A review on geopolymerisation in soil stabilization

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Abstract. Shear strength of ground is a vital part of foundation design for construction and many researches have been done throughout the years for soil strength improvement. Previously, research has employed various admixtures and chemicals in hope to stabilize soil improving its geotechnical properties. Common binders like cement yield high stabilization potential but it may not be economical viable and contributed to environmental issue. For the past few years, there is much interest in developing a new cementing agent that does not have high carbon dioxide emissions. Efforts have been made to utilize environmentally friendly binding agents with low carbon footprints by employing industrial waste such as fly ash. These eventually leads to the use of such waste by-products in the production of geopolymer binders that can be used to increase the strength of soft soil may be proven to be both environmentally friendly and efficacious. This review highlights previous effort regarding the use of fly ash for geopolymers production as a stabilizer for inorganic soils and discuss on potential and possible limitation on alkaline activation of alumina-silicate materials (geopolymerisation) as a cement replacement.

1. Introduction

As both industrialization and population have grown rapidly, the construction of building and infrastructure on soft soil has become imperative. Several processes for stabilising soil have been employed to increase the extent to which soft soil can bear loads. Such processes include vacuum consolidation, prefabricated and granular vertical drains, reinforcing rib granular columns (vibrated stone columns, sand compaction piles), and stabilization techniques (deep mixing, pre-mixing, lightweight treated soil) [1]. One of the most widespread techniques for stabilizing soil, which was first developed three decades ago, involves using treated soil columns with deep soil mixing [2, 3].

Broadly speaking, the deep stabilization process modifies soil on site by employing stabilizing agents to treat underperforming soil to mitigate against shear deformation, increase the load-bearing capacity, and reduce settlement [1, 4, 5]. Published research has highlighted how this technique can yield several benefits: accelerated construction times, reliability, flexible application, and effective use of resources [1, 6, 7]. Binders with a calcium basis (lime/cement), which are highly robust and easy-to-use, were traditionally used to stabilize the soil and will produce a firmer and stronger ground improvement; i.e., soil-cement or soil-lime columns [8, 9]. Recently, the use of such binding techniques has been scrutinized, as manufacturing the binders is detrimental to the environment and they are also costly [9]. The processed by which cement is manufactured currently contribute approximately 7% of man-made CO2 emissions globally due to carbonate decomposition [10, 11]. Researchers have calculated that a tonne of CO2, the greenhouse gas held chiefly responsible for global warming, is produced for every tonne of manufactured cement [12]. As well as emitting CO2,
manufacturing cement creates NOx. Cement kilns produce much of this nitric oxide, which is a major contributor to acid rain and the greenhouse effect [13]. Also, there is global overconsumption of the raw materials for cement production. Thus, the civil engineering industry is continually searching for a cement replacement in terms of soil stabilization that is viable and sustainable. In recent times, geopolymers have become the centre of attention as they appear to use solid waste and by-products, thereby offering cost-effective solutions to issues involving hazardous residue that needs to be treated and stored [14].

2. Geopolymer
Geopolymer is the product of a blend of materials that are high in alumina (Al₂O₃) and silica (SiO₂); it is inorganic [15]. Polymerization uses an exceptionally quick chemical reaction in alkaline conditions with Si-Al minerals, resulting in 3-D polymeric chains and a ring structure comprised of Si-O-Al-O bonds [16]. Geo-polymerization requires Al and Si to be dissolved in the alkaline solution before the dissolved species is transported. Polycondensation subsequently forms a three-dimensional network of aluminosilicate structures [17]. Three examples of standard geopolymer structures are shown in Table 1. below:

| Geopolymer Structure                     |
|------------------------------------------|
| Poly(sialate)Si : Al = 1                  |
| (−Si −O− Al −O−)                         |
| Poly(sialate - siloxo)Si : Al = 2         |
| (−Si −O− Al −O− Si −O−)                  |
| Poly(sialate - disiloxo)Si : Al = 3       |
| (−Si −O− Al −O− Si −O− Si −O−)           |

Table 1. Examples of geopolymer structures.

The geopolymer matrix exhibits ion exchange properties that replicate those of zeolites as a result of the inclusion of rings of various sizes that are formed of cross-linked tetrahedral silica and alumina units within the network [18, 19]. Geopolymers exhibit a semi-crystalline structure, while zeolites are typically crystalline. When the geopolymers of the fly ash are combined with an alkaline dissolution, the vitreous constituents rapidly dissolve. As such, there is insufficient space and time for the gel to develop into a crystallized structure that evolves into an amorphous, semi-amorphous, or microcrystalline structure [20-22].

It is widely recognized that the major binding component of Portland cement is calcium silicate hydrate (CSH) [23-25]. However, the binding constituents of geopolymers result from the development of a 3D-amorphous aluminosilicate network [19, 26-28]. There is no requirement for calcium-silicate-hydrate gel with geopolymers, as they use silica and alumina precursor polycondensation to increase their strength [29]. These materials are generally synthesized by employing a raw material of aluminosilicate and activated with a solution chiefly comprising the alkalis sodium or potassium, along with water glass [30, 31]. The innovative element of geopolymers is that they will harden at room temperature; there is no need for additional temperature application, which thus reduces CO2 emissions, offering a more ecologically responsible cement alternative [32]. Geopolymerisation allows the use of significant quantities of both hazardous and non-hazardous waste to make new products and reduce the environmental footprint [33]. Geopolymer technologies can take solid industrial waste containing aluminosilicates and turn them into usable products, as the waste can be immobilized and stabilized within the geopolymer network [34]. In theory, any industrial waste that has enough silica and alumina contained within it may be used for geopolymerisation [27].

3. Fly ash act as Alkali-activated material
Amongst industrial by-products, fly ash and slag have shown potential for turning into geopolymers. Fly ash is highly regarded as it has a fine particle size compared to slag, and so has a high level of reactivity [21]. Furthermore, fly ash is produced in enormous quantities globally and is very workable; this makes it the most popular material for geopolymerisation in the world [35, 36]. Fly ash derives from burning coal powder and is collected with mechanical and electrostatic separators from the gas outputs of power plants [37].
In fly ash, SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} are in amorphous phase, which can react effectively with NaOH and Na\textsubscript{2}SiO\textsubscript{3} [38]. Fly ash is divided into two classes based on which of these oxides it contains, Class C and Class F. In Class C fly ash, there will be a combined content of ferric oxide, silica, and alumina of between 50% and 70% of the total, with a CaO percentage of over 20%. Fly ash in Class F will contain the first three oxides in a percentage over 70%, with the last named below 10% [39]. Low calcium fly ash (ASTM Class F) is generally preferred as a raw element compared to Class C. High amounts of calcium can alter the microstructure and interfere with the process of polymerization. It should be noted that an extensive study undertaken by the US Department of Energy concluded that fly ash, properly employed, can be used for soil stabilization without damaging the environment [40].

4. Alkali-activated Solution
The alkaline liquid most commonly used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) with sodium silicate or potassium silicate [41]. It has been shown to be possible to use a single alkaline activator. It has also been noted that an important part of the polymerization process relates to the type of alkaline liquid employed [42]. If an alkaline liquid holds soluble silicate (sodium/potassium), reactions occur at a faster rate than when only alkaline hydroxides is used. It has been confirmed that an enhanced reaction between source material and solution can be achieved if a solution of sodium silicate is added to the solution of sodium hydroxide being used for alkaline liquid [30, 43].

5. Using geopolymer to stabilize soil
Many studies have focused on geopolymers, and they are employed in the manufacture of ceramics, earth bricks, mortar and concrete [44-48]. Using geopolymer binders to stabilize soil is a relatively new concept. Palm oil fuel ash (POFA) and fly ash (FA) based geopolymers have been employed, respectively, for the stabilization of clay and sandy soil, and long-term high-strength results have been reported [9, 31, 38, 41, 49-53]. Experiments have been undertaken using fly ash based geopolymers to stabilize soft soils, though it has been found that to achieve the target strength for fly ash compared to Portland cement requires a longer curing time [49, 50, 53].

Phetchuay, et al. [38] performed study regarding the carbon footprint and strength of soft Coode Island Silt (CIS) stabilized using a class F fly ash (FA) – calcium carbide residue (CCR) geopolymer. Their findings demonstrated that FA-CCR geopolymer enhanced the strength of CIS and its carbon emissions were comparatively low as compared with CIS stabilized using cement. The strength of FA-CCR geopolymer-stabilized CIS exceeds that of FA geopolymer-stabilized CIS at 25°C and 40°C.

Yaghoubi, et al. [15] proposed that a liquid alkaline activator (L) comprising 30% NaOH and 70% Na\textsubscript{2}SiO\textsubscript{3}, with 15% S and 5% FA would be an appropriate geopolymer combination for the stabilization of Coode Island Silt (CIS) in DSM. NaOH used in their study was prepared to 8 Molarity while Na\textsubscript{2}SiO\textsubscript{3} had SiO\textsubscript{2}/ Na\textsubscript{2}O ratio of 2.00.

Cristelo, et al. [50] made a study of the use of fly ash as a silica and alumina amorphous source for the improvement of soft soil (sandy clay). This study found that increasing fly ash led to a gain in strength. Increasing activator concentration up to 15 Molar did not confer benefits, as similar results could be obtained at 12.5 Molar, with 12.5 Molar being more economical and more chemically stable. This concurred with the studies of [49]. Compared to curing with ambient temperatures and humidity, buried curing did not offer the same strength, but the patterns of strength evolution were similar, and the final values were significant.

When materials are formed by employing silica/alumina reactions with alkali agents such as sodium or potassium, they have a very similar molecular structure to natural rock, and are as stiff, durable and strong. The alkaline activation of alumina-silicate materials (geopolymerisation) is already being seen as a viable replacement for OPC, as these new materials are able to overcome most of the familiar drawbacks of using OPC [21]. The use of DSM technology has already been closely examined [54, 55]. However, in those studies, the chief binder was OPC, or OPC admixed with S or FA. FA and S have been employed as a replacement for OPC for ground improvement. However, it
has been noticed that when it is utilised alone, it is not as strong as OPC. By employing alkaline activation (geopolymisation) with such waste, then these issues might be resolved, making geopolymer binders that were even stronger [49, 51].

Researchers have examined the extent to which alkali-activated low-calcium and high-calcium FA are effective as alumina and silica amorphous sources [49, 50, 56, 57]. Primarily investigations involving analysis of the microstructure have found that binding gels (either N-A-S-H and/or C-A-S-H) develop within the soil voids, assisting the formation of more compact microstructures which, in turn, lead to greater compressive strength. Furthermore, researchers have found that short-term strength gains in stabilized soil occur more quickly if high-calcium FA is employed as a precursor.

Phummiphan, et al. [17] were the first to employ high calcium FA-based geopolymer with stabilized marginal lateritic soil for the creation of an eco-friendly base for pavement in Thailand. They demonstrated that the early strengths of geopolymer stabilized marginal lateritic soil could be increased by the addition of waste calcium carbide residue (CCR) [17, 58]. Small-sized CCR was shown to work as a binder, reacting with the alumina and silica in the soil and FA, creating Calcium Silicate Hydrate (CSH) [59].

Phummiphan, et al. [60] investigated the possibilities of employing two different waste types (Class C FA and GBFS) with liquid alkaline activators for the stabilization of marginal lateritic soil to create "green" base material for pavements. GBFS replacement enhanced the early seven-day UCS of FA geopolymer stabilized LS in the high sodium silicate (Na$_2$SiO$_3$, NS) solution sodium hydroxide (NaOH, NH) ratios tested (particularly NS:NH $\geq$ 80:20). The ideal level of GBFS concentration offered the best seven-day UCS decreases in line with the NS:NH ratio. GBFS had no significant influence on the early/long-term UCS of FA geopolymer stabilised LS at low NS:NH of 50:50 the greatest UCS at 28 and 60 days was discovered to be for ratios of 60:30:10 LS:FA:GBFS and 90:10 NS:NH, and these are the recommended practical ratios. Analysis of the microstructure showed that calcium silicate hydrate (CSH) and sodium alumina silicate hydrate products coexist within FA geopolymer-stabilized LS/GBFS blends. These findings show that GBFS, previously generally seen as a waste product, can be employed as a replacement, partially reactive, material for FA geopolymer pavement applications.

Research work was undertaken by Sargent, et al. [61] regarding the possibility of employing certain alkali-activated by-products; for example, fly ash (FA), blast furnace slag (GGBS), and red gypsum (RG) to modify the geotechnical properties of soft soil (alluvial soil). Tests showed that untreated soil could be significantly strengthened by employing alkali-activated GGBS, GGBS-FA, and GGBS-RG.

Phetchuay, et al. [62] examined whether a pavement material with a compressive strength meeting the specifications of the local national road authority of Thailand could be produced by employing silty clay with fly ash as a precursor and calcium carbide residue (CCR) as an alkali activator. This research has shown that CCR may be employed as a sustainable alkaline activator with geopolymer stabilized subgrade materials, and this will enable notable amounts of what used to be regarded as a waste product to be usefully employed rather than dumped in landfill [62]. It has been shown to be feasible in experiments to employ geopolymers effectively as a soil stabilizer for clay soil [63]. The use of a geopolymer based on slag with marine clay has been investigated [64].

6. Potential Research opportunities

While there is a wealth of literature available on using fly-ash based geopolymers, they nearly always refer to their use in building material. There are some researches reporting the usage of geopolymer for soil stabilization. In the investigation of strength development of geopolymer stabilized soil, unconfined compressive strength is employed as a practical indicator. Shear behaviour as well as consolidation behaviour of geopolymer stabilized soil has not been investigated. Triaxial tests could be used to study the shearing behaviour of geopolymer stabilized soil. Oedometer tests can be used to investigate the consolidation behaviour of soil when it has been treated with fly ash based geopolymer. These tests should investigate both short-term and long-term curing periods.
7. Conclusion

The current paper reviewed on geopolymerisation to stabilize soil. Geopolymers have become the centre of attention as they appear to use solid waste and by-products, thereby offering cost-effective solutions to issues involving hazardous residue that needs to be treated and stored. The alkaline activation of alumina-silicate materials (geopolymerisation) is already being seen as a viable replacement for OPC, as these new materials are able to overcome most of the familiar drawbacks of using OPC. It has been confirmed that an enhanced reaction between source material and solution can be achieved if a solution of sodium silicate is added to the solution of sodium hydroxide being used for alkaline liquid. The FA-CCR geopolymer-stabilized soil demonstrates efficiency than FA geopolymer-stabilized soil due to two geopolymerisation products coexist: Sodium Aluminosilicate Hydrate (N-AS-H) and Calcium Silicate Hydrate (C-S-H).

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