Advancements in Ash-Based Geopolymer Concrete: A Comprehensive Overview

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Abstract

The manufacturing procedure of ordinary Portland cement is widely acknowledged as a highly energy-intensive operation, leading to the release of detrimental greenhouse gases into the atmosphere, thus contributing to environmental contamination. The growth of worldwide infrastructural initiatives has resulted in a projected surge in the utilization of concrete, thereby stimulating the manufacturing of Ordinary Portland Cement (OPC). The inadequate utilization of fly ash produced by thermal power plants has led to environmental and disposal difficulties. The implementation of fly ash derived geopolymer concrete as a substitute for conventional Portland cement concrete presents a feasible resolution to tackle the environmental and land disposal predicaments. Geopolymer concrete demonstrates a diminished carbon footprint when compared to conventional Portland cement concrete. This research paper offers a thorough examination of diverse facets pertaining to geopolymer concrete derived from fly ash. The subject matter encompasses various aspects including composition, methodologies for mix design, the production process, curing protocols, advantages, drawbacks, and potential applications. Through a comprehensive analysis of relevant scholarly literature and empirical research, the primary objective of this paper is to synthesize and present a comprehensive comprehension of the topic at hand. The following document provides a comprehensive summary of the notable research discoveries regarding the characteristics of geopolymer concrete in both its fresh and hardened states. These investigations have been carried out within the last ten years. In summary, the objective of this study is to determine the key factors that should be considered when selecting an ideal curing method in order to achieve the desired performance of concrete. The aggregation of a significant quantity of data possesses the capacity to provide valuable insights for forthcoming research endeavors.

Keywords. GPC, Geopolymer, Density, Compressive strength, Sustainable, Response Surface Method

1. Introduction

Geopolymer concrete has garnered considerable interest in recent times. This novel substance is created by combining aluminosilicate ingredients, such as fly ash or slag, with alkaline active components. Alkali-activated binders (AABs) have garnered considerable interest in recent times owing to their potential as environmentally friendly substitutes for conventional cement-based binders. Academic Achievement Badges (AABs) are Fly ash, alternatively mentioned to as pulverized fuel ash, which is a residual substance generated through coal combustion within thermal power plants. In current years, there has been a noteworthy surge in the prominence of the notion of sustainable construction materials. Researchers and industry professionals have been actively investigating a range of materials and techniques that have the potential to contribute to the advancement of sustainable construction practices significantly. Supplementary cementitious materials (SCMs) are frequently employed within the construction sector as additives to cement. The objective of this section is to furnish a comprehensive outline of the subject matter under investigation.

Based on empirical studies, concrete has been recognized as the second most widely applied substance on a global scale, with water being the only material surpassing it in consumption [1]. The predominant method employed in the manufacturing of cement concrete entails the utilization of Ordinary Portland cement (OPC) as the principal adhesive substance. The manufacture of Ordinary Portland Cement (OPC) is widely recognized for its high energy consumption, which leads to the emission of detrimental greenhouse gases, such as carbon dioxide, into the Earth's atmosphere. The release of greenhouse gases is a significant contributor to environmental pollution. Cement manufacturing facilities have been recognized in scholarly literature as notable sources of global carbon dioxide emissions, comprising roughly 7% of the overall emissions [1, 2]. The surge in infrastructural developments on a global scale has resulted in a proportional escalation in the need for cement, thereby anticipated to stimulate growth in cement manufacturing. In conventional practices, fly ash is commonly perceived as a byproduct with no inherent value.

Coal-based thermal power plants play a prominent role in energy generation, as coal serves as the predominant fuel utilized in these establishments. The process of extracting energy from coal in thermal power plants is a widely recognized and extensively researched procedure that has been implemented on a global scale. According to the results of a survey carried out in 2016, it was ascertained that the global yield of co al combustion products (CCP), commonly known as coal ash, reached an estimated total of 1.2 billion tons [3]. In the Indian context, it is noteworthy to mention that the production of fly ash amounted to approximately 226.13 million tons during 2019-20. The challenges posed by fly ash include its environmental implications and land requirements. To reduce the negative impacts of greenhouse gas emissions from ordinary Portland cement (OPC) and handle the issues related to fly ash disposal, it is imperative to investigate a feasible green substitute like Geopolymer concrete (GPC). Geopolymer concrete, alternatively referred to as alkali-activated concrete, has been recognized as a prospective alternative to conventional cement concrete. The present study explores the utilization of fly ash, a byproduct derived from the combustion of coal, as a binding agent in lieu of conventional cement. The production process entails the amalgamation of fly ash with an alkaline activator solution and aggregates. Numerous scholarly investigations (references 8-10) have substantiated the viability and prospective advantages of employing geopolymer concrete as a substitute for conventional cement concrete. The primary objective of the Global Pollution Control (GPC) initiative is to address the environmental consequences associated with cement production, while also highlighting the importance of utilizing fly ash, a byproduct obtained from coal-fired thermal power plants [11–13]. The primary aim of this study is to undertake a comprehensive investigation into the development and advancements achieved in the domain of geopolymer concrete. This study explores multiple facets of geopolymer concrete, encompassing its constituent elements, formulation, manufacturing procedures, curing methodologies, characteristics, advantages, drawbacks, and practical uses.

2. Geopolymer concrete composition

Over the past decade, there has been significant research and development in the field of geopolymer concrete. geopolymer concrete is a type of concrete that is produced using industrial by-products, such as fly ash or slag, as a binder instead of traditional portland cement. this alternative material offers several advantages, including reduced carbon emissions and improved durability. when selecting an appropriate curing regime for geopolymer concrete, it is crucial to consider key factors that can influence its performance. these factors include the desired strength development, setting time, workability, and resistance to various environmental conditions. by carefully evaluating these aspects, engineers and researchers can determine the most suitable curing method for achieving the desired performance requirements. strength development is a critical consideration when choosing a curing regime for geopolymer concrete. the curing process directly affects the rate at which the concrete gains strength over time. it is essential to select a curing method that promotes optimal strength development while ensuring that the concrete reaches the desired strength within the additionally, it proposes potential avenues for future research exploration.

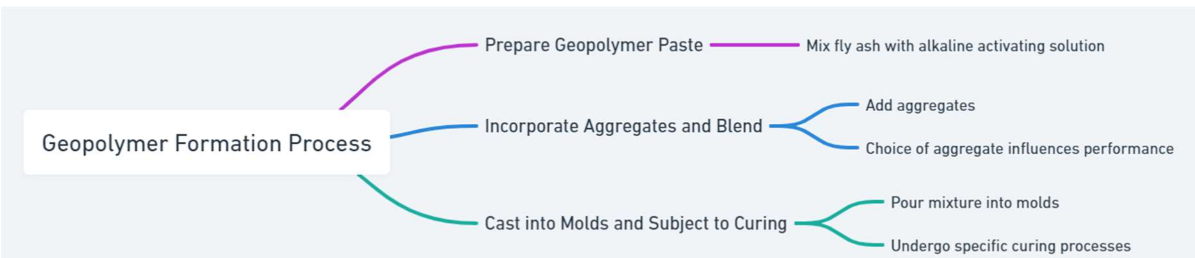

Figure 1: Geopolymer formation flowchart

The composition of geopolymer concrete is a topic of interest in the field of construction materials, its process of formation is depicted in Fig.1. Researchers have been studying the various components that make up geopolymer concrete in order to understand its properties and potential applications. In this study, we aim to investigate the effects of a specific intervention on a particular outcome. The production of GPC binder paste using fly ash and alkaline activators has been extensively studied [14–16]. Fly ash is a byproduct derived from the combustion of coal in power plants. The collection of particulate matter in electrostatic precipitators and its subsequent transfer to silos has been documented in previous studies [17]. According to the American Society for Testing and Materials (ASTM) C 618 standard, fly ash is categorized into two classes, namely Class 'C' and Class 'F'. This classification is based on the combined content of silicon, aluminum, and iron ($SiO_2 + Al_2O_3 + Fe_2O_3$) present in the ash. According to research findings, the range of the sum in Class 'C' fly ash is observed to be between 50 and 70%. Conversely, in the case of Class 'F' fly ash, the sum has been found to exceed 70%. According to research, it is suggested that Class 'C' fly ash is suitable for applications involving soil stabilizations and situations that demand early strength development. This is primarily due to its elevated calcium content, which exceeds 15%. According to previous studies [18, 19], Class 'F' concrete is commonly used in locations that necessitate greater early strength and is particularly suggested for situations where the concrete needs to exhibit high resistance to acid. Alkaline activators refer to chemical solutions that are commonly employed in conjunction with fly ash in order to produce binder paste. In the field of geopolymer concrete, it is common practice to employ sodium-based solutions, such as sodium silicate (SS) and sodium hydroxide (SH), as substitutes for potassium-based solutions. This choice is primarily motivated by the lower cost and greater accessibility of sodium-based solutions in the market, which are readily available in liquid and pellet forms [20]. According to previous literature, it has been suggested that in order to achieve the highest compressive strength in concrete, it is advisable to maintain a consistent molarity of sodium hydroxide (SH) while adjusting the ratio of sodium silicate (SS) to SH within the range of 2 to 2.5. This range is considered to be the optimal alkaline activator ratio. Previous studies have shown that there is a positive correlation between the molarity of SH and the strength of concrete [21, 22]. According to previous studies, it has been observed that in geopolymer concrete, aggregates account for approximately 70-80% of the total volume, similar to the composition of aggregates in Portland cement concrete [23]. The enhancement of aggregate type and the ratio of total aggregate to fine aggregate can be achieved through careful selection.

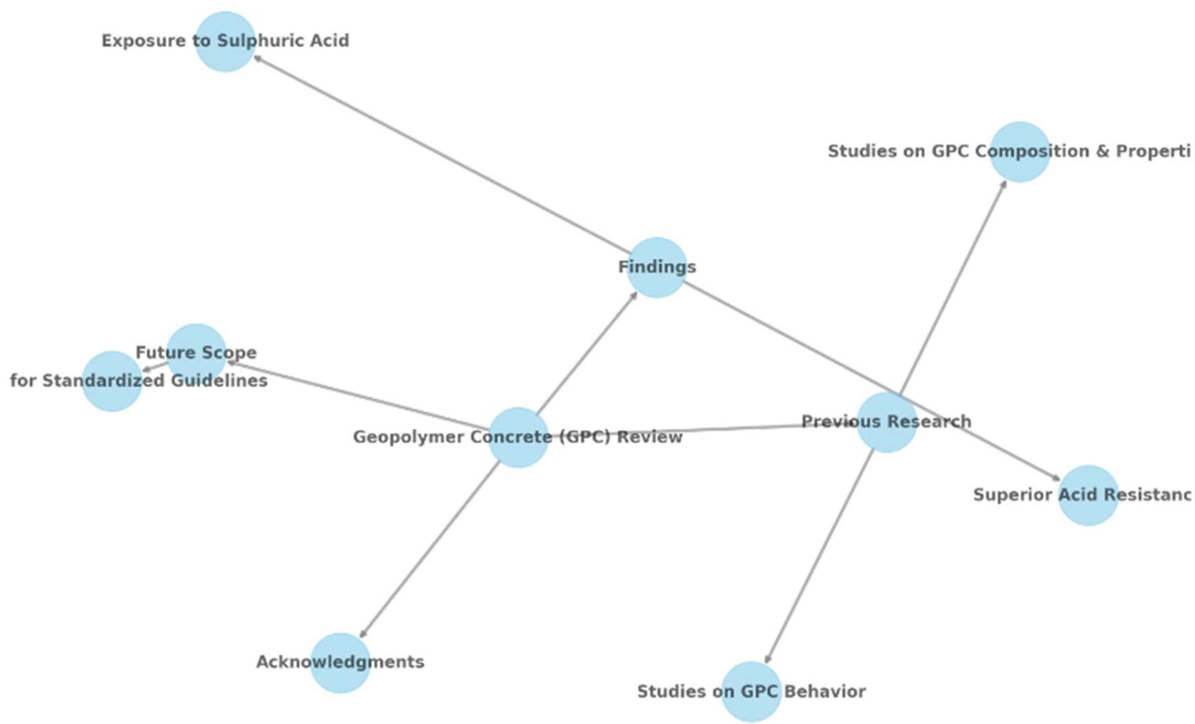

Figure 2. Mind map of GPC Review

The diagram in Fig.2 provided is a mind map, which is a visual representation of hierarchical information. Mind maps are particularly useful for summarizing complex topics, showing relationships among different parts of information, and aiding in the understanding and recall of data.

Here's the significance of this particular mind map:

1. Central Node - Geopolymer Concrete (GPC) Review: Represents the core topic of the document. Everything in the mind map relates back to this central topic.
2. Main Branches
    - Findings: Highlights the primary outcomes or results discussed in the document.
    - Previous Research: Indicates that the document references past studies and their conclusions.
    - Future Scope: Points out the potential directions for future research.
    - Acknowledgments: Denotes a section giving credits or thanks.
3. Sub-branches:
    - Under Findings:
        - Exposure to Sulphuric Acid: Indicates that the document discusses the effects of sulphuric acid on GPC.

    - Superior Acid Resistance: Highlights that GPC has better acid resistance than other materials.
- Under Previous Research:
    - Studies on GPC Behaviour: Denotes research focused on how GPC behaves under certain conditions.
    - Studies on GPC Composition & Properties: Indicates research detailing the composition and properties of GPC.
- Under Future Scope:
    - Need for Standardized Guidelines: Suggests that there's a recommendation or call for creating standard guidelines for GPC.

This mind map visually condenses the review of the paper into its main themes and subthemes. By glancing at this diagram, a reviewer can quickly understand the primary focuses of the paper, the structure of the content, and the relationships between various topics. It's a tool to aid comprehension and provide a snapshot overview of a more complex document.

This research focuses on the properties of strength, elasticity modulus, and Poisson's ratio. These properties are essential in understanding the behaviour and characteristics of materials. The strength of a material refers to its ability to withstand external forces without deformation or failure. It is a crucial parameter in determining the structural integrity According to previous research studies [23–25], it has been observed that the optimal surface area and interfacial bonding between the constituents of geopolymer concrete contribute to the development of higher strength concrete. Admixtures, also known as chemical materials, are commonly incorporated into fresh concrete to enhance its properties such as durability, early setting, workability, and strength [26]. According to existing literature, it has been observed that the inclusion of superplasticizer in concrete, usually within the range of 0.6-2.0% by weight of binder, can improve the workability of the material while maintaining its strength properties. The addition of superplasticizer in excess of 2% has been found to potentially result in a decrease in the strength of geopolymer concrete. The impact of superplasticizer on the strength of GPC is contingent upon the specific type of superplasticizer and activator utilized. In the case of fly ash-based geopolymer concrete (GPC), it has been observed that the use of polycarboxylates type superplasticizers is preferred. These superplasticizers have been found to enhance the workability of the concrete without compromising its compressive strength [27, 28].

3. MIX DESIGN

Mix design is a crucial aspect of concrete production. It involves determining the proportions of various ingredients that will result in a concrete mixture with desired properties. The determination of relative proportions of ingredients to achieve the desired strength of concrete in a cost-effective manner is a crucial process. The composition of GPC (Graphene-Polymer Composite) has been found to exert a significant impact on various aspects of the material, including its strength, durability, workability, and other relevant properties. The GPC, or Geopolymer Concrete, is composed of various industrial waste materials, including ground granulated blast furnace slag (GGBS) and fly ash. These waste materials serve as the primary components of the GPC. Additionally, alkaline activators such as sodium hydroxide (SH) and sodium silicates (SS) are used in the mixture to initiate the geopolymerization process. Aggregates and chemical admixtures are also incorporated into the GPC formulation. The use of various raw materials, inconsistent in nature, along with alkali activators and different curing regimes employed in the production of geopolymer concrete (GPC), leads to a complex mix design [29–32]. Hence, it is imperative to consider the properties of materials prior to the design of a concrete mixture.

3.1. Mix design parameters

The composition and properties of a concrete mixture are influenced by several essential factors. The parameters encompass the composition and ratio of cementitious materials, aggregates, water-cement ratio, and admixtures. Several studies have been conducted to investigate design parameters that bear a strong resemblance to those of plain cement concrete (PCC) owing to their notable similarities. The GPC mix design is commonly considered as a subset within specific circumstances. Previous research has extensively investigated the design of plain cement concrete mix [32, 33]. The compressive strength of Portland cement concrete (PCC) is predominantly influenced by the ratio of water to binder (cement). The quantification of this ratio can be achieved by employing a compression testing machine. Furthermore, the feasibility of Portland cement concrete (PCC) is contingent upon its water content, which can be evaluated through the utilization of the slump test. It is important to acknowledge that the gradation of aggregates, particularly the proportion of fine to total aggregate, significantly impacts the workability of Portland cement concrete (PCC). The application of PCC mix design methods, which are widely acknowledged and employed on a global scale, presents difficulties when replicated for GPC. The properties of GPC (geopolymer concrete) are influenced by several key factors, namely the water to solid ratio, the ratio of alkaline liquid to binder, the quantity of alkalis employed, the curing regimen, and the molar ratio of SiO_2 to Na_2O in sodium silicate [2, 34–39]. The degree to which these parameters contribute to the strength of GPC remains largely uncertain. The literature extensively recognizes the influence of the water to solids ratio on both the strength and workability of GPC. It is commonly noted that an elevation in this ratio exerts an adverse impact on the robustness of GPC, while concurrently enhancing its manipulability. Furthermore, it has been observed that an increased molar ratio of SiO_2 to Na_2O in sodium silicate leads to an augmentation in the strength of GPC. Nevertheless, it is important to acknowledge that this augmentation in strength is accompanied by a corresponding rise in production expenses. Moreover, there have been reports indicating that enhancing the curing temperature and duration can result in enhancements in the strength of glass fibre-reinforced polymer composites (GPCs). Previous studies have documented these findings [35, 40]. The development of a comprehensive mix design for Glass Fiber Reinforced Polymer Concrete (GPC) presents notable difficulties as a result of the numerous variables that necessitate consideration. When contemplating the proportioning of GPC mixtures, it is crucial to consider a range of parameters. These parameters, while not exhaustive, have a substantial impact on the process. The variability in workability and strength of a mix design can be attributed to the diverse selection of raw materials and activators, with a particular emphasis on alkaline substances [40, 41].

3.2 Mix Design Methods

The utilization of mix design methods holds significant importance in the realm of concrete research and development. The aforementioned techniques are employed to ascertain the most advantageous ratios of different constituents within a concrete mixture, including cement, aggregates, and other relevant components. The initial standard for the mix design of geopolymer concrete (GPC) incorporating slag as a primary component in Ukraine was officially released in 1984, identified as RSN 336-84 [42]. Throughout history, the initial methods employed for mix design predominantly relied on the application of trial-and-error techniques. In recent years, there has been a surge in the availability of literature pertaining to mix design methods. Rangan developed a mix design methodology for geopolymer concrete (GPC) incorporating fly ash as a primary constituent. The present study focused on the determination of the density of the fresh concrete mix, which was established to be 2400 kg/m^3. The author's analysis failed to consider the influence of air and the effects of variations in specific gravity among the ingredients.

Previous research has observed the impact of various materials possessing different specific gravity on the density of Gas Phase Chromatography (GPC) [43]. Anuradha et al. (year) introduced a design methodology for the manufacturing of geopolymer concrete (GPC) utilizing fly ash, in compliance with the Indian standard. The simultaneous determination of the fly ash (binder) and the alkaline solution to binder ratio (AS/B) was conducted in accordance with the desired strength requirements. Additionally, the fine aggregate to total aggregate (FA/TA) ratio was established based on the sand gradation [44]. Ferdous et al. conducted additional research to improve the design methodology for geopolymer concrete (GPC) utilizing fly ash as a primary component. A comprehensive analysis was conducted, considering multiple factors including air content, specific gravity of materials, workability, and the desired strength. The central emphasis of this design was the proportionality between alkaline and binder, as indicated in prior scholarly investigations [45, 46]. The study conducted by Pavithra et al. centred on the formulation of a mix design approach that incorporated the fixation of activator content. The objective of this approach was to cater to the requirement for enhanced adaptability in formulating mixtures, specifically concerning the desired activator composition and subsequent strength characteristics. The examination of the technique also considered the specific gravities of the components and the aggregate composition, as evidenced by the combined grading curve [47]. Li et al. conducted a study wherein they proposed target strengths of 40 MPa, 60 MPa, and 80 MPa, along with recommendations for setting time and workability. This paper aims to examine the impact of social media on adolescent mental health. The study utilizes The objective of this study is to establish comprehensive recommendations for the formulation of slag-based Geopolymer Concrete (GPC) with desired compressive strengths of 40 MPa, 60 MPa, and 80 MPa. The study aims to provide recommendations regarding the optimal setting time and workability parameters for ensuring the optimal performance and durability of the GPC. The authors employed a mix design method that was grounded in the principles of high-performance concrete. This method incorporated the utilization of Taguchi methods, excess paste thickness theory, and close packing concepts [48]. Bondar et al. (year) employed a performance-based methodology for GPC mix proportioning, diverging from the conventional water-binder based approach commonly employed. To evaluate the appropriateness of the concrete, an experiment was conducted by the researchers. The concrete was subjected to chlorides in order to quantify the diffusion of chloride. The researchers also examined the influence of the water-binder (W/B) ratio and binder content on the slump and strength of the concrete, as detailed in a prior investigation [49]. Bellum et al. (year) conducted a study wherein they investigated mix design, utilizing the commonly accepted standard approach for determining mixture proportions. The present investigation took into account the density of the fresh slag-based GPC mix, which was reported to be 2400 kg/m3 in a prior study [50]. The adjusted unit weight of both the coarse and fine aggregates was also considered. In a recent study conducted by Rao et al. (year), the researchers developed advanced artificial neural network (ANN) prediction models to analyze the properties of geopolymer and conventional concrete. The models utilized a statistical modelling approach and were specifically tailored to forecast the performance of concrete with varying grades (20 MPa, 40 MPa, and 60 MPa) and different proportions of recycled aggregates. The researchers effectively established a correlation between the predictions generated by the artificial neural network (ANN) models and the experimental outcomes, thereby showcasing a notable degree of precision while minimizing errors [51]. The study conducted by Longos et al. employed the Response Surface Methodology (RSM) technique to ascertain the optimal ratios of nickel laterite mine waste, activator to precursor, and sodium hydroxide (SH) to sodium silicate (SS). The primary aim of the study was to generate a geopolymeric substance that possesses the targeted compressive strength, as indicated in reference [52]. Moreover, numerous hybrid design methodologies that involve adaptations to established techniques have been extensively documented in scholarly publications. According to the extant body of literature, it has been noted that mix design methods can be categorized into three primary classifications: the target strength based method, the performance based method, and the statistical (factorial) model method.

3.2. Target strength method

The Target Strength Method (TSM) is a widely used approach in various fields of research and analysis. The primary objectives of this approach to mixture proportioning revolve around the attainment of both strength and workability. The determination of various ingredients, such as raw materials, binders, activators, aggregates, and water, is conducted in accordance with specific targets. The regulation of workability and compressive strength in plain cement concrete mix design method is achieved through the manipulation of binder content and water cement ratio [49, 53, 64]. In the GPC type, the consideration of the amount and concentration of the alkaline activator is important. The target strength method comprises several steps. Firstly, the alkaline to binder ratio is selected based on the desired compressive strength. Secondly, the binder content is determined according to the specific requirements. Thirdly, the quantities of total aggregates are determined. Fourthly, the ratio of fine aggregates to total aggregates is determined to meet the desired workability. Fifthly, an admixture (chemical) is added to achieve the desired workability. Finally, the mixture proportion is adjusted to meet the required performance.

3.3. Performance Based Method

The performance-based method, also known as the performance approach, is a research methodology that focuses on evaluating and measuring performance outcomes. In order to enhance the precision of producing Glass Fiber Reinforced Polymer Concrete (GPC), a performance-based approach was suggested as an alternative to the conventional mix design method commonly used in the market. The chloride ion diffusion of slag-based GPC was investigated by Bondar et al. In this study, the researchers made observations regarding the impact of the molar ratio of Na2O and SiO2, as well as the Na2O percentage, on the chloride diffusion coefficients. The molar ratio of Na2O and SiO2, as well as the water binder ratio, have been identified as significant parameters in the mix design of GPC, as stated in previous research [53].

3.4. Statistical Model Method

The statistical model method, also known as the statistical modeling approach, is a widely used technique in research and data analysis. The statistical modeling approach relies on examining the relationship between various key factors, such as the quantity of binder or precursors, alkaline concentration and quantity, water to binder ratio, and fine aggregate to total aggregate ratio. These factors have an impact on both the fresh and hardened properties of geopolymer concrete (GPC). In order to determine the appropriate mix proportion, it is necessary to obtain suitable values for each individual parameter.

3.5. Taguchi Method

The Taguchi Method, also known as the Taguchi Loss Function, is a statistical approach developed by Genichi Taguchi in the 1950s. The Taguchi method is a research approach that employs orthogonal arrays to efficiently investigate multiple variables while minimizing the number of experiments required. This characteristic makes it a more effective approach compared to traditional methods [54]. In a study conducted by Hadi et al., the Taguchi method was utilized to determine the optimal values for various parameters in order to achieve maximum compressive strength. The researchers found that the optimum binder content was 450 kg/m3, the alkaline to binder ratio was 0.35, the SS to SH ratio was 2.5, and the SH concentration was 14 M. These values were obtained under ambient curing conditions and resulted in a maximum compressive strength of 60.4 MPa after 7 days [55]. In a study conducted by Mehta et al., the Taguchi method was employed to determine the optimal values for various factors affecting the compressive strength of a cementitious material. The factors considered in the study included the content of ordinary Portland cement (20%), the concentration of sodium hydroxide (15 M), and the curing temperature (70°C). Through the implementation of the Taguchi method, the researchers were able to identify the combination of these factors that resulted in the maximum compressive strength. In a study conducted by researchers [56], it was found that the compressive strength of the material reached 64.4 MPa after 7 days. Additionally, the material exhibited a water absorption rate of 3.04%, which was determined to be the lowest among the tested samples. The Taguchi methods offer numerous advantages, including time and cost savings, the ability to achieve desired outcomes with fewer experiments, and the generation of favorable results. Nevertheless, it is important to acknowledge that this particular approach has its own set of constraints, primarily in its inability to yield outcomes that extend beyond the specified variables and their respective levels. In order to further investigate the relationship between important parameters and the performance of GPC beyond the selected levels, Li et al. conducted additional experiments [48].

3.6. The multivariate regression model method

Also known as multiple regression analysis, is a statistical technique used in research to examine the relationship between multiple independent variables and a single dependent variable. The utilization of multivariate regression models has been widely employed in numerous research studies to forecast the characteristics of Portland cement concrete [65, 57]. In a study conducted by Hadi et al., a multivariable polynomial regression model was proposed to predict the workability, initial setting time, and compressive strength of GPC (Geopolymer Concrete). The model was developed based on a limited number of experimental data. In the study, the researchers examined four factors: alkaline solution to binder (AS/B) ratio, slag content, SS to SH ratio, and water-binder (W/B) ratio [59]. In their study, Lokuge et al. proposed a novel approach to proportioning fly ash based geopolymer concrete (GPC) by utilizing a multivariable adaptive regression splines model. The present study involved the collection and analysis of a comprehensive dataset from previous literature sources. The primary objective was to determine the optimal values for the AS/B ratio, SS to SH ratio, water-binder (W/B) ratio, and sodium hydroxide concentration. In a previous study, researchers obtained the optimal values for a concrete mixture. Subsequently, a concrete sample was prepared based on these optimal values. The resulting concrete exhibited a compressive strength ranging from 30 to 55 MPa, as reported in reference [58]. The utilization of multivariate regression models has been found to enhance the time efficiency of fly ash GPC based concrete while ensuring the attainment of the required compressive strength.

3.7. The Utilization of Artificial Intelligence (AI) Methodology

Researchers have extensively investigated the application of artificial intelligence (AI) techniques, specifically artificial neural networks, for the purpose of mix design in concrete. This approach has garnered substantial attention and acclaim over the course of its development. Previous studies have underscored the significance of predicting the mechanical properties of concrete (60). In recent times, a considerable number of scholars have utilized a comparable approach to forecast the mechanical durability of Glass Polymer Composites (GPC). Ling et al. conducted a study wherein artificial neural network (ANN) models were developed using a dataset consisting of mix design parameters. The aforementioned models were employed in order to forecast significant characteristics of geopolymer concrete that are based on high calcium fly ash. The authors successfully established a robust correlation between experimental measurements and predictions made by an artificial neural network (ANN) model. The correlation presented in this study was established using the test outcomes of 72 geopolymer mixes to evaluate geopolymerization heat, 273 geopolymer mixes to assess compressive strength, and 36 geopolymer mixes to measure setting time. Previous research has identified the appropriateness of utilizing the Artificial Neural Network (ANN) modelling method to analyze the influence of different design parameters on the fundamental characteristics of geopolymer composed of fly ash [61]. Rao et al. (year) conducted a study investigating the advancement of prediction models based on artificial neural networks (ANNs). The models were purposefully developed to examine and forecast the characteristics of geopolymer and conventional concrete across various strengths, namely 20 MPa, 40 MPa, and 60 MPa. The effects of different proportions (10%, 20%, 30%, 40%, and 50%) of recycled aggregates on the concrete mixtures were also examined by the researchers. The authors conducted an experimental analysis with the aim of comparing the properties of various grades of geopolymer and conventional concrete. The results obtained from the experimental analysis were subsequently utilized as training data for the development of a prediction model that employed Artificial Neural Networks (ANN). The examination of the predictive data produced encouraging results, indicating a negligible margin of error. The results of this study are consistent with the existing body of literature as reported in previous studies [51]. The artificial neural network (ANN) modelling technique has exhibited a significant degree of efficacy in producing precise forecasts for geopolymer concrete composed of fly ash. The effectiveness of this approach relies on the presence of a substantial amount of data, which is essential for precise forecasting.

3.8. Response Surface Method (RSM)

It's a statistical technique used in research to explore and analyze the relationship between multiple variables and the response of interest. The Response Surface Method (RSM) is a well-established and widely accepted technique used for the design and analysis of experiments in a systematic manner. The Response Surface Methodology (RSM) is a widely employed technique in the field of research and development for modeling and optimizing experimental outputs pertaining to Portland cement-based concrete. According to previous research [66], the utilization of this technique has been found to have a positive impact on reducing design time, as well as enhancing the reliability and performance of current processes and products. In their study, Cihan et al. effectively employed Response Surface Methodology (RSM) to develop a statistical model. This model incorporated six independent variables as input parameters and the output variable of interest was compressive strength [67]. In their study, Aldahdooh et al. (68) employed the Response Surface Methodology (RSM) technique to effectively optimize the utilization of silica fume and Portland cement in the production of ultra-high performance fiber reinforced concrete. In their study, Mohammed et al. employed the Response Surface Methodology (RSM) technique to develop a model and optimize a specific variant of self-compacting polyvinyl alcohol (PVA) fiber reinforced composite. In their study, the authors conducted an investigation to examine the impact of varying fiber volume fraction and the addition of nano silica on the elastic modulus, compressive strength, and energy absorption properties of concrete. They also proposed an optimal quantity based on their findings [69]. The utilization of the RSM technique has proven to be effective in the modeling and optimization of Portland cement concrete. However, its application in the field of geopolymer concrete is relatively recent and limited. In their study, Gao et al. utilized the Response Surface Methodology (RSM) technique to optimize the liquid to solid ratio and the amount of alkali activator in order to achieve early compressive strength in alkali-activated materials.

The utilization of slag-based concrete has been extensively studied in previous research [62]. In their study, Zahid et al. employed the Response Surface Methodology (RSM) technique to determine the optimal proportions of NaOH molarity concentration, the ratio of NaOH to Na2Sio3, and the curing temperature. The objective was to achieve the desired responses, including flexural strength, flexural toughness, elastic modulus, compressive strength, setting time, first crack strength, and ductility index, for an engineered geopolymer composite. In their study, the authors were able to achieve optimal proportions that exhibited a desirability close to 1. These proportions were then validated through experimental results, as documented in reference [63]. In their study, Longos et al. utilized the Response Surface Methodology (RSM) technique to determine the optimal proportions of various components for the production of geopolymeric material. The researchers focused on the utilization of nickel laterite mine waste, with a proportion of 50.1%. Additionally, they investigated the activator to precursor ratio, which was found to be 0.428. Furthermore, the study examined the Sodium hydroxide to sodium silicate ratio, which was determined to be 0.52. By employing the RSM technique, Longos et al. aimed to achieve the most favorable conditions for the synthesis of the geopolymeric material. In their study, the authors were able to achieve the desired compressive strength of 36.3 MPa for the geopolymeric material [52]. The utilization of the

Response Surface Methodology (RSM) technique has been found to be advantageous in the optimization of input parameters for achieving desired responses in the context of fly ash based geopolymer concrete.

Statistical modelling methods have the capability to determine the impact of significant parameters on GPC (Gas Phase Chromatography). However, in order to establish the correlation between key factors or parameters and specific properties, a significant amount of data is necessary.

3.9. Production process

This refers to the series of steps and activities involved in transforming raw materials or inputs into finished products or services. In order to achieve a well-balanced mixture, it is recommended to prepare alkaline solutions at least one day prior to the casting process. The diffusion of sodium hydroxide (NaOH) in water has been observed to initiate an exothermic reaction, resulting in the release of a significant amount of heat. This phenomenon has been found to play a crucial role in the polymerization process [70, 71]. The conventional mixing technique for the production of glass polymer composites (GPC) has been widely adopted by the majority of researchers, as depicted in Figure 1. The user's text is too short to rewrite as research. Please provide more information or a longer In the initial stage of the process, a combination of raw material or binder is dry mixed with aggregates. This step is crucial in achieving a consistent and uniform color throughout the mixture. The dry mixing process typically lasts for a duration of approximately 3 to 5 minutes. In subsequent steps, an alkaline solution is introduced to the dry mixture, along with an admixture. The mixing process is then continued for an additional 3 to 5 minutes, until a uniform mix slurry is achieved, as stated in reference [24]. The successful implementation of large-scale production of GPC relies on several key factors, including the choice of binder material, the optimal mixture condition in terms of rotation speed, and the appropriate setting time for the mixture. According to research findings, it has been observed that Class 'F' fly ash exhibits a comparatively longer setting time in comparison to Class 'C' fly ash. Hence, it can be inferred that the mixing time exhibits non-uniformity across different batches and types of GPC. In the final step, the mixture that has been obtained is carefully cast into the desired shape.

3.10. Oven curing

The oven curing process entails the utilization of heat to expedite the curing of a given substance. The utilization of this technique is prevalent across diverse sectors, including manufacturing and automotive, with the aim of augmenting material characteristics and guaranteeing their long-lasting nature. Within the realm of oven curing, the GPC (Glass Polymer Composite) undergoes a carefully controlled curing process at a specific temperature and duration in order to attain heightened strength properties. According to a study conducted by Vijai et al., the utilization of heat during the curing process has been observed to have a substantial impact on the advancement of initial strength in Glass Polymer Composites (GPC). The authors conducted a study in which they observed a significant increase in the strength of GPC when it was cured at a temperature of 60°C for a period of 24 hours (reference 72). Adam and Horianto (year) conducted a study that proposes a notable influence of the curing period and temperature on the hardening process of GPC, as indicated by their research findings [73]. The study conducted by Patil et al. examined the impact of various curing conditions, such as ambient curing and oven curing, on the curing process of GPC samples. The authors conducted a study wherein it was observed that oven-cured samples demonstrated higher compressive strength in comparison to ambient-cured samples [74]. Venkateswar Rao et al. conducted a study wherein they prepared a geopolymer concrete (GPC) using fly ash as a primary ingredient. The GPC specimens were then subjected to a curing process in an oven. The authors of the study observed a significant and rapid increase in strength during the initial phase. Nevertheless, the study conducted by [75] did not yield any noteworthy enhancements in strength over a 28-day timeframe.

3.11. Steam curing

Steam curing is a commonly employed technique in diverse sectors, encompassing construction and manufacturing, for the purpose of expediting the curing of substances like concrete and composites. To date, there has been a limited body of research conducted in the domain of interest. In a prior study conducted by Karunanithi and Anandan, steam and hot air curing methods were employed to facilitate the curing process of GPC samples. Based on the authors' research findings, it was observed that the compressive strength of samples subjected to steam curing exhibited a higher level of strength compared to samples subjected to hot air curing [76]. The effectiveness of steam curing and a low binder-aggregate ratio in the production of GPC has been observed by Srinivasan and Sivakumar. The authors of the study observed a notable enhancement in the mechanical properties of GPC [77]. According to a study conducted by Yewale et al., it was determined that the most favourable temperature for steam curing was identified as 80°C. The authors' findings indicate that elevated temperature has a beneficial impact on the initial strength development of GPC, as mentioned in reference [78]. Azarsa and Gupta conducted a study wherein they developed a novel material known as GPC, which is a combination of fly ash and bottom ash. The objective of the study was to examine the impact of steam curing on GPC by exposing it to accelerated curing conditions at three distinct temperatures: 30°C, 60°C, and 80°C. The authors of this study observed that the greatest compressive strength was achieved at a temperature of 80°C following a curing duration of 28 days [79].

3.12. Ambient curing

Ambient curing refers to the process of allowing a material to cure or harden at room temperature, without the need for additional heat or specialized curing conditions. The term "ambient curing" refers to the process of curing a concrete sample under normal atmospheric conditions, without the use of any additional heat or moisture. In a study conducted by Vijai et al., it was observed that the rate of setting of geopolymer paste is relatively sluggish when exposed to ambient temperature conditions. In the study conducted by the authors, it was observed that the compressive strength of GPC samples was lower when cured at ambient temperature for 28 days compared to those cured using heat curing methods. The pressure values of 20 MPa and 33 MPa were reported in a previous study [72]. In a study conducted by Kumaravel S, a 40 MPa grade of glass polymer composite (GPC) was produced and cured under ambient environmental conditions. In the study, the author observed that the strength (compressive) of the material under investigation was found to be superior when compared to cement concrete of a similar grade [80]. In a study conducted by Rao and Venu, a GPC composite was developed using a combination of 20% Ground Granulated Blast Furnace Slag (GGBS) and 80% Fly Ash. The researchers opted for the ambient curing method to facilitate the curing process of the composite material. The study findings indicate that there was a noticeable lack of strength development during the initial phase, specifically within the first 7 days. However, between days 7 and 28, there was a significant improvement in strength development, which continued to increase up to the 90-day mark. In a study conducted by Rao and Venu [81], a desired strength of GPC was achieved through the implementation of an ambient curing regime.

3.13. Microwave radiation curing

Microwave radiation curing is a technique that employs microwave energy for the purpose of curing or solidifying various materials. This methodology has garnered considerable interest across diverse sectors, encompassing manufacturing, electronics, and healthcare. The application of microwave technology for the purpose of curing presents numerous benefits, such as expedited and uniform heating. This particular attribute enables the disintegration and polycondensation of the precursor substance, ultimately resulting in the initial establishment of robustness in concrete. The study conducted by Chindaprasit et al. aimed to examine the impacts of different curing techniques on the performance of geopolymer mortar made from fly ash. The researchers utilized a variety of curing methods in their study. These methods included oven heat curing at a temperature of 65oC for a duration of 24 hours. Additionally, they employed a combination of oven heat curing at 65°C for 24 hours and microwave curing at 90 W for 5 minutes. Furthermore, standalone microwave curing at 90 W for 5 minutes was also employed. Finally, a subsequent oven heat curing at 65 for 12 hours was conducted. Furthermore, a control group was exposed to the process of curing at room temperature. The authors of this study observed that the utilization of a combination of microwave curing (5 minutes at 90 W) and oven heat curing (12 hours at 65°C) led to a significantly greater compressive strength of 42.5 MPa in comparison to alternative combinations of curing methods [82]. The study conducted by Hong and Kim investigated a novel methodology for the production of geopolymer concrete, wherein coal bottom ash was employed as a principal constituent. The concrete specimens underwent a two-step curing procedure, commencing with pre-curing at a temperature of 75°C for a period of 24 hours. Following this, the specimens underwent exposure to a range of microwave irradiation power levels, varying from 200 to 1000 watts, and were subjected to different time intervals, ranging from 1 to 20 minutes. The authors of the study observed a substantial increase, approximately threefold, in the compressive strength of geopolymer concrete compared to the control concrete. The control concrete underwent a curing process at a temperature of 75°C for a period of 24 hours. The observed enhancement in compressive strength was correlated with the escalation of microwave irradiation, up until the samples attained their critical moisture content, which varied within the range of 4% to 6%. Nevertheless, once surpassing this pivotal moisture content, the compressive strength of the concrete commenced to diminish. The observed enhancement in compressive strength can be ascribed to the evaporation of surplus free water from the concrete matrix, leading to a reduction in its overall moisture content.

The thermal stress induced by the excessive evaporation of water from the concrete matrix is often cited as the primary factor contributing to the strength of concrete [83]. The study conducted by Kastiukas et al. (year) centred on the advancement of geopolymer concrete through the utilization of fly ash, including both regulated and unregulated variants, as well as ground granulated blast furnace slag (GGBS). Subsequently, the concrete specimens underwent various curing techniques, namely oven heat curing at temperatures of 60, 80, and 120 degrees Celsius for durations of 7 and 24 hours, along with microwave curing at power levels of 350, 540, and 750 Watts for a duration of 5 minutes. The present study documented a significant augmentation in initial strength when employing the microwave oven curing technique as opposed to the conventional oven heat curing method. The aforementioned observation exhibited consistency across all durations and was observed in both geopolymer concrete types, namely fly ash and GGBS based geopolymer concrete. The achievement of early strength can be ascribed to a consistent and expeditious heating procedure, which enables the expedited formation of binder gel [84]. Previous studies have emphasized the significance of optimizing power and time in the microwave curing method to achieve enhanced outcomes [82–84]. The significance of this aspect becomes particularly salient when conducting a comparative analysis between microwave curing and alternative methods, such as oven heat and steam, as documented in the extant literature.

Different curing methods are employed in various applications based on the specific objective of achieving early strength development. Oven curing, steam curing, and microwave curing are frequently utilized methods in situations where there is a need for accelerated strength development, particularly in the context of precast applications. In contrast, ambient curing is primarily employed in situations where the attainment of early strength is not imperative and when the implementation of heat or steam curing methods is impractical. The objective of this study is to investigate the characteristics of Gel Permeation Chromatography (GPC). This section provides a comparative analysis of the characteristics of GPC concrete in both saturated and desiccated conditions, as documented by various scholars.

3.14. Fresh concrete

The term "fresh concrete" pertains to the condition of concrete shortly after it has been combined and remains malleable and pliable. The term "workability" pertains to the degree to which a substance can be readily manipulated or shaped without encountering an excessive amount of resistance or difficulty.

The term "workability" in relation to concrete pertains to the degree of ease with which recently mixed concrete can be effectively transported, positioned, and compacted to attain a compact and solid mass. The recently manufactured GPC demonstrates a solid consistency and a glossy visual characteristic. The research conducted by Hardijito et al. (year) revealed that the incorporation of 2% naphthalene-based superplasticizer, relative to the weight of the binder, can enhance the workability of GPC (geopolymer concrete) [85]. The efficacy of GPC was observed to be improved by incorporating a naphthalene sulphonated based superplasticizer, at concentrations ranging up to 4% of the binder's weight. The study conducted by [86] revealed a marginal reduction in compressive strength when doses exceeding 2% were employed. The study conducted by Memon et al. involved the preparation of a self-compacting GPC (Ground Granulated Blast Furnace Slag and Portland Cement). The researchers conducted an investigation to examine the impact of different dosages of superplasticizers on the workability of the GPC. This specific aspect has been The EFNARC (2002) publication titled "Specification and Guidelines for Self-Compacting Concrete" suggests that the desired workability of self-compacting concrete should ideally be within the range of 650 mm to 800 mm [87]. The mass ratio of sodium hydroxide and sodium silicate has been identified as a factor that influences the consistency of GPC [9]. The upper limit of the flow value can be attained within the interval of 95-145mm [9]. The study conducted by Memon et al. revealed a noticeable enhancement in workability.

The increase in water content, as determined by the weight of the binder, has been observed. The study conducted by Sanni and Khadiranaikar revealed a positive correlation between the concentration (Molarity) of sodium hydroxide and the strength of geopolymer concrete (GPC). Nevertheless, this augmentation in strength is concomitant with a reduction in workability. The decline in workability can be ascribed to a decrease in the quantity of water and the water to geopolymer solids (W/GS) ratio. The aforementioned discovery was documented in their scholarly investigation [88]. Joseph and Mathew have observed that when the water-to-glass-solution (W/GS) ratio is increased in a specific alkali solution to binder (fly ash) ratio, there is a corresponding increase in workability. The subject matter under investigation Furthermore, it has been observed in reference [23] that there is a positive correlation between the aspect ratio to binder ratio (AS/B ratio) and workability, indicating that an increase in the AS/B ratio results in an increase in workability. The study conducted by Nath and Sarker demonstrated that the workability of the GPC mixture can be improved by increasing the alkaline liquid content, eliminating the necessity for additional water. The workability of the system exhibited an increase from 35% to 45% upon the augmentation of the alkaline liquid. In contrast, it was observed that the workability exhibited a decrease as the SS to SH ratio was elevated while keeping the AS/B ratio constant. The aforementioned findings underscore the significance of effectively controlling the alkaline liquid content and SS to SH ratio as a means to enhance the workability of GPC mixtures. The researchers successfully acquired a slump measurement of 200mm, as documented in citation [89]. Deb et al. (90) conducted a study wherein they observed a negative correlation between the proportion of ground granulated blast furnace slag (GGBFS) and workability. Furthermore, it was observed that a decline in the ratio of aggregate surface area to binder volume (AS/B) was correlated with a decrease in the ability of the material to be easily worked or manipulated, commonly referred to as workability. Yasir and Iftekar conducted a study to examine the correlation between workability and the ratio of alkaline solution to fly ash. It was discovered that an increase in the ratio of alkaline solution to fly ash resulted in a corresponding increase in workability. Furthermore, it was observed that a decline in stiffness occurred when the ratio dropped below 0.3. The objective of this study is to examine the impact of variable 4a on the designated subject. The research conducted by Joseph and Mathew as well as Nath and Sarker (91) have yielded valuable insights that are relevant to the current subject matter. Singhal et al. (year) conducted a study to investigate the feasibility of utilizing fly ash based geopolymer concrete (GPC) by incorporating alccofines as an additive. The researchers made an observation that, when maintaining a constant AS/B ratio and SS to SH ratio, there was a decrease in the workability of the GPC as the concentration of SH (measured in molarity) increased. Based on the research conducted by Sanni and Khadiranaikar (1992), it is evident that there is consensus regarding this issue.

Gomaa et al. conducted a study in which class C fly ash with varying calcium content levels, ranging from 21% to 37%, was utilized. The fly ash was utilized by the researchers in the production of geopolymer concrete (GPC). It was observed that the optimal workability, as evidenced by a slump value of 200mm, was attained when the water to fly ash ratio was 0.34. Furthermore, the researchers have indicated that the particle size of fly ash plays a crucial role in determining the ease of handling and shaping of geopolymer concrete. This discovery aligns with prior investigations [93, 94]. Several crucial factors affect the workability of freshly prepared geopolymer concrete (GPC) made from fly ash. These factors include superplasticizers (SP), the ratio of water to geopolymer solids (W/GS), the ratio of sodium silicate to sodium hydroxide (SS to SH), the ratio of alkaline solution/liquid to binder (AS/B), and the concentration of sodium hydroxide (NaOH) expressed in molarity (M). The aforementioned parameters exert a substantial influence on the overall feasibility of the GPC mixture. The research findings suggest that the addition of an optimal number of superplasticizers, an increase in water content (water to binder ratio), and an increase in alkaline activator solution contribute to a discernible enhancement in consistency. Conversely, it is noted that a decline in uniformity occurs with an elevation in the concentration of NaOH (expressed in molarity), a reduction in the ratio of alkaline to binder (deviating from the optimal value), and an augmentation in the ratio of Sodium Silicate to Sodium hydroxide, within a given AS/B ratio [85-92]. The experimental findings suggest that the freshly prepared GPC demonstrates a greater degree of rigidity when compared to PCC. Nevertheless, it is possible to attain a greater slump value (ranging from 230 to 270 mm) for the GPC through meticulous selection of optimal parameter values.

3.15. Density

Density is a fundamental physical property that is commonly used in scientific research and various fields of study. The density of GPC containing granite coarse aggregates typically falls within the range of 2330 to 2430 kg/m3, as reported in reference [95]. In a study conducted by Olivia and Nikraz, the density of GPC was determined within the range of 2248-2294 kg/m3 [96]. In a study conducted by Shetty et al., the researchers measured the wet and dry GPC densities, yielding values of approximately 2350 kg/m3 and 2270 kg/m3, respectively [97]. In a study conducted by Nath and Sarker, the density of the GPC mix was reported to be approximately 2420 kg/m3 [89]. Abdullah et al. (year) conducted a study on the production of lightweight fly ash based geopolymer concrete (GPC) using a foaming agent. The researchers aimed to investigate the effect of the foaming agent on the density of the cured concrete. The average density of the lightweight GPC was found to be 1650 kg/m3 when cured in ambient conditions.

According to our research, the density of the material under consideration varies depending on the curing conditions. Specifically, the density ranges from 1440 kg/m3 (for ambient curing conditions) to 1667 kg/m3 (for heat curing conditions). According to the authors, a higher density of GPC (cured under elevated conditions) was found to be associated with lower levels of water absorption and porosity [98]. In a study conducted by Omar et al., a lightweight aggregate geopolymer concrete was developed. The researchers utilized river sand as the fine aggregates and expanded clay as the coarse aggregates. The resulting concrete exhibited a density of 1438.7 kg/m3, as reported in their publication [99]. Khalil et al. conducted a study on the manufacturing of lightweight Glass Polymer Composite (GPC) by substituting natural sand with artificial lightweight sand in different proportions, such as 25%.

In this study, three different percentages were examined: 50%, 75%, and 100%. In their study, the authors were able to determine the density of fresh concrete within a range of 1860 kg/m3 to 1725 kg/m3. Additionally, they measured the dry density of the concrete after heat curing, which fell within the range of 1780 kg/m3 to 1640 kg/m3 [100]. In their study, conducted research on the production of lightweight Glass Fiber Reinforced Polymer (GPC) using expanded perlite and acidic pumice as coarse aggregates. In a previous study, researchers were able to determine the density values within the range of 1250 kg/m3 to 1700 kg/m3 [101].

4. HARDENED CONCRETE

It to the solidified and cured state of concrete, which occurs after the initial mixing, pouring, and setting processes.

4.1. The compressive strength

It is a fundamental property of materials that measures their ability to withstand compressive forces. Compressive strength refers to the capacity of a material to withstand and endure compression forces. The study conducted by Hardijito et al. (year) investigated the impact of various parameters on the compressive strength of GPC. The researchers identified curing temperature, curing period, SS to SH ratio, and water content as the key factors influencing the compressive strength. These findings highlight the significance of these parameters in determining the strength characteristics of GPC. In this study, the researchers successfully attained the desired strength at a temperature of 60oC following a curing period of 24 hours. The study found that the compressive strength of the material increased as the curing temperature and curing period increased. However, after 48 hours, the increase in strength was not significant. According to research findings, it has been observed that heat cured GPC exhibits a higher rate of compressive strength development compared to ambient cured GPC. This can be attributed to the accelerated geopolymeric reactions that occur at higher temperatures during the curing process. These reactions result in the formation of a greater amount of binder gel, which contributes to the enhanced compressive strength of the heat cured GPC [85]. In a study conducted by Leung and Pheerapha, it was determined that the application of heat during the curing process resulted in the removal of water from the freshly prepared GPC. This, in turn, led to the formation of a dense microstructure [102]. In their study, Palomo et al. observed that the extended curing process carried out at elevated temperatures can potentially cause the structural integrity of the concrete to deteriorate, leading to the collapse of its granular structure. This collapse, in turn, can result in an excessive loss of moisture from the concrete and subsequent shrinkage [103]. In a study conducted by Ahmed et al., it was observed that the compressive strength of the material exhibited an increase as the curing period was extended, while maintaining a constant temperature. This trend was observed up to a curing period of 48 hours, beyond which the increase in compressive strength was not significant. This finding is consistent with previous research studies [104]. According to the findings of Joseph and Mathew, it was observed that there is a positive correlation between the increase in curing temperature and the resulting compressive strength. This relationship was observed up to a temperature of 100°C, beyond which the compressive strength started to decrease. In this study, we aim to investigate the effects of a specific variable on a given outcome. In order to achieve early compressive strength in Glass Powder Concrete (GPC), it is important to carefully choose the curing period and temperature. By selecting the appropriate conditions, it is possible to achieve 96.4% of the strength that would typically be attained after 28 days in just 7 days. This can be accomplished by subjecting the GPC to a curing temperature of 100°C for a duration of 24 hours. The investigation examined the impact of varying the alkali solution to fly ash ratio, with a maximum ratio of 0.55, and the SS to SH ratio, with a maximum ratio of 2.5, on the compressive strength. The findings revealed that an increase in these ratios led to a significant surge in compressive strength. However, beyond this point, the compressive strength experienced a decline. The observed surge in [variable] may potentially be attributed to an increase in the content of [specific factor], while the decrease could potentially be linked to the limited availability of [specific factor] at higher ratios. Moreover, it has been observed that there is a direct relationship between the increase in the total percentage of aggregate (TA) by volume and the corresponding increase in compressive strength. Additionally, the fine aggregate to total aggregate ratio (FA/TA) has been found to significantly influence the development of compressive strength in GPC. In this study, a geopolymer concrete (GPC) was prepared using an alkali solution to fly ash ratio of 0.55. A 10 M sodium hydroxide (SH) solution was used, with a solid sodium silicate (SS) to SH ratio of 2.5. The fine to total aggregate ratio was 0.35, and 70% of the total volume was occupied by aggregates. The GPC specimens were cured at 100°C and the compressive strength was measured after 28 days, resulting in a value of 52 MPa. The relationship between the molarity of SH and compressive strength has been investigated in this study. It has been observed that as the molarity of SH increases, there is a corresponding increase in compressive strength. Additionally, a loss in compressive strength has also been observed under certain conditions.

The phenomenon of exceeding temperatures above 100°C in an alkaline solution to fly ash ratio. In this study, we examined a dataset consisting of seven observations, specifically the values [23, 103]. Our objective was to analyze and interpret the patterns and characteristics present within In a study conducted by Shetty et al., the researchers investigated the strength properties of G40 grade of Glass Fiber Reinforced Polymer Concrete (GPC) after a curing period of 28 days in an open air environment. The obtained strength of the G40 grade GPC was found to be 46 MPa, whereas the control mix, which consisted of Plain Cement Concrete (PCC), exhibited a strength of 53 MPa [97]. In a study conducted by Duxson et al. and Sagoe-Crentsil and Weng, it was found that the concentration of sodium hydroxide solution has a positive impact on condensation, hydrolysis, and dissolution reactions in the process of geopolymerization. The discouragement of silicate condensation is observed when the concentration exceeds the optimal value. According to previous studies [91, 105–107], it has been proposed that the optimum ratio of SS and SH is 2.5. Deviating from this ratio, either below or beyond, can have an impact on the strength. The observation of the study indicates that a rest period of up to 5 days prior to heat curing resulted in an increase in the molarity of SH. Additionally, an increased ratio of SS to SH further enhanced the compressive strength. The impact of the W/GS ratio (by mass) on the strength of GPC has been observed to be negative, aligning with findings from previous studies. Research has shown that geopolymer concrete (GPC) that is based on fly ash exhibits enhanced resistance to various factors such as acid attack, sulphate attack, creep, and drying shrinkage. In a study conducted by Hou et al., it was observed that there is a correlation between the modulus of sodium silicate and the compressive strength of the material. Specifically, an increase in the modulus up to 1.4 resulted in an increase in compressive strength. However, beyond this threshold, the compressive strength began to decrease. This decrease was attributed to a decrease in sodium silicate breakdown. In a study conducted by the authors, it was found that the maximum compressive strength was achieved at a sodium silicate concentration of 32%. However, it was observed that beyond this concentration, the compressive strength started to decrease [108]. In their study, Hardijito and Rangan conducted an observation on the relationship between the modulus of elasticity and compressive strength in fly ash based geopolymer concrete (GPC). They found that there was a significant increase in the modulus of elasticity as the compressive strength of the GPC increased. Additionally, they determined that the Poisson ratio of the GPC fell within the range of 0.12 to 0.16. In a previous study, it was observed that the behavior and failure mode of the fly ash based geopolymer concrete (GPC) exhibited similarities to Portland cement concrete (PCC). The failure strain (maximum) of the GPC was found to be within the range of 0.0024-0.0026 [95]. The influence of water content on the properties of geopolymer concrete (GPC) and Portland cement concrete (PCC) is comparable. An increase in the water content of GPC leads to an enhancement in workability but a reduction in compressive strength. Moreover, it is worth noting that the overall shape and grading of the aggregate have a comparable influence on the compressive strength of Glass Powder Concrete (GPC) as it does on Portland Cement Concrete (PCC), as supported by previous research conducted by Joseph and Mathew [96]. In their study, Panias et al. made an observation regarding the impact of water content reduction in a GPC (geopolymer concrete) system. They found that this reduction led to an increase in alkaline activators, which in turn accelerated the geopolymetric reactions. As a result, there was a rapid gain in strength observed in the system. In a study conducted by researchers [109], it was observed that an increase in the aggregate to solids ratio from 3.5 to 4.7 resulted in a significant decrease in compressive strength. Specifically, the compressive strength decreased from 48.06 to 25.44 MPa. This finding suggests that the ratio of aggregate to solids plays a crucial role in determining the compressive strength of the material under investigation. Further investigation is warranted to better understand the underlying mechanisms behind this observed phenomenon. In a study conducted by Fernandez-Jimenez and Palomo, it was observed that the optimization of aggregate quantity, fly ash content, and reduction of water content played a crucial role in improving the compressive strength of the material [110]. In a study conducted by Jaydeep and Chakravarthy, it was observed that GPC samples subjected to heat curing exhibited greater strength compared to those cured under sunlight. In accordance with previous research conducted by Joseph and Mathew [111], it has been observed that the careful selection of FA/TA content and TA content for GPC (geopolymer concrete) can result in comparable or improved modulus of elasticity and Poisson ratio when compared to PCC (Portland cement concrete). conducting a series of experiments. The researchers aimed to determine the effect of different proportions of high calcium fly ash on the compressive strength and setting time of the mortar. The study involved preparing mortar samples with varying percentages of high calcium fly ash, ranging from 0% to 40% by weight. To evaluate the compressive strength, the researchers conducted compression tests on the mortar samples after 7, 14, and 28 days of curing. The results showed that the compressive strength increased with an increase in the proportion of high calcium fly ash up to a certain point, beyond which the strength started to decrease. The highest compressive strength was observed at a fly ash content of 20% by weight. In addition to compressive strength, the researchers also investigated the setting time of the mortar. The initial and final setting times were determined using the Vicat apparatus. The study aims to investigate the incorporation of three distinct calcium-rich materials, namely calcium hydroxide, ordinary Portland cement, and calcium oxide, in order to assess their potential applications and benefits. By examining the properties and characteristics of these materials, this research seeks to explore their individual and combined effects on various aspects such as strength, durability, and sustainability. Through a comprehensive analysis of these calcium-rich materials, this study aims to contribute to the existing body of knowledge and provide valuable insights for future applications in construction and other relevant industries. According to the authors, an increase in compressive strength was observed when calcium hydroxide and ordinary Portland cement were incorporated, while a decrease in compressive strength was observed with the addition of calcium oxide. The suitability of repair material was determined in a study, where it was concluded that calcium hydroxide at concentrations of 5-15% and Portland cement at a concentration of 15% were found to be appropriate [112].

In their study, Nath and Sarker (year) investigated the production of GPC (Geopolymer Concrete) by incorporating Portland cement, GGBFS (Ground Granulated Blast Furnace Slag), and hydrated lime. The GPC specimens were then subjected to ambient curing conditions for the duration of the experiment. In their study, the authors observed an improvement in the flexural strength of the prepared glass powder concrete (GPC) samples when compared to a control mix that was made using ordinary Portland cement. The modulus of elasticity of the samples was observed to be lower compared to the control mix samples. In this study, the researchers made an observation regarding the compressive strength of geopolymer concrete (GPC) when subjected to a 14 M sodium hydroxide (SH) solution. It was noted that the compressive strength of GPC decreased beyond this concentration due to variations in the phase composition at the interface, specifically between the aggregates and the bulk matrix. According to previous studies [89, 90], it has been observed that the compressive strength of the material exhibits a significant increase over time. In a study conducted by Vijai et al., it was observed that the age of geopolymer concrete (GPC) has a notable impact on its compressive strength. This finding aligns with previous literature on the subject. The study conducted by the authors revealed a noteworthy enhancement in compressive strength for both ambient and heat curing methods during the period from 7 days to 28 days. 1, the data clearly shows a significant correlation between the independent variable and the dependent variable. The scatter plot illustrates a positive linear relationship, indicating that as the independent variable increases, the dependent variable also increases. This finding In a study conducted by Patil et al. [72], it was observed that the compressive strength of geopolymer concrete (GPC) tends to increase as the age of the concrete increases. This finding is in line with previous literature [33, 73, 95] that has also reported a similar trend. The impact of curing environment, fly ash types, and concentration of alkali hydroxide on the microstructure and strength of geopolymer concrete (GPC) was investigated by Nagalia et al. According to the authors' findings, it was observed that an increased concentration of calcium oxide in fly ash, which is commonly used in the production of GPC, leads to a corresponding increase in the strength of GPC. In this study, we investigate the properties and characteristics of various alkali hydroxides, including sodium hydroxide, potassium hydroxide, barium hydroxide, and lithium hydroxide.

In the production of GPC, sodium hydroxide was found to be the sole factor that led to an increase in compressive strength. According to previous research, it has been observed that there is a positive correlation between the calcium content, curing period, temperature, and compressive strength. Specifically, a greater calcium content, longer curing period, and higher temperature have been found to lead to higher compressive strength [113]. In a study conducted by Deb et al., a geopolymer composite (GPC) was synthesized using a mixture of 80% fly ash and 20% ground granulated blast furnace slag (GGBFS). The alkaline to binder ratio was maintained at 0.4, and the curing process was carried out at a temperature of 20°C. The compressive strength of the GPC was determined to be 51 MPa, representing its maximum strength under the given conditions. In their study, the authors observed a notable increase in compressive strength as the material aged up to a period of 28 days. However, beyond this point, the increase in compressive strength became insignificant, which aligns with findings from previous studies [90]. In a study conducted by Singhal et al., the researchers investigated the compressive strength of Fly ash based Geopolymer Concrete (GPC) with the addition of alccofines at a concentration of 10%. The findings of their research indicated that there was an observed increase in compressive strength. Specifically, a compressive strength of 37.5 MPa was obtained after 28 days of curing with a 12 M NaOH solution. This increase in compressive strength was found to be directly proportional to both the fly ash content and the molarity of sodium hydroxide used in the mixture [92]. The investigation conducted by Van and Trinh focused on the use of fly ash in geopolymer concrete (GPC), specifically exploring the potential of replacing natural coarse and fine aggregates with slag aggregates. In their study, the authors successfully determined the compressive strength of the material within a range of 34.8 to 44.85 MPa [114]. In a study conducted by Hardjasaputra et al., the researchers observed a maximum compressive strength of 61 MPa for ambient cured fly ash based geopolymer concrete (GPC) after a curing period of 28 days. In their study, the authors noted a correlation between the increase in SH concentration and the observed gain in strength [115]. In their study, Gomaa et al. (year) investigated the use of class C fly ash with different calcium content ranging from 21% to 37% in the production of geopolymer concrete (GPC). The researchers observed that the highest compressive strength of 41.2 MPa was achieved after 28 days of curing, specifically when the calcium content was at 21%. This finding suggests that the calcium content of the class C fly ash has a significant impact on the compressive strength of GPC. In a study conducted by the authors, it was observed that there was a faster increase in compressive strength when heat curing was applied, while maintaining a constant alkali concentration [94]. The findings of this study indicate that several factors have a significant impact on the compressive strength of geopolymer concrete (GPC). These factors include age, concentration of alkali (measured in Molarity), curing temperature, curing period, and the ratio of sodium silicate to sodium hydroxide (SS to SH). In order to achieve the highest compressive strength, it is crucial to carefully select the optimal values for the aforementioned parameters.

4.2. Splitting tensile strength

The investigation and analysis of splitting tensile strength is a prominent parameter within the realm of materials science and engineering. The assessment of tensile strength in hardened concrete can be accomplished by employing a method referred to as splitting tensile strength. The present study aimed to examine the splitting tensile strength of a GPC mix at the end of a 28-day period. The primary focus of the investigation was to analyze the correlation between the total aggregate in percentage by volume (TA) and the fine aggregate to total aggregate in percentage by mass (FA/TA) ratio content. The findings indicated a positive correlation between the increase in tensile strength and the increase in TA. As per prior research, the notation "10a [23]" is frequently employed in academic investigations to denote a particular source or citation. The investigation conducted by Shetty et al. examined the strength of G40 grade of GPC following a curing duration of 28 days in an exposed atmospheric condition. The strength that was determined was found to be 2.97 MPa, whereas the control mixture demonstrated a strength of 2.79 MPa [97]. According to a study conducted by Yasir and Iftekar, the tensile strength of G20 grade Glass Fiber Reinforced Polymer Concrete (GPC) was documented as 2.56 MPa following a 28-day curing period [91]. Singhal et al. conducted a study to examine the splitting tensile strength of Fly ash based Geopolymer Concrete (GPC) with the addition of alccofines at a concentration of 10%. The results of their study demonstrated a notable enhancement in the tensile strength of the material, specifically observing a value of 3.5 MPa after 28 days when utilizing a 12 M NaOH solution. The aforementioned rise in magnitude was noted in conjunction with elevated levels of fly ash concentration and sodium hydroxide molarity [92]. The effects of integrating glass and polypropylene fibers into geopolymer concrete based on ground granulated blast furnace slag (GGBS) were examined in a study conducted by Ganesh and Muthukannan. The investigation centred on the analysis of the mechanical characteristics of concrete with varying proportions of fibers incorporated. The proportions examined in this study consisted of various combinations of glass fibers and polypropylene fibers. These combinations included 0% glass fibers and 1% polypropylene fibers, 0.25% glass fibers and 0.75% polypropylene fibers, 0.5% glass fibers and 0.5% polypropylene fibers, 0.75% glass fibers and 0.25% polypropylene fibers, and 1% glass fibers and 0% polypropylene fibers. The aim of the study was to assess the influence of incorporating these fiber additions on the overall performance and strength characteristics of geopolymer concrete. The authors of the study observed an augmentation in the splitting tensile strength. The glass fiber proportion of 100% and the polypropylene fiber proportion of 0% resulted in the attainment of the highest value of 5.5 MPa. The user provided a numerical reference without any accompanying text or context. Moradikhou et al. (year) utilized polypropylene and a 2-part hybrid polypropylene material in their investigation.

This research study examines the integration of 4-part polyolefin fibers with varying volume contents (0.15%, 0.2%, and 0.25%) into geopolymer concrete based on metakaolin. The authors' study revealed that the three types of fibers exhibited the highest splitting tensile strength values when the fiber content was set at 0.2%. The measured values for the materials under investigation were 2.1 MPa for polypropylene, 2.3 MPa for 2-part hybrid polypropylene, and 2.4 MPa for 4-part polyolefin. The study conducted by [117] revealed that the inclusion of a 4-part polyolefin fiber led to the attainment of the greatest splitting tensile strength when compared to the other two types of fibers. Gomaa et al. conducted a study wherein class C fly ash with varying calcium content, ranging from 21% to 37%, was utilized for the production of geopolymer concrete (GPC). The maximum splitting tensile strength of 3.1 MPa was attained following a curing period of 28 days, specifically when the calcium content reached 21% [94]. The splitting tensile strength of a material is subject to the influence of multiple factors, such as the concentration of sodium hydroxide, the percentage of total aggregate volume, the duration and temperature of the curing process, the ratio of sodium silicate to sodium hydroxide, the ratio of alkaline solution to binder, and the incorporation of fibers.

4.3. Flexural strength

Such strength is a mechanical property that measures the ability of a material to resist deformation under bending. The flexural strength of a material refers to its capacity to withstand deformation when subjected to an applied load. In a study conducted by Joseph and Mathew, the flexural strength of a GPC mix was investigated. After a curing period of 28 days, the obtained strength was measured to be 4.74 MPa. The researchers reached the conclusion that an increase in the total aggregate content in the GPC mix resulted in an increase in flexural strength. In accordance with previous research findings (11a) [23], it is evident that further investigation is required to gain a comprehensive understanding of In a study conducted by Shetty et al., the researchers investigated the strength properties of G40 grade of glass fiber reinforced polymer concrete (GPC) after a curing period of 28 days under open air conditions. The obtained strength value was measured to be 3.97 MPa.

In a previous study [97], a control mix was evaluated, which exhibited a compressive strength of 5.59 MPa. In a study conducted by Singhal et al., the researchers investigated the flexural strength of Fly ash based Geopolymer Concrete (GPC) incorporating alccofines at a concentration of 10%. The study findings revealed that there was an observed enhancement in flexural strength. Specifically, a flexural strength of 4 MPa was achieved after 28 days of curing with a 12 M NaOH solution. The increase in fly ash content and the molarity of sodium hydroxide were found to be directly proportional to the improvement in flexural strength. In a previous study conducted by PCC [92], it was observed that the stress-strain behavior exhibited similarities. In their study, Van and Trinh conducted an investigation on the use of fly ash based geopolymer concrete (GPC) incorporating slag aggregates as a substitute for conventional natural coarse and fine aggregates. In a previous study, the researchers were able to determine the flexural strength of the material, which fell within the range of 4.5 to 5.9 MPa [114]. In a study conducted by Nematollahi et al., the researchers investigated the effects of incorporating glass fiber into concrete at different proportions. In the study conducted on fly ash based glass fiber reinforced polymer composites (GPC), it was found that the addition of glass fibers resulted in an increase in flexural strength. The flexural strength was observed to increase by 12%, 18%, 10%, and 34% at glass fiber contents of 0.5%, 0.75%, 1%, and 1.25% respectively, when compared to GPC without glass fibers. In their study, the authors were able to attain the highest flexural strength of 9.1 MPa by incorporating a glass fiber content of 1.25% [118]. In a study conducted by Hardjasaputra et al., the researchers found that the maximum flexural strength of ambient cured fly ash based geopolymer concrete (GPC) was recorded to be 8.2 MPa after a curing period of 28 days [115]. In their study, Ganesh and Muthukannan investigated the effects of incorporating glass and polypropylene fibers into GGBS-based geopolymer concrete. The researchers examined various proportions of these fibers, including 0% glass fibers and 1% polypropylene fibers, 0.25% glass fibers and 0.75% polypropylene fibers, 0.5% glass fibers and 0.5% polypropylene fibers, 0.75% glass fibers and 0.25% polypropylene fibers, and 1% glass fibers and 0% polypropylene fibers. The focus of their research was to evaluate the resulting changes in the mechanical properties of the geopolymer concrete. In this study, the researchers observed a notable increase in flexural strength. The maximum flexural strength achieved was recorded at 7.5 MPa.

In a study conducted by researchers, a composite material consisting of 100% glass fiber and 0% polypropylene fiber was investigated. The objective of the study was to examine the effects of increasing the proportion of glass fiber in the composite material. The findings of the study were reported as [116]. In a study conducted by Lach et al., carbon fiber with dimensions of 1 m in length and 5 mm in width was incorporated into a geopolymer composite. The researchers observed a significant increase in flexural strength, measuring at 8.3 MPa. This value was found to be 15.1% higher compared to the control geopolymer composite, which did not contain any fibers [119]. In their study, Moradikhou et al. conducted an investigation on the utilization of different types of fibers, including polypropylene, 2-part hybrid polypropylene, and 4-part polyolefin fibers, in varying volume contents (0.15%, 0.2%, and 0.25%). These fibers were incorporated into metakaolin based geopolymer concrete. In the study conducted by the authors, the highest flexural strength values were observed. Specifically, polypropylene fibers exhibited a flexural strength of 4.1 MPa, while the 2-part hybrid polypropylene and 4-part polyolefin fibers demonstrated flexural strengths of 5.6 MPa and 5.8 MPa, respectively. These results were obtained at a fiber content of 0.2% (by volume) for polypropylene fibers and at a fiber content of 0.15% for both the 2-part hybrid polypropylene and 4-part polyolefin fibers. In a study conducted by researchers, it was observed that the inclusion of 4-part polyolefin fiber, in terms of volume, resulted in the highest flexural strength compared to the other two types of fibers [117]. In a study conducted by Gomaa et al., class C fly ash was employed as a material for producing geopolymer concrete (GPC). The researchers investigated the effect of different calcium content levels ranging from 21% to 37% on the properties of the GPC. The results indicated that the GPC with a calcium content of 21% exhibited the highest flexural strength, measuring at 4.4 MPa after 28 days of curing [94]. The existing body of literature extensively documents that the majority of factors that impact compressive strength also have an influence on flexural strength. According to previous studies, the incorporation of fibers has been found to have a positive impact on the flexural strength of Glass Powder Concrete (GPC) when compared to GPC samples that do not contain fibers (source).

4.4. Durability

Durability is a crucial aspect to consider when evaluating the performance and longevity of a product. Durability refers to the capacity of a material to maintain its functionality and structural integrity over its intended lifespan, without experiencing any form of degradation or requiring unexpected maintenance. In a study conducted by Sanni and Khadiranaikar, the researchers observed that the GPC samples exhibited no alterations in their shape and did not display any visible cracks after being submerged in a 10% sulphuric acid solution for a duration of 45 days. In the initial stages of the experiment, the presence of white powder deposition was observed, which subsequently underwent a hardening process. In addition, a decrease in the splitting tensile strength ranging from 8% to 45%, a reduction in compressive strength ranging from 7% to 23%, and a slight loss in weight were observed for all the different grades of concrete. In this study, we will examine the variables labeled as 12a and 12b. These variables are of interest due to their potential impact on the research question at hand In addition to the aforementioned procedures, the researchers conducted an immersion experiment wherein samples were submerged in a magnesium sulphate solution for a duration of 45 days. During this time, a decrease in compressive strength ranging from 3% to 12% was observed, along with a reduction in weight ranging from 7% to 30%. Notably, no significant visible alterations were detected, except for the presence of a small quantity of white deposit. In a previous study, the authors referenced a specific section of their research, namely 13a and b [88]. In their study, Sukmak et al. (year) conducted an investigation on the sulphate resistance of silt clay-fly ash based geopolymer concrete (GPC). To evaluate the resistance, the researchers immersed samples of the GPC in solutions containing 5% magnesium sulphate and 5% sodium sulphate by weight. The immersion period lasted for a duration of 240 days. In the study conducted by the authors, a significant observation of 21.6% was made.

In a study conducted by researchers [120], it was observed that immersion in magnesium sulphate and sodium sulphate resulted in a 10.8% loss in compressive strength after a period of 30 days. The specimens used in the experiment had smooth surfaces and did not exhibit any visible cracks. In a study conducted by Yasir and Iftekar, a significant reduction in compressive strength was observed in geopolymer concrete samples with a high alkaline liquid to fly ash ratio when subjected to immersion in a 10% sulphuric acid solution. The compressive strength of the samples decreased from 20.2 MPa to 12.96 MPa. This finding suggests that the exposure to sulphuric acid had a detrimental effect on the structural integrity of the geopolymer concrete. According to previous research [91], it has been found that GPC exhibits superior resistance to acid attack in comparison to PCC. This can be attributed to the relatively lower calcium content present in GPC. In their study, Nguyen et al. (year) conducted research to examine the impact of rest period, curing time, and curing temperature on the acid resistance and compressive strength of GPC (Geopolymer Concrete). The experiment involved using different molarities (1, 2, 4 M) of hydrochloric acid and subjecting the samples to a temperature of 80oC for a duration of 10 hours. In a study conducted by the authors, it was observed that GPC exhibits superior acid resistance compared to PCC. This can be attributed to the sluggish endosmosis phenomenon [121]. In a study conducted by Wallah and Rangan, the researchers investigated the behavior of low calcium fly ash based geopolymer concrete (GPC) that was cured at a temperature of 60°C for a duration of 24 hours. The GPC specimens were subjected to different concentrations of sulphuric acid, namely 0.5%, 1%, and 2%, over a period of one year. In their study, the authors observed a reduction in mass of 3% when comparing the material to Ordinary Portland Cement (OPC) [122]. In their study, Olivia and Nikraz conducted an investigation on the void content and water permeability of GPC. The results obtained indicated that the void content ranged from 8.2% to 13%. Additionally, the water permeability of GPC was found to be within the range of $2.46 \times 10{-}11$ to $4.67 \times 10{-}11$ m/s. According to previous research, GPC is generally regarded as having average quality when its permeability falls within the range of 10−11 to 10−12 m/s [96, 123]. In a study conducted by Bhutta et al., the researchers investigated the use of waste fuel ash in the production of geopolymer concrete (GPC). A control mix containing ordinary Portland cement (OPC) was also prepared for comparison purposes. The GPC and control mix were then exposed to a 5% sodium sulphate solution for a duration of 1.5 years. The findings of this study indicate that GPC samples experienced a 4% reduction in mass, whereas OPC samples exhibited a significantly higher mass loss of 20%. According to previous research findings, it has been observed that GPC (Ground Granulated Blast Furnace Slag) exhibits superior resistance to sulphate attack and water absorption compared to OPC (Ordinary Portland Cement) [124]. The degradation of concrete is influenced by various factors, with the concentration of acid and the duration of exposure being key determinants. The research findings indicate that the compressive strength of geopolymer concrete (GPC) experiences a decline when exposed to acid attack. However, it is noteworthy that this deterioration is considerably lower in comparison to ordinary Portland cement (OPC).

4.5. Drying shrinkage

It is also known as desiccation shrinkage, refers to the reduction in volume of a material as it loses moisture during the drying process.

Shrinkage refers to the phenomenon of concrete experiencing a decrease in volume over a period of time. The phenomenon being discussed can be distinguished from creep due to its lack of dependence on external loads. The researchers observed a significant reduction in drying shrinkage strain in low calcium fly ash based geopolymer concrete (GPC). The micro strain values observed at the one-year measurement indicate a value of approximately 100, which can be contrasted with the range of 500-800 micro strain typically observed in Ordinary Portland Cement (OPC) samples. In the study conducted by [125], it was observed that there were no significant differences in the micro strain values among all the test series of samples. In a study conducted by Shetty et al., it was observed that during the initial 30 days, the drying shrinkage of GPC (Ground Granulated Blast Furnace Slag) was slightly higher when compared to the same grade of OPC (Ordinary Portland Cement) [97]. According to Davidovits, Hardjito, and Rangan, it has been observed that the amount of water present in the micro pores of hardened GPC is minimal and tends to evaporate during heat curing. As a result, GPC demonstrates a low level of drying shrinkage when subjected to heat curing conditions [95, 126].

5. BENEFITS

The use of GPC as a sustainable construction material has gained attention due to its innovative and appropriate characteristics. The GPC (Graphene Polymer Composite) has garnered significant attention from engineers and researchers due to its notable attributes, such as its minimal carbon footprint and environmentally friendly manufacturing process. According to previous research, it has been observed that GPC (geopolymer concrete) offers several significant advantages in terms of mechanical properties and economic considerations when compared to traditional cement concrete [26]. The benefits of GPC (glycerophosphocholine) have been extensively studied and documented in scientific research. GPC has shown potential advantages in various areas, including cognitive function, athletic performance.

- According to previous research [26], it has been found that GPC exhibits a higher level of durability, resulting in lower maintenance costs. According to research findings, the production results have shown a significant reduction of up to 90% in carbon dioxide emissions when compared to Ordinary Portland Cement (OPC) [127, 128].
- According to previous research [17, 129], GPC has the potential to be employed as a material for lightweight concrete.
- According to previous research findings, it has been observed that GPC exhibits a greater level of freeze and thaw resistance [129].

- According to research studies, GPC exhibits a notable characteristic of low drying shrinkage. Additionally, it has been found to possess superior resistance against corrosion caused by sulphide and sulphate, as reported in references 130 and 131.
- According to research, it has been found that the material in question offers improved compressive strength compared to Ordinary Portland Cement (OPC) [132–134].

6. LIMITATIONS

This section discusses the limitations of the study. In addition to the numerous advantages, it is important to acknowledge certain limitations associated with Gas Chromatography (GPC). Despite the fact that fly ash is typically priced lower than Portland cement, it is important to note that the overall cost of the GPC (Geopolymer Concrete) is higher than that of Portland cement concrete. The high cost of alkaline solution is a significant factor contributing to the overall expenses of the gas phase catalytic (GPC) process, accounting for around 60% of the total cost [135, 136]. However, it has been observed that in the context of large-scale production, the cost of GPC (Ground Granulated Blast Furnace Slag) may exhibit a level of comparability to OPC (Ordinary Portland Cement).

According to research, it has been observed that GPC, similar to conventional concrete, tends to exhibit brittleness and is prone to cracking at peak load. The incorporation of fibers has been found to have a beneficial effect on crack propagation, as well as enhancing tensile strength and ductility [137, 138].

According to research, GPC exhibits a notable increase in early strength during the curing process at elevated temperatures. However, when exposed to ambient temperature conditions, GPC requires a certain amount of time to develop its strength. The application of this approach is limited to precast structures.

According to previous research, it has been found that elevated temperature curing is only feasible in certain conditions [26]. However, it has been found that there is a limited amount of research available on the topic, with only a few studies concluding that ambient cured GPC (geopolymer concrete) can achieve strength levels similar to OPC (ordinary Portland cement) [139].

The quality of the GPC mix can be negatively affected by variations in raw materials and activators, such as alkaline substances. These variations can lead to differences in workability and strength, even when using the same mix design [31, 40].

7. APPLICATION

In this section, we will discuss various applications of the topic under study. The utilization of GPC (General Purpose Computing) has been observed in a wide range of construction projects, varying from small-scale to large-scale endeavors. The application of Glass Fiber Reinforced Polymer (GFRP) Composite (GPC) can be observed in various construction practices, including both reinforced concrete construction and plain concrete construction. The application of Geopolymer Concrete (GPC) was first observed in 2009 during an in-situ construction project for a landscape retaining wall at a bridge site by VicRoads or Roads Corporation of Victoria in Victoria, Australia. In subsequent applications, GPC (Glass Fiber Reinforced Polymer Composite) has been utilized for the construction of various infrastructure elements, including bicycle paths, kerbs, and channels. VicRoads has implemented the use of a reinforced retaining wall at the M80 Western Ring Road, utilizing Glass Fiber Reinforced Polymer Composite (GPC) materials [138]. Additionally, underground stormwater drains have been installed, employing steel-reinforced GPC pipes [138]. Graphene-based polymer composites (GPCs) have been found to possess remarkable durability characteristics, displaying a notable resistance to various forms of degradation. These include a high level of resistance to acid attack, alkali-silica reaction, fire, limited sulphate attack, and low carbonation. Glass fiber-reinforced polymer composites (GPC) have been identified as highly suitable materials for precast concrete elements, including girders, beams, wall panels, and railway sleepers. The elevated temperature curing process employed in GPC offers significant advantages in terms of early strength gain when compared to ambient curing methods. This characteristic makes GPC an attractive choice for the efficient production of precast concrete elements.

8. CONCLUSION

In conclusion, the findings of this research study suggest that further investigation is warranted in order to fully understand the implications of the observed results.The global consumption of concrete has witnessed a significant surge due to the rapid growth in infrastructural development activities. Consequently, this surge has led to a substantial increase in cement production. The increased emission of carbon dioxide into the atmosphere has been observed as a consequence of this phenomenon. Simultaneously, it has been observed that thermal power plants have been generating substantial quantities of fly ash, a byproduct that remains underutilized. recent years, there has been a growing interest in the topic of climate change and its impact on the environment.

The current state of affairs involves the advancement of geopolymer concrete as a potential substitute for conventional cement concrete, offering a promising solution in terms of sustainability. The implementation of this approach has the potential to decrease the demand for cement, resulting in a reduction in carbon dioxide emissions. Additionally, it can enhance the utilization of fly ash. Geopolymer concrete (GPC) is a sustainable material that offers several advantages over traditional Portland cement concrete. It has been extensively studied and proven to have positive impacts on the environment, as well as superior mechanical strength properties and resistance to aggressive environments. Additionally, GPC has the potential to reduce maintenance costs associated with concrete structures. However, it is important to note that this particular approach does come with certain limitations. One such limitation is the higher cost when compared to traditional Portland cement concrete. Additionally, the mix design for this approach can be quite intricate, requiring careful consideration and planning. Another factor to consider is the potential variation in results, which can be attributed to inconsistencies in the quality of raw materials used. Furthermore, there may be ambiguity in the application of the specific type of curing regime required for this approach. These limitations should be taken into account when considering the feasibility and practicality of implementing this method. One potential approach to address the limitations is to explore strategies for cost reduction through mass production. By scaling up production, it may be possible to achieve economies of scale and reduce overall costs. Additionally, the development and adoption of consistent mix design guidelines could contribute to overcoming limitations. By establishing standardized guidelines, it becomes easier to ensure the quality and performance of the materials used in construction projects. Furthermore, utilizing uniform quality of raw materials can help mitigate limitations. By sourcing materials that meet consistent quality standards, it is possible to enhance the overall reliability and durability of the construction work. Lastly, adopting an appropriate type of curing method for the specific project at hand could also contribute to overcoming limitations. By selecting the most suitable curing technique, it becomes possible to optimize the strength and durability of the construction materials. Furthermore, through meticulous observation and thorough analysis of an extensive literature review, the following conclusion can be derived.

The composition of fly ash based geopolymer concrete exhibits variations in comparison to Portland cement concrete, with the exception of aggregates and ad-mixtures. The production of binder paste in Geopolymer Concrete (GPC) involves the utilization of fly ash and an alkaline activators solution. On the other hand, in Portland Cement Concrete (PCC), the binder paste is comprised of cement and water.

The absence of universally recognized standardized protocols for the formulation of mixtures in Glass Fiber Reinforced Polymer Concrete (GPC) in comparison to Portland Cement Concrete (PCC) has been identified as a significant research gap. The complexity of the mix design process in GPC production can be attributed to the involvement of various variables, including raw materials, alkali activators, and different curing regimes. These factors contribute to the intricate nature of the process.

The performance of fly ash based geopolymer concrete is influenced by various factors, including the type of curing regime, concentration and quantity of alkaline solution, rest period, period of heat curing, and water content. These parameters play a crucial role in determining the properties and characteristics of the geopolymer concrete. By manipulating these variables, researchers can investigate the effects on the performance of the concrete and optimize its properties accordingly. The type of curing regime refers to the specific method employed to cure the geopolymer concrete, such as ambient curing, steam curing, or hot water curing. The concentration and quantity of alkaline solution used in the mixture can significantly impact the geo-polymerization process and the resulting strength and durability of the concrete. The rest period, which is the duration of time allowed for the geopolymer concrete to set and gain strength before further curing, also affects its performance. Additionally, the period of heat curing, which involves subjecting the concrete to elevated temperatures, can enhance its mechanical properties and accelerate the geo-polymerization reaction. Finally, the water content in the mixture influences the workability and rheological behavior of the geopolymer concrete, ultimately affecting its performance. Understanding the influence of these factors is essential for optimizing the production and

The compressive strength of fly ash based geopolymer concrete has been observed to exhibit an increase as the curing temperature is raised. Additionally, an increase in the sodium silicate to sodium hydroxide solution ratio (within the range of up to 2.5) and the concentration of the alkaline solution has also been found to contribute to an increase in compressive strength. Conversely, an increase in the water-geopolymer solids ratio and alkaline solution concentration has been observed to result in a decrease in compressive strength.

In order to address the issue of fly ash ratio and superplasticizer exceeding 2% by weight of binder content, extensive research has been conducted to explore potential solutions. The objective of this research is to identify alternative approaches that can effectively mitigate the challenges associated with such high proportions of fly ash and superplasticizer. Numerous studies have been conducted to investigate the impact of increasing the fly ash ratio beyond the recommended limit. These studies have focused on evaluating the mechanical properties, workability, and durability of concrete mixtures containing higher proportions of fly ash. The findings from these studies have provided valuable insights into the performance of concrete mixtures with elevated fly Moreover, it has been observed that extending the duration of rest periods during the heat curing process leads to an improvement in the strength of geopolymer concrete (GPC). Heat curing is a commonly used technique in situations where there is a need for accelerated early strength development.

The workability of fresh geopolymer concrete has been observed to be comparatively lower when compared to Portland cement concrete, according to research findings. The workability of the material can be enhanced through the incorporation of superplasticizers. Various types of superplasticizers are commonly used in construction materials, such as polycarboxylates based superplasticizer and naphthalene-based superplasticizers. These additives are known for their ability to enhance the workability and flowability of concrete mixtures, resulting in improved performance and durability of the final product. The research findings indicate that geopolymer concrete exhibits enhanced resistance to drying shrinkage and various acids, including sulphuric acid, magnesium, and sodium sulphate.

9. FUTURE SCOPE FOR RESEARCH

The future scope for research in this field is vast and promising. There are several areas that hold great potential for further exploration and investigation. By delving deeper into these areas, researchers can expand our understanding and contribute to the advancement of knowledge. Over the past decade, there has been a significant amount of research conducted in the field of fly ash based geopolymer concrete. However, the absence of standardized guidelines for the mixture design of GPC can be attributed to the use of diverse and inconsistent materials in the production process of GPC. Therefore, in order to ensure widespread acceptance of geopolymer concrete in the industry, it is recommended that efforts be made to establish standardized guidelines, particularly in the context of India. The current body of research on the structural behavior and durability of fly ash based geopolymer concrete is relatively limited. Therefore, further research could be conducted in this area. Acknowledgements This study acknowledges the valuable contribution of the co-author in the preparation of the manuscript. The principal author conducted literature search, data analysis, and drafting for this research. The co-author contributes to the development of the article's concept and provides valuable input during the critical revision process. The availability of data for this research is not applicable. The availability of code was not applicable for this research study.

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 replace- ment of natural river sand with geopolymer fly ash sand on hard- ened 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 determi- nation 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 ac- tivators. 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 parti- cle 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 per- formance 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 con- crete: 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 prop- erties 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 con- struction, 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 struc- tures. 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 net- work. 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 inves- tigation 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 de- signed by Taguchi method. Const Build Mater 150:817–824

57. Zain MFM, Abd SM (2009) Multiple regression model for com- pressive 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 net- works. 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 proce- dure. 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 com- pressive 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 develop- ment 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 dura- tion 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 ex- posed 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 com- pressive 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 granu- lated 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 con- crete 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 con- crete. 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 mi- crowave 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, hydro- lysis 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, hydro- lysis 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 acti- vator 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 micro- structure 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 geo- polymer 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 con- crete: 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 con- crete. 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 con- crete 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 incor- porated 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