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REVIEW ARTICLE

From Lime to Geopolymers: Emerging Trends and Advances in Sustainable Soil Stabilization

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ABSTRACT

Soil stabilization remains a critical challenge in geotechnical engineering, particularly for weak and expansive soils that compromise the safety and serviceability of infrastructure. Traditional stabilizers such as lime and cement have been widely applied; however, their limitations in terms of long-term durability, carbon footprint, and performance under aggressive environmental conditions necessitate alternative approaches. In recent years, geopolymer-based stabilizers derived from industrial by-products such as fly ash (FA), slag, and bottom ash (BA) have emerged as promising substitutes. This review critically examines the comparative performance of lime and geopolymer stabilization with respect to strength development, durability, compressibility, environmental impact, and economic viability. Emphasis is placed on their influence on unconfined compressive strength, resistance to wetting–drying and freeze–thaw cycles, and improvements in bearing capacity. Furthermore, the review highlights the environmental advantages of geopolymers, including reduced greenhouse gas emissions and valorization of waste materials, against the well-established field performance and low initial costs of lime stabilization. Key challenges such as activator cost, curing sensitivity, and field-scale application of geopolymers are also discussed. The paper concludes with perspectives on integrating both methods and advancing sustainable soil stabilization practices. The insights provided are intended to guide researchers, practitioners, and policymakers toward more durable and environmentally responsible ground improvement strategies.

Keywords: Geopolymer, Soil Stabilization, Alkali Activation, Industrial Waste, UCS, Durability

1. Introduction

In civil and geotechnical engineering, soil stabilization, also known as ground improvement, is a crucial process aimed at enhancing the engineering properties of soil. Its primary objective is to improve the strength, load-bearing capacity, and overall performance of in-situ soils that may otherwise be unsuitable for supporting structural loads [1, 2]. The main goals of soil stabilization include improving strength and durability, reducing swell and shrink behavior, optimizing permeability, and promoting the efficient use of locally available or marginal materials [1, 3–5]. Through chemical, mechanical, or physico-chemical modification, stabilization ensures that soils meet the strength and deformation requirements essential for the long-term performance of civil infrastructure.

Soil stability is fundamentally governed by the type and strength of interparticle bonds. These may be intrinsic, such as ionic or covalent, or may develop through mineral precipitates like calcite, silica, or iron oxides that bind adjacent particles. When these bonding mechanisms are weak or absent, as in soft, organic, or expansive clays, soils exhibit poor strength and high deformation tendencies under moisture variation [6, 7]. Problematic soils such as expansive clays, soft organic deposits, and clayey sands often display high compressibility, low shear strength, and significant shrink and swell behavior [8–10]. Rich in

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minerals such as montmorillonite, illite, and vermiculite, these soils undergo considerable volumetric change when exposed to wetting and drying cycles. Such changes can result in differential settlement, loss of bearing capacity, and even foundation failure [11–13].

In many regions, wet or soft terrain poses persistent geotechnical challenges. Water saturation weakens soil fabric, reduces shear strength, and increases the risk of slope instability, erosion, and ground heave [14–17]. On construction sites, wet soft soils often cause delays, increase project costs, and disrupt critical operations such as excavation and compaction. Prolonged rainfall or high groundwater conditions exacerbate compressibility and reduce interparticle friction, resulting in instability and deformation under load [17–19]. These adverse behaviors rarely occur in isolation. They are often interdependent, with one weakness intensifying another. For example, high moisture content can trigger swelling in expansive clay, which simultaneously reduces shear strength and increases settlement potential. This inherent coupling of geotechnical weaknesses highlights the need for better stabilization techniques capable of addressing multiple soil deficiencies.

Given the growing demand for infrastructure development across different soil environments, the search for efficient, durable, and sustainable soil stabilization methods has intensified. Traditional stabilizers such as cement and lime have long been used to improve soil performance. However, their high energy requirements and carbon emissions make them less compatible with current sustainability goals [20–23]. In response, the field has shifted toward alternative binders that combine high mechanical efficiency with lower environmental impact.

1.1. Justification and contribution of this study

This review examines the emerging approach of geopolymer-based soil stabilization as a sustainable alternative to traditional lime and cement treatment. Geopolymers, which are aluminosilicate materials activated by alkaline solutions, offer substantial reductions in embodied carbon while achieving superior mechanical and durability performance. Their amorphous gel network forms strong chemical bonds with soil particles, leading to high early strength, reduced permeability, and enhanced resistance to moisture-induced degradation. While numerous studies have explored the laboratory performance of geopolymer-stabilized soils, there remains a knowledge gap in consolidating these findings into a cohesive framework that links mechanistic understanding, microstructural transformation, and field applicability. This review addresses that gap by:

(i) synthesizing recent advances in the use of lime and geopolymer binders for various soil types;
(ii) evaluating mechanical, durability, and microstructural trends across stabilization methods;
(iii) analyzing cost-effectiveness and environmental performance; and
(iv) identifying barriers and opportunities for large-scale implementation.

Furthermore, this study provides a comprehensive, research-driven reference for geotechnical engineers, practitioners, and policymakers seeking sustainable solutions for problematic soils. By integrating mechanical behavior with microstructural insights and lifecycle assessment, it positions geopolymer stabilization as a next-generation, low-carbon pathway for resilient and environmentally responsible ground improvement.

2. Soil stabilization methods

2.1. Traditional soil stabilization

Traditional stabilization is a widely adopted technique in geotechnical and pavement engineering to improve the strength, durability, and workability of weak soils. Unlike mechanical method, traditional stabilization modifies the inherent physicochemical properties of the soil through chemical reactions between soil particles and stabilizing agents such as lime, cement, and various industrial or agro-wastes [30–32].

2.1.1. Lime-based stabilization

2.1.1.1. Lime Stabilization Overview. Lime stabilization remains a widely adopted and effective technique for enhancing the engineering properties of problematic soils. The improvement mechanism occurs through two primary processes: short-term physicochemical reactions and long-term pozzolanic reactions. Upon lime addition, calcium ions (Ca^{2+}) replace exchangeable cations (Na^{+}, K^{+}) on the clay surface, resulting in flocculation, aggregation, and a reduction in plasticity. This initial cation exchange decreases the diffuse double layer, enhancing soil workability and reducing swelling potential [33]. Over time, the released SiO_2 and Al_2O_3 from clay minerals react with calcium hydroxide to produce cementitious calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels, which are mainly responsible for strength gain and microstructural densification [34]. The comparative reactivity between quicklime (CaO) and hydrated

Fig. 1. Wet soil failure in different geotechnical forms: a.) Typical expansive soil [24] b.) Heaving of flexible pavement caused by expansive soils [25] c.) Highway slope failure on Khao Sok Mountain triggered by intense rainfall [26] d.) Weak plane failure along a section of the Mae Moh Dam access road [27] e.) Structural damage at the corner of a house resulting from soil heave [28] f.) Building damaged by a sinkhole collapse on April 23, 1997, above Permian gypsum in Ripon, NE England [29].

lime ($Ca(OH)_2$) has been widely reported. CaO is ideal for wet, waterlogged soils because its rapid, heat-generating reaction quickly dries them out, while ($Ca(OH)_2$) is better for clay-rich soils, as it effectively reduces their plasticity and makes them less sticky [33]. These reactions progressively transform the soil into a more stable and denser matrix, mitigating expansive behavior.

Recent experimental studies show that lime addition substantially improves UCS and CBR across a wide range of soils. [35] reported that 5–7 % lime increased UCS from 0.441 MPa (untreated) to approximately 1.5 MPa after 28 days, meeting subgrade design requirements. Similarly, [33] found that CaO-treated lateritic soil achieved 0.928 MPa UCS compared to 0.625 MPa with ($Ca(OH)_2$) at equivalent dosage. When lime was blended with supplementary pozzolanic materials such as sawdust ash, UCS and CBR values improved by 83.5 % and 206 %, owing to the additional formation of secondary C–S–H gels [36]. Hybrid binders combining hydrated lime and ionic liquid stabilizers further enhanced CBR, achieving up to three times the improvement of lime-only mixtures [37]. However, in high sulfate soils, lime can lead to excessive levels of ettringite, a hydrated mineral that triggers expansive reactions. This suggests that while C–S–H and C–A–H are beneficial for bonding, ettringite formation in this context is detrimental, not beneficial for creating a compact framework [34].

The durability of lime-stabilized soils under cyclic wetting–drying or sulfate exposure largely determines long-term field performance. [38] observed a 36–64 % reduction in UCS after six wetting–drying cycles in gypseous soils due to dissolution of gypsum and ettringite formation. In contrast, [35] demonstrated that lime-treated lateritic soils retained over 85 % of their original UCS after repeated wet–dry cycling, indicating improved cohesion and pore refinement in non-sulfatic mixtures. Incorporating sawdust waste ash (SDA) mitigated carbonation and maintained over 90 % of long-term strength after 90 days [36]. Lime stabilization reduces soil permeability by forming cementitious products that clog pore channels. [33] reported hydraulic conductivity reductions to the order of 10^{-6}–10^{-7} m/s for both hydrated and quicklime-treated lateritic soils. Volume stability improved markedly as expansive minerals, particularly montmorillonite, transformed into non-expansive phases such as calcite while concurrently enhancing workability and compactability [34]. This mineralogical transition effectively suppresses swelling and shrinkage, improving structural stability under moisture variation.

The introduction of lime (CaO or $Ca(OH)_2$) into fine-grained soils triggers a sequence of chemical and physicochemical reactions including cation exchange, flocculation-agglomeration, and pozzolanic processes that collectively modify the microstructure of the soil to improve its engineering properties. The primary mechanism of lime stabilization involves cation exchange, where Ca^{2+} replaces monovalent cations (e.g., Na^+, K^+), reducing the diffuse double layer and inducing flocculation. This results in an open, granular soil fabric that improves workability

and lowers plasticity [39, 40]. The progression of curing promotes a highly alkaline milieu (pH $\geq$ 12), which liberates silica and alumina from the clay lattice. These solubilized constituents then undergo a pozzolanic reaction with Ca^{2+}, yielding cementitious compounds such as C–S–H and C–A–H gels [41, 42]. Microstructural analysis via SEM confirms that property enhancements including increased strength, reduced plasticity, and lower water absorption are attributable to cementitious gels binding particles and occluding pores, a process that intensifies with curing. Concurrently, XRD analysis suggests this strength gain originates not from new amorphous phases, but from a recrystallization or ordering of the native clay minerals (smectite, illite, kaolinite) and quartz [40, 43]. [44] reports that Mercury Intrusion Porosimetry (MIP) and SEM analyses document a microstructural evolution characterized by a transition from a unimodal to a bimodal pore size distribution, accompanied by a reduction in total porosity and an increase in matrix density. The microstructural evolution from a dispersed, open fabric to a consolidated, gel-bonded mass over a 28–90 day curing period is directly associated with a marked enhancement in key mechanical properties, including UCS, cohesion, and CBR [42, 43]. The degree of microstructural change depends on clay mineralogy and conditions. Montmorillonitic soils show higher reactivity and gel formation than kaolinitic soils [39].

2.1.2. Geopolymer soil stabilization

Chemical stabilization is one of the most widely adopted soil stabilization methods, aiming to improve soil stability by boosting its strength and durability while reducing its compressibility [45–49]. It involves mixing cement or lime with the soil, which creates synthetic cementation linkages between the soil particles. However, products of traditional stabilizers have a great amount of embodied energy and release significant amounts of greenhouse gases. Moreso, the cement manufacturing sector contributes between 8% and 10% of annual global artificial CO_2 emissions [50–52]. The construction industry also faces additional environmental challenges, such as depletion of raw materials and the excessive reliance on coal quarries for energy production [53]. For these reasons, the use of traditional stabilizers has been increasingly discouraged within the construction industry. This has driven the development of alternative binders with lower environmental impacts, while still maintaining effective soil stabilization performance.

The use of traditional stabilizers for soil stabilization can be significantly reduced in some applications by recycling waste materials from aluminosilicate industrial by-products (such as FA, slag, BA and glass waste) through alkali-activated cement types [54–58]. Silica and alumina are often dissolved using a basic (high pH) liquid phase as part of the alkali activation process of industrial aluminosilicate wastes in treated soils. Artificial cementitious products are then formed, improving the soil properties. The general term for this technique, which uses low calcium aluminosilicate materials, is geopolymerization [50]. Geopolymer is an inorganic blend of materials with high contents of silica (SiO_2) and alumina (Al_2O_3). Alkali activator solution, a second raw ingredient, is required to activate all aluminosilicate compounds. Geopolymerization is a comprehensive method for producing geopolymers, encompassing leaching, diffusion, structural rearrangement, polymerization, and condensation [59]. According to [60], it is an emerging area of research focused on the beneficial use of solid waste and industrial by-products. It offers a well-established and economical approach to addressing challenges related to the treatment and containment of hazardous residues, particularly in environmentally sensitive conditions. The procedure for preparing compaction and UCS samples is shown in Fig. 2.

Geopolymerization in stabilized soils leads to the formation of sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-(A)-S-H) gels, which serve as the main cementitious phases binding soil particles. These gels progressively occupy interparticle voids, resulting in a denser and more cohesive microstructure that lowers porosity and enhances mechanical strength [19, 61]. Microscopic analyses such as SEM and XRD confirm the generation of a dense aluminosilicate gel matrix that effectively binds soil particles. Luo et al. (2022) [62] reported that metakaolin-based geopolymer (MKG) stabilization of silty clay forms compact N–A–S–H and C–A–S–H gels, significantly improving interparticle bonding and reducing porosity. Similarly, [63] Wassie and Demir (2024) demonstrated that MKG treatment produces continuous gel coatings around particles, enhancing both shear strength and ductility. In volcanic ash–GGBS blends, Miraki et al. (2022) [61] observed that FESEM/EDS analysis confirmed the development of interpenetrating gel networks, responsible for void filling and strength enhancement. The curing duration significantly influences the rate and completeness of geopolymerization. Increasing the curing temperature and duration accelerates the dissolution of SiO_2 and Al_2O_3, promoting gel formation and microstructural densification. Ahmari et al. (2012) [64] found that dry-heat curing at 60–90 °C raised compressive strength by approximately 16% compared to steam curing, due to enhanced

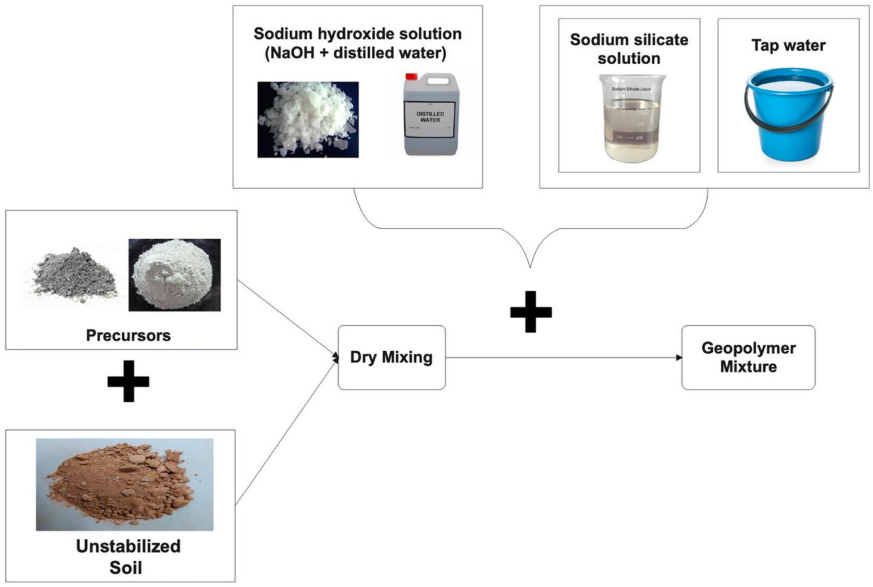

Fig. 2. Compaction and UCS sample preparation procedures.

gel nucleation and reduced capillary porosity. However, excessive heat exposure can cause shrinkage cracking [65] (Zhonging Yang, 2025). Optimal curing thus facilitates amorphous gel connectivity, leading to a more cohesive and microcrack-resistant structure. XRD analysis of geopolymer-stabilized soils typically reveals weakened crystalline peaks and an increase in amorphous phase content, signifying advanced gel formation. Miraki et al. (2022) [61] reported that this transformation from crystalline aluminosilicates to amorphous N-A-S-H/C-(A)-S-H gels results in higher UCS and improved water stability. In particular, the incorporation GGBS in VA–GGBS geopolymers brings about the suppression of crystalline phases and elevated amorphousness, directly correlated with enhanced mechanical performance. Due to their three-dimensional cross-linked aluminosilicate framework, geopolymers offer superior chemical resistance against acidic, sulfate, saline, and frost environments. Their zeolite-like gel morphology minimizes permeability changes and resists ionic attack under cyclic exposure [66] (Yaghoubi et al., 2018). In sulfate and freeze–thaw tests, stabilized samples retained structural integrity, validating the durability of the gel matrix. Long-term studies further demonstrate that geopolymer-treated soils maintain microstructural stability during wetting–drying cycles. Fakhrabadi et al. (2021) [67] found that copper slag–based geopolymers resist crack propagation and preserve gel integrity under repeated moisture fluctuations, outperforming traditional lime- and cement-treated soils.

3. Geopolymer soil stabilization: Mechanism and evolution

3.1. Historical development of geopolymer technology

Geopolymer, a material named by Davidovits in the 1970s, is also known by several other names. These include alkali-bonded ceramic, inorganic polymer concrete, alkali-activated cement, geocement, and hydroceramic. The geopolymer constituents made up of inorganic alkaline aluminosilicate and alkaline activators demonstrated outstanding engineering performance, owing to their superior mechanical strength, chemical durability and resistance to shear stress [68]. The origin of geopolymer can be traced back to the pioneering work of Glukhovsky in the Soviet Union during the 1950s and 1960s. He developed early forms of alkali-activated by having a synergistic combination of volcanic materials with NaOH-based activating solutions. In doing so, hydrated calcium silicate phases (C-S-H) which are known as soil silicates were produced. This served as foundational work for other geotechnical engineers and researchers. Davidovits, whose contributions were significant, developed alkali-activated materials. He utilized natural materials rich in silicon and aluminum and activated them with alkaline solutions. The final product of the reaction resulted in geopolymer. It is important to note that this is an inorganic process. In 1994, Davidovits advanced the understanding of geopolymers by presenting a detailed microstructural analysis based on polysialate networks. Around the same time,

Table 1. Geopolymer application in civil engineering.

Application	Characterization	Reference
Soil Stabilization	Early and high strength gain, low shrinkage and swelling, enhanced durability, improved bearing capacity.	[56]
Concrete Production	Substitution in cement in concrete mixtures, low CO_2 emissions, high durability and early strength.	[77]
Superior-Quality Materials	Used in vital infrastructure, such as precast elements and bridges, fire-, sulphate-, and acid-resistant; increased lifespan.	[78]
Waste Immobilization	Radioactive or toxic material absorption in a geopolymer mixture, stabilizing heavy metals and decreased leachability.	[79]
Retrofitting and Repair	Use as a coating or mortar to fix concrete buildings, Durability, corrosion resistance, and strong connection.	[80]
3D Printing in Building Construction	Additive manufacturing binders made of geopolymers producing quick, modular, and sustainable building.	[81]

Wang and Scrivener in 1995 investigated calcium-rich alkali-activated materials, enhancing knowledge of their chemical composition and performance behavior. Habert, in 2011, assessed the environmental footprint of geopolymer concrete through a life cycle comparison with traditional Portland cement. His findings revealed the ecological benefits of alkali-activated concretes and demonstrated their promise as a more sustainable substitute for traditional cement materials [69–75].

Consequently, many researchers have developed applications and methodologies in the use of geopolymer in civil engineering [76] for instance, carried out soil stabilization by utilizing laboratory tests including Atterberg limits, particle size distribution, sieve analysis, California bearing ratio (CBR), UCS. Table 1 shows the different applications of geopolymer in civil engineering. These studies contribute to a foundational understanding and outline the characteristics of each application.

3.2. Geopolymerization mechanism and chemistry

Geopolymerization provides a sustainable alternative to traditional cement stabilization by using aluminosilicate-rich waste materials. Through alkali activation with agents like NaOH and Na_2SiO_3, these materials form cementitious gels that bind soil particles, modifying the structure and mineralogy of the soil. The fundamental structural unit of a geopolymer is a tetrahedral complex in which silicon or aluminum atoms are covalently bonded to four oxygen atoms. These tetrahedral units interconnect to form an extended three-dimensional aluminosilicate network. Within this framework, the incorporation of tetrahedrally coordinated Al^{3+} introduces a net negative charge, which is electrostatically balanced by small alkali metal cations such as Na^+, K^+, or Ca^{2+}. These charge-balancing cations are often ion-exchangeable and exhibit characteristics analogous to non-framework cations in zeolitic structures [82, 83].

The geopolymerization process can be divided into three primary stages: (1) dissolution of Si and Al species from the solid precursors in an alkaline medium, (2) polycondensation of these dissolved species into aluminosilicate oligomers, and (3) gelation and hardening through the formation of a continuous three-dimensional network [59, 84]. Materials with high SiO_2 and Al_2O_3 contents, such as FA and MK, are particularly favorable for this mechanism due to their chemical makeup and reactivity. According to [59], geopolymerization begins when the alkali solution dissolves the source materials, breaking the aluminosilicate link and releasing silica and alumina, mostly in the source materials. This crucial phase involves the breakdown of Si-O-Si and Si-O-Al bonds through a reaction with hydroxide (OH^-) ions present in the alkaline activator. The negative charge of the aluminosilicate chain is balanced by alkali cations, typically K^+, Na^+, or Ca^{2+}. The silica and alumina content of the precursor material plays a critical role in determining the overall performance of the geopolymer. As the alkalinity of the activating solution increases, the dissolution rate of aluminosilicate phases also increases, thereby reducing the time required to reach saturation. Upon reaching a supersaturated aluminosilicate solution, the condensation process initiates, resulting in the precipitation of aluminosilicate gels in the form of oligomers, which subsequently form larger and more stable polymeric networks. This initial polymeric phase forms when the solution exhibits high concentrations of both silica and alumina. As the reaction progresses, additional silicon is released into the solution, leading to the formation of gels with increased silicon content. The setting of the geopolymer begins when the rate of condensation of aluminosilicate species surpasses their dissolution rate. Eventually, polycondensation and structural rearrangement processes give rise to

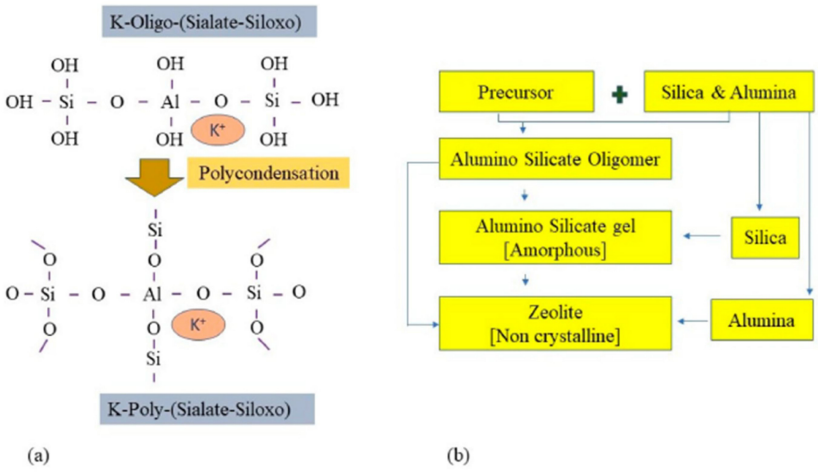

Fig. 3. The (a) procedure and (b) sequence of geopolymerization.

an interconnected three-dimensional network, which constitutes the final hardened geopolymer matrix [59, 85–87]. Fig. 3 shows a schematic illustration for geopolymerization mechanism according to [88].

The reactivity of these precursors is governed not only by their chemical composition but also by their morphology and particle size. Amorphous or semi-crystalline structures in materials such as MK, SF, BFSC, and FA allow for easier dissolution in alkaline [89]. For example, spherical FA particles enhance workability and promote strong, durable binding in soil matrices [59, 90], whereas the platy morphology of MK may lead to increased water demand and rheological challenges [91].

The efficiency of geopolymerization is largely dictated by the rapid dissolution of reactive aluminosilicate species in a highly alkaline environment, as this step limits the rate of subsequent polycondensation. High pH conditions, often enhanced by elevated temperatures, promote the breakdown of Si-O-Si and Si-O-Al bonds, releasing soluble silicon and aluminum ions necessary for gel network formation. This chemical activation renders the precursor reactive, enabling polymerization [92]. Thus, appropriate selection and pre-treatment of raw materials, such as clay calcination to increase amorphous content and surface area, are vital for optimizing reactivity. Additionally, controlling the alkalinity of the activator solution is crucial for governing reaction kinetics, dissolution extent, and the resulting mechanical and microstructural properties of the stabilized soil.

In summary, the geopolymerization mechanism plays a viable pathway for eco-friendly soil stabilization, leveraging the inherent reactivity of waste-derived aluminosilicate materials in alkaline environments to generate cementitious binding gels. This process, when optimized, yields mechanically robust and environmentally sustainable ground improvement solutions.

3.3. Industrial waste-based geopolymer precursors

3.3.1. Fly Ash (FA)

Fly ashes are tiny particulates resulting from the burning of coal in thermal power plants, often categorized as class F and C [76, 93]. The combustion of bituminous coal yields Class F FA, a commonly produced variant characterized by its low calcium oxide (CaO) content. Lignite and sub-bituminous coals are commonly employed as fuel sources in power generation, resulting in the production of Class C FA, which is distinguished by its high calcium content [49]. Specifically, low-calcium (ASTM Class F) FA is generally preferred over high-calcium (Class C) variants, as excessive calcium content can interfere with the polymerization process and alter the resulting microstructure [94].

Class C FA, distinguished by elevated CaO levels, has an accelerated geopolymerization rate and earlier strength attainment. In [95], calorimetry and Avrami kinetic modeling shown that Class C geopolymers attained up to 93% reaction completion within 20 minutes, mostly attributable to the exothermic reaction of Ca with water and the formation of C–S–H that accelerated nucleation and polymerization. Class F FA, on the other hand, has a low CaO content and a high Si/Al ratio, shows a slower reaction rate and extended geopolymerization process, often continuing beyond 28 days under ambient curing. Studies by [96] observed that the amorphous phase content of Class F FA-based geopolymers increased gradually over 28 days, with strength developing

continuously without decreasing, indicative of ongoing geopolymer network formation. This sluggish rate is explained by the fact that amorphous Si and Al are less soluble in Class F ashes and that there is no calcium-driven heat release, which results in a more progressive polymerization process. Amorphous gel, residual voids, and unreacted or partially reacted cenospheres are among the heterogeneous microstructures found in Class F FA, which exhibit considerable long-term geopolymer network growth. [97] used synchrotron nano-imaging and nuclear magnetic resonance (NMR) to show that Class F FA with higher glass content and finer particles had greater conversion of aluminosilicate materials (Al(V,VI) to Al(IV)) and formation of Si–O–Al linkages, showing more complete geopolymerization despite slower initial kinetics. By using SEM and XRD, [96, 98] further verified that Class F geopolymers get denser and more continuous during curing time, as unreacted FA particles dissolve gradually to produce N–A–S–H gels. This is consistent with lower initial amorphous gel fractions (82–90%) that increase steadily with curing. Conversely, Class C FA geopolymers have a denser microstructure at an early stage, as demonstrated by the presence of C–S–H and N–A–S–H hybrids. This results in lower long-term reactivity after Ca-driven reactions settle, but higher early compressive strength.

Despite its promising performance, the commercial adoption of FA-based geopolymer for soil stabilization is constrained by several challenges. These include: (1) the lack of standardized mix design and performance criteria for field application; (2) the cost associated with high activator content required for ambient curing; and (3) limited understanding of long-term behavior and cyclic load response of geopolymer-treated clays Furthermore, high plasticity and buffering capacity in some clays interfere with effective geopolymerization, restricting universal applicability [57, 99].

FA-based geopolymers, especially those formed using Class F FA and Na_2SiO_3 activators, have demonstrated clear potential in enhancing the mechanical and microstructural properties of problematic soils. Nonetheless, practical implementation demands further optimization of mix design, performance standards under varying environmental conditions, and economic feasibility for widespread field adoption. Continued research into FA geopolymer formulations, particularly those that blend with calcium sources to form hybrid N-A-S-H and C-A-S-H gels, may provide a pathway to more effective ambient temperature stabilization solutions.

3.3.2. Ground granulated blast furnace slag (GGBS)

GGBS is a by-product of pig iron production in blast furnaces, where iron ore, coke, and limestone are smelted. During this process, impurities form a molten slag composed mainly of silicates and aluminosilicates, which separates from the molten iron at temperatures between 1300˚C and 1600˚C. The cooling method significantly influences the slag's properties. Air cooling produces a dense, crystalline air-cooled blast furnace slag (ABFS), while rapid quenching with water yields granulated blast furnace slag (GBFS) which is a glassy, granular material with a disordered structure that inhibits crystallization. GBFS is then ground to form GGBS, a latent hydraulic material with pozzolanic and cementitious properties, widely used as a supplementary cementitious material in concrete. Due to its high silica and alumina content, GGBS is also suitable for geopolymer production, offering a sustainable alternative for utilizing industrial waste. While it cannot fully replace cement, partial substitution has demonstrated both environmental and mechanical benefits in construction [5, 23, 91]. GGBS has been identified as a highly effective additive in the stabilization of weak soils through geopolymerization. [100] reported that geopolymers synthesized with GGBS significantly enhance the strength characteristics of soft clayey soils. However, prior to its application, it is essential to evaluate the mechanical, physical, and hydraulic behavior of the target soil to ensure effective treatment. Compared to traditional lime stabilization methods, GGBS demonstrates superior performance due to its inherently high cementitious reactivity. This advantage is particularly evident in sulphate-rich soils, where its use has been shown to reduce swelling potential and improve load-bearing capacity, making it suitable for pavement construction.

Chemically, GGBS comprises calcium, silica, magnesium, aluminum, and oxygen, which contribute to its binding properties [101]. According to [100], the hydration of GGBS begins immediately upon contact with water, although at a relatively slow rate, supporting gradual strength gain and long-term stability in treated soils. GGBS enhances early strength development in geopolymers due to its high calcium content, which promotes the rapid formation of C-S-H and C-A-S-H gels, while also improving the workability of geopolymer mixtures, particularly when blended with precursors like FA or dolomite. Additionally, GGBS improves the durability of geopolymers by reducing permeability, increasing resistance to chemical attacks, and providing excellent heavy metal immobilization through its low porosity and strong chemical affinity for metal ions

[100, 102] however, because of its use in the replacement of cement in concrete, [103] suggests that GGBS should be used judiciously, focusing on technical requirements (such as durability, temperature or crack control) to produce specific properties in large scale.

3.3.3. Bottom Ash (BA)

BA is produced as a residue during the combustion of pulverized coal in thermal power plants. About 80% of ash becomes FA, while the heavier, coarser fraction settles at the base of the boiler as BA [104, 105]. BA is typically collected in hoppers and may be managed either in a dry or wet form. Dry BA is more easily recyclable, and innovative systems have emerged to recycle BA by re-feeding it into combustion chambers to transform it into more marketable FA [106]. Boiler slag, a form of BA formed under high-temperature combustion, is also included under the broader BA classification in countries like Japan [107]. BA production generally accounts for 5–20% of total ash production, depending on boiler type and coal quality [105, 108]. BA exhibits distinct physical, mechanical, and chemical properties. Physically, BA is porous, angular, and dark-colored with irregular particle sizes ranging from gravel (40 mm) to fine silt (0.075 mm) [109, 110] Mechanically, its rough texture gives it a higher angle of shearing resistance and CBR compared to standard aggregates [111]. However, [112] reports that due to the coarse and porous nature of BA as compared to FA, it is often abandoned, causing air and groundwater pollution.

The dumping of bottom ash in landfills leads to serious environmental pollution and health hazards due to the leaching of toxic heavy metals into groundwater [113]. Furthermore, the accumulation and disposal of wastes add significantly to CO_2 emissions, which compounds climate change worldwide [114]. Due to the above reasons, the use of BA in geopolymer soil stabilization is grossly underutilized. Chemically, BA comprises mostly silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), with variable amounts of calcium and magnesium oxides depending on coal type. The pozzolanic potential of BA allows for its reactivity in cementitious mixtures. BA, when used in combination with FA and activated with NaOH and Na_2SiO_3. significantly enhances the physical properties of expansive clay soils. This includes improvements in specific gravity, Atterberg limits, and grain size, which collectively contribute to better soil stability and reduced swelling potential [76]. According to [54], UCS increased markedly with finer BA, surpassing the 1034 kPa threshold for ground improvement. Mineralogical and microstructural analyses revealed enhanced BA decomposition and a denser matrix. The study confirms that BA-based geopolymers are a viable, sustainable alternative for soil stabilization, with BA fineness and column design critically affecting strength and bearing capacity. Moreso, [115] stated that the mechanical properties of soil, including UCS and bearing capacity, improved with the use of BA. The increased strength was attributed to enhanced workability, lower porosity, and the notable influence of silica peaks during hydraulic reaction. UCS values at 28 days were consistently higher than those at 7 days, indicating ongoing strength gain over time.

Utilizing BA in geopolymers provides an eco-friendly solution by recycling industrial waste, thus reducing environmental contamination from direct dumping. The stabilization process also effectively immobilizes heavy metals in contaminated soils, converting them into stable mineral forms and preventing leaching, which is crucial for environmental protection [116]. While BA-based geopolymers offer numerous benefits, long-term durability and performance under varying environmental conditions require further investigation. The interaction with other materials rich in aluminosilicate properties can influence the strength and stability of the stabilized soil. Additionally, the optimization of bottom ash content and the choice of alkaline activators are critical to achieving the desired soil stabilization outcomes [54, 115]. In conclusion, BA geopolymer soil stabilization presents a viable and sustainable method for improving soil properties, particularly in expansive and contaminated soils. However, ongoing research is necessary to address potential challenges and optimize the process for broader applications.

3.3.4. Other precursor materials

The scope of usable precursors extends to a variety of other industrial wastes, including metakaolin (MK), silica-fume (SF), palm-oil fuel ash (POFA), red mud (RM), rice husk ash (RHA), recycled glass powder (RPG), cement kiln dust (CKD), calcium carbide residue (CCR), steel slag (SS), copper mine tailings (CMT), and flue gas desulfurization gypsum (FGDG). The impacts of industrial based precursors in geopolymer are illustrated in Table 2.

3.4. Alkali activator composition and dosage design

3.4.1. Types of activators and their role in geopolymerization

Alkali activators (AAs) play a crucial role in the geopolymerization process by facilitating the dissolution of aluminosilicate precursor materials and supplying essential ionic species such as Si^{4+}, Al^{3+}, Na^+, and K^+ that drive the resulting polycondensation reactions integral to geopolymer formation.

Table 2. Impact of industrial-based precursors in geopolymer.

Precursor	Soil Type	Dosage	Significant Findings	Authors
MK	Clayey sand (SC)	6%, 8%, 10%, 12%	The study found that a 1:2:17 ratio of alkali activator, metakaolin, and silty clay, with 15 wt% geopolymer binder, optimized strength reaching 0.85 MPa, by forming aluminosilicate gels that densify and strengthen the clay's microstructure.	[117]
SF	Silty Clay Loam (CL)	10%, 15%, 20%	Silica fume boosts strength and densifies cadmium-contaminated soil in geopolymerization, while effectively reducing cadmium leaching through immobilization.	[118]
POFA	Low plasticity clay (CL) and high plasticity clay (CH)	10%, 20%, 30%, 40%	POFA-based geopolymer enhances low plasticity clay by increasing strength and compaction, driven by N-A-S-H gel formation and soil densification confirmed via microstructural analysis.	[119]
RM	Low plasticity clay (CL	10%, 20%, 30%	Red mud-based geopolymer raised clayey soil UCS from 0.29 to 2.14 MPa, with 20% RM mix proving most effective via N-A-S-H gel formation. Microstructural analysis confirmed ongoing densification, supporting its use in sustainable soil stabilization and red mud reuse.	[120]
RHA	Clayey Soil (NAT)	4%, 6%, 8%, 10%	A geopolymer combination based on rice husk ash and 10% cement kiln dust to subgrade soil improved its mechanical strength and effectively enhanced the performance of failing subgrade.	[121]
RPG	Low-plasticity clay (CL)	1%, 2%, 3%, 4%, 5%	RGP improved low-plasticity clay by boosting UCS and CBR, attributed to its rich silica and alumina content. Microstructural analysis showed a denser, well-bonded geopolymer matrix.	[122]
CKD	Clayey Soil (NAT)	10%	CKD enhances geopolymer stabilization by raising pH, reducing activator needs, and promoting $Ca(OH)_2$ and CSH formation, which improves soil strength	[121]
CCR	High-plasticity clay (CH)	5%, 10%, 15%, 20%, 30% (CCR:CG = 1:1)	CCR activates coal gangue (CG) in geopolymers, enhancing geopolymerization and forming amorphous products that improve marine soil strength and microstructure, while promoting eco-friendly waste reuse.	[123]
SS	Silty clay	5%, 10%, 15%, 20%, 25% (SS:FA= 1:2)	SS improves loess strength by forming C-S-H and C-A-S-H gels that fill pores and densify the soil, especially when combined with FA, boosting friction angle, cohesion, and UCS for effective, eco-friendly stabilization.	[124]

Table 3. Activator types and their effect in geopolymer mechanism.

Activator	Role	Mechanism	Effect on Geopolymer	Reference
NaOH	Primary alkali source	Dissolves silica/alumina from soil, forms soluble silicates/aluminates.	Accelerates geopolymerization; enhances strength and durability	[58]
KOH	Alternative alkali source	Similar dissolution to NaOH but with larger ion size.	Similar dissolution to NaOH but with larger ion size.	[59]
Na_2SiO_3	Soluble silica supplier	Provides reactive silica for polycondensation with aluminates.	Enhances gel formation, strength, and reduces setting time.	[74]
K_2SiO_3	Soluble silica supplier	Similar to Na_2SiO_3 but with potassium ions.	Improves microstructure refinement; reduces shrinkage cracks.	[130]
Na_2CO_3	Mild alkali activator	Slower reaction: forms NaOH in situ via hydrolysis, then dissolves silica.	Delays setting, improves long-term strength, promotes heavy metal immobilization.	[131]
$Ca(OH)_2$	Hybrid activator (alkali/calcium)	Forms C-S-H gel alongside geopolymer gel.	Hybrid gel matrix improves early strength but may limit long-term stability.	[132]

These cations play a pivotal role throughout the geopolymerization process, influencing stages that span from the initial dissolution of precursor materials to the structuring and stabilization of the final gel. During the early phases, they help organize dissolved ionic species, while in later stages, they guide the formation of the gel network and contribute to the development of crystalline phases. Their fundamental characteristics, including ionic radius, charge density, and coordination behavior, profoundly affect the atomic level arrangement of the forming geopolymer matrix. This microstructural control ultimately governs the material's macroscopic physical and mechanical performance, underscoring the central importance of cation chemistry in tailoring geopolymer properties [125–127].

Alkaline activators, including NaOH, potassium hydroxide (KOH), Na_2SiO_3, potassium silicate (K_2SiO_3), sodium carbonate (Na_2CO_3), and calcium hydroxide ($Ca(OH)_2$) are commonly employed to initiate the activation of aluminosilicate precursors. Although KOH exhibits a higher intrinsic alkalinity relative to NaOH, empirical observations indicate that NaOH demonstrates a superior ability to solubilize and release silicate and aluminate monomers essential for the geopolymerization process [59]. The various types of alkaline activators and their effect on geopolymer soil stabilization are listed in Table 3.

In addition to their functional role, alkaline activators are generally cost-effective and readily accessible worldwide, making them practical for large-scale geopolymer applications. When dissolved in water, alkali hydroxides dissociate into alkali cations and hydroxide anions, establishing a highly alkaline environment with a pH typically exceeding 10. Maintaining a pH above 10.5 is crucial to facilitate both effective geopolymerization and sustained pozzolanic reactions over time. In cases where the precursor material is deficient in silicon dioxide, alkali silicates are commonly introduced to supplement the silica content. Beyond this, they also contribute significantly to the formation of a cohesive binder matrix, enhancing the structural integrity of the resulting geopolymer [90, 128, 129]. It is important to note that addition of silicates plays a catalytic role in accelerating the chemical reactions fundamental to the geopolymerization process. In use, sodium-based alkaline solutions are frequently preferred as activators due to their relatively high efficacy in dissolving aluminosilicate minerals, broad commercial availability, and lower cost compared to their potassium-based counterparts [59, 90]. According to [15], geopolymers activated with a dual solution of NaOH and Na_2SiO_3 demonstrate significantly superior strength in soil stabilization compared to those activated solely with NaOH. This enhanced performance is attributed to accelerated gel formation and a denser microstructure, leading to higher UCS and CBR values.

The selection of a suitable alkaline activator plays a pivotal role in enhancing the mechanical performance of geopolymers, particularly under ambient temperature and traditional curing conditions. Achieving desirable strength characteristics under these conditions increases the practicality and appeal of geopolymer soil stabilization for widespread field implementation.

3.4.2. Effect of dosage and molarity

Research indicates that variations in the composition and concentration of alkaline activators significantly affect the microstructure and strength of geopolymer treated soil. The dosage is simply the weight ratio between alkaline solution and precursor materials; it controls the kinetics of the process and influences the mechanical properties of the geopolymer matrix. [129]. The relationship between activator dosage and the mechanical performance of geopolymers is inherently nonlinear, showing

improvement up to an optimal level, beyond which performance declines.

This behavior is primarily linked to the availability of OH^- ions and Na^+ cations, which promote effective polymerization. However, when activator concentrations exceed the optimal threshold, the formation of amorphous gels, increased porosity, and the emergence of microcracks can occur. These factors that collectively compromise the mechanical integrity of the geopolymer matrix. [133–135]. With increasing geopolymer content, the permeability of the treated material progressively decreases, potentially approaching a nearly impervious state.

A rise in activator dosage enhances the availability of OH^-, which accelerates the dissolution of Si^{4+} and Al^{3+} species, thereby promoting geopolymerization. Concurrently, sodium ions Na^+ introduced by the activator help balance the negatively charged aluminosilicate framework and tend to accumulate within the matrix. This ionic interaction encourages the binding of fine soil particles into larger agglomerates, leading to a coarser particle structure and contributing to strength development. However, beyond the optimal activator concentration, excessive dissolution of reactive species and surplus hydroxide ions can result in the formation of amorphous C–A–S–H gels. These secondary gels may interfere with the integrity of the geopolymer network, potentially hindering further strength gain [55, 133, 134]. Conversely, however, the permeability of soil is significantly influenced by factors such as pore interconnectivity, pore size, and the distribution of pores. Geopolymer-treated expansive soils show reduced permeability due to changes in pore structure. Their SEM imaging showed that at higher activator dosages, pore sizes shrank, and interconnectivity was minimized, effectively clogging water flow paths [136]. The effect of ground GGBS-based geopolymers and hybrid alkali-activated cements in stabilizing organic soils showed reduced permeability at high binder doses [137]. Therefore, it is important to identify the appropriate dosage to achieve the required outcome in geopolymer soil stabilization. Experimental tests enable the selection of the best result that balances the performance requirement.

3.4.3. Curing conditions and strength development

The selection of a suitable alkaline activator plays a pivotal role in enhancing the mechanical performance of geopolymers, particularly under ambient temperature and traditional curing conditions. Achieving desirable strength characteristics under these conditions increases the practicality and appeal of geopolymer soil stabilization for widespread field implementation. Section “4.1.2” further explains the impact of curing conditions of geopolymer in soil stabilization.

4. Comparative analysis between lime and geopolymer stabilized soil

4.1. Mechanical performance

4.1.1. Mechanical performance of lime-stabilized soils

The UCS test is the most widely used method for evaluating the strength behavior of lime-stabilized soils. While other tests such as the CBR and Shear Strength are occasionally employed, they are generally considered less representative for capturing the mechanical response of lime-treated materials under unconfined loading conditions. Lime stabilization has been shown to enhance UCS significantly, up to six times after 28 days of curing, largely due to pozzolanic reactions that form cementitious bonds between soil particles [33, 138]. The strength gain is influenced by several interrelated factors, including the mineralogical composition of the soil, the silica-to-alumina (Si/Al) ratio, soil pH, lime type, moisture content, curing duration, and ambient temperature.

Soils with high clay content typically require larger lime dosages to first satisfy plasticity modification demands, which may reduce the lime available for long-term pozzolanic reactions [139]. In contrast, soils with lower clay fractions require less lime for plasticity adjustment, allowing a greater portion of the lime to contribute to strength development through chemical bonding. Curing time plays a critical role in strength evolution. As [140] explains, UCS increases rapidly during the initial seven days due to early-stage hydration and flocculation processes. However, beyond this period, strength gain slows down as pozzolanic reactions continue at a more gradual rate. The long-term development of cementitious phases such as calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H) contributes to sustained strength improvement [141] emphasized that the interaction between lime and specific mineral phases in the soil is a dominant factor controlling UCS. Soils rich in reactive clay minerals such as montmorillonite or kaolinite tend to produce more cementitious products upon lime addition. On the other hand, lime-stabilized soils under acidic conditions show reduced strength development compared to those in alkaline environments, highlighting the importance of pH in facilitating pozzolanic activity. Notably, lime treatment can still produce substantial strength gains in low plasticity soils, including silty clays and clayey silts [138, 140]. Even in these cases, modest amounts of reactive minerals are sufficient to initiate beneficial chemical transformations that enhance strength and stiffness.

As summarized in Table 4, the mechanical response of lime-stabilized and hybrid lime–pozzolan soils demonstrates strong dependence on binder composition, curing time, and reaction environment. Optimal lime contents between 4 and 10 % consistently yield substantial increases in UCS (120 –700 %) and CBR (200 –850 %) under ambient curing conditions, attributed to progressive formation of C–S–H and C–A–H gels that densify the soil matrix and enhance particle bonding [35, 142]. Extended curing beyond 28 days, particularly at moderate temperatures, further enhances reaction efficiency, as observed in lateritic and clayey soils where UCS peaked at 2–3 MPa after 56–180 days [143, 144]. However, excessive lime or prolonged curing may induce oversaturation and microcracking due to unreacted $Ca(OH)_2$, reducing strength and cohesion [145]. Hybrid blends integrating agricultural and industrial pozzolans such as RHA, SDA, PSA, or CSA demonstrate superior performance over pure lime mixtures. These blends enhance pozzolanic activity, improve workability, and accelerate gel formation at ambient temperature, resulting in UCS gains exceeding 400 % and CBR improvements of up to 700 % [36, 146]. The incorporation of secondary reactive silica optimizes Ca/Si ratios, promoting a denser and more durable microstructure capable of retaining > 80 % strength after cyclic wetting–drying exposure. Curing temperature plays a secondary but reinforcing role elevated thermal conditions expedite hydration kinetics but excessive heat (> 60 °C) may cause premature drying and reduced cohesion. Overall, the comparative data reveal that lime–pozzolan hybridization achieves higher reaction efficiency and long-term stability than traditional lime stabilization, particularly under extended curing and moderate-temperature conditions, confirming its suitability for sustainable, durable subgrade and base-layer applications.

4.1.2. Mechanical performance of geopolymer-stabilized soils

UCS is a pivotal property that significantly influences the performance of geopolymer-stabilized soils. It measures the ability of the soil to withstand compressive stress, which is essential for ensuring stability and load-bearing capacity in construction applications. The geopolymerization reaction, which occurs when precursors react with soil particles, enhances the mechanical properties of the soil, including UCS [156]. The composition of geopolymer precursors and the conditions under which curing takes place are pivotal in achieving optimal UCS. Variations in these parameters can substantially alter the characteristics of the binding matrix, thereby impacting the mechanical behavior of the stabilized soil. Furthermore, the mineralogical makeup of the soil itself plays a crucial role in the geopolymerization process, further shaping the resulting strength and performance outcomes [54].

The data consolidated in Table 5 establish the superior mechanical performance and accelerated strength gain of geopolymer stabilized mixtures. This efficiency stems from the alkaline activation of silica- and alumina-rich precursors like FA and GGBS, which fosters a synergistic formation of interlinked C–A–S–H, C–S–H, and N–A–S–H gels. Optimal alkali molarity typically ranges from 8 M to 12 M, while activator ratios between $Na_2SiO_3/NaOH$ = 1.0–1.5 yield the highest reaction efficiency. Under these optimized conditions, UCS improvements of 400–10,000 % and CBR increases of up to 2,700 % were achieved within 28 days, confirming the accelerated geopolymerization reactions relative to lime stabilization [157, 158]. Furthermore, high-calcium pozzolans such as FA–GGBS [159] and GGBS–Jarofix [160] blends exhibited rapid early-age hardening due to calcium-enhanced cross-linking. This early-age strength (3–7 days) in high-molarity mixes (≥ 12 M) is attributed to accelerated polymerization and calcium–aluminosilicate co-gelation [161]. In contrast, low-calcium FA or kaolin-based mixes benefited from extended curing periods (60–90 days) and elevated curing temperatures (40–60 °C) to complete the geopolymerization process, whereas long-term curing (60–90 days) favors gradual reorganization and secondary gel growth, enhancing stiffness and durability [162]. Similarly, rubber-wood fly ash (RWFA) blend with laterite soil shows synergistic reinforcement by improving particle packing and internal curing, producing dense matrices with lower porosity and 10–15 % lower CO_2-equivalent emissions [163].

The relationship between water content and UCS in geopolymer stabilized soils is complex, with lower water-to-binder (w/b) ratios typically resulting in higher UCS values. This phenomenon occurs because reduced water content minimizes voids between clay particles, enhances bonding, and preserves the concentration of alkaline solutions necessary for geopolymerization [164]. According to [165], the highest UCS was achieved at a modulus ratio (Ms) between 0.9 and 1.2 using both alkaline activators: anhydrous sodium metasilicate (ASM) and NaOH. Strength declined when the Ms exceeded 1.2, attributed to reduced silicate monomer concentration and diminished alkalinity, which are critical for effective aluminosilicate dissolution and gel formation. Additionally, increased GGBS content and reduced water content significantly improved UCS by enhancing binder availability and reducing pore space in

clay. [164] reports that initial water content significantly impacts the UCS of geopolymer-stabilized soil, with higher water content leading to reduced strength and slower development, often requiring more FA to compensate. Concurrently, the secant modulus (E_{50}) shows a strong direct correlation with UCS, where $E_{50} = 81$ UCS, indicating stiffness and ductility of the geopolymer matrix. Therefore, controlling initial water content and understanding the modulus ratio are crucial for optimizing the performance of geopolymer-stabilized soils. It is also important to state that [166] investigated the alkali-to-binder ratio (A/B), finding that increasing the A/B ratio generally leads to higher UCS of geopolymer-stabilized soil within the tested range. This is because a higher A/B ratio increases the Na/Al ratio, which is crucial for geopolymerization kinetics and strength. They also reported that lower water content improved strength, while excessive water diluted activator concentration, inhibited geopolymerization, and weakened particle bonding. [167] similarly found that decreasing water content enhanced UCS, due to frictional resistance among particles and reduced cation immobilization. Conversely, the elastic modulus (Es) of soilcrete specimens shows a strong direct correlation with UCS, meaning higher Es values indicate greater strength. These relationships are crucial for predicting strength and designing soilcrete columns in deep mixing applications.

Geopolymer soil stabilization presents a compelling and sustainable alternative to traditional lime method for soil improvement. Although mix design plays a crucial role in enabling geopolymer gel formation, the resulting mechanical performance, typically assessed through UCS, is ultimately governed by the intricate microstructural and morphological characteristics that evolve throughout the reaction and curing stages. A deeper understanding of this structure property relationship is essential for refining mix protocols and accurately forecasting long term performance. [167] reports that microstructural analysis of samples tested for UCS after 28 days of curing indicates that silica compounds are the primary contributors to strength development. EDX analysis shows that higher silica peak intensity corresponds to stronger pozzolanic activity and denser aluminosilicate gel formation, resulting in a more compact microstructure and increased UCS in geopolymer-stabilized soils. Similarly, [159] emphasized how the strength of geopolymer-stabilized soil is closely tied to its mineralogy and microstructure, with NaOH activation of amorphous alumino-silicates from FA and GGBS promoting the formation of strength-enhancing geopolymeric compounds. These gels fill pore spaces and bind soil particles, as confirmed by SEM observations, resulting in a denser, stronger matrix. [164] observed that increasing the FA content in geopolymer-stabilized soil led to reduced porosity and the development of a denser microstructure, as soil particles became more effectively bonded by geopolymeric gels. This structural improvement corresponded with a rise in UCS, reaching 1.3 MPa. Additionally, the broad hump observed in the XRD patterns of the FA-treated clay confirmed the formation of amorphous aluminosilicate gels. [162] made use of slag-clay based geopolymers, XRD analysis of kaolinitic clay treated with 20% binder after 28 days at 45°C showed reduced kaolinite peak intensity and the appearance of new crystalline phases, including C–A–H and C–S–H. These changes indicate the formation of cementitious products and flocculated structures resulting from cation exchange reactions.

4.1.3. Comparative mechanical performance of lime and geopolymer stabilized soils

The comparative analysis of Tables 4 and 5 reveals distinct mechanistic and performance trends between lime- and geopolymer-based soil stabilization. Lime stabilization relies on a gradual pozzolanic process dominated by C–S–H and C–A–H gel formation, leading to steady strength gain over extended curing periods, typically reaching 1–4 MPa UCS after 28–90 days at ambient temperatures [35, 36]. The rate of strength development depends strongly on lime dosage, curing duration, and moisture retention. In contrast, geopolymer stabilization exhibits accelerated reactivity due to rapid dissolution of aluminosilicate precursors under high-alkalinity conditions, forming amorphous N–A–S–H and C–A–S–H gels within the first 24–48 hours [158]. As a result, UCS values often exceed 10–20 MPa even under moderate curing temperature, representing a five- to ten-fold improvement compared with lime stabilization.

Although geopolymers surpass lime in terms of strength, durability, and permeability reduction, their performance strongly depends on factors such as activator concentration, precursor composition, and curing temperature. Higher curing temperatures (40–80°C) accelerate geopolymerization but can restrict practical application in tropical climates where thermal regulation is difficult. In contrast, lime stabilization is more adaptable to field conditions, requiring only ambient curing and simple mixing. Hybrid lime–geopolymer mixtures address these contrasts by integrating lime's early cation exchange and hydration reactions with the rapid gel network formation of geopolymers, resulting in balanced mechanical strength, enhanced chemical stability, and reduced carbon footprint. Overall, the comparison

Table 4. Comparative mechanical performance of lime-stabilized and hybrid lime-pozzolan soils.

Reference	Soil Type	Optimum Lime %	Other Binder Constituents	Optimal UCS (MPa)	Optimal CBR (%)	% Improvement (SDI)	Key Observation
[142]	Laterite soil	8%	20% RHA	2.221	72.4	11.14	20% RHA + 8% lime yielded densest matrix, forming C–S–H and C–A–H gels; achieved highest UCS and CBR, meeting Thai DOH standards for subbase material.
[36]	Laterite soil	4%	8% SDA	0.365	18.0	UCS (83.5%), CBR (206%)	Optimum 8% SDA + 4% lime formed C–S–H and C–A–H gels that improved strength and durability while reducing plasticity and lime use
[147]	Clayey soil	12%	8% SBA	0.0676	1.71 (unsoaked), 1.44 (soaked)	UCS (300–400%); CBR 61% (unsoaked), 50% (soaked)	C–S–H and C–A–H gel formation improved UCS and CBR; achieved peak performance with enhanced durability and sustainability.
[145]	Inorganic clay	2%	Nickel Slag + Aluminum Hydroxide	21.83kg/cm^2 (2.139 MPa)	-	17.2	Excess lime (>4%) caused oversaturation, reduced C–S–H and C–A–H efficiency, and strength decline over long curing.
[148]	Marine clay	6%	6% Coconut Shell Ash (CSA)	0.231	-	~21	Strength rise due to C–S–H, C–A–H, and C–A–S–H formation; excessive CSA (>8%) reduced strength by over-compaction.
[35]	Laterite soil	5%	-	1.014	48.29 (soaked) / 85.25 (unsoaked)	UCS (130%); CBR (582%) soaked)	UCS > 1 MPa, durable through 12 wet–dry cycles; formation of C–S–H and C–A–H gels enhanced cohesion, friction angle (φ from 14.5°→28°), and shear strength stability.
[149]	Clayey soil	5%	-	1.722	-	UCS (386.5%)	17.8% OMC gave UCS of 1.722 MPa (hard consistency); pozzolanic C–S–H and C–A–H formation enhanced strength; excess water (w = 19.5%) reduced UCS by ~14%.
[150]	Gypsum clay	6%	-	2.36	-	3.23	Strength tripled due to C–S–H and C–A–H formation; curing age significantly affected strength and stiffness (elastic modulus increased 2.58 × compared to raw soil).
[151]	Clayey soil	20%	10% RHA	0.1217	-	54.05%	Pozzolanic reaction improved cohesion and friction angle (increased 60.48%), while PI dropped 56.7%, showing durable and eco-efficient stabilization.
[146]	Lateritic soil	8%	8% Periwinkle Shell Ash (PSA)	2.67	91.2 (unsoaked) / 79.3 (soaked)	UCS (~578%); CBR (~693%).	Microstructural analyses (SEM, FTIR, XRD) confirmed densified matrix and improved durability for sub-base applications.

(Continued)

Table 4. Continued.

Reference	Soil Type	Optimum Lime %	Other Binder Constituents	Optimal UCS (MPa)	Optimal CBR (%)	% Improvement (SDI)	Key Observation
[152]	Silt-sized low-plasticity soil	8%	30% Zeolite	~4.5	-	-	Pozzolanic C–S–H and C–A–H gels improved cohesion, density, and microstructure integrity; optimal mix reduced mass loss and maintained >80% strength after 8 freeze–thaw cycles.
[143]	Clay soil	8%	-	2.885	-	~757%	8% lime produced peak UCS (2.885 MPa) after 180 days; durability maintained after 12 wet–dry cycles with only 42% UCS loss.
[144]	Bangkok clay	12%	20% RHA	1.33	>90 (unsoaked) / >95 (soaked)	UCS (~425%), CBR (~395%)	Formation of C–S–H and C–A–H gels enhanced particle bonding, reduced swelling to <0.04%, and ensured long-term strength and durability under soaking.
[112]	Bangkok clay	12%	50% BA	~1.1	-	192%	Pozzolanic C–S–H and C–A–H gels enhanced cohesion and water resistance; minimal strength loss after wet–dry cycles confirmed suitability for subgrade and base layers.
[153]	Loess	23%	-	~0.95	-	2.92	Strength increased linearly with curing time and inversely with porosity; SEM confirmed denser matrix and C–S–H, C–A–H, and ettringite formations enhanced long-term durability and microstructural bonding.
[154]	Clayey soil	5%	1.5% Polyethylene fibre	1.26	29.0 (soaked)	UCS (670%), CBR (690%)	Improved modulus, residual strength, and toughness, enabling subgrade use with 39 cm pavement thickness reduction.
[33]	Lateritic soil	10%	-	0.928 (CaO) / 0.625 ($Ca(OH)_2$)	76 (CaO) / 65 ($Ca(OH)_2$)	UCS (570%) (CaO), CBR (850%)	CaO-stabilized soil outperformed $Ca(OH)_2$ with 1.5 × higher UCS and 12.5% higher CBR at 10% lime.
[155]	Kaolin Clay	5%	-	0.390	-	UCS (113%)	Improved plastic and liquid limits, reduced plasticity index, and formed C–S–H and C–A–H gels observed via SEM, showing densified flocculated microstructure and durable long-term strength.

Table 5. Comparative mechanical performance of geopolymer-stabilized soils.

Reference	Soil Type	Geopolymer Constituents	Alkaline Activator & Molarity	Optimal UCS (MPa)	Optimal CBR (%)	% Improvement	Key Observation
[157]	High liquid limit soil	FA + GGBS	NaOH + Na_2SiO_3 (modulus 1.0, 1.2,1.4, 1.6)	4.55	13.2	UCS (~780%), CBR (~1000%)	Strength and stiffness increased with dosage due to C–A–S–H, C–S–H, and N–A–S–H gel formation; exceeded subgrade design standard; improved density and reduced porosity confirmed by SEM–EDS.
[168]	High plasticity clay	GGBS + FA + Recycled Demolition Waste	NaOH	3.63	9.16	UCS (~830%) CBR (~184%)	Synergistic action of RDW aggregates and geopolymer gel (C–A–S–H/N–A–S–H) improved strength and water stability.
[158]	Expansive clay	FA (85%) + BA (15%)	8M NaOH + Na_2SiO_3, ratio 0.5:1, activator/binder 0.6	20.59	13.22	UCS (633%), CBR (753%),	8M NaOH improved setting time and long-term strength; suitable as subgrade material meeting >6% CBR requirement.
[163]	Lateritic soil	Rubber wood fly ash (RWFA) 30% of soil	8M NaOH + Na_2SiO_3	2.419	-	434–259–145% higher UCS vs 1%, 3%, 5% cement.	Dense microstructure (C–S–H & N–A–S–H gels), and 11% lower CO_2-eq than cement stabilization.
[169]	Expansive Clay	FA	6.5M NaOH + Na_2SiO_3	0.414	39–43 (soaked), 50 (unsoaked)	UCS (350–450%)	20% geopolymer was optimum; eliminated swelling pressure, improved UCS by ~400%, and raised soaked CBR above 32%, making soils suitable for subgrade/subbase applications.
[158]	Poorly graded fine sand	FA + GGBS (1:1)	NaOH + Na_2SiO_3 (modulus 2.4)	9.6	112	UCS (~1900%), CBR (~2700%)	Geopolymer reduced cost by 60% and CO_2 emissions by > 60%; Si/Al = 2.5 and Na/Al = 0.8 ensured rapid setting and strong C–A–S–H/N–A–S–H gel formation.
[160]	Clayey soil	Jarofix + GGBS (20%)	5M NaOH + Na_2SiO_3	2.41(AC) 6.90 (DC)	-	UCS 617% (AC), 627% (DC)	Alkali-activated Jarofix–GGBS blend formed C–A–S–H and N–A–S–H gels, yielding high UCS and durability suitable for road subbase applications.
[161]	Lateritic soil	FA	15M NaOH + Na_2SiO_3 (70:30 ratio)	4.25	-	UCS (~4800%)	Optimum FA/AA = 2.5 yielded highest UCS after 3-day curing; excessive FA/AA (>2.5) reduced workability and strength due to low moisture.
[164]	Soft clay	FA	10M NaOH + Na_2SiO_3 (ratio 2:1)	1.30	-	UCC (~1200%)	Optimum 30% FA at 1.0 LL achieved 1.3 MPa UCS with continuous long-term strength gain; permeability decreased sharply at 12% FA;
[159]	Granular soil	FA + GGBS	8M NaOH, 0.35 mL/g	7	416	UCS (900%), CBR (800%)	Optimum 30% geopolymer showed dense C–S–H, C–A–S–H, and N–A–S–H gels; excellent durability under wet–dry, freeze–thaw, and chemical exposure.

(Continued)

Table 5. Continued.

Reference	Soil Type	Geopolymer Constituents	Alkaline Activator & Molarity	Optimal UCS (MPa)	Optimal CBR (%)	% Improvement	Key Observation
[100]	Clay soil	FA, GGBS	10M NaOH + Na_2SiO_3, ratio 2.0	3.15	-	UCS (~450%)	GGBS addition improved C–S–H and C–A–S–H gel formation, reduced PI & LL, meeting ASTM D4609 subgrade (> 0.8 MPa).
[162]	Kaolinite clay	GBFS, BOFS, CaO, MgO	10M NaOH + Na2SiO3.	8.44	-	UCS (~4600%)	BOFS-based geopolymers showed high UCS and stiffness; dense C–S–H and C–A–S–H gel structure improved compressibility, toughness (Eu = 22 kJ/m^3), and stiffness (E_{50} = 207 MPa).
[133]	Silty clay	FA, BFS	5M, 10M, 15M NaOH	12	-	-	Microstructure showed dense N–A–S–H gels; BFS enhanced packing density and geopolymerization efficiency.
[170]	Cohesive soil	FA, BFS	4–15 M NaOH + Na_2SiO_3	24.26	-	-	Highest UCS achieved at 15 M NaOH, A/B ≈ 0.6; strength increased with BFS and molarity; dense N–A–S–H and C–S–H gel networks confirmed through sensitivity trends.
[11]	Black Cotton Soil	FA	5M NaOH + Na_2SiO_3	2.5	-	UCS (~1600%)	Optimum 20% FA75 and 5M NaOH produced 2.5 MPa UCS after 28 days; dense aluminosilicate matrix (N–A–S–H gel) improved bonding, reduced swelling, and met subgrade strength criteria.
[57]	Kaolin clay	FA, GGBS	14M NaOH + Na2SiO3	~3.5	-	UCS (~1500%)	20% FA–slag geopolymer markedly increased UCS and effective cohesion, producing denser structure and higher stiffness.
[171]	Silty Sand	FA	14M NaOH + Na_2SiO_3	1.35	34.32	UCS (~1600%), CBR (~1940%)	30% geopolymer (dry-mix method) yielded max UCS = 1.35 MPa and CBR = 34.32%; dense N–A–S–H gel matrix formed, upgrading soil from Poor Subgrade to Good Base/Subbase classification.
[172]	Lateritic soil	FA, GBFS	5M NaOH + Na2SiO3	20.21	-	-	Optimum mix LS:FA:GBFS = 60:30:10 at NS:NH = 90:10 achieved 20.2 MPa UCS after 60 days; coexistence of C–S–H and N–A–S–H gels gave dense matrix; met Thai and Australian road base standards without cement.
[173]	Kaolinite clay	FA	8-14M NaOH + Na2SiO3	5.12	-	UCS (~10000%)	Improved gel densification (N–A–S–H + hydroxysodalite), significantly increasing strength compared with clay soils (25–400 kPa range).
[132]	Soft marine clay	FA, CCR	3–18 M NaOH + Na2SiO3	~1.8	-	UCS (~3500%)	CCR addition enhanced C–S–H and N–A–S–H gel coexistence, yielding 1.5 × strength improvement over FA-only geopolymer and 43% lower CO_2 emissions than cement stabilization.
[174]	Black cotton soil	-	12M NaOH + Na2SiO3	0.513	-	UCS (~141%)	Strength increased with dosage and curing due to extended polymerization and Al–Si gel network formation.

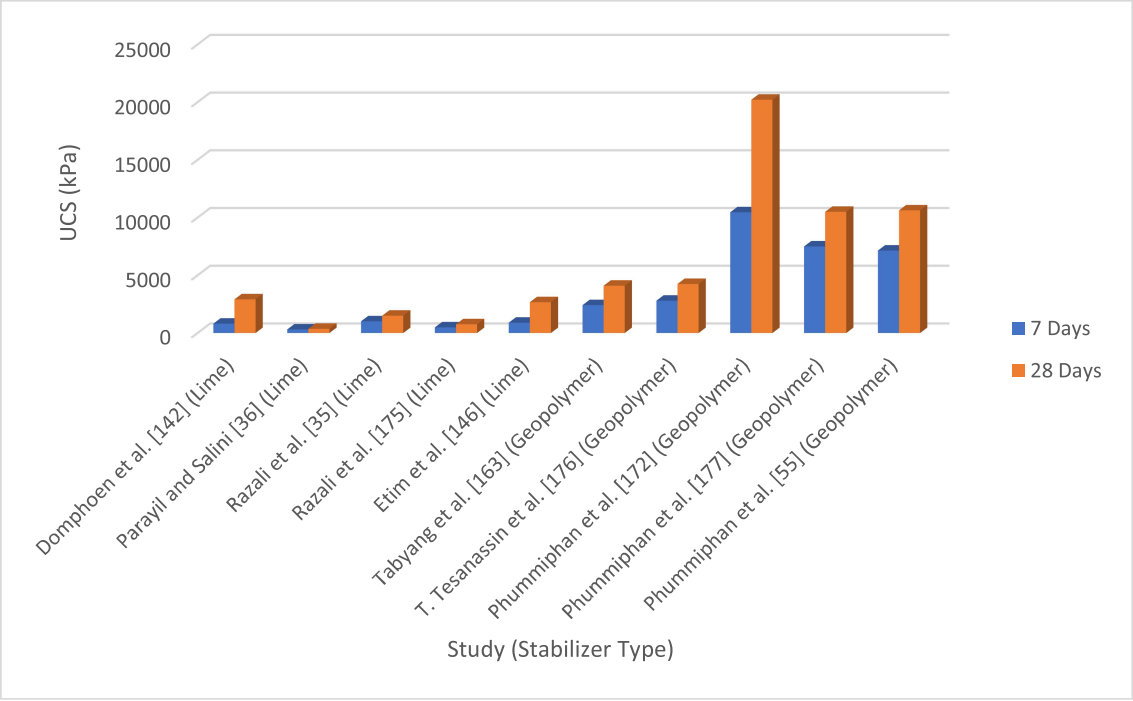

Fig. 4. Comparison between UCS of lime- and geopolymer stabilized laterite soil.

indicates that lime stabilization offers greater ease and cost-effectiveness, while geopolymer mixtures provide superior durability and sustainability together presenting complementary solutions for developing optimized, low-carbon ground improvement technologies.

Fig. 4 presents UCS data for lateritic soils stabilized using traditional lime and geopolymer binders, with UCS values measured after 7 and 28 days of curing. This comparative visualization facilitates an evidence-based assessment of the performance of both stabilizer types in enhancing the strength of lateritic soils. The data indicate that both lime and geopolymer binders improve the UCS of lateritic soils with curing time. However, geopolymers exhibit a significantly higher UCS gain compared to lime, particularly after 28 days. Lime-stabilized samples generally show 28-day UCS values ranging from 0.365 to 2.918 MPa [35, 36, 142, 146, 175]. [175] reports that lime addition significantly enhances the compressive strength of lateritic soil over time, confirming pozzolanic reactions that form cementitious bonds and effectively bind soil particles. The strength increase is primarily attributed to cation exchange, clay particle flocculation and agglomeration, and pozzolanic reactions, all fundamental to the lime stabilization process [146]. In contrast, geopolymer-stabilized samples demonstrate substantially higher 28-day UCS, ranging from 4.1 to 20.21 MPa, a strength increase of over 7 to 10 times in some studies [55, 163, 172, 176, 177]. This supports existing findings that geopolymer stabilization continue to develop strength post-curing due to prolonged polycondensation and microstructural densification.

4.2. Durability

4.2.1. Impact of lime on durability

Lime stabilization significantly enhances the durability of various soil types by improving their mechanical properties and resilience to moisture fluctuations, freeze thaw cycles, and long-term strength degradation [35, 112, 142, 178]. These enhancements are primarily attributed to pozzolanic reactions between lime and reactive soil minerals, which form cementitious compounds that bind soil particles and develop a stronger, denser matrix.

For instance, [112] reported that lateritic soil treated with 5–9% lime exhibited UCS improvements up to the fourth wet-dry cycle, maintaining values above 800 kPa even after 15 cycles. This demonstrates lime's long-term potential under cyclic wetting. Similarly, [112] found that Bangkok clay stabilized with 12% lime and 50% bottom ash retained strength after a single wet-dry cycle under soaked conditions, suggesting the role of supplementary pozzolans in enhancing durability in tropical environments. Nonetheless, lime-stabilized soils are not without limitations; [31] observed that repeated wet-dry cycles can reduce the cohesion between lime

and soil particles, resulting in volume increase due to structural disruption. However, strength development can continue if curing time is extended or lime content increased [178]. [179] further supported these findings with XRD and SEM analyses showing progressive mineralogical transformations and microstructural densification, contributing to improved resistance against moisture and thermal cycles.

Despite its performance, lime stabilization faces chemical degradation challenges. Carbonation, wherein free lime reacts with atmospheric CO_2 to form calcium carbonate, leads to weakening of interparticle bonding and depletion of reactive calcium. Additionally, sulfate attack may result in expansive ettringite formation, causing cracking and strength loss. These adverse reactions can be mitigated through longer mellowing periods, staged lime application, and higher moisture content during treatment [180]. The comparative review supports these observations. For example, [13] reported mass losses between 20–29.5% and UCS loss of up to 60% in expansive soils stabilized with lime after 12 FTCs, underscoring lime's vulnerability under freeze–thaw conditions. [181] showed better performance in lime-treated kaolinite clay with silica fume and fibers, achieving strength retention of 62.5%, demonstrating how additives can bolster durability.

4.2.2. Impact of geopolymer on durability

Geopolymer stabilization has emerged as a superior alternative to traditional binders due to its excellent durability and lower environmental footprint. [182] reported that geopolymer-treated soils exhibited modest weight loss (<4.5%) over 12 wet-dry cycles. [159] showed that FA-GGBS-based geopolymers limited mass loss to 6%, outperforming Portland cement thresholds, with most degradation occurring in the initial cycles and stabilizing thereafter.

These outcomes are linked to the dense microstructure and strong binding produced by geopolymerization and hydration reactions, particularly when using industrial by-products like FA, GGBS, and copper slag. [13] found that slag-based geopolymers significantly outperformed both lime and cement in stabilizing expansive soils, with higher resistance to wet-dry and FTCs, reduced swell-shrinkage behavior, and decreased microstructural voids. Likewise, [12] reported that alkali-activated FA geopolymers with liquid alkali activator (LAA)/FA ratio of 1.5 drastically improved UCS (up to tenfold), reduced leaching, and maintained strength across cycles, indicating robust chemical stability and erosion resistance. [183] observed that bearing capacity degradation ratios (BDR) for slag/FA geopolymers were as high as 90%, substantially better than cement-stabilized controls. Even at low dosages, geopolymer-treated soils preserved integrity under repeated FTCs, with frost resistance enhanced through FA inclusion and optimized alkali content.

Despite their advantages, geopolymer-stabilized soils are not impervious to degradation. [184] highlighted that FTCs and chloride erosion can reduce UCS and damage the microstructure of geopolymer-stabilized soils. These effects are aggravated by low curing temperatures, which inhibit geopolymerization and limit the formation of protective gels. Though geopolymer matrices can self-repair to some extent via polymerization of residual monomers, chloride-induced formation of Friedel's salt can disrupt bonding and impede strength recovery.

Supporting data from the comparative review revealed consistent trends. [185] documented <2% mass loss in geopolymer-treated clay after 12 FTCs, [186] reported significantly reduced mass loss in copper slag-stabilized soils compared to untreated controls. [123] showed that marine soils stabilized with 15% coal gangue (CG)-calcium carbide residue (CCR) geopolymer maintained strength better than lime-based alternatives, with durability primarily linked to mass retention. [187] further demonstrated that FA–GBFS geopolymer-treated A-4 soil exhibited only 4.09% mass loss and negligible volume change after 12 wet-dry cycles, exceeding Colombian standards for durability.

4.2.3. Comparative performance of the durability performance of lime and geopolymer stabilized soils

From both literature findings, it is evident that geopolymer-stabilized soils consistently outperform lime-stabilized counterparts in terms of mass retention, strength durability, and resilience to environmental cycles. Table 5 shows a comparative analysis of the durability properties between lime-stabilized soil and geopolymer-stabilized soil. Lime-stabilized soils tend to experience rapid strength decay beyond the fourth or fifth cycle, especially in the presence of sulphates or carbonation-prone conditions. In contrast, geopolymer-stabilized soils, particularly those using FA, GGBS, or slag show minimal strength loss and superior microstructural integrity under the same conditions. Table 6 shows a comparative analysis of the durability properties of lime- and geopolymer-stabilized soils.

Lime stabilization suffers from:

- High mass and strength losses under cyclic exposure.
- Early failure due to microcracking and moisture sensitivity.

- Low suitability for long-term or high-moisture applications.

Geopolymers, on the other hand:

- Maintain structural integrity with mass losses typically $<10\%$ even after 12 cycles.
- Exhibit strong gel-bonding and reduced porosity, enhancing moisture resistance.
- Perform best when constituents include FA, GGBS, copper slag, and optimized molarity (8–10 M NaOH).

Despite their clear advantages, geopolymer-stabilized soils also face challenges such as brittleness at higher fiber loadings and sensitivity to curing time. Nonetheless, the broader environmental benefits and superior durability make geopolymer stabilization a compelling alternative to traditional lime stabilization, especially for infrastructure exposed to aggressive environments.

4.3. Comparative cost–benefit and sustainability analysis of lime and geopolymer soil stabilization

Lime is considered a low-cost stabilization method because it is readily available worldwide, easy to produce, and effective in small quantities, typically making up only 3–10% of the soil's dry weight [41, 140, 192]. It substantially improves strength and durability at much lower cost than cement or geopolymers, lowering overall expenses by 24.77–43.47%, particularly in road and subgrade projects that use on-site mixing and locally sourced lime[41, 193]. [194] reported that the unit cost of lime averages around \$0.14/kg, with transportation often being a key cost factor. Their decision-making model indicated that lime stabilization minimizes economic and environmental problems associated with the extraction, transportation, and disposal of natural materials that would otherwise be used for replacement. According to [142], the cost of lime for stabilizing a 1-km layer with a width of 20 m is estimated at 17 THB/kg (\$0.5/kg). Besides being affordable, lime provides economic advantages through its easy handling, low mixing energy demand, minimal equipment needs, and its ability to improve soil workability during compaction, which reduces on-site mechanical energy use [36]. However, the calcination process in lime production is a substantial source of CO_2 emissions, generating approximately 0.75–1 ton per ton of output. Consequently, recent studies have prioritized the use of waste-derived lime and alternative binders as a means of reducing this environmental burden. For instance, [195] demonstrated that lime derived from eggshells can lower life-cycle CO_2 emissions when compared to traditional lime, without compromising stabilization performance. The study by [196] confirmed similar mechanical and environmental benefits using eggshell lime for expansive soils. Additionally, a study by [197] comparing lignin-based and lime stabilization road embankments revealed a critical trade-off. Lime stabilization, despite its higher embodied CO_2 emissions, demonstrated greater durability and reusability, positioning it as a solution favoring long-term performance over short-term sustainability gains.

The economic and environmental performance of geopolymer soil stabilization shows a compelling balance between sustainability and engineering viability. Studies have shown that alkali-activated materials, particularly those derived from industrial by-products such as FA, slag, and metakaolin, substantially reduce lifecycle emissions and resource consumption compared with traditional lime and cement stabilization. [198] demonstrated a 31% reduction in greenhouse gas emissions relative to Portland cement through the use of alkali-activated soil waste, equating to savings of approximately 110 kg CO_2 eq per m^3 of stabilized material. Similarly, [199] found that metakaolin-based geopolymer concrete reduced the global warming potential by 61% compared with cement-based mixtures, while improving human health metrics by 9.4% through lower particulate and chemical emissions. However, environmental advantages are partially offset by the production burdens of sodium silicate and sodium hydroxide activators, which may elevate ecosystem and resource depletion impacts by up to 68% when unsustainably sourced. From an economic standpoint, the initial cost of geopolymer stabilization remains higher than that of lime due to activator expenses, with [199] estimating a unit production cost of ≈ 92 USD/m^3, roughly three times higher than ordinary cement concrete. Yet, field-scale studies indicate that this disparity narrows over time owing to superior durability, reduced maintenance, and extended service life. Yu et al. (2024) reported that coupling recycled demolition waste with GGBS–FA geopolymers increased UCS by up to eightfold while simultaneously lowering embodied carbon through waste valorization. Likewise, [200] emphasized that metakaolin-based geopolymers offer a more sustainable and socioeconomically balanced alternative to lime, delivering equivalent strength gains with markedly lower emissions and resource use. Collectively, these findings position geopolymers as an environmentally superior, circular-economy-aligned

Table 6. Comparative analysis of the durability properties of lime- and geopolymer-stabilized soils.

Stabilizer Type	Soil Type	Constituents	Lime %/AA and Molarity	Curing Period	Soaking Period	Durability Properties and Result	Reference
Lime	Black Cotton Soil	FA	3%	28 days	5h/cycle	Lime stabilization improved initial shear strength but failed after one wet–dry cycle, while alkali-activated FA resisted up to five. Rapid mass loss and cracking highlighted lime's vulnerability to moisture fluctuation	[188]
	Silty Sand + Red Mud	FA	3%	7, 28, 90 days	12h/cycle, 12 wet-dry cycles	Strength initially decreased, then stabilized after cycles. High level of cracks at early stages. Mass loss rate at 6–7% after 10 cycles.	[189]
	Laterite Soil	Rice Husk Ash (RHA), Coir Fiber (CF)	8%	56 days	5h wetting, 48h drying (6 cycles)	Compressive strength declined after six wet–dry cycles, and UCS samples failed the durability test, deeming them unsuitable for road applications.	[190]
	Laterite Soil	None	3%, 5%, 7%, 9%	7 days	5h wetting, 42h drying per cycle	Strength increased up to the 4th wet–dry cycle in soils with 5–9% lime, driven by cementitious compound formation and activation of unreacted lime through microcracks.	[35]
	Expansive Soil	None	4%, 12%, 15%	30 days	32 days	After 12 FTCs, the samples exhibited a mass loss of 20–29.5% and a strength loss of 60%. Exhibited very low slaking durability (SDI < 60%).	[13]
	Black Cotton Soil	Iron Ore Tailings (IOT)	8%	7 days wax-cured	7 days	Lime contributes to strength gain but falls short of the 80% requirement. Peak resistance to loss in strength: 37.6% at 8% lime/8% IOT	[191]
	Kaolinite clay	Silica fume and polypropylene fibers	5%	28 days	Not specified	Lowest strength loss of 37.5% due to enhanced cementation and interlock effects. Lime-silica fume reactions filled pores, minimizing ice lens formation during freezing.	[181]
Geopolymer	Clayey soil	PPF and FA	NaOH (10 M) + Na_2SiO_3 (70:30)	7 and 28 days	0, 1, 3, 6, 12 FTCs	Mass <2% after 12 FTCs, which caused gel dissolution, cracking, and reduced Young's modulus with increasing PPF content, while 28-day curing enhanced FTC resistance.	[185]
	Clayey sand	Copper slag (CS)	NaOH (8 M and 11 M) + Na_2SiO_3 (70:30)	14 days	0, 1, 3, 6, 12 FTCs	UCS reduction after initial cycles but stabilized. Untreated soil showed 13% mass loss; stabilized soils exhibited lower loss.	[186]
	Marine soil	CG and CCR	NaOH (8M) + Na_2SiO_3 (1:1)	28 days	5hr/cycle, 12 wet-dry cycles	15% CG-CCR geopolymer provided the highest resistance to strength decay after 12 wetting-drying cycles. Mass loss had a greater impact on strength deterioration than moisture intrusion.	[123]

(Continued)

Table 6. Continued.

Stabilizer Type	Soil Type	Constituents	Lime %/AA and Molarity	Curing Period	Soaking Period	Durability Properties and Result	Reference
	Low-plasticity clay	Jarofix and GBFS	NaOH (5M) + Na_2SiO_3	7 days	5hr/cycle,12 wet-dry cycles	Mass loss, less than 10% after 12 cycles Adequate for use as a subgrade and subbase material. Wet-dry samples showed higher weathering resistance.	[160]
	Granular soi	FA and GGBS	NaOH (8M)	7 days	30, 90, 180, 365 days and 12 FTCs	Strength improved under wetting–drying and freezing–thawing cycles but remained below that of ambient curing, with mass loss limited to 6%.	[159]
	Clayey sand	CS	NaOH (8 M and 11 M) + Na_2SiO_3 (70:30)	14 days	5hr wet + 42h dry per cycle, 12 wet-dry cycles	Maximum mass loss $<6\%$ (below ASTM D559 limit). UCS dropped sharply after cycle 2 but stabilized. Reduced plasticity index (PI) minimized swell/shrinkage.	[67]
	A-4 soil	FA + GBFS	NaOH + Na_2SiO_3	7 and 28 days	4 hr/cycle, 12 wet-dry cycles	The stabilized soil showed just 4.09% mass loss and minimal volume change (0.20% expansion, 0.24% contraction) after 12 cycles, outperforming Colombian standards due to low carbon content and GBFS inclusion.	[187]

Table 7. Comparative advantages and disadvantages of lime and geopolymer soil stabilization.

Criteria	Lime Stabilization	Geopolymer Stabilization
Advantages		
Proven and widely used	Long history of successful use in cohesive soils	Emerging as a high-performance, sustainable alternative
Effective for fine-grained soils	Especially suitable for clayey and expansive soils	Applicable to a wider range of soils, including soft and silty soils
Improves workability and strength	Reduces plasticity, increases UCS over time	Achieves high early strength due to rapid gel formation
Economical	Low cost and locally available	Utilizes industrial by-products (e.g., FA, GGBS, BA), reducing waste
Simple application	Well-known methods and equipment	Reduces compressibility and permeability more effectively Highly resistant to environmental degradation (chemical, freeze–thaw, wet–dry cycles)
Disadvantages		
Environmental concerns	High CO_2 emissions during production	Alkali activators (e.g., NaOH, Na_2SiO_3) are costlier than lime.
Performance limitations	Less effective in non-cohesive or low-reactivity soils	Complex interactions with high-plasticity soils may hinder performance
Slow strength development	Requires longer curing times for full pozzolanic reactions	Optimal mix design requires precise control and standardization
Durability under harsh conditions	Susceptible to degradation in sulphate-rich or saturated environments	Limited field data and lack of standardized protocols for implementation Technology adoption still emerging; requires further validation in large-scale projects

binder for soil stabilization, one whose cost efficiency improves significantly when evaluated over long-term service life.

5. Optimization and modelling in geopolymer soil stabilization

5.1. Machine learning and predictive models

Due to the complex nature of geopolymer behavior, shaped by various mix design and curing parameters, researchers have increasingly turned to predictive modelling, particularly machine learning (ML) techniques, to optimize formulations and minimize the need for time consuming laboratory experiments [170, 201–203]. Machine learning models have become essential tools for predicting the UCS of geopolymer-stabilized soil, significantly enhancing the efficiency and precision of these predictions compared to traditional methods. Various models, including artificial neural networks (ANN) and support vector machines (SVM), are employed to analyze complex relationships within the data, allowing for accurate UCS predictions based on critical input parameters such as soil plasticity index and activator-to-binder ratio [201, 202, 204, 205]. Overall, the use of machine learning in geotechnical engineering reduces reliance on costly lab tests and improves understanding of geopolymer-stabilized soil behavior. It enables accurate UCS prediction, supporting sustainable and effective soil stabilization in construction [201, 205]. However, further research is necessary to support the application of this technique, particularly in advancing the use of predictive models for accurately estimating the mechanical properties of geopolymer-stabilized soils.

5.2. Numerical modelling (fem and simulation approaches)

Numerical modelling, particularly through the Finite Element Method (FEM), plays a vital role in assessing the effectiveness of geopolymer additives in enhancing soil behavior under various conditions. FEM not only validates experimental results but also simulates complex geotechnical scenarios, offering flexible parameter adjustments. This enables deeper insights into load transfer mechanisms and soil–structure interaction beyond what can be captured through laboratory testing alone [2]. For instance, [206] employed Plaxis 8.2 to simulate soil–footing interaction using the Mohr-Coulomb model for soil and a linear elastic plate for the footing. Load–settlement curves were generated for both untreated and lime-mixed geopolymerized RHA (LGR)-stabilized soils under dry and flooded conditions. The model facilitated the prediction of ultimate and allowable bearing capacities and demonstrated improved performance of stabilized collapsible soils, particularly after flooding. Further, [2] showed that geopolymer treatment

significantly enhances the load–displacement behavior and bearing capacity of sabkha soils. Their findings also emphasize the importance of optimizing the geometry of the stabilized layer to achieve improved geotechnical performance. [207] developed a 3D response surface modelling framework to predict the mechanical behavior of geopolymer-stabilized expansive clay. By analyzing variables such as mellowing time (MT), geopolymer fly ash (GFA) content, and curing period, the model effectively quantifies MT-influenced strength and brittleness, providing a generalized predictive tool for field applications.

Overall, the integration of numerical modelling with experimental data significantly improves the understanding and practical application of geopolymer-stabilized soils. It allows engineers to simulate complex soil behaviors, optimize mix designs, and reliably predict in-situ performance, making it an indispensable tool in modern geotechnical engineering.

6. Conclusions

The research concludes that geopolymer soil stabilization presents a viable and sustainable alternative to traditional methods, particularly for improving problematic soils. Geopolymers, formed through the alkali activation of aluminosilicate-rich industrial by-products like FA and GGBS, significantly enhance soil strength, durability, and microstructural integrity. They offer clear environmental benefits, including reduced CO_2 emissions compared to traditional lime.

Specifically, geopolymer-stabilized soils consistently outperform lime-stabilized counterparts in terms of mass retention, strength durability, and resilience to environmental cycles such as wetting-drying. FA-based geopolymers show substantial UCS gains (up to 400% in laterite soil) and reduced compressibility. GGBS also demonstrates superior performance, especially in sulphate-rich soils, by reducing swelling potential and improving load-bearing capacity. However, challenges remain for wider adoption. These include the lack of standardized mix designs and performance criteria for field applications, the cost associated with high activator content for ambient curing, and a limited understanding of long-term behavior under cyclic loads. High plasticity and buffering capacity in some clays can also interfere with effective geopolymerization.

The integration of numerical modelling with experimental data significantly improves the understanding and practical application of geopolymer-stabilized soils. It allows engineers to simulate complex soil behaviors, optimize mix designs, and reliably predict in-situ performance, making it an indispensable tool in modern geotechnical engineering.

Based on these findings, the following recommendations are made:

- Broader Waste Utilization: Explore the potential of other industrial wastes beyond FA and GGBS as geopolymer precursors to further enhance sustainability and waste recycling efforts. For example, the utilization of BA, which is usually abandoned owing to its coarse nature.
- Hybrid Formulations: Investigate hybrid geopolymer formulations that blend calcium sources with FA to develop more effective ambient temperature stabilization solutions.
- Development of hybrid stabilizers (lime + geopolymer), that would enhance mechanical properties of problematic soils.
- Long-Term Performance Studies: Conduct extensive long-term studies on the behavior of geopolymer-treated soils under various environmental and cyclic loading conditions to ensure reliability and predictability in diverse field applications.
- Optimize Activator Cost: Research cost-effective alternatives for alkaline activators to reduce the overall expense of geopolymer stabilization, especially for ambient curing conditions.
- Develop Standardized Guidelines: Establish standardized mix design and performance criteria for geopolymer soil stabilization to facilitate wider commercial adoption and consistent quality in field applications.
- Integration with predictive models and artificial integration (AI).
- Advanced Integration of Predictive, Numerical Modelling and Artificial Intelligence: Promote and conduct more studies on numerical modelling of geopolymer-stabilized soils to further understand complex soil behaviors, optimize mix designs, and accurately predict long-term in-situ performance. This will help bridge the gap between laboratory research and practical field applications.
- Prioritize Geoenvironmental Responsibility: The selection of environmentally responsible precursor additives, avoiding high-carbon, hydrogen sulfide-producing, or heavy metal-containing substances. Integrate comprehensive geoenvironmental assessments, considering factors like soil pH and potential additive interactions, to ensure long-term ecological safety and sustainability.

Authors' contributions

Favour Chukwuebuka Egwu: Conceptualization, Data collection and analysis, Writing the original draft, **Amin Eisazadeh**: Conceptualization, Supervision, Formal analysis, Writing—review and editing.

Data availability

Data will be made available on request.

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