (2005) Development and properties of low-calcium fly ash-based geopolymer concrete. Report, Curtin University of Technology, Perth
96. Olivia M, Nikraz H (2011) Strength and water penetrability of fly ash geopolymer conrete. J Eng Appl Sci 6:70–78
97. Shetty KK, Gopinatha N, Pandit P, Karkera J, Kiran Kumara SS (2015) Strength and shrinkage characteristics of geo-polymer concrete. Int J Earth Sci Eng 8:169–172
98. Abdullah MMAB, Hussin K, Bnhussain M, Ismail KN, Yahya Z, Abdul Razak R (2012) Fly ash-based geopolymer lightweight concrete using foaming agent. Int J Mol Sci 13(6):7186–7198
99. Omar AA, Al Bakri Abdullah MM, Hussin K, Khairul Nizar I (2013) Lightweight fly ash-based geopolymer concrete. Adv Mater Res 626:781–785
100. Khalil WI, Abbas WA, Nasser IF (2019) Dynamic modulus of elasticity of geopolymer lightweight aggregate concrete. In: IOP Conference Series: Materials Science and Engineering, Iraq
101. Top S, Vapur H, Altiner M, Kaya D, Ekicibil A (2020) Properties of fly ash-based lightweight geopolymer concrete prepared using pumice and expanded perlite as aggregates. J Mol Struct 1202: 127236

102. Leung CK, Pheeraphan T (1995) Very high early strength of microwave cured concrete. Cem Conc Res 25:136–146
103. Palomo A, Grutzeck MW, Blanco MT (1999) Alkali-activated fly ashes: A cement for the future. Cem Conc Res 29:1323–1329
104. Ahmed MF, Nuruddin MF, Shafiq N (2011) Compressive strength and workability characteristics of low-calcium fly ash-based self-compacting geopolymer concrete. Int J Civ Env Eng 5:64–70
105. Duxson P, Lukey GC, Separovic F, Van Deventer JSJ (2005) Effect of alkali cations on aluminum incorporation in geopolymeric gels. Ind Eng Chem Res 44:832–839
106. Sagoe-Crentsil K, Weng L (2007) Dissolution processes, hydrolysis and condensation reactions during geopolymer synthesis: Part II. High Si/Al ratio systems. J Mater Sci 42:3007–3014
107. Weng L, Sagoe-Crentsil K (2007) Dissolution processes, hydrolysis and condensation reactions during geopolymer synthesis: Part I—Low Si/Al ratio systems. J Mater Sci 42:2997–3006
108. Hou Y, Wang D, Zhou W, Lu H, Wang L (2009) Effect of activator and curing mode on fly ash-based geopolymers. J Wuhan Univ Tech Mater Sci Ed 24:711
109. Panias D, Giannopoulou IP, Perraki T (2007) Effect of synthesis parameters on the mechanical properties of fly ash-based geopolymers. Coll Surf A: Phys Eng Asp 301:246–254
110. Fernández-Jiménez A, Palomo A (2005) Composition and microstructure of alkali activated fly ash binder: Effect of the activator. Cem Conc Res 35:1984–1992
111. Jaydeep S, Chakravarthy BJ (2013) Study on fly ash based geopolymer concrete using admixtures. Int J Eng Trends Technol 4:4614–4617
112. Chindaprasirt P, Chareerat T, Sirivivatnanon V (2007) Workability and strength of coarse high calcium fly ash geopolymer. Cem Concr Compos 29:224–229
113. Nagalia G, Park Y, Abolmaali A, Aswath P (2016) Compressive strength and microstructural properties of fly ash–based geopolymer concrete. J Mater Civ Eng 28:04016144
114. Van Dao D, Trinh SH (2020) In: Cuong H-M, Van Dao D, Benboudjema F, Sybil D, Huynh DVK, Tang AM (eds) Mechanical properties of fly ash based geopolymer concrete using only steel slag as aggregate. Springer, Singapore
115. Hardjasaputra H, Cornelia M, Gunawan Y, Surjaputra IV, Lie HA, Ng GP (2019) In: Lie HA, Garrecht H, Sharma A, Hardjasaputra H (eds) Study of mechanical properties of fly ash-based geopolymer concrete. In IOP Conference Series: Materials Science and Engineering, Germany
116. Ganesh AC, Muthukannan M (2019) In: Muthusamy R (eds) Experimental study on the behaviour of hybrid fiber reinforced geopolymer concrete under ambient curing condition. In IOP Conference Series: Materials Science and Engineering, India
117. Moradikhou AB, Esparham A, Avanaki MJ (2020) Physical & mechanical properties of fiber reinforced metakaolin-based geopolymer concrete. Constr Build Mater 251:118965
118. Nematollahi B, Sanjayan J, Chai JXH, Lu TM (2014) Properties of fresh and hardened glass fiber reinforced fly ash based geopolymer concrete. Key Eng Mater 594:629–633
119. Łach M, Hebdowska-Krupa M, Mierzwiński D, Korniejenko K (2019) In: Lach M (eds) Mechanical properties of geopolymers reinforced with carbon and aramid long fibers. In IOP Conference Series: Materials Science and Engineering, Uruguay
120. Sukmak P, De Silva P, Horpibulsuk S, Chindaprasirt P (2015) Sulfate resistance of clay-portland cement and clay high-calcium fly ash geopolymer. J of Mater in Civi Eng 27:04014158
121. Nguyen KT, Lee YH, Lee J, Ahn N (2013) Acid resistance and curing properties for green fly ash-geopolymer concrete. J Asian Archit Build Eng 12:317–322
122. Wallah E, Rangan BV (2006) Low-calcium fly ash-based geopolymer concrete: Long-term properties. Report, Curtin University of Technology, Perth
123. Rendell F, Jauberthie R, Grantham M (2002) Deteriorated concrete: Inspection and physicochemical analysis. Thomas Telford, Scotland
124. Bhutta MAR, Hussin WM, Azreen M, Tahir MM (2014) Sulphate resistance of geopolymer concrete prepared from blended waste fuel ash. J Mater Civ Eng 26:04014080
125. Wallah SE (2009) Drying shrinkage of heat-cured fly ash-based geopolymer concrete. Mod Appl Sci 3:14–21
126. Davidovits J (1999) In: Davidovits J (ed) Chemistry of geopolymeric systems terminology. Proceedings of International Conference on Geopolymers, France, p 1999. https://www.tib.eu/en/search/id/BLCP:CN057039461/Chemistry-of-Geopolymeric-Systems-Terminology-pp?cHash=e692c081d1b646aed83bdb4a07970e96
127. Davidovits J (2013) Geopolymer cement. A review. Geop Insti Tech Pap 21:1–11
128. Sakthidoss DD, Senniappan T (2020) A study on high strength geopolymer concrete with alumina-silica materials using manufacturing sand. Silicon 12:735–746
129. Zhao R, Yuan Y, Cheng Z, Wen T, Li J, Li F, Ma ZJ (2019) Freeze-thaw resistance of class F fly ash-based geopolymer concrete. Const Build Mater 222:474–483
130. Abdelmseeh VA, Jofriet JC, Negi SC, Hayward GL (2005) Corrosion of reinforced concrete specimens exposed to hydrogen sulphide and sodium sulphate. Agric Eng Int CIGR J 7:1–15
131. Kishan LJ, Radhakrishna (2013) Comparative study of cement concrete and Geopolymer masonry blocks. Int J of Res in Eng Tech:361–365. https://ijret.org/volumes/2013v02/i13/IJRET20130213068.pdf
132. Oyebisi S, Ede A, Olutoge F, Omole D (2020) Geopolymer concrete incorporating agro-industrial wastes: Effects on mechanical properties, microstructural behaviour and mineralogical phases. Const Build Mater 256:119390
133. Ostwal T, Chitawadagi MV (2014) Experimental investigations on strength, durability, sustainability and economic characteristics of geopolymer concrete blocks. Int J Res Eng Technol 3:115–122
134. Ojha A, Gupta L (2020) In: Chauhan A, Sehgal S (eds) Comparative study on mechanical properties of conventional and geo-polymer concrete with recycled coarse aggregate. Materials Today: Proceedings, Chandigarh, Punjab, India
135. Mathew BJ, Sudhakar M, Natarajan C (2013) Strength, economic and sustainability characteristics of coal ash–GGBS based geopolymer concrete. Int J Comp Eng Res 3:207–212
136. Sun P, Wu HC (2008) Transition from brittle to ductile behavior of fly ash using PVA fibers. Cem Conc Comp 30:29–36
137. Yunsheng Z, Wei S, Zongjin L, Xiangming Z, Chungkong C (2008) Impact properties of geopolymer based extrudates incorporated with fly ash and PVA short fiber. Constr Build Mater 22:370–383
138. Andrews-Phaedonos F (2014) Specification and use of geopolymer concrete. Austroads bridge conference, 9th, 2014, Sydney, New South Wales, Australia (no. 6.2). https://trid.trb.org/view/1341131
139. Goriparthi MR (2017) Effect of fly ash and GGBS combination on mechanical and durability properties of GPC. Adv Conc Const 5:313