Journal of Mines, Metals and Fuels, *73(2): 401-417; 2025. DOI: 10.18311/jmmf/2025/47459*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Geopolymer Concrete Optimization: A Critical Review of Supplementary Materials and Performance Enhancement

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Abstract

In the realm of environmentally friendly building materials, geopolymer concrete stands out as a viable substitute for traditional concrete made of cement. This literature review explores recent developments and innovations in geopolymer concrete, with an emphasis on optimizing its properties through the use of various supplementary materials. The aim is to enhance both the mechanical strength and geopolymer concrete's microstructural properties, while also investigating the cost efficiency of these enhancements. The review systematically examines different combinations of supplementary cementitious materials, analyzing their impact on mechanical stability and long-term performance. Additionally, the study delves into the creation of precise Artificial Neural Network models using mixed synthetic data to accurately predict geopolymer concrete properties. Microstructural properties of geopolymer concrete are evaluated through XRD and SEM analyses, providing valuable insights into its structural integrity. Furthermore, a comparative analysis of the cost parameters between traditional concrete and geopolymer concrete is conducted, shedding light on the economic viability of GPC in construction projects. This thorough evaluation aims to support ongoing research and development in the field of geopolymer concrete, offering valuable insights for engineers, researchers, and industry professionals seeking sustainable and efficient construction materials. Incorporating supplementary cementitious materials, such as fly ash, slag, and metakaolin, significantly enhances the mechanical strength and durability of geopolymer concrete (GPC), providing superior resistance to environmental degradation, such as sulfate attack, compared to traditional Portland cement concrete. The application of artificial intelligence, specifically ANN modeling with mixed synthetic datasets, demonstrates a high degree of accuracy in predicting the compressive strength and long-term performance of GPC. This facilitates the development of optimized and reliable mix designs tailored to diverse construction needs. A detailed cost analysis highlights the economic and environmental viability of GPC. While its initial production costs may be higher due to specialized materials, its long-term cost-effectiveness is evident through enhanced durability and reduced maintenance. Its lower carbon footprint makes GPC a sustainable alternative for future projects while using industrial by-products promotes a circular economy.

Major Findings: *Geopolymer Concrete (GPC) can significantly enhance mechanical strength and microstructural properties through various supplementary cementitious materials. Advanced techniques like Artificial Neural Networks (ANN) and microstructural analyses (XRD, SEM) provide deeper insights into GPC's stability and performance. Additionally, GPC demonstrates economic viability compared to traditional concrete, offering sustainable benefits for construction projects.*

Keywords: *Cost Efficiency, Geopolymer Concrete, SEM, Supplementary Cementitious Materials, XRD*

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1.0 Introduction

In modern construction practices, there is a growing emphasis on finding sustainable and efficient building materials as substitutes for traditional concrete. GPC has become a viable eco-friendly option since it can drastically carbon emissions associated with cement production while maintaining or even enhancing performance. This literature review focuses on recent advancements in geopolymer concrete, particularly its optimisation through various supplementary materials. This paper attempts to give a comprehensive review of GPC technology and its implications for sustainable construction practices by looking at the mechanical, microstructural and cost-related elements. To lower carbon emissions and energy waste in the building industry, GPC is considered a good substitute for conventional Portland cement.

The ability of Materials activated by alkali, like geopolymers, to reuse trash and industrial byproducts to create sustainable building materials is becoming more widely acknowledged[1]. Geopolymer concrete (GPC) is gaining popularity as a sustainable alternative to traditional Portland cement due to its use of industrial by-products like fly ash, slag, and metakaolin, activated with alkaline solutions. GPC offers environmental benefits by reducing carbon emissions from cement production and provides superior mechanical properties, fire resistance, and durability. Ongoing research focuses on optimizing its mix design, performance, and long-term behavior to meet the growing demand for sustainable construction materials[2]. GPC solves cost and environmental issues by providing a sustainable substitute for conventional Portland cement. This study assesses its strength, sustainability, and optimal mix designs using advanced analytical and experimental methods. Its originality lies in enhancing sustainable concrete by evaluating various precursors, such as silica fume, GGBS, and RHA, with the potential to replace conventional concrete in numerous applications[3]. The substantial demand for cement has driven its extensive production, resulting in significant carbon dioxide emissions. Geopolymer binders, utilizing surplus industrial and agricultural aluminosilicate waste, offer a cement-free substitute[4]. Geopolymer concrete is gaining popularity in the industry, but its performance is often restricted when using a single precursor. To enhance its properties, it is recommended to use a combination of precursors in geopolymer concrete production[5]. Although geopolymer has strong mechanical qualities at high temperatures, substantial thermal property discrepancies between the aggregate and geopolymer may make geopolymer concrete less effective. This disparity can result in notable thermal stresses, especially in elevated temperature conditions[6]. Rising carbon emissions in construction drive the adoption of eco-friendly substitutes like geopolymer concrete. Ensuring durability in harsh conditions is crucial, prompting the exploration of robust geopolymer formulations. This study examines how adding hooked-end steel fibers to ambient-cured GPC with low NaOH concentrations improves its strength and durability[7]. Environmental pollution, particularly from the construction sector's Portland cement production, is a significant global challenge. Using industrial byproducts in construction, such as GGBS and fly ash, can mitigate these emissions. Recent research focuses on geopolymer concrete, where FA and GGBS fully replace Portland cement. Fine aggregate is substituted with quarry sand and M-sand, while 10 mm of coarse aggregate is used in place of 20 mm., bound together using alkaline solutions[8]. Geopolymer concrete offers a sustainable alternative to traditional cement by utilizing industrial by-products like fly ash and slag, reducing carbon emissions, but challenges with material availability and consistency hinder its large-scale adoption[9]. Ambient-cured GPC is an eco-friendly substitute to OPC-based concrete, offering a denser microstructure with fewer cracks and voids, especially with a 60/40 fly ash/slag ratio[10]. Geopolymer concrete, a cement substitute using fly ash and alkali activation, was studied for mix design. A procedure based on fly ash quantity, water content, and aggregate gradation was proposed. Sodium hydroxide and sodium silicate solutions were employed consistently, maintaining ratios for workability and strength[11]. Efforts to standardize greenhouse gas emission measurement aim to reduce emissions. Concrete, reliant on energy-intensive OPC, is a major CO_2 emitter. Finding substitutes requires strong, cost-effective, globally available materials[12]. GPC is a sustainable substitute to OPC concrete. This study investigated the recyclability

of GPC across different strength grades (C40 to C100) under freeze-thaw conditions. The results showed that higher strength GPC (C100 and C80) endured 350 cycles, while lower strength GPC (C40) did not. Recycled aggregates from higher-strength GPC exhibited better performance, aligning with higher recycling class standards[13]. Diatomite was studied as an additive in geopolymer materials. Adding 1% and 3% diatomite reduced the strength of compression by up to 28% when replacing main geopolymer precursors. However, using 5% diatomite as a sand substitute increased strength by up to 24%[14]. Commercial NaOH and SS are extensively used as activators in GPC, but their availability and CO_2 emissions are concerning[15]. Geopolymer composites are a sustainable alternative to cement, offering durability and environmental benefits. Research highlights factors like raw materials, mix design, and curing, with applications in sustainable infrastructure. Challenges like material variability and standardization require further study[16]. Researchers are investigating the application of additional Supplementary Cementitious Materials (SCMs) to reduce the environmental impact of Ordinary Portland cement. Studies suggest that adding 5–20 % of SCMs like bentonite, kaolin, and biomass can improve the mechanical characteristics and durability of cement composites[17]. Low-calcium fly ash-based geopolymer mortars are valued for their durability and environmental advantages. Curing conditions, including temperature and time, critically affect mechanical properties and long-term performance. Optimizing curing enhances strength, durability, and sustainability in construction[18]. Transportation of raw materials increases negative impacts. Cost reduction and environmental benefits are achieved with FA - Silica fume GPC, indicating its potential to increase the building industry's sustainability[19]. Geopolymer concrete, replacing cement with fly ash and alkaline solutions, shows promise as a sustainable construction material. Tests for workability and strength of compression after oven heating indicate its viability as an eco-friendly substitute[20]. Geopolymer concrete, primarily using fly ash as a binder, provides a sustainable alternative to traditional concrete. Its compressive strength and other mechanical properties can be accurately predicted using machine learning techniques like optimized neural networks, enhancing material utilization and performance in construction[21]. Geopolymer Self-Compacting concrete (GSC) is an emerging alternative to conventional concrete, and machine learning is increasingly applied to estimate its compressive strength. These predictive models help improve mix designs by considering factors like binder content and curing temperature, boosting both strength and sustainability[22]. Machine learning has shown significant potential in analyzing fly ash-based geopolymer concrete, accurately predicting compressive strength while reducing trial-and-error during mix optimization by accounting for various influencing factors such as mix proportions and curing conditions[23]. The use of machine learning to predict compressive strength in fly ash-based geopolymer concrete streamlines the development of improved mechanical properties, enhancing its design and performance[24]. Advancements in machine learning have improved the accuracy of predicting compressive strength in geopolymer concrete made from a mix of fly ash and ground Granulated Blast Furnace Slag (GGBFS), optimizing the mix to enhance strength and sustainability[25]. AI, particularly machine learning, is transforming geopolymer concrete production by predicting material properties and aiding in the development of optimized mix designs, thus improving

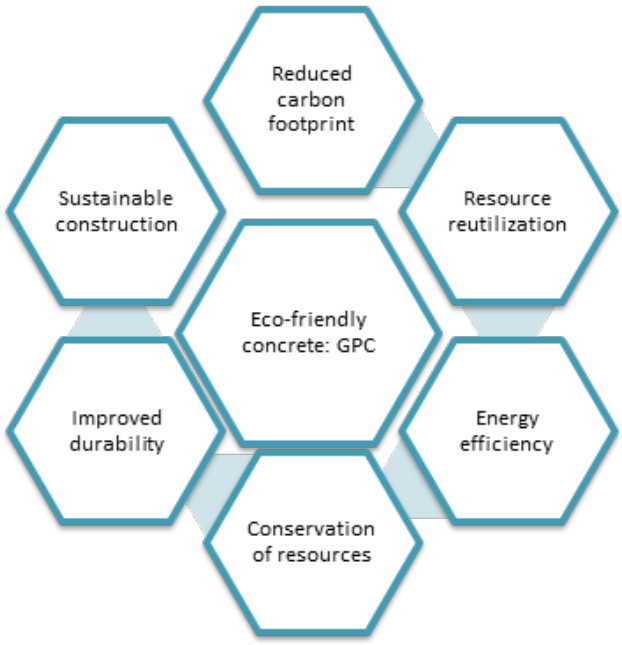


Figure 2. Schematic depiction of the advantages of geopolymer composite utilising waste materials[29].

overall performance and promoting wider adoption in the construction industry[26]. Artificial Neural Networks (ANNs) are used to predict the mechanical and durability properties of geopolymer composites, identifying optimal material combinations that result in stronger, more durable concrete for sustainable construction practices[27]. Machine learning models applied to geopolymer self-compacting concrete accurately estimate its strength, enabling engineers to design optimal mix proportions with reduced reliance on experimental methods[28]. AI-based machine learning techniques are now employed to predict the strength of geopolymer concrete, determining the ideal composition to achieve desired strength properties while considering factors like curing time and environmental conditions (Figure 1). This Figure provides a schematic depiction of the advantages of geopolymer composite utilizing waste materials[29]. Cross-validation techniques in Artificial Neural Networks (ANNs) are being used to predict the material design of eco-friendly geopolymer composites, optimizing mix designs for more accurate and sustainable concrete alternatives[30].

2.0 Findings from Literature

Water, fly ash, fine and coarse aggregates, and alkaline solutions like sodium hydroxide and sodium silicate are the main components of geopolymer concrete. Changing each parameter has a considerable impact on the GPC properties of both freshly poured and cured concrete. Identifying different base materials, determining alkaline activator ratios, raising curing temperatures, increasing sodium hydroxide concentrations, and determining sodium hydroxide to sodium silicate ratios are all topics covered in the literature referenced above.

3.0 Research Gap

The existing research in the field of geopolymer concrete has made significant strides in understanding its properties and applications. However, there remains a notable research gap concerning the optimization of geopolymer concrete using diverse supplementary materials while ensuring enhanced mechanical and microstructural properties alongside cost efficiency. Despite advancements, there is a lack of systematic exploration into the varied combinations of supplementary cementitious materials in GPC and their influence on mechanical stability and long-term execution. Furthermore, the absence of precise Artificial Neural Network models using mixed synthetic data hinders accurate predictions of geopolymer concrete properties, limiting the optimization potential of the material. Additionally, while some studies have delved into the microstructural properties of geopolymer concrete through techniques like XRD and SEM, there is still a need for comprehensive analysis to fully understand the material's behavior and characteristics. Lastly, to evaluate the economic feasibility and competitiveness of geopolymer technology in the building sector, a cost comparison between GPC and traditional concrete is required. In addition to advancing GPC technology, filling these research gaps will open the door for its broader use in environmentally friendly building techniques.

4.0 Review of Various Parameters

The review encompasses several research papers focusing on different aspects of geopolymer concrete. Firstly, there's a concerted effort to systematically explore diverse combinations of supplementary cementitious materials in geopolymer concrete. These studies aim to analyze the influence of these combinations on mechanical stability and long-term performance. Secondly, researchers use artificial neural network models with mixed synthetic data to create precise predictive tools for geopolymer concrete properties. An emphasis is also placed on analyzing the microstructural characteristics of GPC using methods such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). Lastly, comparisons between the cost parameters of geopolymer concrete and conventional concrete are being made to assess the economic viability of geopolymer technology. Through these varied approaches, researchers aim to enhance our understanding and utilization of geopolymer concrete in construction applications.

5.0 Effect of Various Binding Materials

Leandro B.O and Afonso R.G.A[1]. published a paper about the durability and sustainability of GPC, emphasizing

Using industrial byproducts like glass waste, fly ash, blast furnace slag, and FGD residue. These aluminosilicate-rich byproducts are usable as a good substitute for OPC by activating them with alkaline solutions to create geopolymers. Their research emphasizes how employing these materials might help the environment by lowering CO_2 emissions linked to the manufacturing of conventional cement. The paper also examines the durability of geopolymers made from these by-products under various conditions, including carbonation, acid corrosion, and thermal shock, indicating their potential for sustainable construction applications. J. Wang, C. Zheng, H. Liu, H. G. Rao, and R. Liang[2]. created a process to recycle leftover glass fiber-reinforced polymer powder in the manufacturing of geopolymers by combining it with GGBS. Their study found that while GFRP powder alone showed slow early strength development and higher brittleness, Compressive, and flexural strengths were among the mechanical qualities that were greatly enhanced through the application of GGBS with the maximum strength and least amount of brittleness, the ideal mixture of 30-weight percent GFRP powder and GGBS showed promise as a sustainable building material.

T. V. Nagaraju and A. Bahrami[3]. the study assesses the creation of high-performance, sustainable geopolymer mortar, and concrete utilizing agricultural biomass, such as Rice Husk Ash (RHA). utilizing models like artificial neural networks and multi-linear regression for strength prediction, the study evaluates compressive and flexural strengths utilizing a variety of precursors, including silica fume and GGBS. The study found that geopolymer concrete blends with up to 15% RHA enhanced strength of compression and sustainability performance, showing potential as a cost-efficient and environmentally friendly substitute for conventional Portland cement. S. Lekshmi and J. Sudhakumar[4]. The study evaluated the durability of a geopolymer mortar made of fly ash and clay that was supplemented with lime and GGBS. They found that incorporating a combination of lime and GGBS improved the durability and mechanical performance, with optimal contents of 6% lime and 30% GGBS for one clay type, and 8% lime and 35% GGBS for another. The enhanced mixes showed better compressive strength, sorptivity, water absorption, and resistance to acid and sulfate attacks, making them suitable for lightweight construction applications. Min Yu *et al*[5]. investigated the residual mechanical characteristics of GPC made from a blend of GGBS, FA, and Silica Fume (SF), after being exposed to high temperatures, both with and without steel fibers. They found that the residual strength of compression and elastic modulus decreases with increasing temperature. The presence of steel fibers generally improved the residual strength of compression and deformation capability, though the benefit varied between mortar and concrete. Significant strength loss occurred above 700°C because of the breakdown of C-A-S-H and gel dehydration. The study also proposed a temperature-dependent stress-strain model for practical applications. Tan Wang *et al*[6]. examined, Steel fibers both with and without the mechanical characteristics of geopolymer concrete that contain a blend of Fly Ash (FA), SF, and GGBS at high temperatures. They discovered that while peak strain and ductility rise with temperature, compressive strength, and elastic modulus fall. Steel fibers improved the strength of compression and ductility at lower temperatures. The study proposed empirical temperature-dependent stress-strain constitutive equations for geopolymer concrete to aid in fire safety analysis and design. G. Laxmi *et al*[7]. investigated the application of fly ash and GGBS as byproduct materials in low-NaOH ambient-cured Geopolymer Concrete (GPC). The strength and durability of GPC were greatly enhanced by the insertion of hooked-end steel fibers. Optimal fiber dosing at 1% enhanced the strength of compression to 41.44 MPa, split tensile strength to 4.28 MPa, and flexural strength to 5.32 MPa. Moreover, steel fibers reduced water penetration depth and effectively restricted crack propagation, as evidenced by SEM analysis. These findings highlight the potential of using industrial byproducts and steel fibers to create durable, low-carbon construction materials. Leandro B. de Oliveira and Afonso R.G. de Azevedo[8]. investigate the use of industrial by-products in geopolymer concrete, offering eco-friendly substitute alternatives to Portland cement. Their study shows that materials like FGD residue, fly ash, blast furnace slag, and glass waste when activated with alkaline solutions, enhance concrete durability and reduce CO_2 emissions. The research also highlights the positive impact of these by-products on geopolymer

performance. Additionally, the inclusion of steel fibers improves mechanical characteristics, with higher sodium hydroxide concentrations boosting the strength of compression and split tensile strength. Overall, the study underscores the potential of geopolymer concrete for environmentally friendly building techniques.

Assi *et al.*'s[9] assessment evaluates the source material availability for sustainable concrete and geopolymer. They discovered that although GPC is a good substitute for OPC in the US and Europe, there are drawbacks in other places, such as China. FA-based GPC is highlighted for its low cost and global abundance. However, global adoption is currently limited to 7% due to constraints in sodium hydroxide supply. The study emphasizes the ongoing investigation to reduce sodium hydroxide use and improve geopolymer concrete availability and cost. Negahban *et al.*[10] a study comparing ambient temperature-cured GPC to regular Portland cement-based concrete (OPCC), the study looks at the pore structure of GPC and how it affects engineering qualities. They find that GPC, with a dominant slag content and low water content, exhibits a denser and more uniform microstructure with fewer microcracks and voids. The fly ash/slag ratio of 60/40 shows the most refined pore structure. In contrast, OPCC shows a more uniform pore structure throughout its cross-section. The study underlines the significance of comprehending microstructural features to optimize engineering parameters and shows the possibility of one-part GPC for industrial applications. Patankar, Ghugal, and Jamkar[11]. the study focuses on FA-based geopolymer concrete, a sustainable substitute for regular Portland cement-based concrete, which is the subject of this study's mix design. The research proposes a mixed design procedure based on the quantity and fineness of fly ash, water content, fine aggregate grading, and fine-to-total aggregate ratio. The sodium hydroxide and sodium silicate solutions employed as activators are kept constant throughout the investigation. Workability and strength of compression are measured, with the results showing that the proposed mix design achieves the desired workability and compressive strength. Lopes, Lopes, and Pinto[12]. To find a practical alternative to traditional concrete, the study looks at how the curing temperature affects the strength of metakaolin-based geopolymers. Unlike other pozzolanic materials, such as FA and slag, which benefit from higher curing temperatures, metakaolin geopolymers exhibit reduced strength at temperatures above 30°C. The research recommends curing temperatures below 30°C to maintain strength, as curing at 50°C led to over 35% reduction in flexural strength and over 60% reduction in compressive strength. The study also compares white and brown metakaolin geopolymers, noting differences in strength but within acceptable limits. The findings underline the importance of carefully controlling curing temperatures for metakaolin-based geopolymers to achieve optimal strength, highlighting their potential as environmentally friendly construction materials. Liu *et al*[13]., examined the recycling potential and durability of metakaolin-based geopolymer concrete (GPC) under freeze-thaw conditions for different strength grades such as (C- 40, C- 60, C- 80, and C- 100). GPC samples were subjected to 350 freeze-thaw cycles & the resulting recycled geopolymer coarse aggregates (RGAs) were analyzed for physical properties and microstructure. The study found that GPC with higher strength grades such as (C-100, C-80, and C-60) showed better frost resistance, enduring over 350 freeze-thaw cycles, while C-40 did not withstand these conditions. RGAs from C-100 and C-80 met Class-II recycled aggregate standards, while C-60 met Class-III criteria. The study concluded that higher strength grades in GPC result in better physical properties in RGAs, suggesting a linear correlation between parent concrete strength and recycled aggregate performance. Nykiel, *et al*[14]., investigated the application of diatomite as a geopolymer additive, aiming to explore its potential as an alternative to fly ash, metakaolin, and sand in geopolymer composites. The investigation examined the physical characteristics of geopolymer composites including 1%, 3%, and 5% diatomite additions, morphology, thermal behavior, and compressive strength. The research found that replacing fly ash and metakaolin with 1% and 3% diatomite negatively impacted the strength properties of geopolymers, reducing up to 28% in compressive strength. However, substituting 5% of sand with crushed diatomite increased the strength of geopolymers by as much as 24%.

Oti *et al*[15]., study on GGBS-based GPC activated by an alternative alkaline activator composed of sodium

hydroxide and rice husk ash. They determined that a water-to-binder ratio of 0.50 was ideal and looked into how the alkali/precursor ratio affected the characteristics of the concrete. The strength of compression peaked at an A/P ratio of 0.4, and the GPC mixes demonstrated appropriate workability. Geopolymer concrete has advantages for the environment even if it has less mechanical strength than OPC. GPC2 is recommended for balanced workability and structural performance, having a ratio of 0.4 A/P and 0.5 W/B. Improving geopolymer concrete's mechanical qualities for optimal performance, and sustainable mixes should be the main goal of future research. Yang *et al*[16]., conducted a bibliometric analysis and literature review on Geopolymer Composites (GPC), highlighting their potential as a sustainable substitute for cement in concrete production. The study employed scientometric techniques to analyze data gathered from the Scopus database, revealing key insights such as leading publication sources, keywords, authors, articles with the most citations, and active research regions in GPC. The analysis also identified important research concerns and gaps, providing guidelines for future studies. This scientometric review aims to foster knowledge exchange, encourage collaboration, and promote GPC development, as shown in Figure[2] below. Fode *et al*.,[17] review focuses on using waste materials or byproducts as Supplementary Cementitious Materials (SCMs) in cement composites. They discovered that strength is maximized when SCMs such as bentonite, kaolin (at 15%) and biomass ash, or volcanic ash (at 20%) are substituted for cement. Properties are additionally enhanced by adding silica fume, fly ash, and zeolite (at 10%). Natural SCMs show promise for reducing energy consumption and pollution. SCMs enhance cement matrix microstructure and durability by filling pores and reacting with lime to form additional C–S–H. Future research should explore the durability effects of silica fume and volcanic ash. Yılmaz, Degirmenci, and Aygörmez[18]. studied the impact of initial curing conditions on geopolymer mortars made from low-calcium fly ash. They found that longer curing times and higher temperatures improved compressive strength, with the best results seen at 80°C for 72 hours. However, high temperatures reduced the mortars' resistance to elevated temperatures, while increasing their resistance to freeze-thaw cycles. This research highlights the potential of fly ash, a byproduct, as a sustainable substitute in geopolymer production. Bajpai, Choudhary, Srivastava, Sangwan, and Singh[19]. they have evaluated the environmental impact of GPC concrete made with FA and silica fume. They found that these materials offer lower global warming potential than OPC. The mixture containing activated FA-silica fume geopolymer without sodium silicate had the least negative effects on the environment. and reduced costs

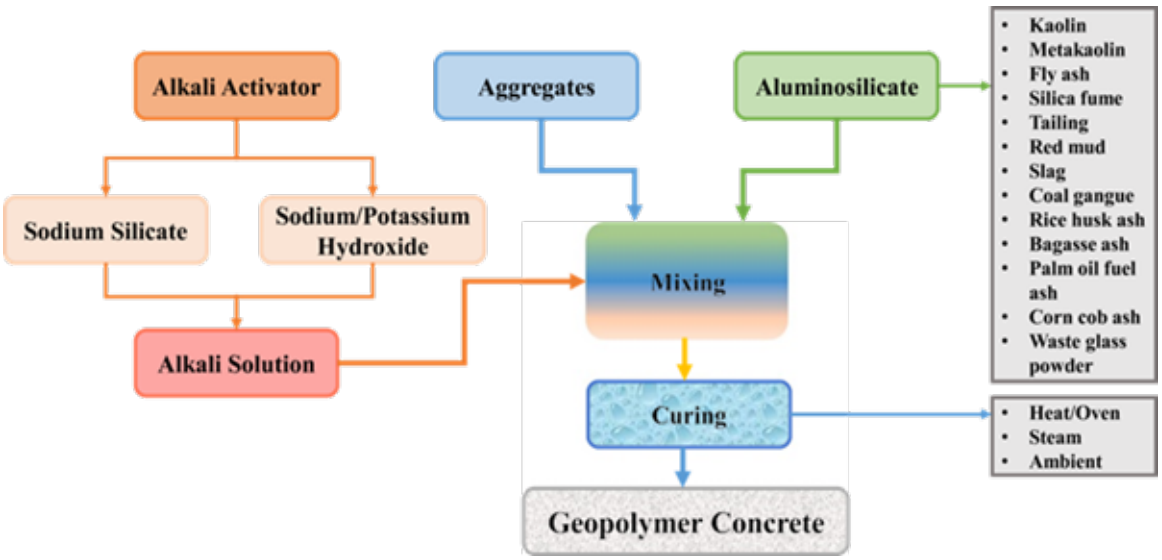


Figure 2. Geopolymer concrete production process schematic[16].

by 10.87% to 17.77% per unit volume. Their study suggests that fly ash and silica fume blended geopolymer concrete could significantly enhance sustainability in construction. Kurhade, Patankar, and Rupwate[20]. study on the effect of FA fineness and quantity on Geopolymer Concrete (GPC) properties provides crucial insights into sustainable construction practices. Their research, emphasizing the replacement of cement with fly ash in GPC, showcases its viability as a binding agent when combined with alkaline solutions like NaOH and Na_2SiO_3. The study's experimental approach, including slump cone tests and strength of compression evaluation, demonstrates that finer fly ash enhances workability and strength, indicating its potential for eco-friendly construction materials. However, caution is advised against exceeding certain fly ash quantities, as this can reduce both workability and strength. This insight provides a foundation for developing GPC formulations suited to a range of structural applications, and it opens up future avenues for investigating other supplementary materials and waste products, potentially leading to more resilient construction solutions.

6.0 Precise Machine Learning Methods for GPC

Khalaf, Kopecskó, and Merta[21]. conducted a comprehensive study on predicting the strength of compression FA GPC using an optimized feedforward layered neural network model. The study sought to address the concrete industry's demand for sustainable development. Ten input variables and the outcome variable were used to analyze the 189 samples with different FA GPC mix designs that were gathered for the study. With a small Mean Squared Error (MSE) of 10.4 for training and 15.0 for testing, a strong correlation value (R) of 96.0 & 97.5, with a comparatively low training and testing Root, Mean Squared Error (RMSE) of 3.22 and 3.87 MPa, respectively, the researchers were able to create a highly predictive tool by optimizing the FLNN model using Matlab. According to the study's findings, FLNN performed better than alternative machine learning approaches and offered a trustworthy instrument for forecasting the compression strength of FA GPC, greatly promoting the production of sustainable concrete and furthering this area of study.

Paul O. Awoyera *et al.*,22 attempt to estimate the strength qualities of geopolymer self-compacting concrete (GSCC) by utilizing machine learning approaches, notably Artificial Neural Networks (ANN) and Genetic Programming (GEP). The goal of the study is to address the need for a standardized framework in the creation of environmentally friendly concrete. For the geopolymer reaction, the study employed a 12M sodium silicate and sodium hydroxide alkaline solution with a fly ash ratio of 0.33. GGBS and silica fume were used in place of some of the fly ash. The concrete's fresh mix qualities, filler and passing abilities, and compressive, split-tensile, and flexural strengths were among the many attributes that were assessed. The experimental data was well predicted by the models created using GEP and ANN. GEP models provided straightforward equations from the process, while ANN served as a predictor. According to the study's findings, using mineral admixtures improved the concrete's fresh and hardened qualities, making it a viable strategy for the concrete industry's sustained growth. Dina A. Emarah's[23] research uses machine learning (ML) methods, particularly Deep Neural Networks (DNNs), Artificially created Neural

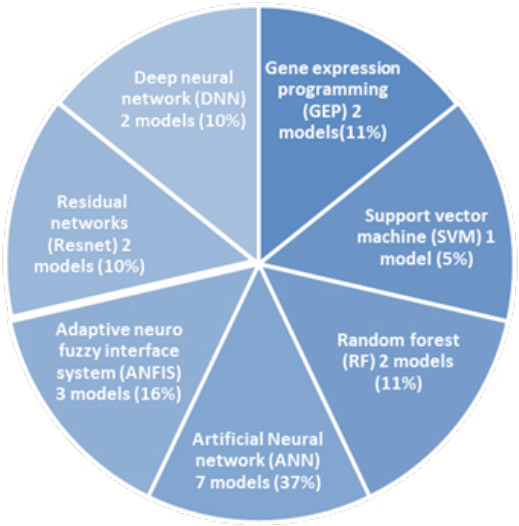


Figure 3. Machine learning techniques were utilized to predict the strength of compression geopolymer concrete[24].

Networks (ANNs), as well as deep residual networks (ResNet), to estimate the strength of compression(C-S) of FA-based GPC (FA-GPC). The study emphasizes the environmental benefits of geopolymer concrete, which reduces greenhouse gas emissions compared to traditional concrete manufacturing. By utilizing fly ash as a binder, GPC offers a sustainable substitute. A dataset of 860 samples was gathered for the study, and 12 input parameters—such as fly ash content, aggregate kinds, alkaline liquid composition, curing conditions, and sample age—that affect the C-S of FA-GPC were examined. The ResNet model performed the best when the effectiveness of the constructed models was assessed using a variety of statistical criteria. The study's conclusion, which emphasizes the promise of geopolymer concrete for sustainable development, is that ML models can accurately forecast the C-S of FA-GPC. Rathnayaka *et al.*,[24] analyzed the application of Machine Learning (ML) techniques to predict the compressive strength of fly ash-based GPC, highlighting its potential as a sustainable alternative to Ordinary Portland Cement (OPC) concrete. The study emphasizes the limitations of traditional mix design methods and the need for standardized procedures in GPC applications. It focuses on feature selection/extraction and techniques like nonlinear regression, ensemble learning, and evolutionary programming, while also classifying input parameters and ML methodologies. The paper discusses the impact of hyperparameters on model efficiency and input variable sensitivity, offering insights for future model development, as shown in Figure 3 below. Yejia Wang[25] used artificial intelligence methods to forecast the compressive strength of geopolymer concrete, incorporating techniques such as Gene Expression Programming (GEP), Adaptive Neuro-Fuzzy Inference System (ANFIS), and Artificial Neural Networks (ANN). The study aimed to predict the strength of geopolymer concrete, which is crucial for assessing its potential in sustainable construction. The results demonstrated that GEP outperformed the other AI methods in terms of accuracy and efficiency, providing simplified models that are more reliable for future predictions. This finding is significant for the development of sustainable concrete solutions because it enables faster and more precise predictions of material performance, reducing experimental costs and time. The use of GEP for compressive strength forecasting also allows for easier integration into real-world applications, making it a promising tool for enhancing the sustainability and performance of geopolymer concrete in construction. Alaneme *et al.*,[26] investigated the application of AI techniques, including Fuzzy Logic, ANFIS, ANN, and GEP, in the production of geopolymer concrete. Their study emphasized AI's potential in optimizing materials, reducing environmental impact, and enhancing sustainability in concrete construction. They highlighted how these AI methods could be employed to improve the efficiency of the mix design, predict the mechanical properties of geopolymer concrete, and reduce energy consumption during production. Furthermore, the study pointed out that AI models can assist in fine-tuning the performance of geopolymer concrete by identifying the optimal ratios of raw materials, thus reducing waste and contributing to more sustainable practices.

The researchers conducted a systematic literature search, critically analyzing various AI methodologies and their efficacy in predicting the strength of compression of geopolymer concrete. They underscored the importance of AI in addressing challenges in concrete production and highlighted the need for further research in this evolving field.

Manikandan *et al.*,[27] studied sustainable geopolymer composites, concentrating on the durability and mechanical properties of geopolymer mortars made of fly ash. The impact of adding polypropylene (PP) fiber and Rice Husk Ash (RHA) on these characteristics was examined. The study found that while PP fiber did not significantly improve compressive strength, a 0.3% addition showed promising results in enhancing flexural behavior. Water absorption and sorptivity increased with higher RHA substitution levels. ANN model was proposed to predict durability and mechanical properties, achieving good agreement with experimental results. The study highlights the potential of geopolymer mortars in structural repairs and suggests further research in this area. Paul O. Awoyera[28] used methods for machine learning to examine the strength characteristics of geopolymer self-compacting concrete. They Employed Genetic Programming (GEP) and Artificial Neural Networks (ANN) to model the strength characteristics of the concrete, which was made

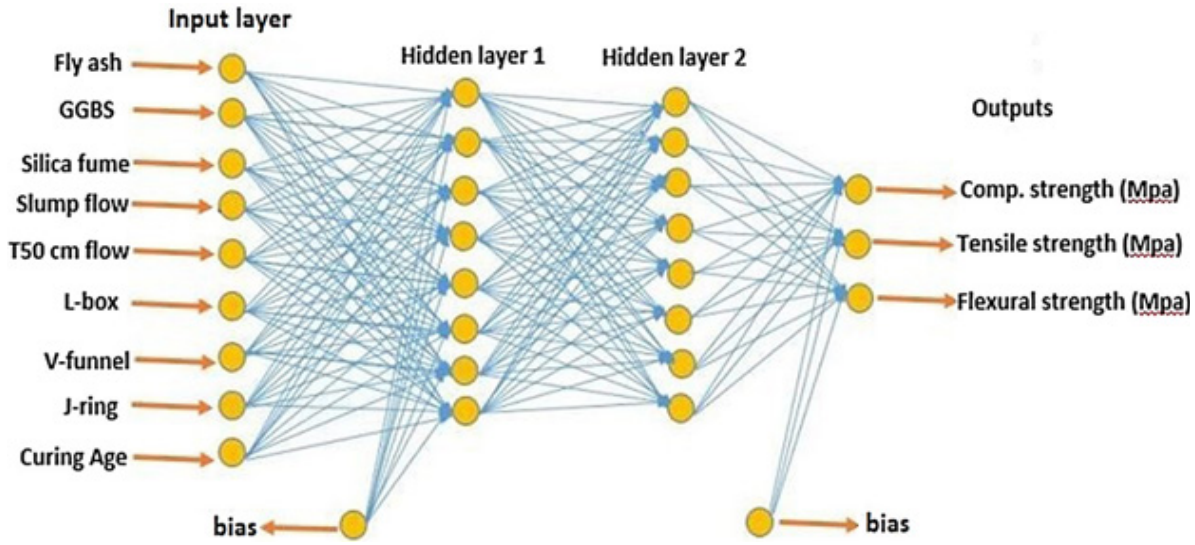


Figure 4. ANN architecture that most accurately simulates concrete performance[28].

by adding mineral admixtures. For the geopolymer reaction, the study employed a 12M sodium hydroxide and sodium silicate alkaline solution with a fly ash ratio of 0.33. Additionally, granulated blast furnace slag and silica fume were used in place of some of the fly ash. The concrete's filler ability, fresh mixture passage ability, and the hardened concrete's compressive, split-tensile, and flexural strengths were among the many characteristics that were examined. The findings demonstrated that adding admixtures enhanced the concrete's fresh and toughened qualities. The experimental data was successfully predicted by both GEP and ANN approaches, although GEP models produced simpler equations from the process than ANN, as illustrated in Figure[4].

Yong Zou[29] assessed several Artificial Intelligence (AI) techniques for determining the geopolymer's strength of compression to lessen the environmental effect of concrete production. They employed Supervised Machine Learning (SML) methods to forecast the strength of compression of Geopolymer Concrete (GPC), such as Random Forest (RF), Bagging Regressor (BR), Gene Expression Programming (GEP), and Decision Tree (DT). In predicting GPC compressive strength, the ensembled SML techniques (BR and RF) performed better than the individual techniques (DT and GEP), with R2 values of 0.96 and 0.95, respectively. The study demonstrated how Artificial Intelligence (AI) methods can increase the efficacy and economy of research in the building sector, especially when it comes to creating environmentally friendly materials like geopolymers. Yaswanth Kuppusamy[30] created a cross-validation ANN to forecast the mix design of Engineered Geopolymer Composites (EGC) for the required tensile and compressive strengths. Five ANN models were trained using seven mix-design elements, and the ANN [2:16:25:7] model outperformed the others in cross-validation, achieving 80% accuracy. This approach offers a cost-effective and time-saving method for designing EGC. Ali Abdulhasan Khalaf[31] developed an optimized neural network model in Matlab to forecast the compression strength of Fly Ash (FA) geopolymer concrete. The model, which was based on a Feedforward Layered Neural Network system (FLNN), looked at 189 samples of different FA GPC mix configurations. The optimized FLNN model showed a high degree of accuracy in estimating the strength of compression with a strong correlation coefficient with actual values and a narrow mean squared error range. The design chart of the model, which can be used for both one- and two-part geopolymer concretes, takes into account a variety of mix-design variables to guarantee future applications of geopolymer manufacturing that are both economical and time-efficient. Kolli Ramujee[32]. created a Convolutional Neural Network (CNN) model to forecast the geopolymer concrete's compressive

strength. The goal of their study was to compile a dataset of 162 Nos GPC mixes that contained Class F fly ash, including their composition and strength metrics. Previous studies and their effects within the model's framework were taken into consideration while choosing the ideal input parameters. Using a trial-and-error method to identify the ideal hyperparameters improved the model's performance. Outperforming traditional prediction techniques, the CNN model correctly forecasted the strength of compression of geopolymer concrete.

7.0 Microstructural Properties of Geopolymer Concrete

F. A. Shilar and team[33] examined how the mechanical characteristics of GPC were affected by molarity, the ratio of Sodium Silicate to Sodium Hydroxide (SS/SH), and the alkaline to binder (A/B) ratio. Data on slump, compressive, split tensile, and flexural strength, bulk density, water absorption, and molarity deviations from 5 to 18 M were examined for both fresh and hardened characteristics, with A/B ratios ranging from 0.30 to 0.5. Using kernel density plots, their investigation demonstrated that, up to a certain point, increasing molarity and A/B ratios improve the strength of GPC. The optimal molarity range of 16-18 M and an A/B ratio of 0.35 yielded the highest split tensile, compressive, and flexural strengths. Further increases in these parameters did not significantly improve performance. The review highlights that the structural performance of GPC surpasses that of traditional concrete, particularly when using binders rich in silica and alumina. B. A.Tayeh a, A. Hakamy b[34] investigated how air agents affected the microstructure and mechanical properties of lightweight GPC (LGC) at high temperatures. Utilizing class F Fly Ash (FA) with Ferrosilicon Slag (FSS) and Aluminum Powder (AP) as air agents, they assessed various LGC mixtures. They found that FSS, as an industrial waste, is a viable air agent, enhancing workability and reducing unit weight. Specifically, FSS at 1% FA mass resulted in a unit weight of 1740 kg/m^3 and a strength of compression of 21.8 MPa, outperforming AP. High-temperature tests revealed that LGC with FSS showed less strength of compression loss compared to traditional GPC, with a 60% strength retention after exposure to 800°C, versus 74% for GPC without FSS.

W. Lee, J. Wang, Y. Ding, and T. Cheng[35] studied the microstructural behavior and related characteristics of GGBS/FA-based GPC paste and concrete. They found that the geopolymer concrete, prepared with fly ash, GGBS, and alkali activators, developed a denser C-A-S-H structure due to higher fractions of Q^4 species from more Si and Al ions dissolved from GGBS and FA. The strength of compression of the concrete steadily increased over 270 days of curing, reaching up to 67 MPa, facilitated by the bridging of microcracks with wollastonite microfibers. The study also highlighted the concrete's excellent chloride resistance, as indicated by a significant reduction in chloride ion penetrability over prolonged curing periods. Jumaa, Ali, Nasr, and Falah[36]. investigated the microstructural properties of FA-based GPC enhanced with Nano-Clay (NC) and Nano-TiO_2 (NT). X-Ray Diffraction (XRD) analysis identified Quartz (Q) and Mullite (M) amorphous peaks within the diffraction patterns between 27° and 32° 2θ, indicating the formation of a dense crystalline structure. Scanning Electron Microscopy (SEM) images demonstrated the presence of large hydrate crystals resulting from the pozzolanic activity of the nanomaterials, which effectively filled the empty pores and densified the Interfacial Transition Zone (ITZ). This densification contributed to the enhanced strength of compression and overall durability of the geopolymer concrete, showcasing the potential of NC and NT as key additives for improving the microstructural characteristics of sustainable construction materials. Hakeem *et al.*,[37] provided a state-of-the-art review of the physical, durability, and microstructural behavior of Ultra-High-Performance Geopolymer Concrete (UHPC). They explored various factors influencing its strength and durability, highlighting the role of advanced materials and processing methods to improve performance in extreme conditions. Their review contributes to optimizing UHPC for high-strength and long-lasting applications in construction. Uzbas and Aydin[38]. conducted a microstructural analysis of silica fume concrete using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). Their study revealed the effects of silica fume on the microstructure and strength of concrete, demonstrating how these materials improve the properties and durability of concrete through enhanced bonding and pore structure. J. J. Vijay, Prof. H. Sudarsana Rao, and Prof. V. G. Ghorpade[39] carried out

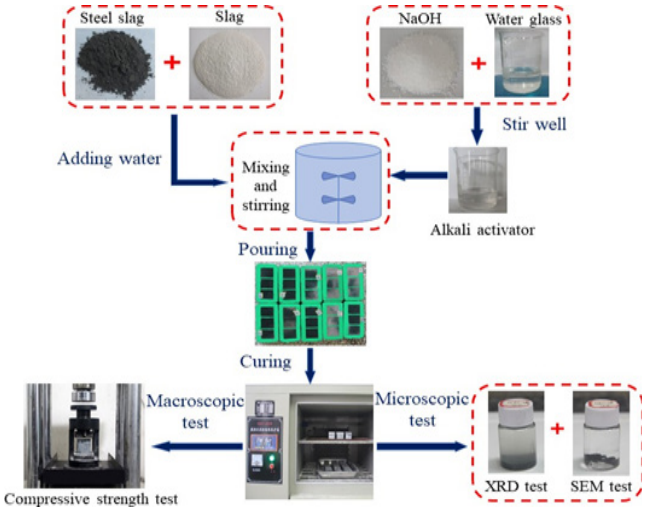


Figure 5. XRD analysis, and SEM examination experimental procedure[41].

XRD and SEM analyses on geopolymer bricks based on fly ash and phosphogypsum. The study's findings suggest that the specimens' carbon content may not be precisely known due to the use of conductive carbon tape, which could impact the accuracy of the results. Despite this limitation, the study successfully corroborates various macrostructure properties with and without fly ash. Samples S1 and S2 were specifically investigated using SEM and EDX scans, revealing a randomly shaped microstructure with varying sizes of pores. The high porosity contributes to low densities, both in dry and wet conditions, while water absorption occurs as the pore spaces fill with water molecules. The study attributes the higher strength of compression of the specimens to the use of a relatively low liquid-solid ratio with a 10M alkali solution. It suggests that future research should explore the effects of different alkaline solutions with varying molarities, as well as investigate the use of different pozzolanic materials like rice husk, corn waste, and bagasse. Additionally, the study recommends more research using techniques like Thermos Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) to have a deeper understanding of the micro-properties of geopolymer paste. Ankit Negi[40] examined GPC using activators such as sodium silicate and sodium hydroxide, as well as fly ash and alccofine. Sodium hydroxide and sodium silicate were used as alkali activating agents to cure the GPC under ambient conditions. The study aimed to assess the mechanical and microstructural properties of GPC using dredging sea sand and manufactured sand as substitutes for river sand. The compression, split tensile, flexural strength, and microstructural characteristics of many DMS and M-Sand combinations were examined. According to the findings, DMS can successfully substitute river sand in geopolymer concrete, particularly when ambient curing conditions are used.

M. Wang, J. Xu, X. Zhang, L. Tan, and Y. Mei[41] examines alkali-activated steel slag–slag cementitious materials in detail, emphasizing how various compositional elements affect mechanical performance. Through the use of a Box–Behnken design, the team analyzed how variables such as steel slag content, alkali concentration, water glass modulus, and water-to-binder ratio contribute to the material's compressive strength. Their findings show that steel slag not only enhances the structural integrity of the cementitious matrix but also interacts effectively with alkali-activated components. X-Ray Diffraction (XRD) analysis further demonstrated that $CaCO_3$ crystals within the slag are crucial in forming a dense microstructure, providing durability along with improved strength. This study underscores the importance of optimizing these mix proportions to develop a resilient material that could serve as a sustainable substitute in construction applications. In addition, the study's microstructural analysis using SEM-EDS revealed that the primary gel phase consists of hydrated calcium silicate and geopolymer gel, which together improve binding capacity and durability. The calcium silicate gel plays a key role in increasing the strength of compression by promoting a denser microstructure.This research is illustrated in Figure above. O. Adeleke, and Matthew Power[42] investigated the incorporation of Waste Plastic aggregate (WP) in geopolymer concrete. They replaced 10 mm of natural coarse aggregates with WP at 30% and 70% for OPC and GPC. The study found that while the addition of WP reduced slump values, GPC showed superior strength development compared to ordinary concrete, with improvements ranging from 46.7% to 58.3%. SEM analysis revealed that WP reduced pore presence in both concrete types, but this reduction was more detrimental to OPC due to weak interfacial bonds. The study concludes that incorporating WP in GPC up to 70% replacement is viable, although further research is needed

to enhance its consistency and strength for structural applications.

8.0 Cost Parameters of Geopolymer Concrete

McLellan, Williams, Lay, van Riessen, and Corder[43] compared the lifecycle costs of geopolymer pastes to Ordinary Portland Cement (OPC), focusing on the financial aspects. The study also emphasized the variability in the sustainability potential of geopolymers compared to OPC, noting that factors such as the source location of materials and transport impacts play a crucial role in determining sustainability performance. It highlighted the need for further study to enhance the understanding of geopolymer performance in different applications and to develop additional sustainability metrics. Additionally, the study pointed out the significance of incorporating lifetime and recyclability considerations in future assessments to give a more comprehensive evaluation of sustainability performance. The findings suggested that while there is significant potential for geopolymers to be cost-effective and environmentally beneficial, careful attention to feedstock selection, transport optimization, and technological advancements is essential for realizing these benefits. With a noteworthy 44% to 64% decrease in greenhouse gas emissions when compared to OPC,

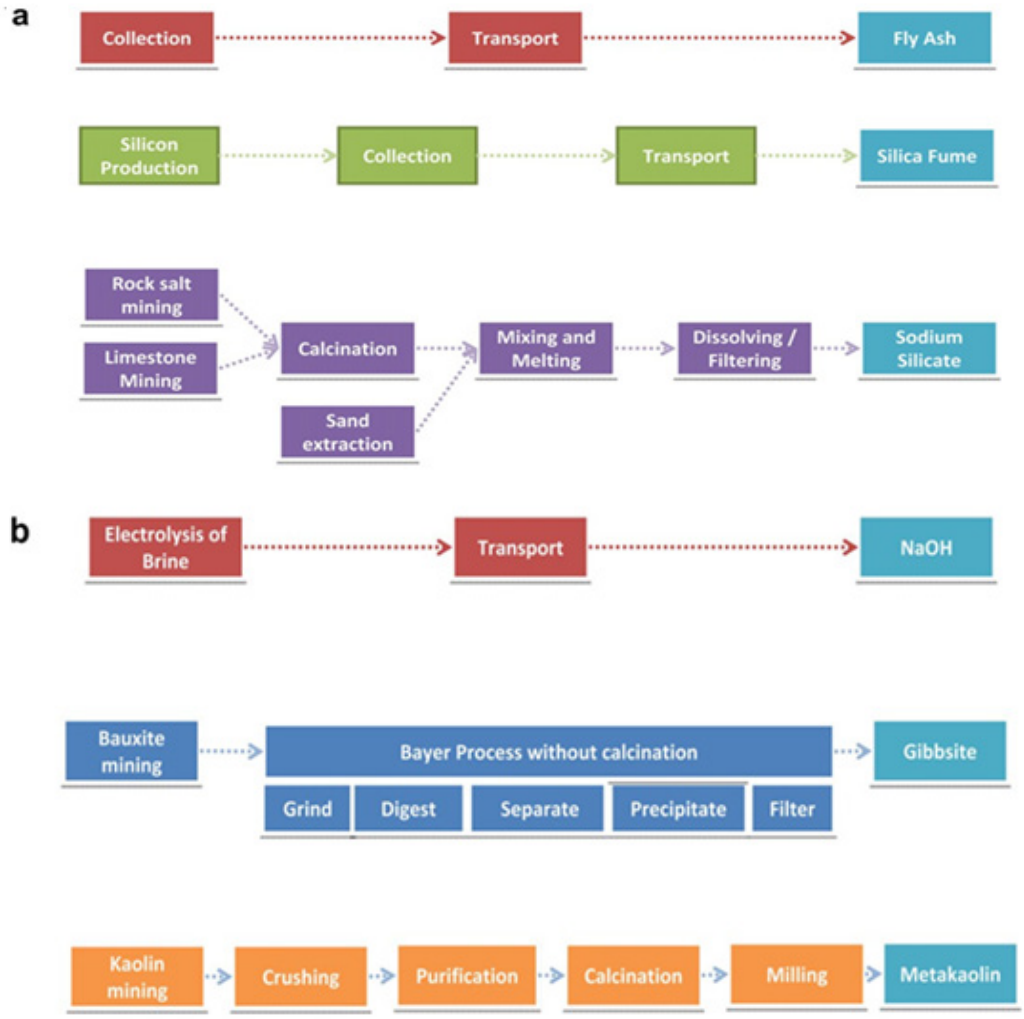


Figure 6. Life cycle steps considered while producing geopolymer feedstock[43].

the study concludes that geopolymers have a significant potential to lessen the environmental impact of cement production. But it also draws attention to how difficult sustainability evaluations may be because of things like feedstock sources and logistics of transportation. Figure[6] illustrates the life cycle steps considered while producing geopolymer feedstock.

S. Kumar's[44] examined the strength of compression of GPC and regular OPC Concrete. OPC is more expensive and less environmentally beneficial than geopolymer concrete, which is produced with raw hypo sludge and recycled coarse aggregate. The study found that GPC is economically viable and suitable for future construction projects, offering a potential solution to reduce environmental pollution. Rajini, N. Rao, and Sashidhar[45] examined the price differences between GPC (GPC) and Conventional Concrete (CC). For the same strength grade, they initially found that GPC's material cost was 32% more than CC's. But when natural resource savings, sustainability, and environmental advantages are taken into account, GPC's overall cost-effectiveness becomes clear. While further research is necessary to optimize costs, GPC is suggested as a novel building material for future applications. Research by Oyebisi, Ede, Olutoge, Ofuyatan, and Alayande[46] compared the economy index and production cost of GPC and PCC. GGBFS and corncob ash (CCA) were utilized as raw materials to produce GPC. For the same quality of concrete, the study indicated that GPC has a higher economy index and is 27.71% less expensive to make than PCC. This suggests that GPC is a more cost-effective and viable solution than PCC, addressing environmental and structural concerns while also combating the high cost of Portland cement. The study recommends adhering to standard specifications and procedures when evaluating GPC production costs and suggests determining the economy index for higher grades of concrete. Thaarrini and Dhivya[47] conducted a study comparing the production cost of GPC and OPC concrete. They calculated the cost of producing $1m^3$ of GPC and OPC based on market rates of ingredients, finding that GPC is cost-effective compared to OPC. For the M30 grade, the production cost of GPC is marginally higher (1.7%) than OPC, while for the M50 grade, OPC is 11% more expensive than GPC. This indicates that savings in cost can be achieved with GPC production, making it a feasible substitute to OPC.

9.0 Review of Various Parameters

The literature review on GPC presents a comprehensive overview of current research and developments in the field, focusing on various aspects such as byproduct utilisation, machine learning applications, microstructural properties and cost parameters.

1. The potential of GPC as a long-term substitute to conventional concrete materials is highlighted by the use of byproducts such as FA, GGBS, metakaolin, RHA and SF, which helps to reduce waste and conserve the environment.
2. The successful application of methods for machine learning, including ANNs and GEP, demonstrates their effectiveness in predicting GPC properties and offers efficient methods for future research and development.
3. Analysis of GPC microstructures shows higher mechanical properties and durability, especially when nano-clay and nano-TiO_2 are added. This suggests the possibility of improved performance in building applications. Further research into optimising the features of GPC for sustainable construction practices is supported by the incorporation of SEM and XRD studies, which offer comprehensive insights into the microstructural behaviour and characteristics of the material.
4. Despite initial higher costs, the long-term cost savings and environmental benefits of GPC compared to OPC concrete emphasise its financial viability and sustainability, supporting its adoption in construction practices.
5. The review identifies key areas for future research, including optimising mix designs, exploring additional waste materials, and investigating the impact of different additives on geopolymer properties, to further advance sustainable construction practices.
6. Studies on geopolymer mortars incorporating various additives demonstrate their potential to enhance mechanical strength, flexural behaviour

and durability, indicating their suitability for structural applications and repairs.

7. When compared to conventional concrete, GPC delivers a notable decrease in greenhouse gas emissions and environmental effects, underscoring its significance in encouraging environmentally friendly building methods.
8. In conclusion, the literature analysis offers insightful details regarding the current status of GPC research, highlighting the material's potential as an inventive and sustainable building material. Innovations that contribute to a more sustainable built environment may result from increased study and development in this area.

10.0 Future Scope

Future studies can explore diverse supplementary cementitious materials in geopolymer concrete for optimized mix designs with improved strength and durability. There is potential to create precise ANN models using mixed synthetic data to accurately predict GPC properties, enhancing reliability. Advanced microstructural analysis techniques like XRD and SEM can provide deeper insights into GPC, aiding in developing more durable materials. Decision-making in the building sector may benefit from comparative studies comparing the cost characteristics of GPC with traditional concrete. Long-term performance studies of GPC in real-world applications could assess durability and sustainability under different conditions. Developing guidelines and standards for GPC use could ensure consistent performance in various applications. Investigating the use of waste materials in GPC may improve its sustainability and lessen its negative effects on the environment. Future research could also look into the possibility of using GPC in high-rise buildings and bridges, among other essential infrastructure applications, to evaluate how well it performs under harsh circumstances.

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