

Comprehensive Analysis of Geo-polymerisation Techniques in Soil Stabilization

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Abstract

The shear strength of soil is a critical factor in the engineering of foundations, and extensive research has been conducted to enhance soil robustness. Historically, studies have incorporated various admixtures and chemical stabilizers to augment soil's geotechnical characteristics. While conventional binders such as cement demonstrate significant stabilization capabilities, their economic feasibility and environmental impact are concerns. In recent years, there has been a growing interest in developing alternative cementitious materials with reduced carbon dioxide emissions. Initiatives have focused on the adoption of eco-friendly binding agents with minimal carbon impact, utilizing industrial by-products like fly ash. This has led to the exploration of such waste materials in the formulation of geopolymer binders, potentially offering an environmentally sustainable and effective solution for augmenting the strength of soft soils. This review emphasizes prior investigations into the utilization of fly ash in the synthesis of geopolymers as a soil stabilizer and examines the prospects and challenges associated with the alkaline activation of alumino-silicate materials (geopolymerization) as a substitute for traditional cement.

Introduction

In the context of burgeoning industrialization and population growth, the imperative for constructing buildings and infrastructure on soft soil has intensified. To augment the load-bearing capacity of soft soil, a variety of soil stabilization methodologies have been implemented. These include vacuum consolidation, the utilization of prefabricated and granular vertical drains, the reinforcement of granular columns through vibration (such as vibrated stone columns and sand compaction piles), and various stabilization techniques like deep mixing, pre-mixing, and the application of lightweight treated soil [1]. Among these, the technique of stabilizing soil using treated soil columns via deep soil mixing, established over three decades ago, is particularly prevalent [2, 3].

The deep stabilization process essentially entails the in-situ modification of soil using stabilizing agents to enhance its shear resistance, amplify load-bearing capabilities, and diminish settlement [1, 4, 5]. Scholarly research underscores numerous advantages of this method, including expedited construction timelines, dependability, adaptability, and efficient resource utilization [1, 6, 7]. Traditionally, calcium-based binders (like lime or cement) have been favored for soil stabilization due to their robustness and ease of use, resulting in the

formation of reinforced soil structures such as soil-cement or soil-lime columns [8, 9, 71]. However, the environmental impact and financial cost of these binding agents have recently come under scrutiny. The production process of cement alone is responsible for approximately 7% of anthropogenic CO₂ emissions globally, primarily due to the decomposition of carbonates [10, 11]. It has been estimated that the production of every tonne of cement results in the emission of an equivalent tonne of CO₂, a greenhouse gas primarily implicated in global warming [12, 70].

In addition to CO₂ emissions, the production of cement also generates significant amounts of nitric oxide (NO_x), with cement kilns being a primary source of this pollutant [68]. NO_x plays a critical role in the formation of acid rain and contributes to the greenhouse effect, exacerbating environmental degradation [73, 13]. Furthermore, there is a global trend of excessive consumption of raw materials necessary for cement production. Consequently, the field of civil engineering is actively exploring alternatives to cement for soil stabilization that are both economically feasible and environmentally sustainable. In recent developments, geopolymers have emerged as a focal point due to their ability to incorporate solid waste and by-products. This not only provides a cost-effective solution but also addresses the management of hazardous residues that require treatment and safe disposal [14].

Geopolymer

Geopolymerization involves the synthesis of a material rich in alumina (Al₂O₃) and silica (SiO₂), forming an inorganic polymer matrix [15]. This process is characterized by a rapid chemical reaction under alkaline conditions with silicon-aluminum minerals, culminating in the formation of three-dimensional polymeric chains. These chains exhibit a distinctive ring structure, primarily constituted of Si-O-Al-O bonds [16]. The geo-polymerization process necessitates the dissolution of aluminum and silicon in an alkaline solution, followed by the transportation of these dissolved species. Subsequent polycondensation leads to the development of a three-dimensional network composed of aluminosilicate structures [17]. An illustration of typical geopolymer structures is provided in Table 1.

The geopolymer matrix demonstrates ionotropic properties akin to those found in zeolites, attributable to the integration of heterocyclic rings of varying dimensions, composed of interconnected tetrahedral units of silica and alumina within its framework [18, 19]. While geopolymers typically exhibit a semi-crystalline morphology, zeolites are characteristically crystalline. The dissolution of fly ash geopolymers in an alkaline medium leads to a rapid disintegration of their vitreous components. This rapid dissolution process limits the time and space available for the gel phase to evolve into a fully crystallized structure, resulting in an amorphous, semi-amorphous, or microcrystalline configuration [20-22].

Contrastingly, the principal binding phase in Portland cement is identified as calcium silicate hydrate (CSH) [23-25]. In geopolymers, however, the binding mechanism is attributed to the formation of a three-dimensional amorphous aluminosilicate network [19, 26-28]. The structural integrity of geopolymers is enhanced through the polycondensation of silica and alumina precursors, eliminating the necessity for calcium-silicate-hydrate gel [29]. The synthesis of these materials typically involves the use of an aluminosilicate raw material activated by a predominantly alkali (sodium or potassium) solution, often supplemented with water glass [30, 31]. A notable feature of geopolymers is their capacity to solidify at ambient temperatures, obviating the need for external heating and thereby reducing CO₂ emissions, presenting a more environmentally sustainable alternative to traditional cement [32].

Geopolymerization technology facilitates the utilization of substantial amounts of both hazardous and non-hazardous waste, thereby diminishing the environmental impact [33]. This technology enables the transformation of solid industrial waste containing aluminosilicates into functional products, as these wastes can be immobilized and stabilized within the geopolymer matrix [34]. Theoretically, any industrial residue with sufficient silica and alumina content can be utilized for geopolymerization [27].

Fly ash act as Alkali-activated material

Industrial residues such as fly ash and slag have demonstrated considerable potential as precursor materials for geopolymer synthesis. Fly ash, in particular, is esteemed for its fine particulate size relative to slag, conferring a higher degree of chemical reactivity [21]. Additionally, fly ash is generated in substantial volumes worldwide and exhibits notable malleability, positioning it as the predominant material for geopolymerization globally [35, 36]. Fly ash originates from the combustion of pulverized coal and is harvested via mechanical and electrostatic precipitation from the gaseous effluents of power generation facilities [37].

Within fly ash, the constituents SiO_2 and Al_2O_3 are predominantly in an amorphous state, facilitating effective chemical interactions with NaOH and Na_2SiO_3 [38]. Fly ash is categorized into two distinct classes based on the composition of these oxides: Class C and Class F. Class C fly ash is characterized by a combined content of ferric oxide, silica, and alumina ranging between 50% and 70% of its total composition, along with a CaO (calcium oxide) concentration exceeding 20%. Conversely, Class F fly ash exhibits a higher proportion of the first three oxides, exceeding 70%, while maintaining a CaO content below 10% [39]. The low calcium fly ash (ASTM Class F) is often preferred as a precursor material over Class C, due to the high calcium content in the latter potentially disrupting the microstructural integrity and interfering with the geopolymerization process (54). It is noteworthy that comprehensive research conducted by the US Department of Energy has established that, when utilized appropriately, fly ash can be employed for soil stabilization without posing significant environmental risks [40].

Alkali-activated Solution

The alkaline solution most frequently utilized in geopolymerization typically comprises a blend of either sodium hydroxide (NaOH) or potassium hydroxide (KOH) with sodium silicate or potassium silicate [41]. Research indicates the feasibility of employing a singular alkaline activator within this process. Additionally, it has been recognized that the specific nature of the alkaline solution plays a crucial role in the polymerization dynamics [42]. When the alkaline solution contains soluble silicates (sodium or potassium), the reaction proceeds at a more rapid pace compared to scenarios where only alkaline hydroxides are used. Empirical studies have validated that an augmented interaction between the source material and the alkaline solution is attainable when a sodium silicate solution is integrated with a sodium hydroxide solution, thereby enhancing the overall efficacy of the geopolymerization process [30, 43].

Using geopolymer to stabilize soil

Extensive research has been dedicated to the application of geopolymers in various fields, including the production of ceramics, earth bricks, mortar, and concrete [44-48]. The concept of using geopolymer binders for soil stabilization is relatively novel. Notably,

geopolymers based on Palm Oil Fuel Ash (POFA) and Fly Ash (FA) have been utilized for stabilizing clay and sandy soils, respectively, with reports of achieving long-term, high-strength outcomes [9, 31, 38, 41, 49-53]. Investigations into the use of FA-based geopolymers for soft soil stabilization have revealed that, compared to Portland cement, FA requires an extended curing duration to attain the desired strength [49, 50, 53, 69].

Phetchuay et al. [38] conducted an investigation on the carbon footprint and strength enhancement of soft Coode Island Silt (CIS) when stabilized with a Class F FA – calcium carbide residue (CCR) geopolymer. Their results indicated that the FA-CCR geopolymer not only improved the strength of CIS but also exhibited lower carbon emissions compared to CIS stabilized with cement. The strength of FA-CCR geopolymer-stabilized CIS was found to surpass that of FA geopolymer-stabilized CIS at both 25 °C and 40 °C.

In the work of Yaghoubi et al. [15], a liquid alkaline activator (L) consisting of 30% NaOH and 70% Na₂SiO₃, with 15% S and 5% FA, was proposed as an effective geopolymer mixture for stabilizing CIS in Deep Soil Mixing (DSM). The NaOH used in their study was prepared at 8 Molarity, while Na₂SiO₃ had a SiO₂/Na₂O ratio of 2.00.

Cristelo et al. [50] explored the use of fly ash as a source of amorphous silica and alumina for enhancing soft soil (sandy clay). Their findings indicated that an increase in fly ash content correlated with improved strength. However, elevating the activator concentration beyond 15 Molar did not yield additional benefits, as comparable results were achievable at 12.5 Molar. This concentration was not only more economical but also chemically more stable, aligning with the findings of [49]. While buried curing did not match the strength obtained under ambient temperature and humidity conditions, the evolution patterns of strength were similar, with the final values being substantial [67].

The synthesis of materials through silica/alumina reactions with alkali agents like sodium or potassium results in a molecular structure remarkably analogous to that of natural rocks, exhibiting comparable stiffness, durability, and strength. The alkaline activation of alumino-silicate materials, known as geopolymerization, is increasingly being recognized as a potential substitute for Ordinary Portland Cement (OPC). This is due to the ability of geopolymers to address many of the common limitations associated with OPC use [21]. The implementation of Deep Soil Mixing (DSM) technology has been extensively investigated [54, 55], with these studies primarily focusing on OPC or OPC combined with Slag (S) or Fly Ash (FA) as the principal binders.

While FA and S have been explored as alternatives to OPC in ground improvement applications, it has been observed that their standalone use does not match the strength imparted by OPC. However, by applying alkaline activation (geopolymerization) to these waste materials, it is possible to ameliorate these shortcomings. This approach potentially leads to the creation of geopolymer binders that are even more robust than their OPC counterparts [49, 51].

Scientific inquiry has delved into the efficacy of alkali-activated low-calcium and high-calcium Fly Ash (FA) as amorphous sources of alumina and silica [49, 50, 56, 57]. Microstructural analyses predominantly reveal that binding gels, such as N-A-S-H and/or C-A-S-H, form within soil voids, facilitating the development of denser microstructures and

consequently enhancing compressive strength. Additionally, it has been observed that the use of high-calcium FA as a precursor leads to more rapid short-term strength gains in stabilized soil.

Pioneering work by Phummiphan et al. [17] utilized high-calcium FA-based geopolymers to stabilize marginal lateritic soil, creating an environmentally friendly base for pavement in Thailand. Their research indicated that the early strengths of geopolymer-stabilized marginal lateritic soil could be augmented by incorporating waste calcium carbide residue (CCR) [17, 58]. The smaller-sized CCR functioned as a binder, reacting with the alumina and silica present in the soil and FA, resulting in the formation of Calcium Silicate Hydrate (CSH) [59].

Further investigations by Phummiphan et al. [60] explored the use of two different waste types (Class C FA and Granulated Blast Furnace Slag (GBFS)) with liquid alkaline activators for stabilizing marginal lateritic soil to develop "green" pavement base materials. The replacement of FA with GBFS in geopolymer formulations enhanced the early seven-day Unconfined Compressive Strength (UCS) of the stabilized soil, particularly with high sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) ratios (NS:NH \geq 80:20). Optimal GBFS concentrations corresponded to the highest seven-day UCS, which decreased in accordance with the NS:NH ratio. GBFS exhibited a significant impact on the early and long-term UCS of FA geopolymer-stabilized lateritic soil at lower NS:NH ratios of 50:50, with the greatest UCS observed at 28 and 60 days for ratios of 60:30:10 LS:FA:GBFS and 90:10 NS:NH. Microstructural analysis revealed the coexistence of calcium silicate hydrate (CSH) and sodium alumina silicate hydrate products within the FA geopolymer-stabilized LS/GBFS blends. These results suggest that GBFS, traditionally considered a waste product, can be effectively utilized as a partially reactive replacement material in FA geopolymer pavement applications.

Sargent et al. [61, 72] conducted research on the potential of utilizing alkali-activated by-products like FA, Ground Granulated Blast Furnace Slag (GGBS), and red gypsum (RG) to modify the geotechnical properties of soft soil (alluvial soil). Their experiments demonstrated significant enhancements in soil strength through the use of alkali-activated GGBS, GGBS-FA, and GGBS-RG.

Phetchuay et al. [62] investigated the production of pavement material meeting the Thai national road authority's compressive strength specifications using silty clay with FA as a precursor and CCR as an alkali activator. This study confirmed that CCR could be sustainably used as an alkaline activator in geopolymer-stabilized subgrade materials, thereby repurposing substantial quantities of material traditionally viewed as waste for landfill. It has been experimentally validated that geopolymers can be effectively utilized as soil stabilizers for clay soils [63]. Additionally, the application of slag-based geopolymers with marine clay has been examined [64].

Potential Research opportunities

The corpus of scholarly literature on fly-ash based geopolymers predominantly focuses on their application in the domain of building materials, with comparatively fewer studies addressing their use in soil stabilization. In the realm of geopolymer-stabilized soil, the unconfined compressive strength (UCS) is commonly adopted as a practical measure for assessing strength development. However, aspects such as the shear and consolidation behaviors of geopolymer-stabilized soil remain under-explored.

To comprehensively understand the shearing behavior of geopolymer-stabilized soil, triaxial testing methodologies could be implemented. These tests, which simulate the conditions that soil would encounter in situ, including pressure and deformation, are instrumental in evaluating the soil's resistance to shear under various stress states. Additionally, the oedometer test, a standard procedure for assessing soil consolidation, can be effectively employed to analyze the consolidation characteristics of soil treated with fly ash-based geopolymer. This test would be particularly valuable for understanding how the soil behaves under long-term loading conditions.

For a holistic evaluation, it is essential that these tests encompass both short-term and long-term curing periods [66]. This approach would allow for a more comprehensive understanding of the behavior of geopolymer-stabilized soil over time, encompassing both the initial setting phase and the subsequent evolution of mechanical properties. Such research would significantly contribute to the field, offering insights into the long-term performance and stability of geopolymer-stabilized soils under various environmental and loading conditions.

Conclusion

This study reviews soil stabilization via geopolymerization, highlighting its effectiveness in utilizing solid waste and by-products for environmental management. Geopolymerization, characterized by the alkaline activation of aluminosilicate materials, offers a promising alternative to Ordinary Portland Cement (OPC) by addressing its limitations. Enhanced reactivity is achieved by combining sodium silicate and sodium hydroxide solutions. In particular, Fly Ash (FA) and Calcium Carbide Residue (CCR) geopolymer-stabilized soils show superior performance due to the formation of both Sodium Aluminosilicate Hydrate (N-A-S-H) and Calcium Silicate Hydrate (C-S-H), thereby improving structural properties.

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