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Utilization of Clay as Source Material in Geopolymer and Alkali Activated Concretes: A State of Art Review

Shaik Sandani Basha[1,*], J D Chaitanya Kumar[2], M. Achyutha Kumar Reddy[3], Pawar Praveen[4]

Abstract

This innovative research looks at the use of clay as source material for geopolymer and alkali-activated concrete, with a focus on how they could promote green construction practices and perhaps replace Portland cement. Alkali-activated concretes and geopolymers offer low-carbon, eco-friendly alternatives by utilizing natural minerals and industrial wastes. Particularly clay is a plentiful and adaptable option for these cutting-edge products. This review looks at different kinds of clay, like bentonite, kaolinite, and montmorillonite, and evaluates which ones work best for alkali-activated systems and geopolymer systems. It explores the activation processes, emphasizing how clay minerals are changed into strong binding phases by alkaline activators such as sodium hydroxide and sodium silicate. Analyzed is the effect of variables such as alkali-activated concretes, mix designs, and curing circumstances on the functionality of clay-based geopolymers and concretes. According to recent research, these clay-based concretes outperform conventional concrete in terms of mechanical strength, chemical resistance, and permeability. The paper highlights their adaptability by talking about possible uses in waste management, soil stabilization, and infrastructure. The analysis also lists present difficulties and suggests future lines of inquiry for maximizing the application of clay in these cutting-edge cementitious systems. This study intends to promote sustainable construction practices by offering insights into material properties, processing methods, and performance characteristics related to the efficient use of clay in geopolymer and alkali-activated concretes.

Keywords: Clay, geopolymer concrete, sustainable concrete, fresh properties, hardness

INTRODUCTION

In geopolymer and alkali-activated concrete, the use of clay as a source material has drawn a lot of interest lately. According to research, geopolymer concretes made from clay-based minerals like kaolin and metakaolin can provide concrete with better mechanical qualities and lower carbon emissions than concretes made with regular Portland cement. Clay also produces less carbon dioxide during manufacture, making it an environmentally favorable raw material for the synthesis of geopolymers [1]. [2]. The kind and temperature of thermal treatment can also affect the reactivity of metakaolin in the synthesis of geopolymers. Another interesting method is to activate clay by utilizing alkali solutions as a binder in geopolymer concretes.

Additionally, the study offers many viable directions for additional research in this area. These include creating concrete or mortars with the proposed geopolymer binders, creating new alkali-activation recipes for geopolymers, and investigating combining the two approaches [3]. [4].

***Author for Correspondence**
Shaik Sandani Basha

[1]Research Scholar, Department of Civil Engineering, Koneru Lakshmaiah Education Foundation Deemed to be University, Vaddeswaram, Guntur, Andhra Pradesh, India
[2,3]Assistant Professor, Department of Civil Engineering, Koneru Lakshmaiah Education Foundation Deemed to be University, Vaddeswaram, Guntur, Andhra Pradesh, India
[4]Research Scholar, Department of Civil Engineering, Koneru Lakshmaiah Education Foundation Deemed to be University, Vaddeswaram, Guntur, Andhra Pradesh, India

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Additionally, it provides a viable and eco-friendly substitute for conventional cement-based concretes, potentially leading to a major decrease in carbon emissions. Furthermore, it may be possible to enhance mechanical qualities and lessen the carbon footprint of concrete production by using clay in place of conventional cement binders in geopolymer and alkali-activated concretes [3].

Geopolymers and alkali-activated concretes represent innovative alternatives to traditional Portland cement-based concretes. These materials have gained significant attention due to their potential for reducing carbon emissions associated with cement production and providing enhanced durability. Geopolymers and alkali-activated concretes are both classified as inorganic polymer concretes, but they differ in their composition and activation mechanisms [5]–[7].

Geopolymer Concrete

The most common aluminosilicate sources include fly ash, metakaolin, and slag. The alkaline activator, typically composed of sodium or potassium hydroxide and sodium or potassium silicate, initiates a polymerization reaction, forming a three-dimensional network of polymeric chains [8][9].

Geopolymer concrete has been extensively researched for its environmental benefits, as it can utilize industrial by-products such as fly ash, reducing the demand for traditional Portland cement. This results in lower carbon dioxide emissions and energy consumption during the manufacturing process. Geopolymer concretes exhibit excellent compressive strength, acid resistance, and fire resistance, making them suitable for various applications [10]–[12].

Alkali-Activated Concrete

Alkali-activated concrete, often referred to as geopolymers, involves the activation of aluminosilicate precursors through the use of alkaline solutions. The activators can be alkali metal hydroxides, silicates, or a combination of both. Unlike geopolymer concrete, alkali-activated concretes may use a broader range of precursor materials, including blast furnace slag, fly ash, and natural pozzolans [3].

The activation process induces the formation of a calcium silicate hydrate (C-S-H) gel, similar to the hydration products in traditional Portland cement-based concretes. However, alkali-activated concretes exhibit unique microstructures and material characteristics. These concrete generally demonstrate good mechanical strength, durability, and resistance to aggressive environments [4].

Importance of Source Materials in Fresh Concrete Production

The choice of source materials in concrete production is of paramount importance as it directly influences the properties, durability, and environmental impact of the resulting concrete. Source materials, such as aggregates, cement, and supplementary cementitious materials, play a crucial role in determining the overall performance and sustainability of concrete structures. Here are key aspects highlighting the importance of source materials in concrete production:

1. *Aggregates*: Aggregates constitute a significant portion of concrete and directly impact its mechanical properties. The type, size, shape, and gradation of aggregates influence the workability, strength, and durability of concrete. Well-graded aggregates with appropriate particle shapes enhance the interlocking of particles, improving the overall strength and resistance to cracking. The use of recycled aggregates, such as crushed concrete or recycled glass, contributes to sustainable construction practices by reducing the demand for natural resources.
2. *Cement*: Cement is a crucial binder in concrete production, responsible for the cohesion and strength of the material. The choice of cement type, such as Portland cement or alternative binders like fly ash, slag, or silica fume, has significant implications for environmental sustainability. The production of Portland cement is energy-intensive and contributes significantly to carbon dioxide emissions. By incorporating supplementary cementitious materials, the environmental impact can be reduced while improving certain performance aspects like sulfate resistance and long-term durability.

3. *Supplementary cementitious materials (SCMs):* SCMs, including fly ash, slag, and silica fume, contribute to the sustainability and performance of concrete. These materials can partially replace Portland cement, offering environmental benefits by utilizing industrial by-products. SCMs improve concrete durability, reduce permeability, and enhance resistance to chemical attacks. The pozzolanic and latent hydraulic reactions of SCMs contribute to the formation of additional cementitious phases, resulting in a denser and more durable concrete matrix.
4. *Water*: Water is a critical component in the concrete mix, affecting the workability and setting time. The quality and quantity of water influence the strength and durability of concrete. Excess water can lead to reduced strength, increased permeability, and a higher risk of cracking. Controlling the water-cement ratio is essential to achieving the desired concrete properties, ensuring both workability during placement and long-term durability.
5. *Admixtures:* Admixtures are chemical additives that can be introduced to the concrete mix to modify its properties. They can enhance workability, accelerate or retard setting times, improve durability, and provide resistance to specific environmental conditions. Admixtures, such as superplasticizers, air-entraining agents, and corrosion inhibitors, allow for more precise control over the concrete mix, enabling the optimization of performance characteristics.
6. *Environmental considerations:* The environmental impact of concrete production is a growing concern. Selecting sustainable source materials and incorporating recycled content can significantly reduce the carbon footprint of concrete. Additionally, using locally sourced materials reduces transportation-related emissions. This emphasis on environmentally friendly practices aligns with global efforts to promote sustainable construction and minimize the ecological impact of infrastructure development.

The importance of source materials in concrete production cannot be overstated. The selection of aggregates, cement, supplementary cementitious materials, water, and admixtures influences the concrete's mechanical properties, durability, and sustainability. As the construction industry continues to prioritize environmental considerations, the responsible choice of source materials becomes instrumental in achieving durable, high-performance concrete structures with minimal environmental impact.

Impact of Source material on Harden Characteristics of Concrete Production

The choice of source materials in concrete production plays a critical role in determining the properties, sustainability, and performance of the resulting concrete structures. Source materials, also known as aggregates and supplementary cementitious materials (SCMs), significantly influence the mechanical, durability, and environmental characteristics of concrete. This discussion will explore the importance of source materials in concrete production, considering various aspects such as strength, durability, environmental impact, and sustainability.

Mechanical Properties

The mechanical strength of concrete is a crucial factor in its structural performance. Aggregates, which constitute the bulk of concrete, directly impact the compressive and tensile strength of the material. The size, shape, and gradation of aggregates influence the packing density and interlocking of particles within the concrete matrix, affecting the overall strength and durability of the concrete [5].

Durability and Performance

Durability is a key aspect of concrete performance, especially in harsh environmental conditions. The selection of appropriate aggregates and SCMs can enhance concrete durability by mitigating issues such as alkali-aggregate reaction, sulfate attack, and corrosion of reinforcing steel. High-quality aggregates and pozzolanic materials contribute to the formation of durable cementitious phases, improving resistance to chemical attacks and increasing the lifespan of concrete structures [6].

Environmental Impact

The environmental impact of concrete production is a growing concern in the construction industry. Traditional Portland cement production is associated with high carbon dioxide emissions. Using alternative source materials, such as fly ash, slag, or recycled aggregates, can reduce the carbon footprint of concrete. These materials often serve as supplementary cementitious materials, contributing to the formation of more sustainable and eco-friendly concrete mixes [7].

Sustainability

The sustainable use of source materials in concrete production involves minimizing the depletion of natural resources and reducing energy consumption. Recycling concrete waste as aggregates and incorporating industrial by-products like fly ash and slag promote sustainability by reusing materials that would otherwise end up in landfills. This sustainable approach aligns with global efforts to adopt more environmentally friendly construction practices [8].

Economic Considerations

The economic viability of concrete production is closely linked to the availability and cost of source materials. Utilizing locally available aggregates and SCMs can reduce transportation costs and support regional economies. Moreover, the use of certain supplementary materials may lead to cost savings and increased economic efficiency in concrete production [9].

The importance of source materials in concrete production cannot be overstated. The careful selection of aggregates and supplementary cementitious materials not only influences concrete's mechanical and durability properties but also contributes to environmental sustainability and economic considerations. As the construction industry continues to prioritize sustainability and resilience, the role of source materials in shaping the future of concrete technology becomes increasingly significant.

CLAY AS SOURCE MATERIAL

Clay is a versatile source material in concrete production, contributing to both mechanical strength and environmental sustainability. Its incorporation as a supplementary cementitious material (SCM) or as a partial replacement for traditional aggregates offers several benefits.

Clay minerals, such as metakaolin, are commonly used as pozzolanic materials in concrete. Metakaolin, obtained by calcining kaolin clay at high temperatures, reacts with calcium hydroxide in the presence of water to form additional cementitious compounds. This enhances the strength and durability of concrete while reducing its permeability.

Research by Duxson et al. (2007) highlights the positive impact of metakaolin on the mechanical properties of concrete, demonstrating improved compressive strength and durability. Metakaolin's pozzolanic reactivity contributes to the formation of additional calcium silicate hydrate (C-S-H) gel, reinforcing the concrete matrix [11].

In addition to enhancing performance, the use of clay in concrete production aligns with sustainability goals by utilizing abundant natural resources and reducing the carbon footprint associated with traditional cement production. The incorporation of clay-based materials showcases the industry's commitment to environmentally conscious practices.

Geopolymerization and Alkali Activation Potential

Geopolymerization and alkali activation represent innovative processes in concrete technology that offer significant potential in terms of sustainability, reduced carbon emissions, and enhanced material performance. Both methods involve the use of aluminosilicate source materials and alkaline activators, leading to the formation of alternative cementitious binders.

Geopolymerization: Geopolymerization is a chemical process where aluminosilicate materials, such as fly ash or metakaolin, react with an alkaline solution to form a three-dimensional polymeric network. The resulting geopolymer exhibits properties similar to traditional Portland cement-based concrete but with reduced environmental impact. Geopolymers have demonstrated high compressive strength, durability, and resistance to various chemical attacks, making them suitable for construction applications [12].

Alkali activation: Alkali activation involves the activation of aluminosilicate materials, such as fly ash or slag, with alkaline solutions. This process induces the formation of cementitious gels, including sodium aluminosilicate hydrate (N-A-S-H) and calcium silicate hydrate (C-S-H), leading to the development of hardened materials with desirable engineering properties. Alkali-activated materials exhibit excellent strength and durability, showcasing their potential as alternatives to traditional Portland cement [12].

Properties that Make Clay Suitable for Concrete

Clay, when used as a supplementary cementitious material (SCM) in concrete, possesses several properties that enhance the performance and characteristics of the resulting concrete mix. These properties contribute to both the fresh and hardened states of the concrete, making clay a valuable additive in the construction industry.

1. *Pozzolanic reactivity*: Clay minerals, especially those subjected to high-temperature processes like metakaolin, exhibit strong pozzolanic reactivity. This reactivity promotes the formation of additional calcium silicate hydrate (C-S-H) gel, enhancing the strength and durability of concrete.
2. *Particle fineness*: The fine particle size of clay allows for better packing within the concrete matrix. This improves the overall density and reduces the porosity of the concrete, leading to increased strength and durability.
3. *Chemical stability*: Clay minerals exhibit chemical stability, contributing to the long-term durability of concrete. The stable nature of clay-based pozzolans ensures that the concrete remains structurally sound over an extended period, even in aggressive environmental conditions.
4. *Water demand reduction*: The use of clay in concrete can lead to a reduction in water demand without compromising workability. This property is beneficial for achieving high-strength concrete with lower water-to-cement ratios, contributing to enhanced durability.

Research by Duxson et al. (2007) emphasizes the effectiveness of metakaolin, a calcined form of kaolin clay, in improving the mechanical properties of concrete. The study highlights the role of metakaolin in enhancing compressive strength and durability, underlining the importance of clay-based materials in sustainable and high-performance concrete production [13].

GEOPOLYMER CONCRETE

Geopolymer concrete is an innovative and sustainable alternative to traditional Portland cement-based concrete. It is formed by activating aluminosilicate source materials, such as fly ash or slag, with alkaline solutions. The activation process leads to the formation of a three-dimensional polymerized network, offering impressive mechanical strength, durability, and environmental benefits. Research by Duxson et al. (2007) discusses the advancements in geopolymer technology, emphasizing its potential in reducing carbon emissions and contributing to a more sustainable future in the construction industry.

Geopolymerization is a chemical process used in the production of geopolymers, which are inorganic polymers that can serve as a cementitious binder in concrete. The process involves the reaction of aluminosilicate materials with an alkaline activator, resulting in the formation of a three-dimensional polymeric network. Several key chemical reactions characterize the geopolymerization process:

CHEMICAL REACTIONS IN GEOPOLYMERIZATION

1. *Activation of aluminosilicate precursors*: The process typically begins with the dissolution of aluminosilicate precursors, such as fly ash, metakaolin, or slag, in the alkaline activator solution. Common activators include sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).

2. *Polymerization*: Aluminosilicate monomers present in the precursor materials undergo polymerization reactions in the presence of the alkaline solution. The alkaline activator initiates the formation of polymeric chains, mainly composed of Al-O and Si-O bonds, creating a three-dimensional network.
3. *Formation of polymeric gel (geopolymer):* The polymerization reactions lead to the development of a polymeric gel, often referred to as the geopolymer. This gel is the binding phase in geopolymers and is analogous to the hydrated calcium silicate gel (C-S-H) in traditional Portland cement-based concretes.
4. *Dehydroxylation and polymer cross-linking*: During the geopolymerization process, dehydroxylation reactions occur, involving the removal of hydroxyl groups (OH-) from the aluminosilicate precursors. This dehydroxylation contributes to the formation of stronger bonds and increased cross-linking within the polymeric structure.
5. *Structural reorganization*: The polymeric structure undergoes further structural reorganization as the geopolymerization reactions progress. This reorganization is critical for achieving the desired mechanical properties and durability of geopolymers.

Research by Davidovits (1994) and subsequent studies on geopolymer technology provide insights into the chemical reactions and mechanisms involved in geopolymerization. Understanding these reactions is crucial for optimizing mix designs, controlling curing conditions, and tailoring the properties of geopolymers for specific applications in construction [14].

CHALLENGES AND SOLUTIONS IN UTILIZING CLAY AS A SOURCE MATERIAL

Utilizing clay as a source material in construction, particularly in geopolymer concrete, presents both opportunities and challenges. While clay offers excellent pozzolanic reactivity and can contribute to the sustainability of construction materials, several challenges need to be addressed. This discussion will explore some key challenges and potential solutions in utilizing clay as a source material in construction.

Challenges

1. *Variability in clay composition*: The composition of clay can vary significantly based on its geological origin. Variability in clay mineralogy, impurities, and particle size distribution can impact the reactivity and performance of geopolymer mixes.
2. *High water demand:* Some clay materials exhibit a high water demand during the mixing process. Excessive water requirements can compromise the workability of the geopolymer mix, affecting its consistency and placing constraints on construction practices.
3. *Drying shrinkage*: Certain clay minerals may contribute to drying shrinkage in concrete, leading to potential cracking issues. This challenge is particularly relevant in applications where minimal shrinkage is crucial for structural integrity.
4. *Potential alkali-silica reaction (ASR):* Some types of clay may contain reactive silica that could contribute to alkali-silica reaction, a deleterious chemical reaction in concrete that can lead to expansive gel formation and cracking over time.

Solutions

1. *Characterization and quality control*: Rigorous characterization of clay sources through mineralogical analysis, chemical testing, and particle size distribution assessments can help understand the variability and establish quality control measures. This ensures consistent performance and mitigates issues related to variable clay compositions.
2. *Optimization of mix design*: Adjusting the mix design parameters, such as the water-to-binder ratio and the type and concentration of activators, can help address high water demand challenges. Optimization ensures a balance between workability and performance in clay-based geopolymer mixes.

3. *Incorporation of supplementary materials*: Combining clay with other supplementary cementitious materials, such as fly ash or slag, can help mitigate drying shrinkage concerns. The synergistic effects of different materials can lead to more balanced and durable concrete mixes.
4. *ASR mitigation strategies*: Screening clay sources for potential reactivity and employing mitigating measures, such as using lithium-based additives or pozzolanic materials with proven reactivity, can help minimize the risk of alkali-silica reaction in clay-based geopolymer concrete.

Research by Provis et al. (2015) on the role of fly ash composition in the geopolymerization process and studies by Fernández-Jiménez et al. (2006) on microstructure development provide insights into the challenges and potential solutions in utilizing clay-based materials in geopolymer concrete.

ENVIRONMENTAL AND ECONOMIC ASPECTS

The utilization of clay as a source material in construction, particularly in geopolymer concrete, has significant implications for both environmental sustainability and economic considerations.

Environmental Aspects: Clay-based geopolymers offer a more sustainable alternative to traditional Portland cement-based concrete, as they often incorporate industrial by-products like fly ash or metakaolin. By reducing reliance on traditional cement production, which is a major source of carbon dioxide emissions, clay-based geopolymers contribute to lower greenhouse gas emissions. Research by Scrivener et al. (2018) emphasizes the potential of eco-efficient cements, including geopolymers, to address environmental concerns and promote sustainable construction practices.

Economic aspects: The economic aspects of utilizing clay-based geopolymers involve considerations such as the availability and cost of raw materials, production processes, and long-term durability. While initial costs may vary, the potential for local sourcing of clay and the use of industrial by-products can contribute to economic efficiency. Kosmatka et al. (2002) highlight the importance of understanding the economic aspects of concrete mix designs, including geopolymers, to ensure cost-effective and sustainable construction practices.

SUSTAINABILITY BENEFITS OF CLAY-BASED CONCRETE

The sustainability benefits of clay-based concrete, particularly in the context of geopolymer technology, are substantial and contribute to more environmentally friendly construction practices. Key aspects include reduced carbon emissions, efficient use of resources, and the potential for recycling industrial by-products.

1. *Lower carbon footprint*: Clay-based geopolymers significantly reduce the carbon footprint associated with traditional Portland cement production. The geopolymerization process utilizes industrial by-products like fly ash or metakaolin, which minimizes the need for energy-intensive clinker production. This results in a substantial reduction in greenhouse gas emissions. Studies, such as those by Davidovits (2013), emphasize the potential of geopolymer cements to mitigate carbon dioxide greenhouse warming.
2. *Efficient use of resources*: Clay-based geopolymers make use of clay minerals, which are abundant natural resources. By incorporating clay, particularly metakaolin obtained through the calcination of kaolin clay, construction materials can be produced without depleting finite resources. This aligns with sustainable development goals by promoting responsible resource utilization.
3. *Recycling industrial by-products*: The incorporation of industrial by-products, such as fly ash, into clay-based geopolymers represents a form of recycling. By repurposing these by-products, the construction industry can contribute to waste reduction and minimize the environmental impact associated with the disposal of such materials.
4. *Enhanced durability and longevity*: Clay-based geopolymers exhibit excellent durability, resisting chemical attacks and providing long-lasting structures. The enhanced durability contributes to longer service life, reducing the need for frequent repairs or replacements. This longevity aligns with sustainability principles by promoting structures that endure over time.

5. *Local Sourcing and regional economic impact*: Clay-based materials are often available locally, minimizing the environmental impact associated with transportation. Utilizing locally sourced clay contributes to a reduction in energy consumption and supports regional economies. This aspect aligns with sustainable construction practices that prioritize local materials to minimize the ecological footprint.

Compressive Strength

The compressive strength of clay soils stabilized with fly-ash geopolymer is significantly improved by increasing the geopolymer content and curing time. The addition of geopolymer considerably elevated the initial stiffness and yield stress of clay soils. The stress-strain behavior changed from a ductile reaction to a post-peak brittle manner as the geopolymer concentration rose [13]. The development of unconfined compressive strength (UCS) in soft clay stabilized with a one-part geopolymer under one-dimensional compressive loading [14].

Compressive strength is a measure of the resistance of a material to withstand axial loading without failure. In this graph, the first set shows the authors investigated the compressive strength of geopolymer mortar (GPM) made from fly ash and clay as source materials. Additionally, they looked at how adding lime, ground granulated blast furnace slag (GGBS), or a combination of the two would improve the clay's compressive strength (GPM). They found that the compressive strength of GPM increased with the incorporation of lime, GGBS, and lime-GGBS in clay, and the optimum combination was 2.5% lime and 37.5% GGBS for both types of clay GPM's compressive strength varied from 10 to 32.38 MPa based on the kind, amount, and techniques used to increase it The authors attributed the improvement in compressive strength to the formation of aluminosilicate and calcium silicate hydrate gels, which filled up the pores and voids in the matrix [4].

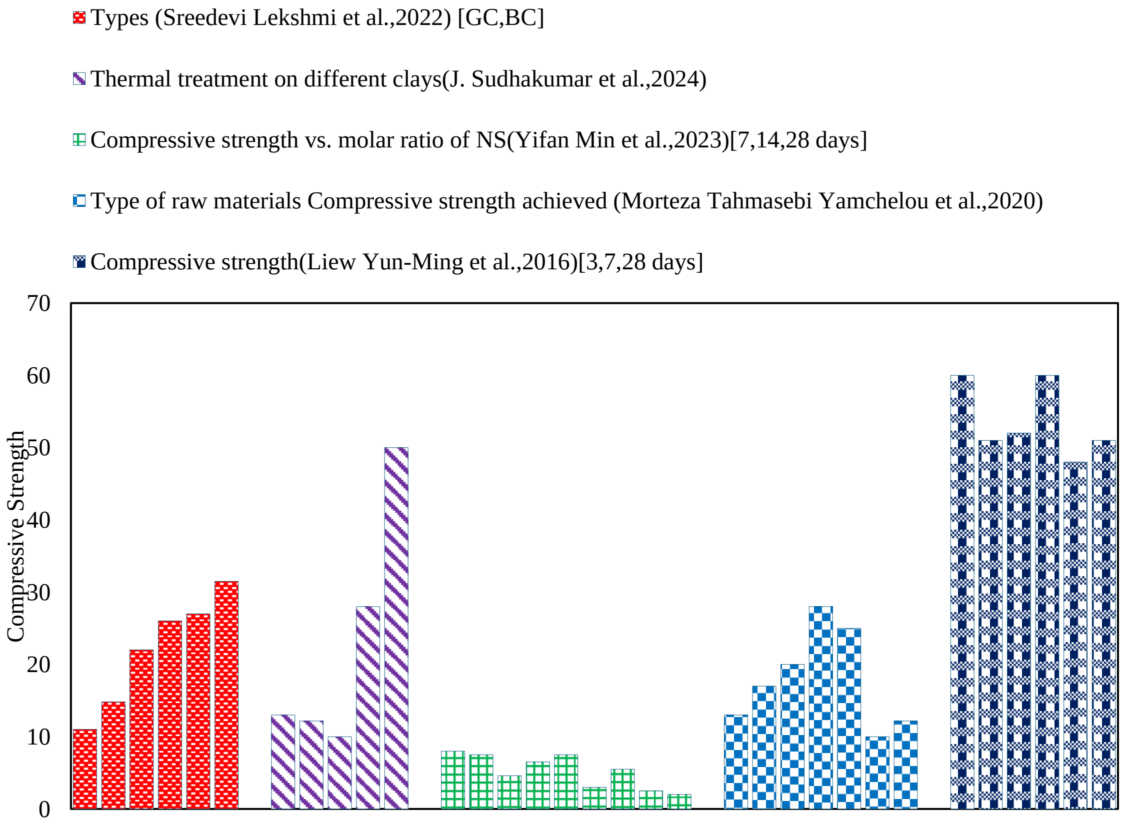

Figure 1. Compressive strength for different mix proportions.

The second set of this graph shows that Calcining the clay at high temperatures (400–950 °C) can enhance its pozzolanic activity and solubility in an alkaline solution, leading to higher geopolymer compressive strength. On the other hand, sintering and a loss of reactivity can also result from over-calcination. The nature, amount, and proportion of the alkaline activator (sodium hydroxide and sodium silicate, for instance) might influence how easily the aluminosilicate species dissolve and polymerize inside the clay. Increases in the molarity of the geopolymer and the ratio of sodium silicate to sodium hydroxide can generally improve its compressive strength, albeit there is a perfect number for every situation. The length and temperature of the curing process can affect the rate and degree of the geopolymerization reaction, which determines the microstructure and strength of the geopolymer. A moderate to high-temperature range of 60 to 90 °C and longer curing times might improve the compressive strength of the geopolymer; however, too much heat can also cause shrinkage and breakage [3]. The third set of bars in Figure 1 displays the values for compressive strength The study investigates a one-part geopolymer (OPG) activated by solid sodium silicate for soft clay stabilization. The OPG binder achieves high early strength with an FA/GGBFS ratio of 0.2, a water/precursor ratio of 1.5, and a 5 mol/L molar concentration. OPG-stabilized soft clay with 0.20 binder content balances economic benefits and meets required unconfined compressive strength (UCS) criteria. SEM-EDS reveals hydrate composition and mineral/phase changes in OPG-stabilized soft clay samples. A nonlinear relationship between UCS and porosity is established for practical engineering use [15].

The fourth set of this graph shows that Clay D was selected for the geopolymer synthesis since it had the highest amorphous percentage and finest particle size. The clay was made more reactive by calcining it at 550°C for an hour, which raised its compressive strength. Compaction Strength Outcomes: After calcination, the strength of untreated clay-based geopolymers improved to about 50 MPa, from 32 MPa at 7 days. The geopolymers' microstructure and reaction kinetics were examined using methods such as EDS, XRD, and CT scans. As a sustainable substitute for traditional cement that may lower CO2 emissions, the research promotes the use of low-grade clays [1]. The compressive strength of clay-based geopolymers is discussed in the study along with factors that affect it, including alkali concentration and curing conditions. It states that the mechanical qualities of geopolymers made from heat-treated or calcined raw materials, such as metakaolin, are superior1. Between 600 and 900 °C2 is the ideal calcination temperature for kaolinite to attain maximal reactivity. The addition of some minerals, such as slag, can promote the growth of strength, but adding too much of it can have the opposite effect. Finally, it says that sodium silicate geopolymers set more quickly than potassium silicate geopolymers [16].

Initial Setting Time

The first bars in Figure 2(a) display the initial setting time FA0-WCB40 Combination With the greatest slag percentage and no fly ash, the fastest initial set was accomplished in 140 minutes. Increased fly ash in the binder mix caused a delay in the hardening process; the FA30-WCB14 mix took 185 minutes to set initially. Ordinary Portland Cement (OPC) mortar set faster in the end than GPM mortar, but both had comparable initial setting durations. A penetration resistance of 3.5 MPa was reached to determine the initial setup time. Setting periods were impacted by the fact that the pace of polymerization reaction was typically lower than the rate of hydration of OPC [17]. The Second bar represents the research that discusses how the molar ratio and concentration of the solid sodium silicate activator, the FA/GGBFS ratio, and the water content1 all affect the one-part geopolymer (OPG) binder's initial setting time. According to the report, the OPG binder's workability and setting time are optimized to satisfy the needs of in-situ ground improvement applications. Since particular figures are not supplied in the context presented [15].

According to the report, Portland cement takes 103 minutes to set initially. This number is essential for comprehending how long concrete mixtures take to work, which affects how soon construction projects get underway. The significance of this parameter is emphasized throughout the study when discussing ternary cementitious concrete that contains powdered limestone and calcined clay[18]. The Portland cement specified in the paper has an initial setting time of 160 minutes. These details are a part of the cement's physical characteristics employed in the study, along with its 3.12 specific gravity and 270-minute ultimate setting time. The study focuses on the life cycle assessment and strength performance of concrete that contains high-volume, low-grade pozzolan kaolin clay[19]. This work discusses geopolymer composites and how their initial setting time is affected by the ratios of silica/alumina, liquid/solid, and Na2O/Al2O3. The study observes that the amount of red mud (RM) added to the mixture affects the setting time. For example, the initial setting time can increase by up to 75% when the RM fraction is adjusted to 75%. Nevertheless, the context does not provide any initial setting times. You might need to consult the entire study or the particular section on establishing timeframes for specific figures [20].

As stated in the research, the inclusion of wastewater affects the initial setting time of the red mud-slag wastewater (RSW) based grouts. As wastewater dosage increases, the setup time first lowers and subsequently increases. In particular, the accelerating effect is more noticeable at wastewater dosages below 60 weight percent, whereas dosages above 60 weight percent tend to slow down the setting process. The study also points out that because of its increased reactivity, sintered red mud-based grout sets up faster initially than Bayer red mud-based grout. Furthermore, compared to sodium silicate-activated grout, RSW grout activated by sodium hydroxide displays a shorter setting time [21].

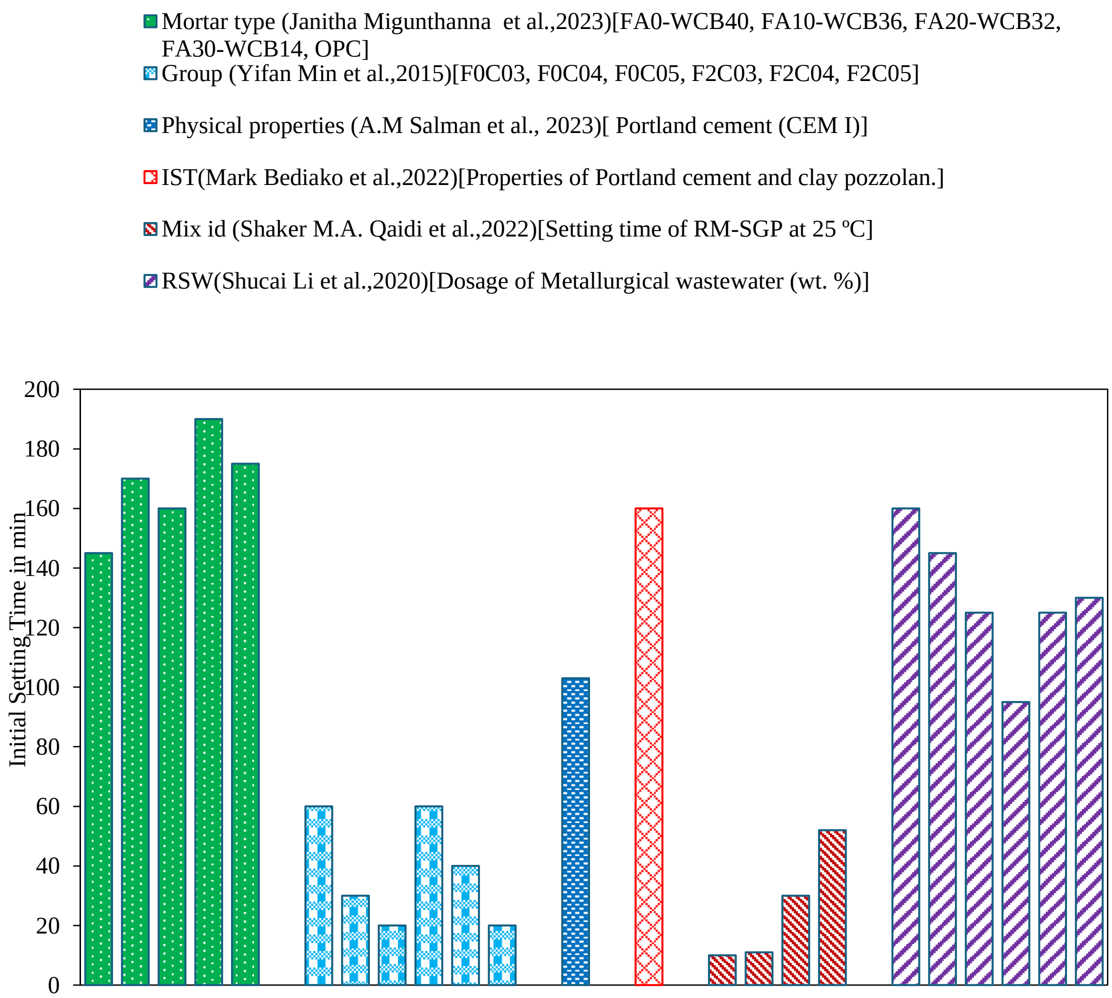

Figure 2. (a). Initial setting time for different mix proportions.

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Final Setting Time

When comparing geopolymer mortar (GPM) with waste clay brick (WCB) to ordinary Portland cement (OPC) mortar, the final setting time of the former is noticeably longer. In around 380 minutes, OPC mortar reaches a final set with a 27.5 MPa penetration resistance, whereas GPM requires 575 to 625 minutes to reach the same degree of hardness. This implies that the rate of OPC hydration is generally faster than the polymerization reaction rate in GPM. Because there was more free water in the fresh mortar, the mix with the highest fly ash content reported the slowest final setting. Though it takes longer to set, GPM is still a good substitute for OPC since it has stronger mechanical qualities and better durability [17].

The Second bar represents in Fig. 2(b) The molar ratio of sodium silicate (NS), water content, and the FA/GGBFS ratio are some of the parameters that affect the one-part geopolymer (OPG) binder's final setting time, as detailed in the paper. According to the study, an OPG binder with a low NS molar ratio—such as 0.8—has a longer final setting time and more fluidity. On the other hand, a greater NS molar ratio—such as 1.7—may cause the substance to dissolve in water more slowly, somewhat prolonging the setting time1. The setting time is also affected by the addition of fly ash (FA) particles; a higher FA/GGBFS ratio results in a longer setting time since there is less water interaction, which slows down the geopolymerization process. The study concludes that to achieve the appropriate workability and mechanical qualities of the OPG binder for soil stabilization applications, it is imperative to optimize these variables [15].

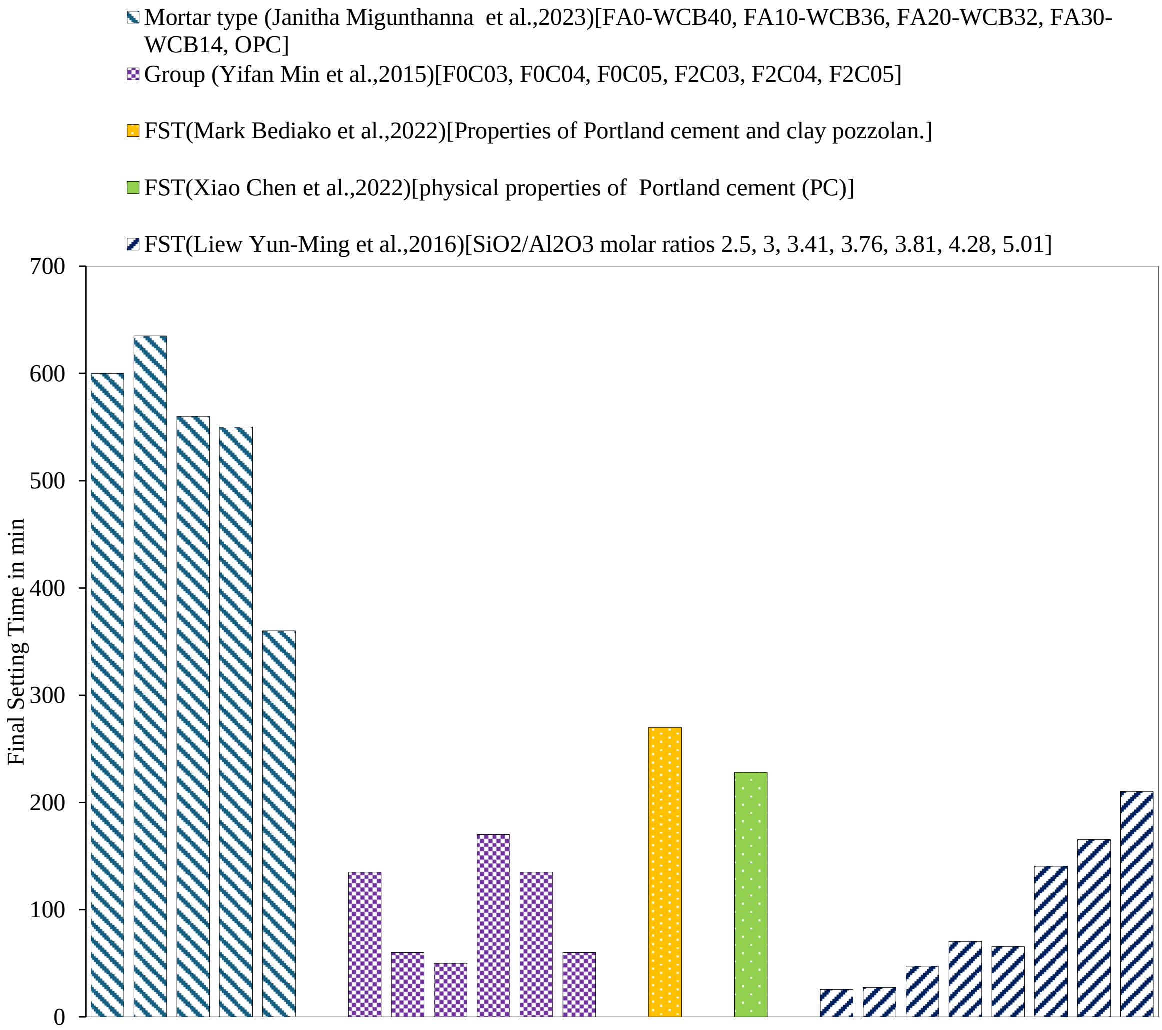

Figure 2. (b). Final setting time for different mix proportions.

The Three bar is represented in Fig. 2(b) One important factor in the building process is the cement or concrete's ultimate setting time. It describes how long it takes for the concrete mix or cement paste to become sufficiently hard and lose its flexibility to withstand a given amount of pressure. The material has not yet significantly strengthened but has enough set to maintain its shape. According to the publication, Portland cement has a final setting time of 270 minutes. This figure is a component of the cement's physical characteristics that were employed in the study, along with its 3.12 specific gravity and 160-minute initial setting time. To evaluate strength performance and environmental effect, the research examines the usage of Portland cement in conjunction with a low-grade kaolin clay pozzolan from Ghana to produce concrete [19].

The Fourth bar is represented in Fig. 2(b) According to the report, Portland cement has a final setting time of 228 minutes. Granulated blast furnace slag (GBFS), red mud (RM), and Portland cement (PC) are the materials used to make geopolymer-based pervious concrete, and this measurement is based on their physical characteristics1. The concrete mix's workability and strength development are largely dependent on the setting period [22]. The Fifth bar is represented in Fig. 2(a) This paper discusses the elements that affect the final setting time of geopolymers, including the alkali content, curing conditions, and the SiO2/Al2O3 ratio. It is stated that at 20°C, geopolymers can reach a compressive strength of 20 MPa in about 4 hours, and that after 28 days, the strength could reach 70–100 MPa. The study also mentions how stable geopolymers are up to 1000–1200°C and exhibit outstanding thermal stability with minimal shrinking (Figure 3-5). For the final geopolymer product to develop mechanical qualities and be durable, the setting time is critical [16].

Workability

Using a flow table test by ASTM C1437-20, the workability of geopolymer mortar is assessed in this paper. Impact of Fly Ash: When fly ash was added to the binder, the mortar's workability usually improved; this improvement was especially noticeable when the fly ash level was 30%. While the spherical shape of fly ash particles helps reduce inter-particle friction, improving workability, the angular shape of slag and waste clay brick (WCB) particles in the binder mix affects flowability. A flow table test was employed in the study to gauge the workability of several geopolymer mortar mixtures. The mix with the highest slag percentage and no fly ash (FA0-WCB40) had the lowest flow, which suggests that it is less workable. Impact of Fly Ash: In general, the workability of the mortar was enhanced by adding fly ash to the binder. The blend containing 30% fly ash (FA30-WCB14) exhibited notably improved flow, indicating the lubricating impact of fly ash that lowers viscosity and enhances workability. The spherical shape of fly ash particles served to improve workability, but the angular shape of slag and WCB particles increased inter-particle friction and decreased it, according to the study [23].

The second graph represents how adding lime, GGBS, or a combination of both to clay affects the workability of geopolymer mortar (GPM). According to the study, the aggregation of clay particles causes the demand for alkaline solutions to decrease with each enhancing technique. Because the high calcium concentration reduces the flowability of the fresh matrix, clay treated with a combination of lime and GGBS achieves the highest workability of 105%. In general, adding lime and GGBS to clay raises its calcium concentration, which decreases its workability as compared to raw clay-based GPM [4]. The third graph shows that the workability of expanded clay aggregates (ECA) in self-compacting lightweight geopolymer concrete (SCLGC) is covered in this paper1. This graph looks at the flow of SCLGC using a slump flow test, which gauges the concrete's flowability by measuring its spread diameter. To determine the concrete's flow rate, the T500 test is also used to gauge how long it takes for the concrete to reach a 500 mm diameter. A V-funnel test is used to assess the segregation resistance of the SCLGC by timing how long it takes for the concrete to pass through the funnel. The J-ring test measures the height differential between the inner and outer borders of the J-ring to ascertain whether the concrete can pass through reinforcement. These examinations aid in the evaluation of the novel characteristics of the SCLGC and its adaptability to a range of uses. According to the report, the incorporation of ECA enhances the qualities of the fresh state because of its lightweight nature [7].

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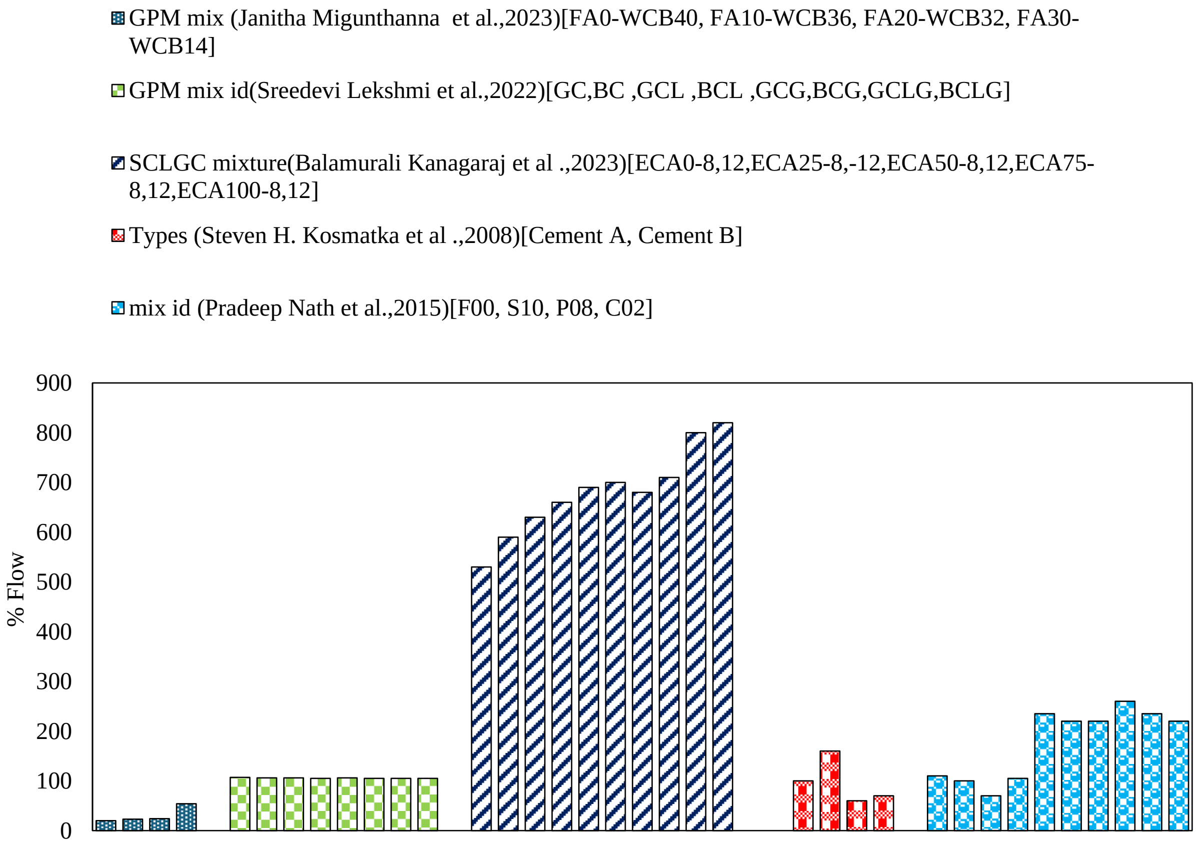

Figure 3. Final setting time for different mix proportions.

The Fourth graph represents The term "workability" which describes how simple it is to handle, install, and finish newly mixed concrete. Admixtures, cementitious materials, aggregate form and size, and water content all impact. A popular method for determining the consistency and workability of concrete is the slump test. To get a homogenous concrete mix without segregation, proper workability is essential. The concrete structure's workability can be modified to meet various construction requirements while maintaining its quality and longevity [24]. The Fifth graph shows that the study discovered that the workability of low-calcium fly ash geopolymer mortar can be affected by the addition of modest amounts of additives such as GGBFS, OPC, or CH. When GGBFS or OPC was added, the mortar flow was reduced; CH had very little effect. It was determined that the ideal binder content would yield the optimal workability. When the binder percentage was between 550 and 650 kg/m, the mortar flow values were at their maximum, indicating that the aggregate and binder should be balanced for better workability. The geopolymer combinations' setting times were likewise sped up by the additions, making them similar to OPC pastes. The mortars' workability was somewhat diminished by this quicker rate of setting. Although the study's main focus was on workability, Additionally, it was observed that the compressive strength rose as the binder content increased, suggesting a connection between the mortar's mechanical qualities and workability [25].

Durability

They have maximized compressive strength and minimal water absorption by optimizing the mix using a central composite design. Tested for sorptivity, abrasion resistance, acid and sulfate attack resistance, and water absorption. Clay-based geopolymer mortar's mechanical and durability qualities were enhanced by the addition of lime and GGBS treatments. The presence of aluminosilicate gel and C-S-H gel, which indicate a thick microstructure, was confirmed by XRD and FTIR investigations. Improved durability is provided by the lime-GGBS combination in clay-based geopolymer mortar, making it appropriate for lightweight construction applications [4]. The second set in the graph represents the resilience of geopolymer mortar using waste clay brick (WCB) in place of some of the binders, paying particular attention to the material's capacity to absorb water, create permeable spaces, and fend off sulfate assault. evaluates the water-interacting properties of geopolymers based on WCB by testing their water absorption rates and performance following extended immersion. determines how resistant WCB-based geopolymer mortar is to external sulfate assault by analyzing the compressive strength degradation and sample length expansion.draws attention to the benefits of employing WCB in geopolymers for sustainability, including how it can help with solid waste management and lower the carbon footprint of the building sector. The study concludes that WCB-based geopolymers, which offer superior performance and environmental advantages, can be a good substitute for Ordinary Portland Cement (OPC) in mortar [26].

The Tird bar in the graph represents The resilience of Expanded Clay Aggregate (ECA)-based Self-Compactable Lightweight Geopolymer Concrete (SCLGC)1. These are the salient features of durability. To assess SCLGC's durability, the paper looks at its mechanical attributes, which are essential for long-term performance and include split tensile strength and compressive strength. To evaluate the compactness and internal structure of SCLGC, which affect its endurance, a microstructural examination is carried out. The analysis of sustainability factors, such as the Environmental Impact Assessment (EIA), assesses energy consumption and CO2 emissions, which are indirectly related to material durability. According to the study, ECA can be used to produce SCLGC as long as the replacement percentage is kept below 50% to preserve durability without sacrificing strength. These considerations show that the paper delves deeply into the factors of durability of SCLGC, taking into account both its external effects and physical characteristics [7].

The Fourth bar in the graph represents the study, The aggregates used in the concrete mix are given specific gravities and water absorption rates. Sodium hydroxide and sodium silicate are two of the alkali activators used in the geopolymer concrete mix. These activators affect the hydrolyzation of fly ash and the porosity of the geopolymer structure, which in turn affects water absorption. Sulfuric acid and sodium chloride solutions were used in durability tests on the concrete specimens, which may affect the concrete's water absorption properties through modifications in porosity and permeability. According to the study, compact and denser fly ash-based geopolymer concrete has good resistance to sulfate, chloride, and acid solutions, indicating a decreased propensity for water absorption. It is anticipated that adding silica fume will enhance this even further by reducing porosity. With an emphasis on creating a denser and less porous material, these points imply that the chemical composition, mix design, and resistance to chemical attacks all have an impact on the water absorption of geopolymer concrete [27].

The Fifth bar in the graph represents Here examines the long-term characteristics and environmental advantages of lightweight expanded-clay fiber concrete (ECFC) reinforced with natural fibers, with an emphasis on its durability. These are three essential ideas regarding durability Utilising plant fibers such as sisal (SF) and coconut (CF) helps produce concrete in a sustainable manner that is consistent with the ideas of resource conservation and carbon emission reduction. Better long-term qualities, like resistance to frost and alkaline corrosion, are demonstrated by ECFC, particularly when paired with foam glass filler or altered with other additives. The use of waste materials in concrete to increase durability while being environmentally friendly is one of the integrated construction and environmental solutions that are emphasized in this article [28]. The Sixth bar in the graph represents The longevity of geopolymer products made from recycled waste-burned clay bricks (Grog) and granulated blast-furnace slag covered in this paper1. The following are the main ideas of durability: Because they are resistant to chemical attacks, geopolymers are noted for their longevity and substantial environmental benefits. Granulated blast-furnace slag is added to geopolymer composites to enhance their physico-mechanical characteristics and durability. Effect on the Environment: In addition to solving the problem of waste disposal, using industrial by-products like slag and grog in geopolymers creates strong building materials. Research Results: Studies show that adding slag to the geopolymer matrix in moderation improves overall durability; up to 60% slag content yields the best results [29].

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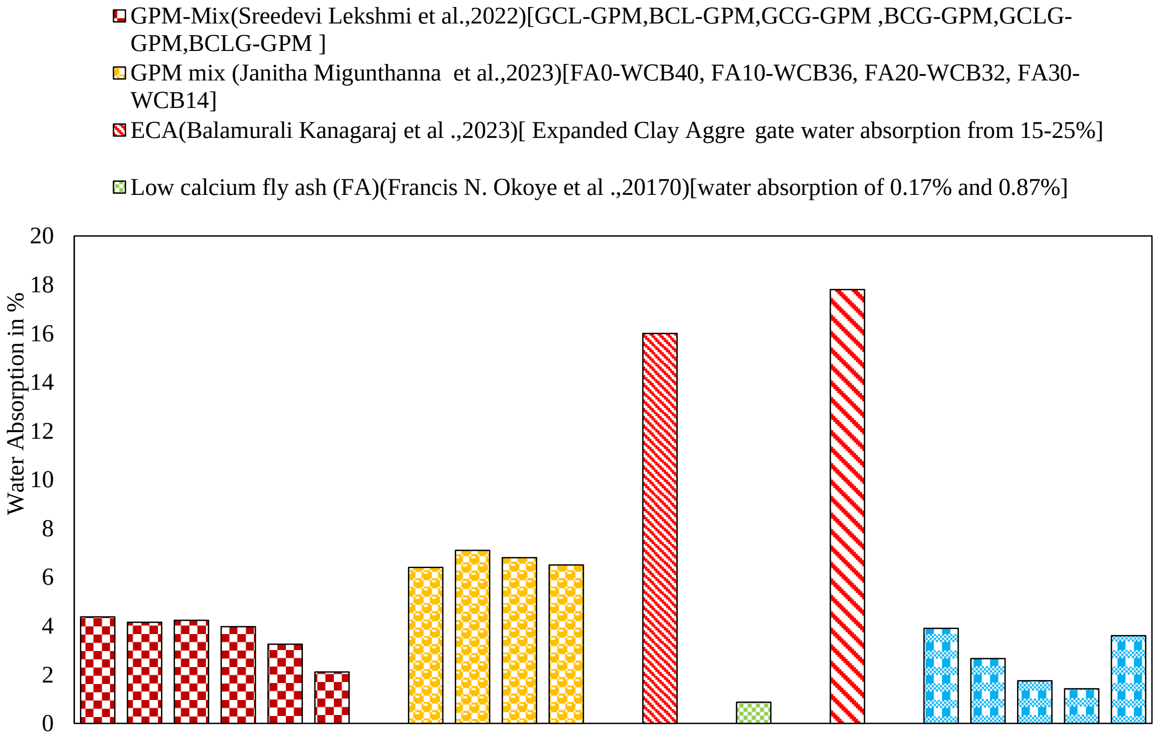

Figure 4. Durability for different mix proportions.

Flexural Strength

The flexural strength of soft clay stabilized by a single-component geopolymer under one-dimensional compressive stress is examined in this paper12. The flexural strength, which is associated with the material's stiffness and strength growth, is improved by the geopolymer binder, which consists of fly ash (FA) and ground granulated blast furnace slag (GGBFS) as raw materials made of silicon and aluminum. 90% GGBFS and 10% FA, activated by a 4.67 mol/L NaOH solution, was found to be the ideal mix ratio for the best results in terms of flexural strength3. The unconfined compressive strength (UCS) and elastic wave velocities (shear wave velocity, V_S, and compression wave velocity, V_P) of this composition significantly improved, suggesting a potent and long-lasting stabilizing impact on the soft clay [14]. To assess the laterite clay-based geopolymer's potential as an adsorbent for the removal of heavy metals from aqueous solutions, the research examines its flexural strength1[30][10].

The paper's section on flexural strength describes how a three-point bending arrangement assesses the flexural strengths of geopolymer mortar (GPM) samples at 7, 28, and 90 days. The findings demonstrated that, compared to the 28-day strength2, all four GPM formulations saw a minor drop in flexural strength at 90 days. The combination FA10-WCB36 showed the largest drop, suggesting that there may be variations in strength over time due to curing conditions and microstructural alterations. The study recommends more research to have a deeper understanding of this behavior [17]. The second set in the graph represents the According to the publication, geopolymers have remarkable thermal stability with minimal shrinking, maintaining their stability up to 1000–1200°C. It suggests that geopolymers have strong mechanical strength and durability even though it doesn't give precise flexural strength values. It goes over elements that affect qualities including bulk density, strength, stability, setting time, and thermal properties in addition to water contents, alkali concentration, mixing parameters, and curing conditions. These elements all have an indirect impact on flexural strength. The flexural strength of the finished product can be affected by the reaction mechanism, which includes the function of kaolinite/metakaolin and the effects of Si/Al and Na/Al ratios on the geopolymer matrix. It explains how to characterize geopolymers using techniques like microstructural and crystallographic analysis, which are crucial for comprehending the flexural strength of these materials [16].

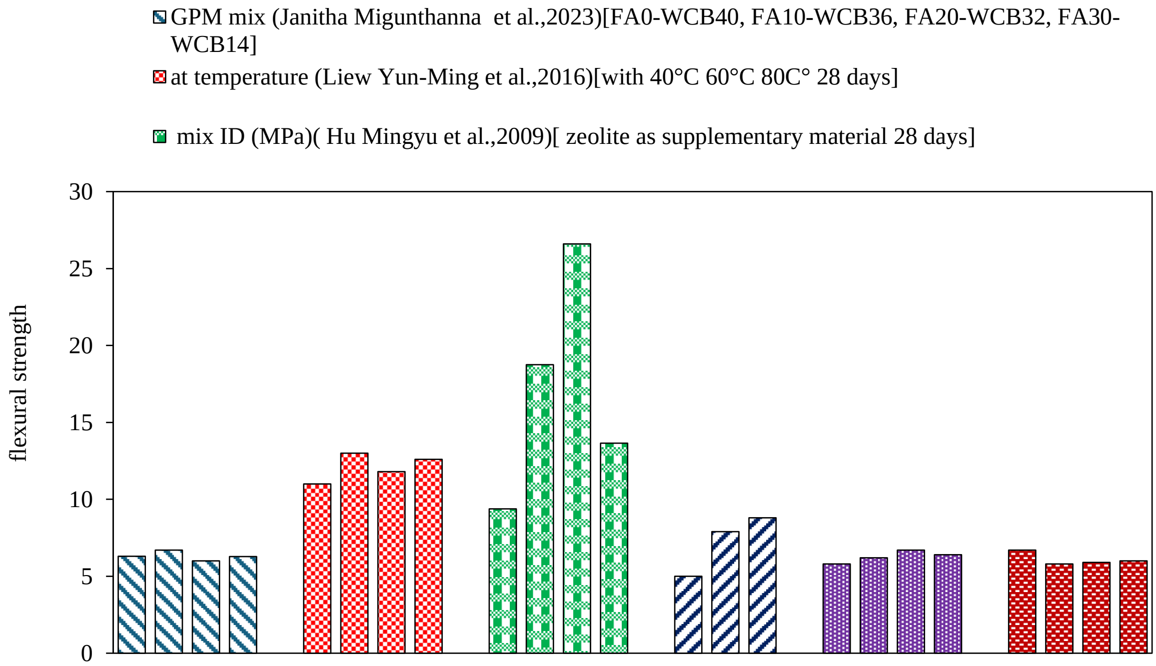

Figure 5. Flexural strength for different mix proportions.

The third set in the graph represents the impact of bentonite and zeolite additions on the flexural strength of fly ash-based geopolymers is covered in this paper. It says that the flexural strength of the geopolymer samples is evaluated at various ages, and the results indicate that the addition of zeolite increases the flexural strength. Using an orthogonal array testing protocol, the ideal mix proportion for the geopolymers which includes the zeolite content is found. The study also points out that when it comes to flexural strength, geopolymers including zeolite perform better than those containing bentonite or no additives at all. This is explained by the fact that adding zeolite to the geopolymer matrix causes a more stable zeolitic structure to form inside it [31]. The fourth set in the graph represents the use of basalt fibers to increase the flexural strength of self-compensating geopolymer composites is covered in this paper. It states that flexural strength increased significantly by 51% with the addition of flexible basalt fibers treated with polyvinyl alcohol (PVA) at a dosage of 4.0 vol%. This rise is explained by the fibers' capacity to lower the stress concentration and stop microcracks from forming and growing inside the geopolymer matrix. The study emphasizes that to improve workability and increase strength in the geopolymer composites, the ideal contents of laponite and basalt fibers were determined to be 3.0–4.0 wt% and 4.0 vol%, respectively [32].

The fifth set in the graph represents the study that looks into adding a few layers of graphene (FLG) to geopolymer composites to increase their flexural strength. According to the study, the flexural strength of the coal fly ash-based geopolymer was considerably enhanced by adding FLG. The addition of 12% FLG produced the best increase of 14.9% in the mixture. The secondary bonding mechanisms between the FLG and the geopolymer matrix, such as hydrogen and van der Waals bonds, are responsible for this improvement1. Furthermore, the composite showed promise for low-cost FLG as an addition for high strength geopolymer applications on an industrial scale by retaining its high flexural strength even after being exposed to a temperature of 300°C [33]. The sixth set in the graph represents the use of waste fiber cement (WFC) to increase the flexural strength of lightweight fly ash geopolymer mortar is covered in this work. The results showed that flexural strength increased significantly with the use of 30–40% WFC by volume, reaching around 20% of the compressive strength. The strengthening of the link between the fiber and the geopolymer matrix is credited with this improvement, and SEM micrographs further corroborate this theory. According to the study's findings, geopolymer mortars that have been produced with WFC are appropriate for uses that call for materials that are lightweight, strong in flexural tension, and have better sound and thermal insulation [34].

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Table 1. Mechanical Properties of Different Types of Clays.

S.N.	Type of clay	Plasticity index (PI)	Cohesion (kPa)	Shear strength (kPa)	Compression strength (kPa)	Permeability (m/s)
01	Kaolinite	Low (10-15)	Moderate (20-30)	Moderate (25-50)	High (300-400)	Low (10^{-9} to 10^{-7})
02	Illite	Moderate (15-25)	High (30-50)	High (50-100)	Moderate (200-300)	Moderate (10^{-7} to 10^{-6})
03	Montmorillonite	High (25-60)	Very High (50-100)	Very High (100-200)	Low (100-200)	High (10^{-6} to 10^{-4})
04	Bentonite	Very High (30-80)	Very High (100-200)	Very High (150-300)	Moderate (200-300)	Very High (10^{-5} to 10^{-3})
05	Chalky Clay	Moderate (15-30)	Low (10-20)	Low (20-40)	Moderate (100-200)	Moderate (10^{-7} to 10^{-6})

Table 1 summarizes key properties of five clay types: Kaolinite, Illite, Montmorillonite, Bentonite, and Chalky Clay, each with distinct characteristics influencing their applications.

Kaolinite has a low plasticity index, indicating limited moldability but high compressive strength, making it ideal for ceramics and construction materials. Its low permeability allows it to retain water effectively.

Illite offers moderate plasticity and high cohesion, providing stability for engineering applications. Its moderate permeability allows for controlled moisture movement, useful in soil stabilization and drilling muds.

Montmorillonite is highly plastic and exhibits very high cohesion and shear strength, making it versatile for heavy-duty applications. However, its low compressive strength and high permeability can lead to challenges in water retention, often utilized in landfill liners.

Bentonite, characterized by its very high plasticity and cohesion, is suitable for various construction and sealing applications, benefiting from its high permeability that allows for moisture retention. Chalky Clay has moderate plasticity and lower cohesion and shear strength, limiting its structural applications. Its moderate permeability makes it useful for drainage solutions. Overall, these clays are essential in civil engineering, environmental protection, and manufacturing, with each type serving specific roles based on its physical properties.

CONCLUSIONS

- The potential of clay as an economical and environmentally friendly source material for alkali-activated and geopolymer concretes, providing improved durability and mechanical qualities over traditional materials.
- The incorporation of clay into geopolymer and alkali-activated concretes offers a feasible approach to mitigate the ecological consequences of building materials, potentially leading to notable decreases in CO2 emissions.
- Advances in the understanding of clay activation processes have paved the way for the development of high-performance geopolymer and alkali-activated concretes, with promising applications in both structural and non-structural elements.
- Geopolymerization of clay demonstrates promising environmental benefits over conventional methods.
- Advancements in clay-based geopolymers contribute to the circular economy in construction materials.
- Key obstacles to using clay as source material are identified by the review, including the need for optimized activation techniques and the variability of clay properties, which point to areas that require more investigation.

- This state-of-the-art review underscores the importance of clay in sustainable construction, with ongoing research poised to enhance its applicability in geopolymer and alkali-activated concrete technologies.
- Kaolinite exhibits low plasticity, making it less workable when mixed with water. Illite and bentonite have higher PI values, indicating they are more plastic and suitable for applications requiring moldability, such as ceramics and some construction materials. Montmorillonite shows the highest PI, contributing to its swelling properties.
- Cohesion is essential for the stability of clay structures. Montmorillonite's very high cohesion allows it to retain strength under varying moisture conditions. In contrast, kaolinite and chalky clay have lower cohesion values, making them less stable under load. Shear strength mirrors these trends; montmorillonite and bentonite have very high shear strengths, making them ideal for applications in engineering and construction.
- Compression strength varies significantly among the clays. Kaolinite stands out with high compressive strength, ideal for structural applications. Conversely, montmorillonite has lower compressive strength, which can limit its use in load-bearing applications but does make it suitable for use in applications where flexibility is required.
- Permeability is critical for understanding how water interacts with clay. Kaolinite has low permeability, making it useful as a barrier in landfill liners and dam construction. In contrast, bentonite's very high permeability allows it to absorb significant amounts of water, which can be advantageous in applications like sealing and as a drilling fluid.

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