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Case study

Role of industrial based precursors in the stabilization of weak soils with geopolymer – A review

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ABSTRACT

The performance and durability of any building component do not only depend on the quality of construction material used but is also defined by the ground condition beneath the structural foundation. Soil properties are difficult to predict and change depending on the soil profile location. Expansive soils, sulfur-rich soils, and hydrocarbon-contaminated soils are considered the most vulnerable due to their sudden shrink-swell assets, pollutants, and complex clay mineral contents. Soil untreated for engineering applications has never been recommended. Numerous geotechnical techniques and natural or man-made additives are available to improve the engineering performance of these soils. But most of those techniques are obsolete due to poor performance. To elucidate this, in recent years, the geopolymer has been introduced in the form of an alkaline activated solution as an alteration to the conservative methods of soil stabilization. It was also hoped that using geopolymer in soil stabilisation would reduce resource exploitation and pollution and improve expansive soil engineering performance. This review examined whether strengthening poorly stabilised soil can improve engineering performance while minimising environmental impacts. The objective of the review was to analyse whether they could be accomplished by accumulating different industrial precursor additives or activators with an alkaline activated solution for soil mechanical behaviour improvement.

1. Introduction

Expansive soil varieties are gauged as most precarious and vulnerable in the worldwide construction industry, owing to their impulsive expansion and shrivelling property. In case, when the structures are built-in waterlogged areas their performance fails due to the influence of the swelling phenomenon. During an earthquake, the contacts of expansive soil particles break down and become loose as which leads to soil shear failure. A countless number of building damages has been previously encountered during sudden soil swelling and shrinkage over past decades, for structures built on expansive soil as shown in Fig. 1. Provis et al. [84], Davidovits, Huaman, and Davidovits (2019) and Vijayan et al., [108] they proposed that as usual, most of the construction sites have adopted

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chemical treatments over those expansive soils at defined proportions, to increase its strength and stability adequately. This is to allow the soil particles to keep the original structure, to support the load impending during the construction of the building or throughout its service life [120]. Typically, the chemical treatment has been acquainted with the soil by the means of applying lime or cement.

The properties of expansive soil get altered by enhancing the stabilization mechanism by rearranging the microstructure of soil followed by the action of flocculation, hydration, and bonding of particles. Although conventional treatment is suggested for most of the geotechnical works, they could harm the environment unintentionally. Enduring exploitation of raw materials and production of cement leads to the sudden depletion of materials and raises the level of global temperature by discharging excess CO_2 into the atmosphere Vijayan et al. [108]. Hence, it is essential to find unconventional materials with sustainable substances as novel and alternative stabilization materials to lime and cement. On the other hand, Marvila et al. [66] have describe that the usage of alkaline activated material has some complications during the difficulty handling this material, which can cause burns or respiratory problems when inhaling the hydroxides dust used in the solution and on the other hand, the alkali-activated materials are linked to activators who still use commercial materials, causing resource exploitation and material price increases. Hence it was recommended to avoid the residue taking a long time, consuming a lot of energy.

In the field of civil engineering, for the past few decades, some of the inorganic alkaline aluminosilicate activated materials have been commonly known as "geopolymer". It was widely used as cementing material in several civil engineering products. Provis et al. [84], Davidovits, Huaman, and Davidovits (2019), Vijayan et al. [108] and Provis and Bernal [87]. The materials made up of those alkaline activated forms are proved as excellent construction materials due to their mechanical, chemical, and thermal resistance properties. Marvila et al. [66] have suggested that historically, Glukhovsky have developed alkali-activated materials in the Soviet Union in the 1950s and 1960s. The researcher created alkaline systems by mixing volcanic materials with sodium hydroxide activating solutions. In response, he obtained hydrated calcium silicate phases (C-S-H) and it was termed as soil silicates. Followed by him, the Davidovits, a French researcher and chemist, developed an alkali-activated material using natural silicon and aluminum-rich materials, such as kaolin clay, activated by alkaline liquid solutions. Geopolymers are materials created by a polymerization reaction similar to that which produces polymeric materials. Geopolymers, unlike polymers, are inorganic. Because of this, these materials are also known as inorganic polymers. Further, the Davidovits presented a complex microstructural analysis of geopolymers using polysialate networks in 1994, and Wang and Scrivener have studied the alkali-activated calcium-rich materials in 1995. These surveys helped researchers learn more about alkali-activated materials. In 2011, Habert has evaluated the environmental impact of geopolymer concrete production by comparing its life cycle to that of portland cement. The author demonstrated the environmental value of alkali-activated concrete as an alternative to conventional portland cement.

In 1950 in Russia, it was notorious that some of the tall buildings were constructed with a kind of alkaline activated compound made by the amalgamation of alumina silicate and C-H-S Vijayan et al. [108]. The success of geopolymer in any application depended on the development of the binding phase within the applied materials. Those phases of binding were, usually achieved by the response of alumina silicate compounds like fly ash, steel slag, and calcined clay particles synthesis with sodium or potassium-based alkaline solution Provis and Bernal [87]. In the year 1957, the term "soil cement" was coined by Glukhovsky of Russia. He states that this kind of binding material, which incorporates together with the clay and alkaline solution in the required proportion, shows that similar properties of Ordinary Portland Cement (OPC) [56]. Chenhui Jiang et al. [48] has described that the potential application of geopolymer in the field of civil engineering, that the concrete structures, transportation infrastructures, steel and other metal structures,

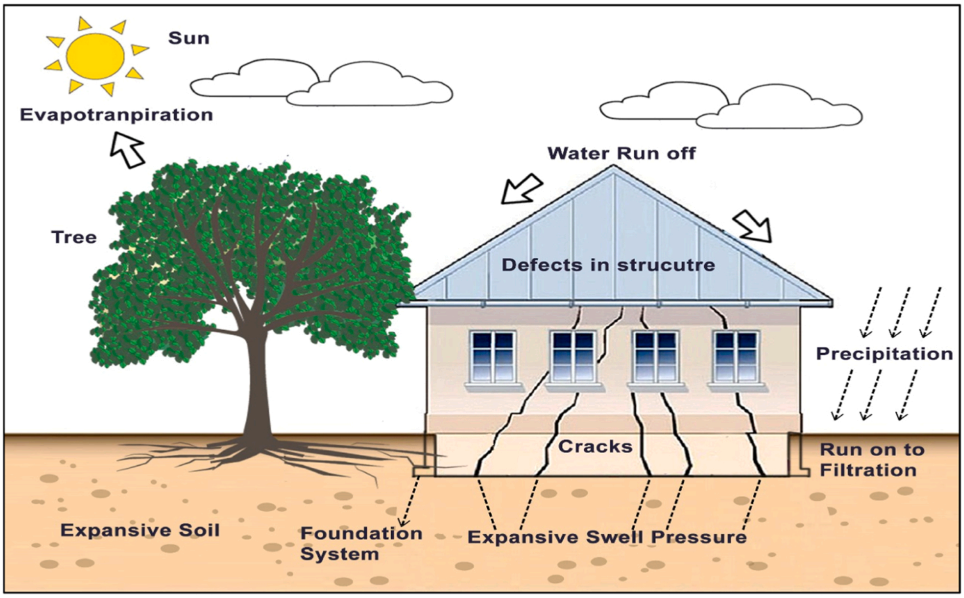

Fig. 1. Structural failure due to the property of expansive soil.

wood structures and products, as well as decorative surface layers of buildings and other structures, have all been protected by Geopolymer concrete. In the case of concrete structures, direct application of Geopolymer concrete seals the exposed surface of the concrete. Another application is to keep the reinforcing bar from corroding.

While compared to OPC, the alkaline activated materials are less aggressive, due to the deprived emission of CO2 into the atmosphere. It was reported that the cement prepared by the method of geopolymers is showing the best performance towards reduction of CO_2 as 26–45% than normal OPC [56]. Further, the activator solution used in the process of geopolymer was prepared in the form of an aqueous solution with a combination of silicates, hydroxides, and carbonates [69]. The alkaline activated materials are mostly composed of the high amount of silica, alumina, and calcium-rich materials. Some of the extensively used materials are fly ash, ground granulated blast furnace slag (GGBS), and steel slag. As per the latest research, it was found that using a single type of activating binders like sodium silicate in the stabilization of soil is considered as a most lavish component. Hence, it was recommended that to develop the novel method should prime with the different nature of activators prepare from the selected less aggressive materials [89]. Similarly, in the present scenario, some of the fibres were derived naturally or synthetically to introduce with the geopolymer polymer reaction as an eco-friendly material. De Azevedo. et al. [12] discuss a comparison of geopolymer matrices reinforced with natural fibres versus those reinforced with synthetic fibres in terms of physical and mechanical performance. Natural fibres, on the other hand, are sensitive to alkaline environments and have substances on their surface that prevent good matrix adhesion. To solve this problem and improve composite performance, fibre pre-treatment is required. Despite a small difference in strength between the two composites, pre-treatment of natural fibres combined with other practises, such as geopolymer trace optimization and curing conditions, can equalise the performances. As a result, natural fibres can be used instead of synthetic fibres without compromising the material's performance.

This present paper, is aimed to review the process and effect of geopolymer in the stabilization of expansive soil. The focus is placed on introducing diverse additive materials selected from industrial wastes and effluents with alkaline solutions under different molar and curing conditions. The major engineering properties like compression strength, permeability, modification of the structural arrangement of stabilized soil were investigated in state of the art analysis. It is believed that this work, reviewing the performance of various additive materials with geopolymer in the stabilization of expansive soil, has laid a better platform to make further research in the field of geotechnical engineering knowledge development.

2. Science behind geopolymerization

Geopolymers are formed by the reaction of alkali-activated silicate or hydroxide, which are introduced in the form of powder with binders to make a solid aluminosilicate material. In general, the term "Geopolymer" was labelled by several researchers as alkali bonded ceramics, hydro ceramics, soil cement, and mineral polymers. The reaction process of geopolymer was first analysed in 1978 [28], to extend the usage of geopolymer as inorganic polymer material for several industrial applications. Usually, the structure of geopolymer was identified as a series of interlocking networks and chains of mineral compounds that are linked by the effect of covalent bonds. The molecular unit involved in the structure of geopolymer was shown in Fig. 2.

Before introducing the process of setting, it is very important to comprehend the steps engaged in the geopolymer formation process. By swotting the rate of reaction, it becomes easy to understand the growth of the geopolymer gel network could occur in any medium [85]. In common, the geopolymer was termed through the combined reaction of alkali silicate or hydroxides for the activation of aluminosilicate binders with high pH concentration [83].

$$M_n[-(siO_2)\text{–}AlO_2]_n\ wH_2O \tag{1}$$

The chemical reaction of geopolymer was designated based mostly on poly siliates and aluminosilicates. The molecular network of siliates contains AlO_4 and SiO_4 connecting through exchanging the oxygens and frame tetrahedra link with negatively charged particles by the reaction of Al^3+ ions. In general, the reaction of tetra-aluminosilicate was expressed using the empirical formula (Eq.1) [26].

Where "M" denotes the particles of cations derived from calcium, sodium, or potassium and "n" indicates the amount of

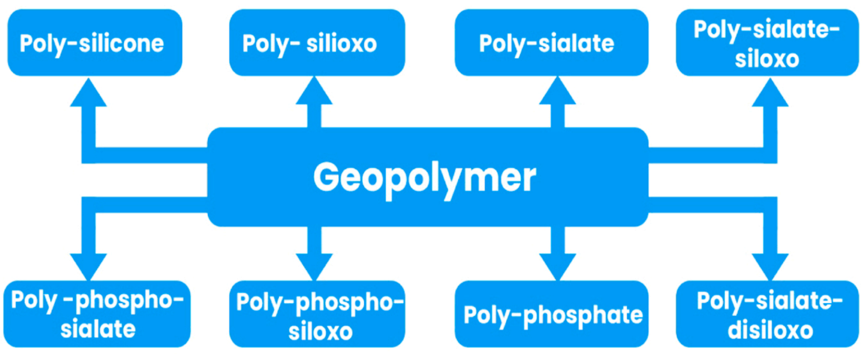

Fig. 2. Molecular units of geopolymer.

polycondensation. In the case of poly siliates, the polymer is created in the shape of a ring and chain through the reaction of Al^{3+} and Si^{4+} compounds with the exchange of oxygen in the shape of semi-crystalline or amorphous. But this stage of polymers framers are not widely used in industrial application. In other case [64] during the alkaline activation reaction of geopolymers, ferrosialates (poly-sialates containing iron oxide) can form. Iron can be found in the ferrosalate chain in three different forms: trapped in the main chain, balancing load in interstitial sites, or as Fe3O4 oxide linked to the chain through secondary bonds. Iron forms [Fe(OH)]2 + instead of [Al(OH)4]-. It can also partially replace [Si(OH)4]- in geopolymer chains. In usual, the alkali-activated materials' reaction mechanism are categorized by the presence of calcium oxide content. Precursors of low calcium content, also known as geopolymers, are consider as primarily aluminium silicate and the calcium-rich materials (Ca/(Si+Al)> 1) exhibit an alkali-activated reaction similar to portland cement, but forming C-A-S-H gels known as tobermorite.

Some researches revealed that, series trials have been made to form the different 3D structures of geopolymer (Rocha, Klinowski, and Adams 1991). But it is very difficult to comprehend the three-dimensional structure of geopolymer in 2D way due to its inherent syndrome. Furthermore, it also noticed that the gel binder of geopolymer has structural similarities while reacting with zeolitic kind of materials. Especially, when high elevated temperature, low proportion of alumina silicate, and high-water content, the geopolymer gel solution were formed nanocrystalline material with zero structural order. Rocha et al. [92] describe the modulation of geopolymer activation by synthesizing the alumina silicate and zeolite together under the controlled hydrothermal condition to find the rate of intermediate reaction of amorphous gel phase with condensed tetrahedral structure.

The geopolymer which was recommended for industries should be used in semi-crystalline or complete crystalline form, and also the hardiness of geopolymer material was decided based on its amount of polymeric reaction. Hence it is recommended that to predict the quality of any geopolymeric material first the degree of reaction and form of crystalline needs to be investigated. Fig. 3 depicts the complete polymeric reaction of a potassium-based geopolymer with successful polycondensation for further reference.

3. Alkaline activators and their concentration in geopolymer

In the process of polymerization, the role of alkali earth and alkali-based cations are vital. The alkaline solution is defined as the type of solution which has a higher pH value than the water. These solutions are prepared either in the form of homogenous or heterogeneous. In general, the synthesis of geopolymer was initiated by an aluminosilicate binder using alkali silicate or hydroxides. Mostly, the anions of alkaline activators are grouped into 4 categories namely alkali carbonates, alkali silicates, alkali sulfates, and alkali hydroxides [27] and [58]. The common aluminosilicate materials used as a precursor are flyash, metakaolin, and blast furnace slag. They are reacted jointly with the alkaline activator solution at an ambient temperature to initiate the chemical synthesis of geopolymer. In the rheology of geopolymer mixture, the dosage and the nature of the activator play a key role to decide the property and structure of a hardened geopolymer material [122]. Hardjito et al. [37] reveals that the geopolymer chemical properties are more similar to zeolite with amorphous microstructure, and to make the high alkaline geopolymer paste, it is essential to use the source materials based on aluminium and silicon. While incorporating alkaline solution in the geopolymer mixture, it not only dissolves the precursor of silica and alumina and also initiates the reaction of hydrolyses over the surface of precursor particles and allows starting the reaction between existing dissolved particles and silicate substances Galiano et al. [61]. The reaction and formation sequence of silica and alumina with an alkaline solution in polymerization was illustrated in Fig. 4.

In general, a common process of geopolymerization is described by the following stages such as dissolution, migration of ions, gelation between the particles, reorganization of molecules, and hardening of particles (Van Jaarsveld et al. [46]). The polymeric structure of silica and alumina are combined as the building units of any geopolymeric structure. During the gel phase, the reaction of

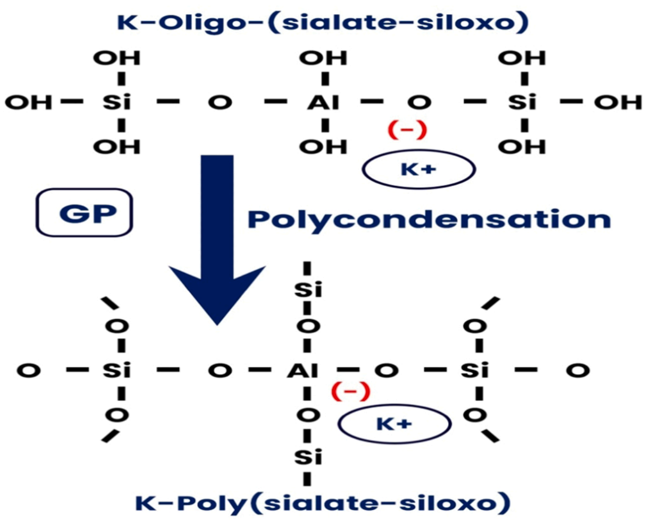

Fig. – 3. Polymerization Process of Geopolymer.

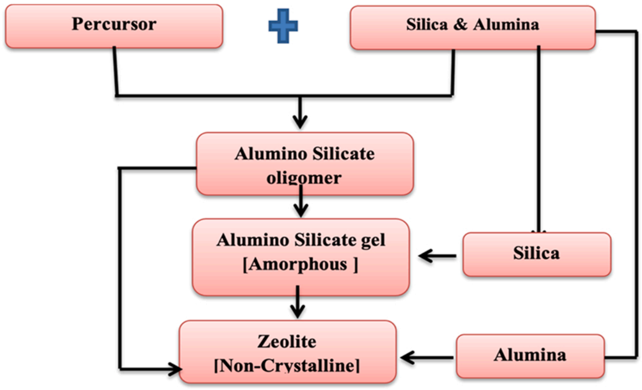

Fig.–4. Sequence of geopolymerization.

aluminosilicate and the alkaline solution was reached a peak stage due to the process of copolymerization of alkali metals (Provis and Van Deventer 2007). Xu et al. [117] pronounce that the activator concentration is one of the major parameters to decide about the property of geopolymer material. They also suggested that an increase in the concentration of activator solution and modulus of sodium silicate can leads to an increase in the mechanical strength of geopolymer. On the other hand, it was noted that increasing activator concentration may limit the mobility of ion particles and delay the time of polymerization [6]. In most cases, when the aluminosilicate materials react with a high concentration of alkaline, they have crumbled the bond of the siliceous compound what leads to the formation of alumina silicate gel with a new phase of alumina (Błaszczyński and Król [17]). The construction industry is currently researching the use of sustainable raw materials (precursors or activators) to reduce its environmental impact. Researchers have also sought to better understand alkali-activation reactions, their kinetics, and the factors that influence them among other things. Mendes et al., (2020) have discussed that the usage of industrial silicates like sodium silicate increases CO_2 and energy emissions associated with alkali-activated binders. These materials are also toxic and costly due to their high pH. In response, new activators rich in silica or alkaline cations have been developed as an alternative alkaline activator that includes rice husk ash, glass waste, silica fume, baggase ash and the residues of calcium and aluminium. These materials are soluble, allowing the release of ions required for alkaline activation. The activating solution must also have a pH high enough to promote aluminate and silicate ion dissolution and hydrolyze the surface of the raw material particles.

De Azevedo et al. [12] have investigated that the addition of glass waste has improved the properties like water absorption in geopolymerized specimens and met normative and literature precepts like mass loss in some mixtures, indicating its suitability for making tiles. Afonso et al. [11] have incorporated glass polishing waste from the flat glass polishing industry into geopolymeric mortars for measuring the durability of specimens for wetting and drying cycles, saline environment, and thermal shock. It was found that the order of raw material addition and mixing affects technological and durability properties, as well as the curing condition of geopolymer materials. He further claims that the glass waste had the potential for use as a geopolymerization precursor, and the specimens with a short curing period and a $SiO2/Al2O3 = 4$ ratios are the most recommended for the production of civil engineering applications.

Commonly, the concentration of sodium hydroxide in alkaline activator solution was expressed in terms of "molarity". In the method of assessing the behavior of geopolymer material, molarity plays a vital role. In the geopolymer, whenever there is an increase of sodium hydroxide, which directly affects the ratio of sodium silicate to sodium hydroxide in alkaline solution. Balaraman et al. [16] clarified that the strength of geopolymer becomes low when there is a decline in the rate of molarity of sodium hydroxide. Hence it is important to analyse the significance of molarity influence between silica and alumina during the dissolution of alkaline activators with individual precursors. It indicates the strength of geopolymer acquired with the complex reaction between activator and precursor materials.

4. Effect of curing in geopolymerization

In the polymerization process, curing time plays a crucial role to build up the strength in any geopolymer material. The three-dimensional unit of geopolymer was framed and completed merely by allowing curing. While curing, a higher temperature is usually applied and it helps to induce the kinetic acceleration in the geopolymerisation process [95]. In some cases, it was observed that the kinetic process of geopolymerisation was altered continuously during the increase of curing temperature and rate of reaction [15]. Duxson et al. [29] proposed that the curing temperature and mix design with the presence of impurities should be used to determine the growth of geopolymer gel hinges in order to achieve the desired strength. Depending on the curing environment and mixture design, geopolymer material can harden immediately or take several days to harden. Hardjito and Rangan [36] stated that the launch of chemical reaction in geopolymer paste was substantially assisted by the curing method and, the strength of geopolymer was greatly influenced by the rate and time of curing. Commonly, the curing was applied to geopolymer paste for the period of 4 h to 4 days, depending on the mode of application. During a longer curing period, the geopolymeric materials attain high strength by increasing the span of the polymerization reaction. However, it was suggested that the period of curing was maintained as above 24 h, to attain rapid strength, especially for practical applications.

Two kinds of curing processes are generally employed in the geopolymer formation. These are dry heat curing or steam curing. The results (Wallah and Rangan [112]) showed that any geopolymer material cured using the dry heat method has gained 16% more compressive strength than the method of steam curing. (Wallah and Rangan [112]) Further, clarify that during dry heat curing, it was estimated that the flyash based geopolymer has faced minimum drying shrinkage at the initial stage and it was expected to reach 100 micro strains per year. While the geopolymer materials are cured at ambient conditions, the water engaged in the geopolymer reactions gets released out due to the evaporation that ensued over a while, and it leads to cause the strains of large drying shrinkage especially in the initial period of curing ([19].). Ahmari and Zhang [5] proposes that, in the metakaolin-based stabilization, when the temperature of curing gets increases, delivers more energy that helps dissolve the alumina and silica, found in the particles of metakaolin. It was further explained that to increase the dissolution of alumina and silica present in metakaolin, it is important to maintain the optimum temperature of curing, between 60 and 90^0 C. Moreover, when the optimum temperature falls it is mainly due to poor NaOH concentration or the reaction efficiency of the source material. It was found that in the geopolymer-based concrete when the curing temperature was maintained at 75 °C with 5–10 molarity of NaOH and similarly at 90^0 C with 15 M of NaOH gives maximum strength [5]. Each precursor materials have a certain optimum curing temperature to reach the maximum strength react with the geopolymer. The optimum temperature of varied precursor material with the concentration of NaOH was given in Table 1 below for future reference.

5. Concept of geopolymer in the stabilization of soils

Stabilization of expansive soil delineates that the alteration of soil molecular properties without its mutable natural condition to increase the stability and durability helps to sustain and transfer the structural load throughout its service life without causing any failure. Conventionally, the expansive soil is treated either using chemicals or some mechanical approaches. Certain materials like lime, cement, bitumen, flyash are used as soil stabilizers in the method of chemical treatment. On the other hand, to control the defects of those chemicals, certain industrial wastes materials, by-products or natural resources are also employed in the soil treatment.

However, all these treatments do not allow use for all kinds of soils. In general, depending on soil condition, its structure, and its properties, each special kind of treatment was recommended. When compared to the mechanical stabilization method the chemical treatment methods can withstand severe environmental conditions such as acid rain, but those are considered non eco-friendly. Hence it is necessary to propose nearly an environmentally safe chemical treatment method called "Geopolymer" to strengthen the expansive soil for the application in the construction industry. Performing geopolymerization in soil stabilization is not a novel one. From the ancient period, most of the monuments were constructed with brick blocks prepared with the concept of geopolymer as shown in Fig. 5.

In general, introducing the alkaline activators for soil stabilization can surge the rate of pozzolanic reaction, by increasing the natural pH value of the soil. Thereby it initiates the bonding reaction of soil particles to occur [75]. Usually, the process of stabilization of untreated soil with geopolymer solutions is completed by an exchange of cations, flocculation, hydration, jelation, and cementation. Rogers and Glendinning [93] defines that, in conventional cement and lime stabilization, the exchange of cation is referred a process where the soil releases calcium ions when the binder is added immediately and it triggers the exchange of metallic ions such as sodium and potassium with the soil (Rogers and Glendinning [93]). During the stage of flocculation, the heat was starting to generate within the soil particles when reacted with an alkaline solution what leads to the process of final stabilization [41].

When the precursor materials are added to the alkaline activators, it was noticed that the dissolution of silica and alumina occurs. Then the soil molecular particles are condensed in the form of gel and the activators strike the inner and outer molecular sphere of the soil particles [114]. By consuming water applied during the mixing of materials, the source of aluminosilicate gets diluted and leads to aluminate and silicate yield. Those dissolutions of silica and alumina as monomerically, have initiated the mechanism of converse the untreated soil particles during this alkaline activation [110]. The particulars present in alkaline aqueous solutions may contain silica, which rapidly produces a supersaturated aluminosilicate solution with a high pH value in an amorphous state. In this phase, the concentrated aqueous solution frames the larger network of oligomers with the formation of gel with hydrolysis [94]. Water present inside the pores of soil mass plays a significant role in the development of biphasic gel pores via the reaction of alkaline activators.

Table 1
Optimum curing Temperature of aluminosilicate material with varying concentrations of NaOH.

Type of percursor material	Concentration of NaoH in molarity	Optimum Temperature of Curing in^{0}C	Citation
Fly ash- Class C	8	60–75	(Guo et al. [35])
Fly ash- Class F	7–7.5	75–80	Vijayan, Parthiban[109]
Metakaolin	14	85	Yao et al.[119]
Natural zeolite	8	45	Villa et al. [110]
Glass cullet	6–10	45	Cyr et al. [24]
Constructional recycled aggregate	7–10	27	(Özbay, Erdemir, and Durmuş 2016)
Municipal solid incinerator ash	5–13	60	Jin et al. [49]
Rice husk ash	6–7.5	27–50	(Swamy, Mamatha, Dinesh.2021)
Blast furnace slag	8–14	45–60	Mozumder et al. [71]
Glass waste	6–6.5	45–65	Blayi et al. [18]
Red mud	5–7.5	60	Hu et al. [42]

Fig.–5. Geopolymer used in kudupinar monument construction.

The time required to form a continuous gel network depends on the reaction of raw materials, synthesis, and composition of aluminosilicate solution. After the gel is formed, the further process like the reorganization and rearrangement of the gel network increases through interconnectivity [78]. As shown in Fig. 6, the dissolution of precursor material with the formation of polymeric network and gel formation can stabilize the untreated soil and it hugely depends on the kinetic and dynamic properties of aluminosilicate solution. After complete polymerization, helps to analyse the microstructure and pores distribution of the alkaline material [79]. The 3D aluminosilicate network is commonly recognized by the growth of N-A-S-H gels. It results in the complete stabilization of untreated soils with the growth of crystals of different sizes [76].

6. Industrial based precursor materials in geopolymer soil stabilization

Alkali aluminosilicate chemical composition, a variety of materials could be found. They are in the form of industrial waste for making the binding material, aiming at reducing environmental footprint. It was reported that using the alkaline activators instead of cement stabilization, can help reduce the CO_2 emission by as much as 50–80%. A particular type of binders is used for a particular soil. The selection is based on the amount of calcium content present in the type of binding materials called precursors. The reaction process of most of the precursor materials is either high or low depending on the presence of calcium content. The mineral compounds such as

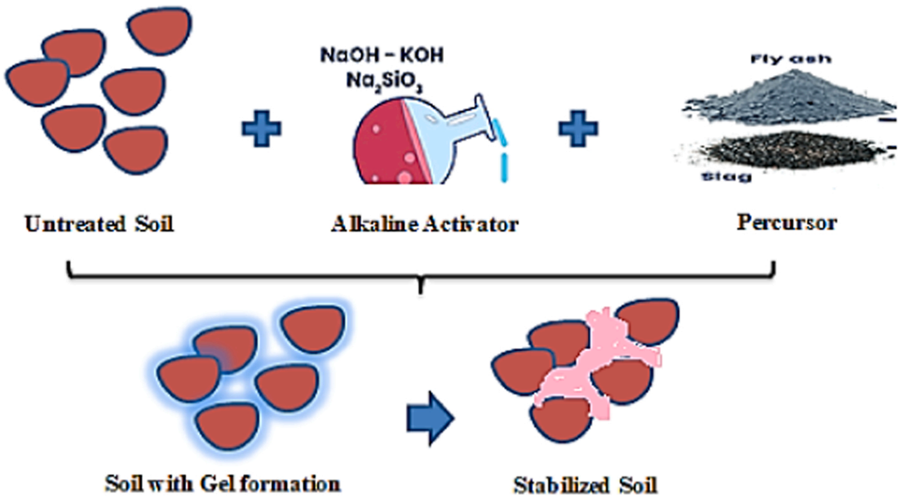

Fig. — 6. Process of soil stabilization using Geopolymer.

alumina and silica also found in precursor materials are reacting together to assemble different binder products based on curing time and gel chemistry. Here, the most common types of different industrial-based precursor or additive materials are discussed. Particular attention is paid to, those filling the pores of soil and microstructure. Soil behaviour and properties until reaching the hardening stage are thoroughly discussed.

6.1. Industrial waste precursor in geopolymer soil stabilization

Waste of complex composition generated from the industries is available world wide. During uncontrolled disposal of Industrial waste, causes irreversible effects on human health and the environment. In general, industrial wastes like flyash, silica fume, steel slag, nuclear waste, red mud, and tailing are widely used in geopolymer development. In this context, as shown in Fig. 7, the way of utilizing, different kinds of industrial wastes in the treatment of poor soil with geopolymer was discussed. The methods for managing and producing a sustainable stabilizer for geotechnical applications, being safe for the environment are also discussed.

6.2. Alkali activated fly ash

In recent years, the fly ash-based (FA-based) geopolymer has been widely used in the replacement of cement to enhance the strength of soil with additional benefits of efficient use of energy and lowering the toxic pollution [2]. Rios et al. [90] proposed that the stabilization of silty sand for the strengthening of the base course of unpaved roads using low calcium flyash with alkaline activator solution was a low-cost material with promising results [90]. Parthiban., et al. [77] proved that while preparing the building blocks with the use of low calcium fly ash as an additive material with the geopolymer have delivered good compressive strength of 18 MPa at 28 days of curing time. When compared to conventional bricks, the water absorption was 19%. Similarly, when the soil stabilized with the flyash alkaline solution under soaked conditions, the unconfined compressive strength (UCS) was estimated to increase by 79% at the 28 days of curing. It was also found that the use of fly ash with alkaline solution has provided long term performance with cost efficiency [91]. Suksiripattanapong et al. [105] have tested the FA-based geopolymer integrated with polyvinyl alcohol to stabilize the soft soil. The concentration and composition of polyvinyl alcohol were found as 15% and 4% and the optimum range of calcium-based FA was preserved as 40% respectively. The results, showed that the UCS at 28 days of curing time was 42% higher than for the plain FA-based alkaline binder. Hence, the use of polyvinyl with flyash has proved to be an effective binder in soft soil treatment.

In the FA-based geopolymer treatment of gypsum soil it is important to analyse the rate of collapsibility of soil, when investigating intrinsic sulfur. Alsafi et al. [7] deliberate that the incorporation of potassium-based alkaline as 12 molarity with the FA-based gypseous soil, can reduce the risk of collapsing potential and maintain the rate of permeability at a longer period of exposure [7]. Most of the gypseous soils expose high content of sulfate along with high collapsibility potential. When the conventional cement stabilization methods are used it could increase the level of sulfate reaction. Thus it is recommended to utilize the alkaline activators with fly ash to neutralize the level of sulfate in those types of soils [77]. Zhang et al. [121] clarifies that the difficulty present in the treatment of sulfate-rich soil is caused due to its prolonged heaving and expansion behaviour. It is recommended to be treated with conventional lime and cement and also recommends using calcium-free geopolymer.

Phetchuay et al. [80] suggested that the soft marine clay is treated with FA-based geopolymer amalgamated with calcium carbide residue, to reduce the rate of the carbon footprint from the atmosphere. Similarly, the soft marine clays are identified as very soft of high compressible nature. Arulrajah et al. [10] examines the treatment of soft marine clay soil with the combination of flyash and slag in the optimum proportion of 5% and 15% added respectively with the alkaline solution. When compared with the conventional

Fig.–7. Industrial based precursor in soil stabilization.

cement, the binder made by the mixture of flyash and slag was used at 30%. It was proved it can provide a profitable increase in the rate of UCS in the strengthening of soft marine clay [10]. While treating the incineration byproducts collected from the municipal landfill the waste could be stabilized using FA-based geopolymer, that is less prone to improve the UCS 1–9 MPa from the 7–28 days of curing at 60°C. Further, it was found that there was a trace of leachate with a high pH value proving the immobilization of metals present in the incineration residues [4].

Coudert et al. [22] address that the alkaline binder which contains high calcium flyash used to improve the engineering behavior of soft kaolin clay soil, in addition with the compound called thenardite can boost the polymeric reaction of soil and binder by forming the chains of calcium silicon with reactive phases. Esaifan et al. [32] have assessed the reaction of alkali activators in the treatment of untreated kaolinitic clay and to produce the stabilizer with flyash based, which works under both saturated and dry conditions of untreated kaolinitic to increase the stability and strength. Dassekpo et al [25] label the chemical reaction of fly-ash based alkaline solution with the loess soil. The researchers have found that, during the treatment of soil the weight proportion of both soil and alkaline are decided based on the long and short term effect of geopolymer at the time of interaction of particles. According to Yaghoubi et al. [118] the use of fly-ash in soil stabilization has provided a reasonable improvement in the shear strength of soil while stabilized with geopolymer.

6.3. Ground granulated blast furnace slag

Geopolymer prepared using GGBS was the finest additive material for the strengthening of poor-quality soil (Singhi et al. [102]). BFS is the by-product of pig iron, which is available in the form of granular, fine, and non-crystalline material. The untreated soil activated with the GGBS based alkaline solution shows maximum UCS value when compared to the soil treated with the conventional cementitious method (Rafiean et al. [40]). Mozumder and Laskar [71] states that when increasing the quantity of GGBS with minimum water content might increase the stability efficiency of clayey soil as well [71]. It is also proven that, the content of GGBS added in the alkaline solution plays an important role which is affecting the assessment of UCS of stabilized soil [71]. Moreover, the lower water content and the content of alkaline activator with GGBS have given higher UCS values because of the close packing of the soil particles. Whenever the water content increases in the alkaline mixture, it creates poor bonding between the soil particles and reduces the concentration of the alkaline solution leads to a decrease in the value of UCS in stabilized soil. Mozumder and Laskar [71] clarify that when the clayey soil was treated with GGBS based geopolymer was gives higher UCS strength, than the samples prepared with FA-based geopolymer for the same content ratio.

Before utilizing GGBS for any treatment, it is more important to analyse the mechanical, physical and hydraulic behavior of soft clayey soils. When compared to lime stabilization, the GGBS is much efficacious when compared to lime stabilization, due to its high cementitious nature. Sharma and Sivapullaiah [98] employed that the treatment of sulfate-rich soils with GGBS in the construction of pavements can reduce the rate of swelling and make the soil sustain higher resistance. Chemical compounds such as calcium, silica, magnesium, aluminium, and oxygen are the main ingredient present in the GGBS. Likewise, the hydration process of GGBS is initiated immediately when in contact with water at a very low rate (Özbay et al. [74]).

Wu, Jiang, and Roy (1990) proposed that the reaction mechanism of GGBS with an alkaline solution was very complex. However, the activator initiates the bond separation of alumina and silica materials present in the GGBS and empowers the development of hydration products (Wu, Jiang, and Roy 1990). It was always recommended that maintaining the pH value of sodium hydroxide induced with GGBS should be more than 12, to initiate the effective hydration of GGBS with the soil. Furthermore, it was stated that the composition and morphology of the hydration products keep on changing depending on the type of activator used [103]. Again, in the strengthening of marine clay soil the mixture of GGBS with lime, shows 90 times better compressive strength than the plain cement stabilization [23]. Marvila et al., [64] has investigated that the properties of alkali materials activated by infusing BFS have changed the type of geopolymer model related to sodium ions in the interstices of the material caused a significant change in the properties of dynamic viscosity that helps the rheological characterization of activated alkali material. Marvila et al., [64] have further investigated that the usages of GGBS in any geopolymeric material have reduced the activated alkali compositions have less porosity. This is a good because cementitious materials main durability issues stem from their porous structure. Thus, reducing this property is beneficial to durability. From most of the studies, it was understood that the usage of plain GGBS has provided some undefined lower and high UCS value or vice versa, while combined with lime at a certain percentage the rate of value was increased in all types of soils.

6.4. Metakaolin

Worldwide, metakalolin was found to be a premium material. It was primarily used as a precursor material in the process of geopolymer production next to fly ash and GGBS. Metakaolin is the synthesized product obtained by heating the natural kaolin clay at the temperature of 700–800^0 C. Because the mixture composition of silica is 51–55% and alumina is 41–45%. Metakaolin was classified as a variety of aluminosilicate. It was a white powder structure with a particle diameter of fewer than 2 nanometers, being finer than the OPC [68]. Luukkonen et al. [62] concluded that, when compared to conventional additive material, the GGBS based geopolymer has average pore width and volume and higher molecular surface area. Khadka et al. [51] stated that treatment of high sulfate clayey soil with lime and cement is ineffective to control swelling due to the formation of excess ettringite. Hence, in these soils, the metakaolin was introduced in the form of alkaline activation and proves reducing the rate of soil swelling. Cantarel et al. [20] showed that the metakaolin based geopolymer when used to treat the soil affected by oil hydrocarbons, could be an effective material. This is due to the production of surfactants by the combination of alkalic acid present in the oil. The activator solution also creates the interfacial tension between the surface of oil during the polymerization reaction.

El-Eswed et al [31] found that the use of metakaolin-based geopolymer in the treatment of soil contaminated by heavy metals was very effective. This is due to its perfect interaction of geopolymer mechanism with the polluted soil. While maintaining the ratio of alumina and silica in the metakaolin-based geopolymer as between in the range of 3.00–3.50, has enhanced the UCS value of preserved soil up to 80 MPa by achieving the unique homogenous structure [30]. Markssuel et al. [64] have discussed that how fires and rains affect the performance of geopolymer tiles in high temperatures and saturation. In general, a decrease in density indicates that the presence of geopolymerization. In the geopolymerization reaction, the aluminosilicates in alkaline solution have reached several stages such as aluminosilicate dissolution, speciation equilibrium, gelation, reorganisation, and polymerization. Except for the first step, all others involve water loss from the reaction. The decrease in mass and density of the formed material is a strong indicator that the reaction is occurring. Duxson et al. [29] state that, when the geopolymer was derived using the metakaolin more water was required due to a decrease of porosity. This allowed making the alkaline solution a more suitable material for geotechnical applications.

6.5. *Red mud*

Red mud is the type of industrial residue spawned through the extraction of alumina from the ore of bauxite. In nature, the red mud is recognised as alkaline material, due to the presence of a surplus amount of metallic ions and minerals, considered damaging the environment. It was estimated that during the production of 1 ton of aluminium, nearly 5 tones of red mud is produced as a by-product. Mukiza et al.,[72] states that the use of red mud-based geopolymer in the application of sub-base material in road construction has shown better performance than conventional stabilizers. Further, when compared to other types of precursors, the red mud-based geopolymer has improved the mechanical, environmental, and economic properties of the road subgrade.

Usually, the red mud has a content of sodium oxide at the rate of 6–21% in its total weight and it makes the red mud more alkaline. It is possible to replace these parts with the other precursor materials as an alkali source for geotechnical works [34]. Along with that, the red mud was naturally admixed with ferric ions which transformed as hematite during the pretreatment and become a part of alumina ions in a complete polymeric structure [42]. While incorporating red mud with geopolymer, the level of soil porosity increases due to its corrosive nature. It is also noted that it decreases the strength of geopolymer when using too much alkali material. Singh, Aswath, and Ranganath (2020) have found that the optimum percentage of red mud geopolymer for the casting of bricks is 30% with the 1:1 binder and aggregate ratio have shown the compressive strength of 8.5 MPa. Similarly, the red mud-based geopolymer was introduced with the brick materials at the range of 30–50% and shows better durability when compared to other types of blocks [101].

Lemougna et al.,[59] outlines that the red mud has usually contained katoite, cancrinite, hematite, and a significant amount of diaspore. Due to such content, it takes much time to dissolve in alkaline solution engaged in the polymerization reaction. However, during appropriate curing time, the high UCS was developed with the bonding between geopolymer gel and the unreacted phase of alkaline activators. He et al. [39] specified that when using red mud-based geopolymer for the treatment of any soil, it takes complete 21 days to achieve the required UCS value due to the presence of organic content. This is also because the compressive strength depends on the duration of curing time and the ratio of alkaline solutions. During the extended period of curing time, an increase of the brittleness and stiffness of the soil was observed [39]. Hence, it was analysed that the usage of red mud-based geopolymer for the stabilization of soils was not recommended as easily due to its physical property and protracted reaction time.

6.6. *Rice husk ash*

The ash which is produced by burning the rice husk collected from the mills is categorized as agro-based waste which is used as a low-cost energy combustion resource. It is an alteration to the coal, for generating electricity [33]. While combusting the rice husk, the organic matter is retained by making 25% nearly of the ash product volume [97]. The rice husk ash possesses a higher specific surface area with a content of 95% amorphous silica. It becomes a superior pozzolanic and cementitious material, and due to the presence of nano-silica oxide, the filling of soil pores gets treated easily. The stability rate is improved with the development of the firm gel phase [96]. Liang et al. [60] investigated that the rice husk ash was replaced by 30% of metakaolin in geopolymer stabilizer. The compressive strength was increased significantly as much as 58% and it reduced the water content in the alkaline solution can enhance the permeability performance of the soil. Adeyanju et al. [4] termed that the improvement of mechanical strength of subgrade soil with of rice husk ash-based geopolymer mixture with 10% of cement kiln dust, have improved the performance of failed subgrade as efficiently.

Swamy et al. [106] stated that in the treatment of laterite soil, the rice husk ash-based geopolymer as a stabilizer adopted at an optimum dosage of 9% and allowed it to cure for zero to thirty days and have shown that the UCS value of treated soil increased by 5% and proved as a sustainable pavement stabilizer. He et al., [38] discuss that the method of utilizing rice husk ash as a cementitious composite with geopolymer, to stabilize the red mud, which is collected from the aluminium refining industry through the bayer process to find the beneficial construction material. Based on the review, it was comprehended that the usage of red mud in subgrade soil stabilization has provided appreciable outcomes.

6.7. *Palm oil fuel ash*

When extracting the oil from the palm tree, the by-products such as kernel, shells, and fibre are produced. During the burning process of such palm by-products, 5% of total products are converted in the form of ash-like substances [107]. The ash from the palm tree contains 45–80% of silica oxide with similar phase composition of flyash. The palm oil fuel ash is using an additional cementitious material in the geopolymer stabilization of soil. Moreover, the palm oil fuel ash contains irregular porous substances with larger particle sizes. To increase the efficiency of palm oil fuel ash with geopolymer in soil stabilization, it is necessary to maintain uniform grain size particles distribution. Islam et al. [44] described that the use of palm oil fuel ash with soil geopolymer can control the rate of dry shrinkage of soil through initiating the process of hydration within the geopolymer matrix. Abdeldjouad et al. [1] investigated that it admixing with the glass fibre improved the plasticity range of sandy soil as well as the compressive strength and tensile strength of soil due to soil-brittle behavior.

Khasib et al. [52] examined that mixing the palm oil fuel ash with geopolymer at the rate of 40% is very effective in the treatment of expansive soil. Following the investigation, the shear strength of soils gets enhanced at the higher contents of palm oil fuel ash. It is also highlighted that the UCS value of soil gets enhanced in the dry state at the curing period of 28 days. For subgrade application, it is crucial to maintain the ratio between binder and alkaline material. Sukmak et al. [104] presented research proving to apply the ratio between the palm oil fuel ash and alkaline activator at a low range. The conclusion was, it required more quantity of NaOH to develop a more stable soil structure. It was recommended to maintain the optimum ratio of alkaline binder as 40:60 to achieve the higher compressive strength of the soil. It was also concluded that, the proper utilization of the palm oil fuel ash with geopolymer can help to diminish the landfill reclamation layer issues.

6.8. Silica fume

During the extraction of ferrosilicon from the smelting process of silicon metal, a finely powdered residue called "Silica fume" was obtained. This residue is having a wide specific surface area, fine size particles with higher pozzolanic performance [55]. Jalal et al. [47] proved that the utilization of silica fume in geopolymer stabilization not only improves the density of geopolymer but also enhances the microstructure of the soil by maintaining the size of voids. Wan et al. [113] investigated the reaction and microstructure of geopolymer at a different molar ratio of silica and alumina. The molarity ratio of NaOH helps to determine the amount of silica fume dissolving with the alkaline solution to form a large amount of N-A-S-H bonding within the soil structure. Due to the extreme fineness of silica fume, the actual consumption of water during the stabilization process increases. Thus it is recommended to use the admixture for the field application. Abo Sawan et al. [3] found that whenever any impurities present in the silica fume while used with geopolymer, it undergoes a redox reaction to generate hydration in the alkaline medium used to make the geopolymer foams as conveniently. To activate the polymerization reaction, the alkali elements cannot be engaged in the hydration process to dissolve the pores of the soil. The reaction triggered due to the presence of is with alkaline activators to form a gel of silicate with swelling potential (Maas et al. [63]). However, another research conducted by Juenger and Ostertag [50] demonstrated that certain commercially available silica fumes can trigger the swelling potential of stabilized soil by increasing its alkali-silica reaction. Hence the selecting of proper silica fume is necessary to achieve the expected result in stabilization.

6.9. Waste glass powder

In the concept of sustainable stabilization, promoting the utilization of recycled glass waste in the powder form can decrease the consumption of energy and allow resources conservation. The glass powder is an inert material that is collected from the segregation of municipal solid waste. In general, the collected glass waste was a non-biodegradable matter which contains large amorphous silica content. It optimizes the gel matrix and soil microstructure with the unreacted alkali particles, which leads to an increase in the mechanical parameters of stabilized soil. Xiao et al. [116] stated that, the powder of soda-lime glass was chosen as a desirable material for the production of geopolymer composite amalgamates with alumina. Based on the study performed by Cyr, Idir, and Poinot [24] the geopolymer prepared with glass powder achieved a promising UCS value as such as the FA- based geopolymer. The mechanical property of glass powder geopolymer treated soil depends on its rate of alkali activation, condition of curing, and particle sizes. Si et al. [99] research results revealed that the poor use of glass powder with geopolymer leads to change in the creep modulus simultaneously with the reduction of water content and the rate of soil shrinkage.

Especially in the construction of pavement subgrade, the strength improvement of expansive soil is a challenging task. Blayi et al., [18] clarifies that the use of glass powder at the rate of 15% with geopolymer as an alkaline reactor, has created an impact on the shear strength and consistency of the expansive soil collected from the subgrade of pavement [18]. To improve the mechanical behaviour of soil, the glass powder geopolymer at the optimum value of 15% was used as an effective stabilizer of soil and found that the compressive strength and strain value of the specimen gets increased by increasing the duration of curing (Bilondi [82]). However, the glass powder has a significant positive effect on soil stabilization, it is important to analyse the ash grain size distribution before incorporating it with the geopolymer muddle.

6.10. Incineration ash from solid waste

Waste incineration is considered an effective and time saving method of municipal solid waste management. Usually, the municipal waste contains solid and metallic materials. Incinerating such wastes allows converting the combustible by-products into ash. When considering the chemical composition of incinerated ash, it is the form of CaO- Al_2O_3-SiO_2 for potential utilization of resources with geopolymer. The most important feature of using municipal incineration ash with the geopolymer is the immobilization of heavy metal [45]. Based on the research of Jin et al. [49] the geopolymer prepared with incineration ash was having resistance against both alkaline and acidic environment soils. When dissolving the aluminium with geopolymer and incineration ash has become a gas-forming agent. Incorporating incineration ash in the stabilization of soil with geopolymer is a novel one and when compared with fly ash and bottom ash the municipal solid ashes contains less toxic substances with having higher soil stabilization potential to the soil.

6.11. Other precursors used in geopolymer

Certain types of industrial wastes are identified as the least usage material with geopolymer stabilization. Arulrajah et al. [9] described that the coffee ground residues and the baggase ash are sourced mostly from agricultural waste. While combined both these materials with the geopolymer stabilization required a longer curing period to control the growth of organic matter and to get the expected UCS value of the road subgrade soils. Waijarean et al., [111] examine that the usage of residues collected from the water treatment plants as a precursor in geopolymer soil stabilization. While adding the residue at the rate of 50% with the geopolymer solution, have shown that increase of soil compressive strength at 28 days curing and the compressive value increased by 34%, while cured at 800^0 C at the short span of curing time. Phetchuay et al. [81] enquire about the optimal range of alkaline solutions such as silica and alumina with calcium residue activator, while treating the soil with geopolymer. It was found that the calcium carbide residue has proved as to be a sustainable alkaline activator for the stabilization of subgrade materials, namely by dissolving the aluminium and silica phase to make efficient binders. Antunes Boca Santa et al. [8] utilized the calcined paper slag into the geopolymer as an aluminosilicate mineral collectively with the bottom ash to enhance the stability performance and microstructure of expansive soil. However, still, so many industrial precursors are not widely used with geopolymer in the stabilization process, it was suggested that to use those materials to the maximum extent, to control the environmental impacts and problem of disposal.

7. Influence of precursors in soil microstructure

The development of the shear strength of soil is one of the major objectives of any geotechnical work [53], [57] When estimating the stability of the soil, the shear strength is a major factor [54]. Usually, the shear strength is calculated based on the mechanical parameter of soil particles. Due to the number of external factors, the particles of the soils get rearranged completely or partially. In such conditions, soils fail to bear or transfer the load what eventually leads to failure of the structure. In any method of stabilization, the completion of the reaction was decided also based on its microstructural analysis.

Each stabilization material referred to in the present review has improved the microstructure property of the soil by making a constricted bonding effect. The growth of microstructure in any soil depended on the character of binder material, curing temperature, time and the concentration of the alkaline solution. In this context, the microstructural property of the soil stabilized with the geopolymer admixed with the industrial precursor activators was discussed. Nath et al. [73] stated that the microstructure of FA-based geopolymer observed using FEG-SEM apparatus was improved. It was found that the morphology of FA-based geopolymer gets enhanced by the increase of temperature of curing and concentration of alkali solution with the formation of gel phase and tubular structure was followed by the alteration of grain size of expansive soil. The bonding network of geopolymer alkaline stabilizers plays a vital role in determining the strength of stabilized soil. Provis et al. [86] deliberate that the microstructure of metakaolin-based geopolymer is developing through indulging stabilized soil samples with scanning electron microscope (SEM) images. The study of silica content present in the metakaolin provided optimum compressive soil strength by the development of the microstructure. If the metakaolin was chosen with low silica content, it would disintegrate the bonding structure of geopolymer and makes the polymeric reaction process tedious, thus a decreases in the strength of stabilized sample was observed.

When compared with conventional cement stabilization, due to the presence of cross-link structure, the geopolymer-based stabilization provided hard and denser microstructure of the soil. The development of C-A-S-H gel of geopolymer with a longer matrix is achieved when compared to the cement matrix of C-A-S-H gel. The presence of aluminium in the geopolymer can improve the strength of soil as well. Collins and Sanjayan [21] suggested that the pore size of geopolymer materials are found to be less than 20 nanometers, which was considered as finer than the pore size of cement ranges between 10 and 100 nanometre. Hence, the finer particles in geopolymer provide more strength to the geopolymer matrix. In general, the techniques such as SEM and Xray Diffraction (XRD) have been widely used in the investigation of the microstructure of geopolymer stabilized soils at the duration of 7–28 days of curing. By using the images of SEM and XRD, have been widely used in the investigation of the microstructure of the geopolymer stabilized soils, at the curing time of 7–28 days. Through the images of SEM and XRD, it is possible to analyse the presence of hydration products and any contaminants present in the soil grout mixture. Zhang et al. [122] examine the microstructure of low plasticity clayey soil through SEM-XRD. They reported that the presence of homogenous cementitious gel within the stabilized soil samples can increase the strength along with increasing the amount of binding material. Hughes and Glendinning (2004) explained that while analysing the microstructure of clayey soil through the images of SEM and XRD, the stabilization performance of soil enhanced widely due to the occurrence of agglomeration and flocculation process taken place during geopolymerization. In some cases, when the zeolite content was noticed together with the alkaline activators, it can detriment the rate of gel formation what affects the mechanical performance of flyash based geopolymer in the soil. On the other hand, when the presence of silica in the precursor material was at a satisfying limit, it would allow controlling the rate of zeolite reaction within the geopolymer and increase the stabilization strength of soil with a lower degree of polymeric reaction [75]. In terms of curing, the rate of temperature has affected the microstructure of geopolymer in several ways. During higher temperatures of curing, the structural properties such as crystallization and sintering get altered. The size of soil pore structure also gets affected due to densification and dehydration of soil particles.

8. Comparison of different precursor in geopolymer soil stabilization

In this section, a comparative analyses were made regarding compressive strength and alkaline binder ratio and curing time. Some notable industrial precursors and their role in the stabilization of different types of soil with the geopolymer are available in the literature as presented in Table 2. Through this separate comparison study, it becomes easy to identify the suitable precursor material for the specific soil during its treatment and future studies.

9. Conclusion

The following conclusions were formed after reviewing various researches. All of them were focused on investigating the potential application of industrial based precursors to improve the engineering performance of weak soil. These concerns using range of geopolymer material to find an alternative alkaline material, minimizing the impact on the natural environment as well as maintaining continuous and more sustainable developmentof the construction sites.

1. Based on the present study, the geopolymer prepared through the combination of the industrial precursor as alkaline activators were found to successfully enhance the stabilization performance of soil. However, the soil properties such as the Atterberg limit were not studied as majorly in all investigated studies. It is recommended to include the study of all mechanical properties as a major factor in the future research of geopolymer soil stabilization.
2. The alkaline solution of sodium silicate and sodium hydroxide can improve strength. Soil stabilisation with slag-based geopolymer can be an efficient and cost-effective way to improve soil and industrial waste mechanical properties.
3. The review's findings suggest that alkaline binder formulations must be optimised for economic and environmental reasons. To reduce the amount of NaOH and/or Na2SiO3, or even replace them with low-cost materials or other wastes like RHA, steel slag, iron slag, GGBS, FA, etc. should be optimised. Production and transportation of NaOH and/or Na_2SiO_3 emit significant CO_2, which should be reduced.
4. In most of the studies exploration, for the geopolymer soil stabilization, only a few materials such as fly ash and metakaolin are discussed widely than other types of precursors. So, the choice of utilizing and disposing of those remaining precursors becomes uncertain. Therefore, it is needed to nourish the knowledge about the remaining type of industrial precursors among the researchers
5. Some of the industrial precursors are found as highly alkaline. Thus it is needed to conduct a preliminary study of the properties of each soil before incorporating geopolymer treatment. If utilized without a preliminary investigation, the alkalinity of soils gets increases and leads to degrading its natural behavior.
6. Most of the precursors have shown, a good result in the increment of compressive or unconfined compressive strength value of the soils. Though, the selection of a particular precursor for particular soil becomes difficult due to considering factors such as soil particle sizes, water content, the concentration of alkaline activator, temperature, and curing time.
7. SEM–XRD confirmed the formation of geopolymer gels in soil. Since no new minerals formed after stabilisation, the binding effect of the geopolymer gels likely improved the soil's mechanical properties.
8. Ground improvement, subbase and base course of flexible pavements could use industrial waste-based geopolymers to stabilise soil. Moreover, this soil stabilisation technique is both cost-effective and environmentally friendly.
9. By using industrial precursors, it becomes possible to control the production of cement and the extraction of lime resources. And the disposal and management of industrial precursors could be very much beneficial.
10. Geopolymer stabilised soils develop high early strength faster than OPC. The ductility of geopolymer stabilised soils can reduce cracking during construction, curing, and operation. The lower shrinkage than OPC can also reduce soil shrinkage cracking damage. The cost issue can be addressed by using industrial wastes or byproducts to synthesise geopolymer
11. The soil stabilised with geopolymers demonstrated exceptional resistance to wetting–drying and freezing–thawing cycles, slaking water, and aggressive chemical environments. The geopolymer content and curing time have a significant effect on the microstructural development, indicating the formation of hydration and geopolymeric reaction products.
12. The use of industrial precursors in the geopolymer soil stabilization can provide the promising stabilization effect, similar to the conventional method and can prove to be a better alternative to the existing methods of soil treatment.
13. It was also found that the, Geopolymers derived from solid wastes promote waste reduction, recycling, and harmlessness, while also being an environmentally friendly and sustainable "Green Material."
14. Ground improvement, subbase, and base course of flexible pavements could all benefit from soil stabilisation using industrial waste-based geopolymers. Furthermore, this soil stabilisation technique not only makes better use of industrial solid waste, but it is also very cost-effective and environmentally friendly.

According to the findings of the review, alkaline binder formulations should be optimised in order to reduce their economic and environmental impacts. Optimizing should aim to reduce the amount of NaOH and/or Na_2SiO_3 used, or even to replace them with low-cost materials or other wastes that have no commercial value, preferably in solid form such as Rice husk ash asphalt, Copper slag, steel slag, GGBS, Fly ash and so on. The production and transportation of NaOH and/or Na_2SiO_3 emit significant amounts of CO_2, which should be minimised to the greatest extent possible in order to reduce global warming.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 2
Role of Industrial Precursors with geopolymer in soil stabilization.

Type of percursor and soil with geopolymer	Compressive strength or UCS of treated Soil	Silica & alumina ratio	Period of curing in days	Citation
Municipal solid waste incineration ash	9 MPa	0.459	28 days	Luna Galiano.Y et al., ($year$)[61]
Flyash in soil blocks	17 MPa	3.90	28 days	Parthiban et al., ($year$)[77]
High calcium fly ash with clayey soil	1000 kPa	0.6	28 days	Suksiripattanapong et al., ($year$) [105]
Fly ash in gypseous soil	29.3 MPa	> 2	90 days	Alsafi et al. [7]
Fly ash with soft marine clay	800 kPa	1	28 days	Phetchuay et al. [80]
Metakaolin with sulfate rich soil	32Mpa	1–3	28 days	Khadka et al. [51]
Redmud with road subgrade	0.1006 MPa	7–10	90 days	Mukiza et al. [72]
Redmud with bricks	24 Mpa	1.65–2.8	07 days	Singh et al. [101]
Rice husk ash with road subgrade	640 kPa	02	28 days	Adeyanju et al. [4]
Glass waste with road subgrade	17.4 Mpa	4–5.4	07 days	Xiao et al. [116]
Glass waste with expansive soil	360.10 kPa	1–2.5	28 days	Blayi et al. [18]

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