Sustainable Ground Engineering: Advancements in Chemical Stabilization for Weak Soils

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ABSTRACT:

Ground improvement is of paramount importance in both current and future geotechnical practices for the design of structures on weak soil. This paper provides a comprehensive review of the recent advancements in ground improvement techniques, with a particular focus on chemical stabilisers. Various chemical stabilisers are identified and compared with other existing methods. While the application of chemicals offers a promising alternative to traditional techniques, there remains a significant gap in understanding their use, handling, application, and long-term environmental impacts. The present paper summarises various chemical stabilisers along with their applicable conditions. Insights into biochemical, electrochemical, inorganic, and organic stabilisers are presented, along with the future potential of these methods and the areas requiring substantial efforts for their industrialisation. The review highlighted the necessity for developing more environmentally friendly and safer methods. A significant concern regarding the limited industrial use of these methods is the lack of extensive data. It is essential to conduct numerous laboratory and field experiments under varying conditions to ensure the safety and efficacy of chemical stabilisers.

Keywords:*Ground improvement, Chemical stabilisers, Biochemical stabilisers, Electrochemical stabilisers, Inorganic and organic stabilisers*

1. INTRODUCTION

Stability, performance, and base soil characteristics of structure or geotechnical engineering are considered together. Any construction activity on weak or problematic soils would normally be much more challenging and would require ground improvement techniques to improve soil properties such as strength, stiffness, permeability, and compressibility. With urban expansion and the construction of infrastructures on marginal lands, the requirement for effective ground improvement techniques has increased more than before [1].

Traditional soil improvement methods, including; nailing soil, grouting, vibro-compaction, preloading, and deep mixing, have always found utility in solving geotechnical problems. Although mechanical or physical means are quite established, sometimes these might prove non-feasible due to site conditions, economic factors, or maybe environmental [2]. Henceforth, other possibilities such as those based on chemical stabilization have gained prominence for considering options which may be more customized, quicker, or sustainably oriented. Chemical ground improvement may be thought of as introducing chemical agents inside the soil matrix and thus effecting change upon the soil's physical or mechanical behavior. These chemicals may react with soil constituents or bind up soil particles to enhance cohesion, reduce plasticity, and perhaps bolster the load-carrying capacity of the soil. These chemical stabilizers include lime, cement, fly-ash, polymers, and enzymatic chemicals, each of which has advantages depending on soil type and engineering requirements [3].

Especially in expansive soils, soft clays, and loose sands, the application of chemical stabilisers tends to bring benefits under the treatment processes that elsewhere would perhaps be insufficient and expensive.[2] And when we look at the forefronts in material science and geochemistry, new ways for biochemical and electrochemical stabilisation appear to be in the incubation stages, hoping to become applicable in the future.[4] Although chemical methods for ground improvement are getting more and more attention, unusual gaps still persist in knowledge concerning long-term durability, environmental considerations, and scale-up potential towards industrial application. Among other things, incompatibility, leaching, toxicity, and costs serve as hindrances to widespread application.[5] Hence, it becomes necessary that a very exhaustive and detailed investigation be conducted in both laboratory and field environments under a wide array of conditions so as to establish the performance and safety aspects of these chemical methods.

With the purpose of literature review, the present paper focuses on a detailed discussion of chemical stabilisation methodologies: inorganic, organic, biochemical, and electrochemical approaches. The present study also analyses recent developments; compares chemical processes with conventional methods; designates current limitations; and proposes necessary directions for further research towards the industrialisation and wider acceptance of the chemical ground improvement technologies.

2. GROUND IMPROVEMENT USING CHEMICAL STABILISERS

Modifications to soil properties through physicochemical reactions have been demonstrated to be more effective in maintaining long-term improvements compared to other methods (Indraratna et al., 2015).Chemical processes, including the incorporation of cement, fly ash, lime, lime byproducts, chemical reagents, and combinations of these materials, can be employed to modify soil characteristics such as strength, compressibility, hydraulic conductivity, swelling potential, and volume change properties (Puppala et al., 1997; Puppala and Musenda, 2000).Foreign materials may be introduced either in-situ or ex-situ, contingent upon the type of additive, project design, and the availability of equipment (Makusa, 2013).The chemicals typically utilized for stabilization consist of industrial by-products or waste materials that possess cementation properties. Numerous chemical additives have been formulated over the past few decades; however, their selection and application are not standardized and instead depend on the specific type of soil and various application factors. Each additive interacts differently with distinct soil types. Therefore, comprehensive knowledge regarding the chemicals and their application requirements is critically important. Based on their nature and chemical composition, the methods of chemical stabilization are generally categorized into four primary subgroups, as illustrated in Figure 1:

1. Biochemical methods
2. Electrochemical methods
3. Inorganic pozzolanic/cementitious material
4. Organic polymeric binders

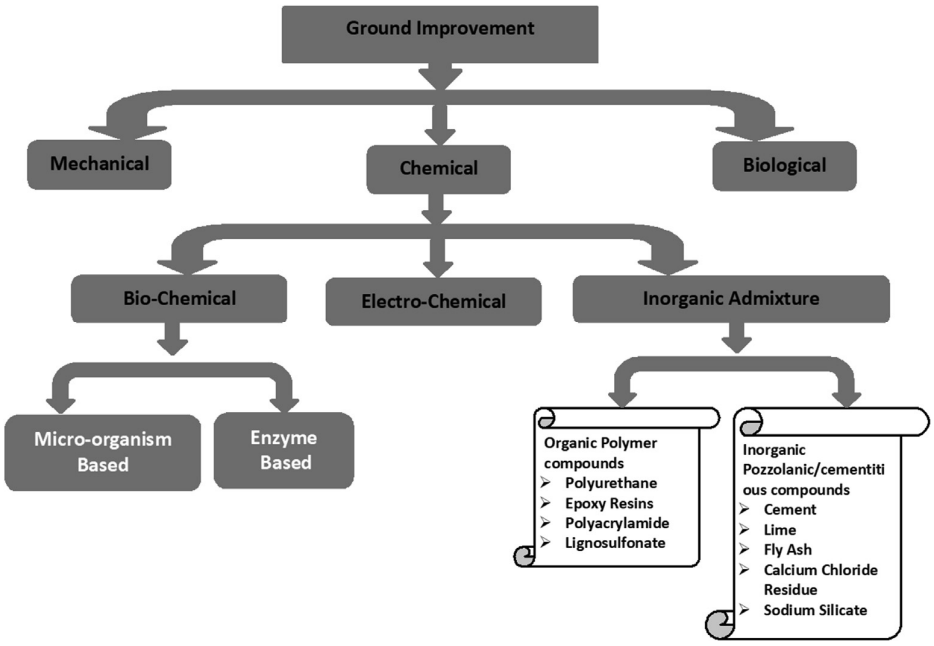

Figure 1. A flow-chart showing the chemical methods of ground improvement.

2.1Ground improvement using biochemical methods

Ground enhancement through biochemical techniques is classified into two primary categories: Microbiologically Induced Calcite Precipitation (MICP) and Bio-enzymes.

2.1.1Microbiologically induced calcite precipitation (MICP)

The technique relies on the environmentally friendly precipitation of Calcium Carbonate (CaCO3) by microorganisms. Bacteria are capable of thriving in a diverse range of environmental conditions, which makes them effective stabilizers. Bio-mineralization takes place at the nucleation site either through bacterial cells or through the precipitation of CaCO3 resulting from an increase in alkalinity due to ureolysis (Bibi et al., 2018). This process can enhance ground conditions through either bio-clogging or bio-cementation. Bio-clogging involves the filling of pore spaces with CaCO3, whereas bio-cementation improves soil strength by increasing the bond strength between soil particles through preferential calcite precipitation at points of particle contact, as illustrated in Figure 2 (DeJong et al., 2010). While various microorganisms can precipitate CaCO3, ureolytic bacteria are typically employed alongside certain chemical reagents (such as CaCl2 and urea) to supply Calcium. In the presence of the urease enzyme, urea undergoes hydrolysis, yielding Ammonia and Carbon dioxide, while simultaneously raising the alkalinity of the medium during the reactions:

$$CO(NH_2)_2(s)+H_2O(l)\rightarrow 2NH_3(aq)+CO_2(g)[riseinpH]$$

$$2NH_3(aq)+CO_2(g)+H_2O(l)\rightarrow 2NH_4^+(aq)+CO_3^{2-}(aq)$$

A diverse range of microorganisms, such as Sporosarcinapasteurii, Idio- marina insulisalsae, Proteus vulgaris, Proteus mirabilis, Helicobacter pylori, and Ureplasmas (Mocllicutes), can be utilized for soil treatment (Umar et al., 2016). DeJong et al. (2010) and Carmona et al. (2016) proposed the laboratory mixing of urease with urea and Calcium Chloride or calcite precipitating agents, which can be directly injected into the soil to bypass the complex process of handling microbes. They observed a decrease in the void ratio as a result of CaCO3 precipitation. Typically, microbes tend to remain close to particle contact due to nutrient availability, and the majority of the calcite formed is located in these areas, which is beneficial for soil enhancement. Cheng et al. (2014) recommended the use of saline water for Ca2+ ion precipitation instead of chemical alternatives. Although the calcification rate was slow, it can considerably lower project costs.

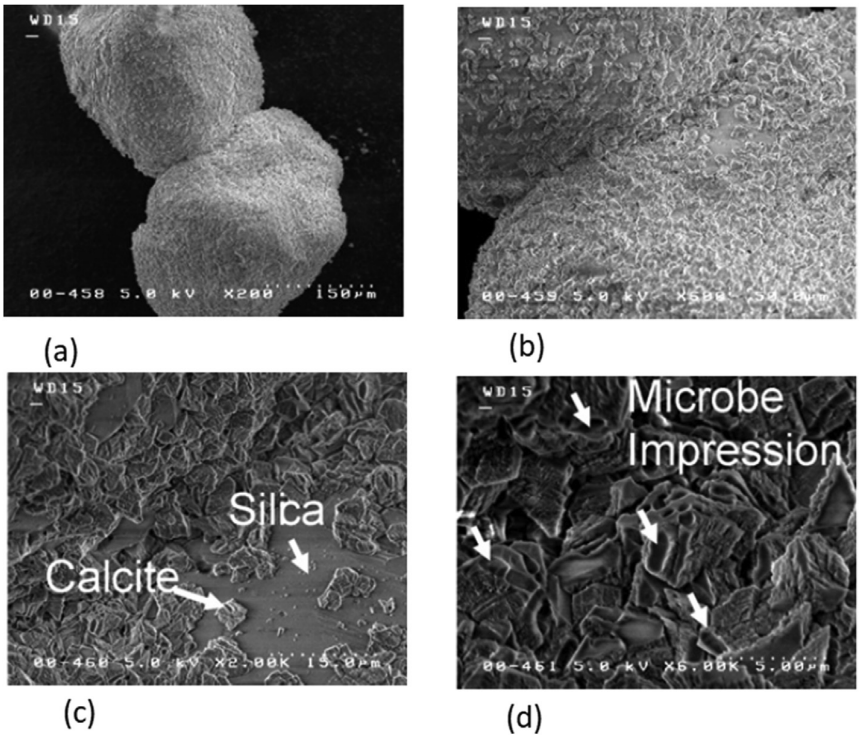

Figure 2. Images (a)–(d) shows the SEM images of the calcite precipitation at particle-particle contact and microbial habitat. Images (b) and (c) reveals that the calcite aggregates form a relatively heterogeneous structure that is feeble as compared to the silica particles (DeJong et al., 2010). Reprinted with permission from Elsevier.

2.1.2Bio-enzyme

The application of Bio-enzyme offers an alternative and cost-effective approach for soil stabilization.

Numerous Bio-enzymes are currently available in the market, such as Renolith, PermaZyme, TerraZyme, and Fujibeton. Their usage is highly tailored to specific soil types; for instance, Renolith is utilized to enhance the tensile strength of granular soil, PermaZyme improves the cohesion of silt and clay, Fujibeton increases the unconfined compressive strength (UCS) and California bearing ratio (CBR) of soil, while TerraZyme boosts the load-bearing capacity of fine-grained soil (Rajoria and Kaur, 2014). TerraZyme, a commonly used enzyme derived from vegetables, is environmentally friendly. According to Navale et al. (2019), TerraZyme creates a cementitious substance by interacting with the organic matter in the soil, which leads to decreased permeability, reduced swelling, and enhanced soil strength. Gupta et al. (2017) found that when working with clayey soil, TerraZyme could neutralize the electrostatic charges surrounding clay particles, allowing for easier compaction. Furthermore, Agarwal and Kaur (2014) reported that the use of TerraZyme with black cotton soil resulted in a decrease in swelling and permeability, while significantly increasing both compaction and UCS of the soil.

2.2Ground improvement using the electrochemical method

Electro-osmosis, or electrochemical techniques, are advantageous for the consolidation and dewatering of fine-grained soils with low permeability. Nevertheless, its application as an effective ground improvement method is still in its early stages. When an electric potential difference is established between two electrodes embedded in the soil, water migrates towards the cathode. This technique can be employed to fill voids with colloidal chemicals or gels (Pamukcu and Winterkorn, 1991). The voids within the soil contain water that holds mobile positively charged ions. Upon the application of the electric field, these ions move and also carry water molecules towards the cathode. Regarding electrode selection, copper is the most suitable choice, as graphite is prone to oxidation due to the heat and oxygen released, while steel and aluminum are susceptible to corrosion, leading to decreased conductivity. Other metals, such as silver, are prohibitively expensive. In the case of copper, Copper Oxide and Hydroxide are generated, which are effective conductors of electricity and help prevent corrosion (Lo et al., 1991).

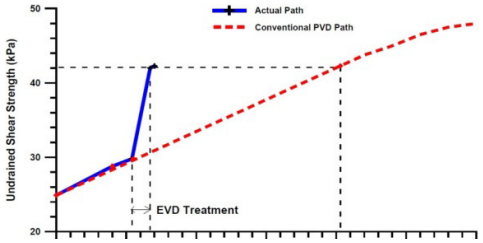

Figure 3. The variation of vane shear strength of soil when electric vertical drains are used compared to prefabricated vertical drains (Chew et al., 2004). Reprinted with permission from Elsevier.

2.3Ground improvement using inorganic pozzolanic/cementitious method

Ground improvement using the inorganic pozzolanic or cementitious method is further subdivided into four types based on the material used for soil improvement.

(a) Cement and lime
(b) Fly ash
(c) Calcium carbide residue
(d) Other inorganic binders such as sodium silicate-based stabilisers

2.3.1Ground improvement using cement and lime

Cement is among the most accessible and commonly utilized admixtures for soil stabilization (Conner and Hoeffner, 1998; Dash and Hussain, 2012). It can greatly enhance the strength, durability, and rigidity of weak soil, particularly in projects where the expenses associated with excavation for a deep foundation could have a significant impact on economic factors. The fundamental principles of stabilization using calcium-based stabilizers include cation exchange, flocculation, pozzolanic reaction, and cementitious hydration. However, it is important to note that cementitious hydration does not take place in lime. Given that cation exchange, flocculation, and agglomeration occur shortly after application, both cement and lime can immediately decrease the plasticity of soil. Each has its unique benefits; lime supplies a substantial quantity of Ca2+ ions, while cement can markedly improve strength and durability through C-S-H bonding. Additionally, the elevated pH of the soil is advantageous for calcium-based stabilizers as it enhances the reactivity and solubility of silica (Prusinski and Bhattacharja, 1999).

Lime and Cement columns could be used if mixing or transporting a large soil volume is not feasible. The strength and rate of reaction of columns depend on the temperature and pH of the soil. The shear strength of such a column is not uniform but sometimes higher than the laboratory determined value. Broms (1991) deduced such columns' utility in reducing settlements (both total and differential) and vibrations in soil due to dynamic loading. Ayeldeen et al. (2016) highlighted the importance of avoiding the cement-soil mixture's storage before compaction. Since cementation starts immediately, disturbed samples offer much lesser strength compared to the undisturbed sample. da Fonseca et al. (2009), while working with fine and residual sand mixed with cement and deduced following relationship between UCS (qu) of the soil and the ratio of void volume (Vv) to the volume of cement (Vce):

$$q_u(kPa) = A[V_v/(V_{ce})^c]^{-b}$$

2.3.2Ground improvement using fly ash

Fly ash (FA) is a byproduct of industrial processes, specifically generated by thermal power plants. In India, approximately 112 million tons of fly ash are produced annually, while globally, the production exceeds 500 million tons each year (Ahmaruzzaman, 2010; Dwivedi and Jain, 2014). Since the early 20th century, engineers have employed this waste material as a soil stabilizer, recognizing its significant binding capacity and low cost (Jacobs and Bennett, 1950). Fly ash is typically categorized into Class C and Class F based on the presence of cementation agents. Class C fly ash is characterized by a high concentration of Calcium Oxide, which grants it superior cementation properties. Conversely, Class F fly ash has limited cementation capabilities due to its lower Calcium content (Misra, 1998; Arora and Aydilek, 2005). In such instances, an activator like lime or cement is necessary to enhance its cementation properties.

The compaction characteristics of soil can be altered by the inclusion of coal ash. It was noted that the optimum moisture content (OMC) for achieving maximum strength occurs at 1%–7% below the maximum dry density (MDD). Further analysis of the moisture density relationship revealed that with a delay following the incorporation of fly ash, the maximum density attained decreased, which in turn reduced the maximum compressive strength. This reduction occurs because the moment fly ash is blended, the cementation process initiates, and a portion of the compaction energy is utilized in breaking the bond. A reduction of 0.6–1.6 kN/m3 in maximum density was recorded with a delay of 1 hour. This delay is contingent upon the hydration rate of the fly ash and varies depending on the source of the fly ash. Pandian and Krishna (2003) conducted experiments by mixing fly ash with black cotton soil in various weight proportions. They observed that the majority of cementation takes place within the first week of addition, and both OMC and MDD decreased as the percentage of fly ash increased.

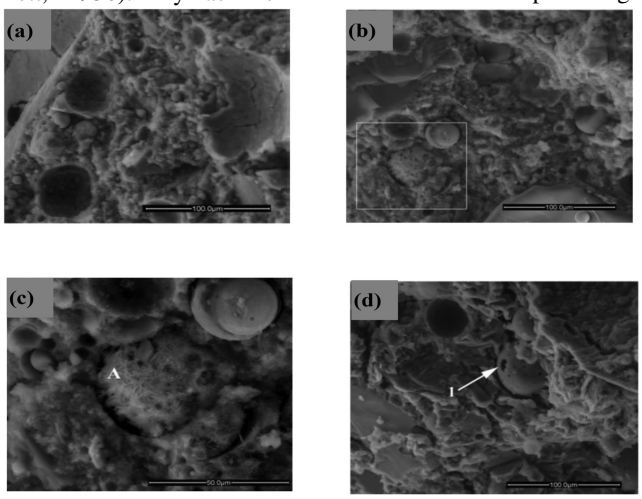

Figure 4. SEM images of soil fly ash mixture after 1 (a), 3 (b and c) and 7 (d) days curing (Cristelo et al., 2012). Reprinted with permission from Elsevier.

2.3.3Ground improvement using calcium carbide residue

Calcium carbide residue (CCR) is generated as a byproduct in the acetylene production process. Similar to fly ash, utilizing it as a stabilizer presents an effective method for its disposal. This

application aids in minimizing swelling and enhancing the friction angle of the soil (Juneja and Shinde, 2019). The primary component of CCR is Calcium Hydroxide ($Ca(OH)_2$), accompanied by minor amounts of Calcium Carbonate. While it is not hazardous for disposal, caution is advised due to its elevated alkalinity. The presence of heavy metals cannot be entirely dismissed. Given the high levels of $Ca(OH)_2$, it is particularly beneficial for clayey soils, which already possess adequate pozzolanic materials such as Calcium and Aluminum. $Ca(OH)_2$ interacts with these minerals to create cementing compounds, as illustrated in Figure 5 (Kampala et al., 2013). It has often been demonstrated to be more effective than lime stabilization (Kampala and Horpibulsuk, 2013). Latifi et al. (2018) performed multiple UCS tests on a clay and CCR mixture, concluding that there was a significant enhancement in strength properties from untreated to treated clay, particularly with curing over the initial 28 days. As the quantity of CCR increases, the soil begins to exhibit advantageous properties that stabilize after reaching a specific threshold, referred to as the optimum CCR concentration.

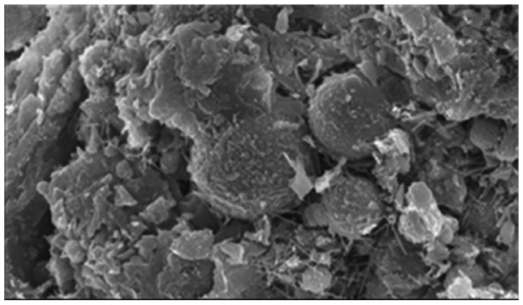

Figure 5. CCR stabilised clay (Kampala et al., 2013). Reprinted with permission from Elsevier.

2.3.4Ground improvement using other inorganic chemicals

Numerous environmentally friendly and safe inorganic chemical compounds, including silicate-based chemicals and certain magnesium and calcium-based salts, are utilized as soil stabilizers. These compounds typically react with the soil to create robust bonds between particles or may harden themselves. Calcium Silicate Hydrate, the primary product of cement, forms as a result of the hydration reaction and is crucial for the settlement of cement. The formation of calcium silicate is critically important not only in cement but also in lime and fly ash-based stabilization (Bullard et al., 2011). Often, sodium silicate and calcium-based compounds are directly injected into the soil, leading to the creation of an inorganic polymeric compound known as Calcium Silicate Hydrate. Huat et al. (2011) recognized sodium silicate (or sodium metasilicate) as one of these traditional additives that is environmentally friendly and can be combined with cement. Its alternative forms, such as sodium orthosilicate and sodium sesquisilicate, when used alone, do not yield satisfactory outcomes. Nevertheless, their effectiveness is enhanced when combined with other stabilizers like lime or fly ash, demonstrating promising results (Rafalko et al., 2007). Madurwar et al. (2013) concluded that this may be attributed to their solubility. Hurley and Thornburn (1971) noted that the injection of sodium silicate followed by calcium chloride leads to the formation of an insoluble gel, which occupies the voids in the ground.

2.4Ground improvement using organic polymeric binders

There is major four organic polymeric that can be used as binders for soil improvement.

(a) Polyurethane
(b) Lignosulfonate
(c) Epoxy resins
(d) Polyacrylamide

2.4.1Ground improvement using polyurethane

Polyurethane (PU) is a type of polymer composed of Polyol (-OH) and Polyisocyanates (-NCO). The various combinations of Polyol and Polyisocyanates lead to a diverse range of polyurethane products. Its quick reaction time, typically ranging from 30 to 120 seconds, along with its lightweight nature, makes it ideal for highway pavement repairs, as it cannot remain blocked for extended periods. The presence of groundwater or moisture in the soil can limit the application of polyurethane, as gas may be released, potentially CO_2, due to the interaction between water and isocyanate, or water vapor resulting from the heat generated by the reaction of Polyol and Polyisocyanates (Yu et al., 2013). Additionally, various catalysts, chain extenders, and surfactants are utilized to achieve specific desired properties (Saleh et al., 2019). The moisture level in the soil also influences the density and yield of the reaction. Generally, PU is viscous and works well with medium-sized sand; however, recent advancements are being made to adapt it for use in silty and clayey soils (Robinson et al., 2012). Hydrophilic PU can absorb a significant amount of water within their structure, causing their volume to expand considerably. They are frequently employed for sealing cracks or enhancing ground stability in areas where the strata contain substantial water (Vipulanandan et al., 2012). When PU grout is

injected, the expansion of the polyurethane grout pushes out water, leading to soil consolidation. Furthermore, most of the stabilization occurs within 15 minutes of application (Fakhar and Asmaniza, 2016).

PU immediately enhances the soil's bearing capacity and serves as an effective stabilizer for compromised foundation soil (Sabri et al., 2018). Liu et al. (2018) investigated the influence of polyurethane combined with polypropylene fiber on the tensile strength of sands. Their findings indicated that a curing period of at least 12 hours is necessary for the solidification of the specimen, with approximately 48 hours required for stabilization. The study demonstrated that polyurethane facilitates the binding of polypropylene to soil particles, resulting in increased tensile strength, which can be 2 to 3 times the initial tensile strength, depending on the level of compaction. Liu et al. (2012) established that polyurethane can significantly enhance soil resistance to erosion, proving advantageous for clay-rich soils. According to Liu et al. (2019a), conventional stabilization methods (such as cement and lime) can effectively improve engineering properties. However, their application may increase soil brittleness, potentially leading to sudden structural failures and environmental concerns. They employed water-based polyurethane stabilizers (activated in the presence of water) at varying concentrations from 0 to 40%, achieving a notable increase in cohesion, friction angle, and tensile strength at 40% PU. Likewise, hydraulic conductivity decreased from 1.43 × 10—2 to 7.23 × 10—4 cm/s with a PU concentration of 3–5%, enhancing the soil's stability against water. Liu et al. (2019a) also pointed out the adverse effects of incorporating PU into the soil, as filling soil voids with PU inhibits vegetation growth since roots cannot expand freely in such conditions. This is illustrated in Figure 6 (Liu et al., 2019a).

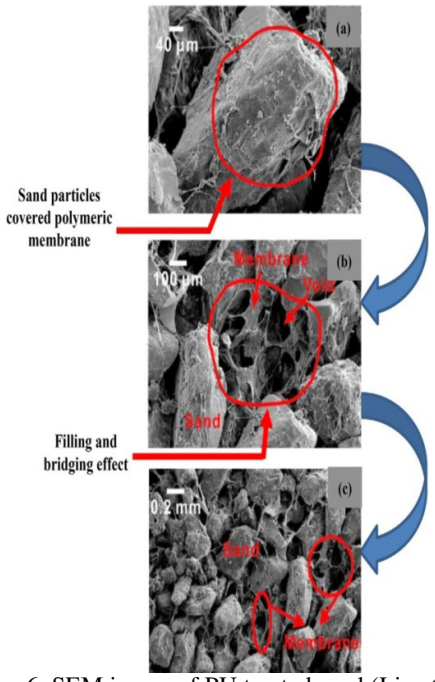

Figure 6. SEM image of PU treated sand (Liu et al., 2019a, 2019b). Image (a) shows the closed enwrapping of sand particles by a fine hard coating of polymeric membranes. Image (b) shows the supplementary improvement of cementation via a chain networking of the interrelated membranes due to growth of the inter-particle voids filling. Image (c) shows the structure completion of the 3D cross-linked network to a huge degree. Reprinted with permission from Elsevier.

2.4.2Ground improvement using lignosulfonate

Lignosulfonate (LS) is a sustainable byproduct produced from the wood and paper industries, known for its remarkable application in soil enhancement, particularly for cohesive expansive soils where alterations in chemical composition are not significant. It is an amorphous polymer based on cross-linked lignin, possessing a net negative charge that facilitates the formation of coordination bonds with metal ions. When incorporated into soil, it enhances compaction and increases amorphousness, which in turn diminishes the soil's capacity to absorb water. The SEM images presented in Figure 7 demonstrate a rise in soil density following the application of LS (Alazigha et al., 2018; Indraratna et al., 2012). Unlike cement and lime-based stabilizers, which can pose risks during dynamic and impact loading, LS does not elevate the pH or brittleness of the soil (Chen and Indraratna, 2015). Vinod et al. (2010) found that incorporating Lignosulfonate into soil decreases the soil erosion coefficient and the thickness of the clay

double layer. Lignosulfonate is particularly advantageous in construction as it does not threaten steel or cement structures with sulfate attacks, nor does it create issues for vegetation or groundwater contamination due to elevated pH.

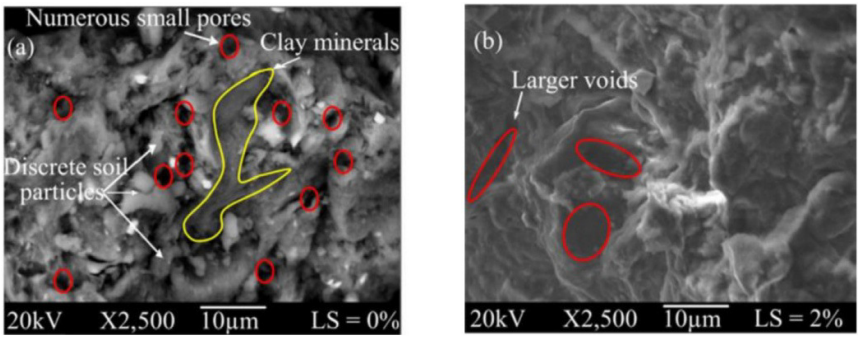

Figure 7. Treated and expansive untreated soil (a) LS 0 % (b) LS 2% (Alazigha et al., 2018). Reprinted with permission from Elsevier.

2.4.3Ground improvement using epoxy resins

Epoxy resins (ER) are liquid pre-polymers that exhibit remarkable tensile and compressive strength. Nevertheless, they pose an environmental risk due to their toxic characteristics (Kazemain and Barghchi, 2012). When mixed with another compound, typically referred to as a hardener (an epoxy component combined with an amine component), epoxy resin undergoes a polymerization reaction. The resulting product is highly stable and resistant to chemicals and heat. However, it may impede the pozzolanic reaction in clay stabilized with cement, making it inadvisable to use in a cement-clay mixture. It enhances the ductility of soil without chemically interacting with soil minerals (Hamidi and Marandi, 2018), as illustrated in Figure 8. The use of epoxy resins is generally more effective than cement stabilization. Due to its high permeability, clogging does not occur at the injection site, allowing for easy application in soils with smaller pore sizes. Key factors influencing the degree of stabilization include water content, curing time, and the quantity of resin added. Anagnostopoulos and Papaliangas (2012) investigated the impact of dilution on the strength and other physical properties of sands, concluding that a decrease in the unconfined compressive strength (UCS) and cohesion occurs with a lower resin-to-water ratio (ER/W). Resins effectively provide high post-failure strength and induce strain hardening; however, this behavior is less pronounced in highly diluted resins. As a result, they noted changes in the bonding between particles and also presented a correlation equation for permeability (k) in relation to ER/W.

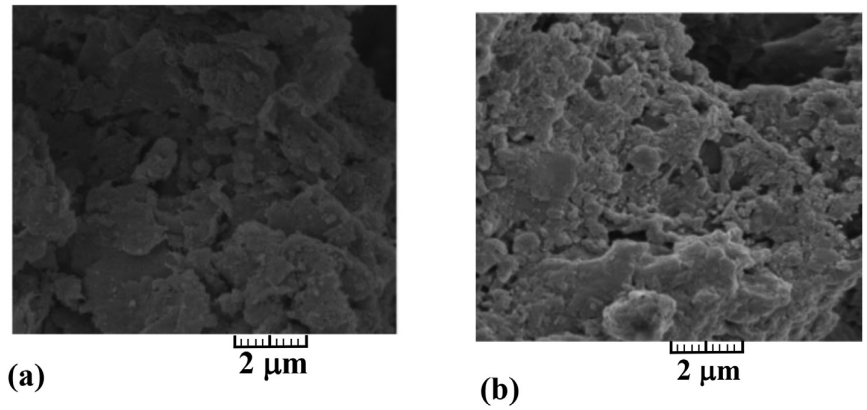

Figure 8. Bentonite treated with epoxy resin (a) bentonite clay (b) bentonite + epoxy resin. Image (a) shows the SEM of the unstable sample. Image (a) shows the SEM of bentonite sample stabilized by the epoxy resin (Hamidi and Marandi, 2018). Reprinted with permission from Elsevier.

Similarly, Anagnostopoulos et al. (2014) investigated the effect of epoxy resin with electro-osmosis and found a further enhancement in the strength properties of sand. Apart from decreasing strength with more water content, time is taken by sample for curing also decrease. Modulus of elasticity decreased from 585MPa to 155MPa for ER/W ratio 2 to 0.5. Usually, the addition of resin results in an increase in MDD and decrease in OMC, but still, these properties are more dependent on soil composi- tion (Ates¸, 2013; Kumar and Kumar, 2015). Anagnostopoulos (2015) used epoxy resins with cement to stabilise silty clay and found it useful and reduced brittleness, unlike other soil cement mix. SEM images showing the effect of ER with soil and cement is shown in Figure 9 (Hamidi and Marandi, 2018). The use of resins was found useful for reducing the dispersivity of clays by Vyas et al. (2011). Toufigh and Rahmannejad (2018) proposed a regression relationship between UCS and curing time (t) for dry sand as:

UCS = a + bt

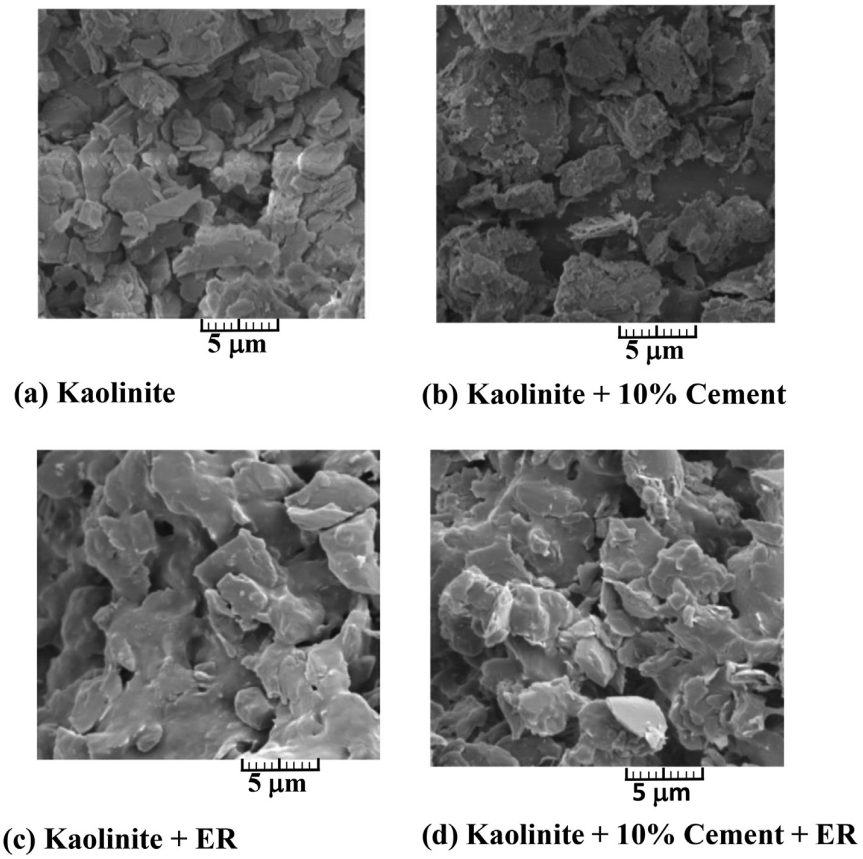

Figure 9.Change in bonding between particles of soilwith the addition of ER and cement (Hamidi andMarandi, 2018). Image (a) shows the SEM of the un-treated Kaolinite sample. SEM of Image (b) shows thenoticeable variations in the structure/morphology ofthe kaolinite sample stabilized with cement. SEM ofImage (c) shows the few variations in the kaolinitestructure due to the inclusion of epoxy resin. Image (c)shows the SEM of the Kaolinite sample stabilized byaddition of epoxy resin and 10% cement. Reprintedwith permissionfromElsevier.

2.4.4Ground improvement using polyacrylamide

Polyacrylamide (PAM) is a polymer that dissolves in water, created from acrylamide as its monomer unit (Green and Stott, 1999). Since the last decade of the 20th century, PAM has been utilized as a stabilizer, aiding in the aggregation and flocculation of soil, which can significantly mitigate erosion. Its primary application is in the stabilization of steep slopes along highways. The aggregation of soil creates adequate void spaces for water to flow, thereby enhancing permeability and decreasing the likelihood of high pore pressure development. Additionally, the reduction in water runoff subsequently lessens soil erosion. PAM effectively binds the aggregates, preventing the dispersion of soil into smaller particles when water flows through, which typically obstructs flow.

Higher molecular weight PAM demonstrates greater effectiveness compared to its lower molecular weight counterpart, likely due to its longer chain length.

3.DISCUSSION AND FUTURE SCOPE OF RESEARCH

In recent years, the swift advancement of infrastructure in metropolitan areas, coupled with the limited availability of usable land, has necessitated engineers to enhance the properties of weak soil to support the loads imposed by infrastructure such as buildings, bridges, roadways, and railways. The aim of ground improvement techniques is to augment the soil's bearing capacity, alter the sub-surface hydrology, and significantly reduce settlement. A variety of techniques are available and continue to evolve, including mechanical, biotechnical, and chemical improvements. Currently, numerous chemical stabilization methods are accessible and widely implemented, particularly for highways. Chemical methods offer several advantages over mechanical soil stabilization techniques, such as the absence of noise and vibrations, which are typically associated with dynamic compaction. Although there is always some level of environmental risk, it can be mitigated with careful management. The inorganic waste materials utilized for ground improvement pose a potential risk of leaching heavy metals; thus, there is a pressing need to develop chemical compounds capable of binding these heavy metal ions in a solid state or forming harmless complexes. Likewise, for polymeric compounds, earnest efforts must be made to address the hazards associated with epoxy resins, PAM, and PU. Given that chemical stabilization induces permanent alterations in soil properties by modifying its composition, it proves to be more effective in expansive clay soils.Chemical stabilization primarily utilizes industrial byproducts as a stabilizing agent, which also aids in waste disposal and may lower the overall project costs. Despite these benefits, the soil is a heterogeneous material with diverse mineral compositions. Since most chemical stabilization techniques rely on the chemical composition and mechanical properties of the soil, it is essential to conduct thorough laboratory and field investigations prior to implementation. While methods like cement or lime mixing may be considered exempt due to the extensive data available, newly developed and less commonly used methods require comprehensive study.

Biochemical methods are generally favored for sandy soil due to the restricted movement of bacteria caused by pore size. While large pore spaces facilitate bacterial movement, an increase in pore size results in a decrease in particle-particle contact, which is essential for cementation, thereby reducing strength. An optimization technique must be devised to reconcile these two conflicting parameters to achieve maximum strength. Additionally, the structural arrangement and particle size should be taken into account prior to the application of the method. When selecting microbes, it is essential to choose bacteria that can thrive in high concentrations of ammonia and are non-pathogenic. Bacteria that precipitate calcite and exhibit low urease activity are the most desirable. The rate of calcite precipitation must be such that it neither obstructs the inlet nor takes an excessive amount of time to stabilize. The ability of bacteria to survive for extended periods enhances the utility of this method; however, predicting their growth, spread, and concentration remains challenging. Therefore, a testing or monitoring system must be developed to assess the growth, spread, and concentration of microbes over time. A significant number of tests should be performed to gather adequate data to forecast the outcomes of applying various types of microbes, with an emphasis on creating an advanced monitoring system to ensure the attainment of consistent strength across the entire area.Biochemical methods offer a superior alternative to conventional mechanical techniques as they do not generate sound or vibrations during treatment, nor do they release harmful chemicals, unlike the significant CO_2 emissions associated with cement production. Furthermore, this method is most effective at room temperature, and its strength continues to improve over time due to the growth of microbial clusters. In addition to subsurface stabilization, it can efficiently bind surface soil, leading to reduced soil erosion and aiding in dust suppression. Nevertheless, it is essential to exercise caution to prevent excessive water infiltration, as inundation may wash away microbes, and the occurrence of acid rain can dissolve precipitated calcium. Therefore, establishing a proper drainage network in the stabilized area is crucial. The effects of temperature, soil mineralogy, ecology, moisture content, and climate must be examined to enhance the effectiveness of this method.

In a similar vein, the application of different bio-enzymes for ground enhancement is limited by the soil type. While a specific bio-enzyme may be appropriate for a certain soil category, it should not be utilized in isolation. Rather, it ought to be employed as a supplementary stabiliser, for instance, in conjunction with cement. Relying solely on these enzymes would not be advisable. Additionally, it is crucial to consider the time factor

before implementing these methods. Given that the establishment and proliferation of a bacterial colony require a certain duration, these techniques are not recommended for projects that demand immediate ground improvement. The emphasis should be placed on identifying various microbial types that can thrive across a broad spectrum of geological conditions and can develop the necessary cementing properties in the shortest possible timeframe.

Table 1. Utility of various chemical stabilisation methods in improving ground properties.

Chemical Stabilisers	Change in UCS (kPa)		Change in C (kPa)		Change in Ø (°)		Note	Source	Curing time (days)	Quantity
TerraZyme	450	2200					Black cotton soil	Navale et al. (2019)	14	300ml/1.5m^2
Bio enzyme	140	185	125	185			Mountain soil	Moravej et al. (2018)	7	400 ml/m^3
Terrazyme	117	125					Illite	Khan et al. (2015)	28	defined by supplier
Bacillus subtilis	12.74	34.3	49	137.2	4.46	35.07	Sandy clay	Harianto et al. (2013)	28	9cc
Rhizopus oligosporus			0	24	27	25	Sand	Lim et al. (2020)		
B. Megaterium			23	61.7	44.2	51.6	Sandy silt	Min Le (2015)		
B. Megaterium	50	125	23.8	61.7			Tropical residue	Soon et al. (2013)		
Ureolytic bacteria	850	2067					Fine sand	Cheng and Ruwisch (2014)		
Electroosmosis			174	121	24	30.9	Ca ion	Abdullah and Al-Abadi (2010)		
Fly ash			152	195	20	35	Expansive clay	Hasan (2012)	21	10%
Fly ash	24.73	63.38					Clayey soil	Sharma et al. (2012)		20%
Fly ash	212	713						Bin-Shafique et al. (2010)		10%
Fly ash	425	1230					At OMC	Misra (1998)		20%
Fly ash			24.5	33.32	30°15′	34°12′		Prabakar et al. (2004)		35.50%
Fly ash			38.25	20.1	29	37		Rajak et al. (2019)		30%
Rice husk ash			60	37.5	17°50′	31	Alluvial soil	Rathan Raj et al. (2016)		30%
Coconut shell ash			24.41	19.5	13	17	Lateritic soil	Amu et al. (2011)		6%
Lime + Fly ash			10	24	35	41	Sandy soil	Consoli et al. (2001)		4%lime +25 % FA
Lime	171	288					Sodic soil	Umesha et al. (2009)		3%
Lime	312.04	1350					Compressive clay	Jha and Sivapullaiah (2015)		6%
Cement	400	4300						Asgari et al. (2015)	21	7%
Cement	1000	3500–5000						Akpokodje (1985)		12%
Calcium carbide residue	800	2100					Silty clay	Kampala and Horpibulsuk (2013)	7	6%
Calcium carbide residue	78.4	855.54					Expansive clay	Isah and Sharmilab (2015)		4%
Calcium carbide residue	300	1400–1800						Latifi et al. (2018)		
Calcium carbide residue	286	1900						Latifi and Meahen (2017)	90	9%
Silica fumes	48.98	198.65	37	120	7	11	Expansive soil	Singh et al. (2020)		40%–60%
$CaCl_2$	49.5	311.8						Krishna and Ramesh (2012)		
Polyurethane	125	216						Saleh et al. (2020)		
Polyurethane	39.43	50.94	0.11	0.87	7.82	8.46	1:1 sand cyay mix	Liu et al. (2012)		5%
Polyurethane	0/difficult to make sample	131.87	4.32	36	30.12	34.56	Sand	Liu et al. (2019a)		30%
Polyurethane			75	250			Marine clay	Saleh et al. (2018)		5%
Polyurethane	66	145					Marine clay	Saleh et al. (2020)	3	6%
Lignosulfonate	120	130						Sezer et al. (2016)		2%
Lignosulfonate	338	496	235	266	10	15	Expansive clay	Noorzad and Ta'negonbadi (2018)		4%
Lignosulfonate	600	1400					Na LS, bauxite dust	Ding et al. (2018)		10%
Lignosulfonate	610	776					Ca LS, lateritic soil	Ravishankar et al. (2017)	28	2%
Epoxy resin	54.831	166.6						Kumar and Kumar (2015)		5%

Similar to FA, CCR is a waste product that primarily consists of Ca(OH)2 along with pozzolanic binders like Ca and Al. Its utilization raises pH levels and facilitates the dissolution of silica, thereby creating optimal conditions for the pozzolanic reaction. It diminishes double layer thickness through cation exchange. However, relying solely on it as a stabilization agent is not recommended; rather, it can be effectively employed to enhance fly ash, particularly class F fly ash, due to its calcium content, which is typically deficient in Class F FA. Likewise, various other inorganic substances, including Sodium Silicate and Calcium Chloride, as well as certain salts such as CaCl2 and NaCl, can also complement other stabilization methods. Theoretically, their use is expected to enhance the overall effectiveness of various conventional stabilization techniques, which necessitates a comprehensive field and laboratory study prior to large-scale application.

The application of Polyurethane as a grouting material is still in its early stages; there are numerous opportunities for enhancement. Although it is costly, it does not contribute to brittleness, offers substantial post-failure strength, minimizes erodibility, and incorporates ductility while enhancing bearing capacity. Stabilization typically occurs through two mechanisms: it combines with soil and envelops soil particles, thereby increasing bond strength, and it expands, filling soil voids and displacing water. Its capacity to occupy pore space also enables it to elevate foundations. However,

due to its natural viscosity, injecting it into clays and fine-grained soils poses challenges as it necessitates very high pressure. Dilution may be beneficial as it enhances permeability, but increased dilution results in a decrease in binding capacity. Therefore, achieving the desired workability within an economic framework requires a balance between dilution and the desired strength. The extended duration of the polymerization reaction is another significant factor, and efforts should be directed towards enhancing its reaction time without compromising effectiveness. Continuous advancements in strength through the addition of fillers and chain extenders are ongoing. Considerable efforts are required to tackle issues related to water to make it viable for wet soils. Its flexible characteristics may also be advantageous in wave attenuation, thus necessitating a detailed study of its effects when the ground experiences dynamic loading.

Table2.Applicabilityandnon-applicabilityofvariouschemicalstabiliserstodifferentsoiltypes.

Method	Applicability	Unsuitable Soil type
MICP	Medium size sandy soil	Soil with a too large or too small pore size
Bio-Enzyme	Highly soil specific	
Electro-Osmosis	Suitable for fine, Impermeable clays	Soils possessing high carbonate buffer and high cation exchange capacities
Cement and Lime		Organic soil with low pH
		Gypsiferous/Bassanitic soils
Fly Ash		Organic soil with low pH
CCR	Clays	
Silica Fumes	Expansive soils	
Sodium Silicate-based stabilisers	Sulphate containing soils which are otherwise problematic with traditional stabilisers such as lime, cement, and fly ash	
NaOH + $CaCl_2$	Useful for in situ improvement	
PU	Repairing highway pavement	Care must be taken when using in wet soil
	medium size sand	Clayey soil
	Sealing cracks or for ground improvement where strata bear a large amount of water	
	When high brittleness may be dangerous	
LS	Minimise disturbance to ecology	
	Dispersive clay	
Epoxy resin	Dispersive clay	
	Reduction in permeability may be harmful	
PAM	Highway slopes	
	Erodible soil	
	Reduction in permeability may be harmful	

LS, PU, and Biochemical techniques should be investigated for dust suppression, particularly in opencast mining operations and active construction sites.Methods utilizing biogas may prove beneficial in mitigating damage caused by ground vibrations, as bacteria that generate biogas diminish the soil's ability to retain water. The attenuation of waves occurs at an exponentially faster rate with increasing gas volumes in voids, leading to a reduction in peak particle velocity (Wang et al., 2004).Similar wave attenuation effects are anticipated from PU due to its enhanced flexibility. The innovation of thin, permeable cement-based grout is set to transform ground improvement practices, as it will replace the need for handling large quantities of material with a more cost-effective solution, particularly for fine clay soils.In addition, employing Sodium Silicate as a stabilizing agent could yield positive results, given its thin consistency, cost-effectiveness, and non-toxic nature. However, soil often begins to lose strength due to its solubility; if this challenge can be resolved, it may serve as a viable alternative to other grout materials.

Comprehensive literature reviews demonstrate the effectiveness of chemical stabilisers in enhancing ground conditions. A key feature of chemical stabilisers is their predominant use in conjunction with other stabilisation techniques or within their own combinations. While a limited number of chemical methods can function independently, the majority serve to augment, accelerate, and enhance the efficacy of ground improvement strategies. The incorporation of waste materials, such as fly ash and calcium carbide residue, not only bolsters soil strength but also offers a more environmentally friendly waste disposal solution. Achieving a consistent composition and strength enhancement presents an additional challenge, as the treated ground may exhibit weak areas. In certain instances, regions with elevated additive concentrations due to improper application can create significant issues, such as in cement, where an excessive quantity leads to increased brittleness. Therefore, meticulous attention must be given to ensure uniform mixing, adhering to the optimal limits. Table 1 provides a summary of the impact of various chemical stabilisers on the overall soil

strength. While it is challenging to recommend a specific stabilisation technique for a given soil type, Table 2 outlines some advantageous and disadvantageous soil types for different stabilisation methods.

4.CONCLUSIONS

Ground improvement is crucial in the construction of various structures, including large skyscrapers, dams, petroleum storage facilities, and highways. Engineers face numerous challenges in the realm of ground improvement. There is a pressing need to create more reliable, environmentally sustainable, and efficient methods. While some older technologies function effectively, others are still in development; however, there is a demand for more application-focused techniques that can be utilized on various types of problematic soils. This study identifies several of these challenges. The work aims to review the evolution of ground improvement techniques over time, with a primary emphasis on chemical stabilizers. Both traditional and conventional stabilizers are examined, along with their conditions of applicability and the potential hazards they may pose.

Among the fundamental issues that require further research are:

- The criteria for selecting appropriate techniques for ground improvement, their long-term serviceability, and the impact of various ecological and environmental factors.
- Emphasis should be placed on creating practical, cost-effective, sustainable, and environmentally safe chemical stabilization methods, taking into account carbon emissions and total costs, including environmental expenses.
- In what ways can industrial waste materials be effectively utilized in ground improvement, offering a cost-efficient alternative to conventional techniques while aiding in their disposal?
- The detrimental effects associated with the use of chemical stabilizers need to be thoroughly examined, and careful planning and design must be implemented prior to the commencement of the project.
- Each chemical stabilizer has an optimal concentration that ensures maximum performance, which must be determined before any project is initiated.
- While chemical stabilizers offer numerous benefits over traditional mechanical stabilization methods, such as reduced noise, vibrations, and dust, their use, storage, handling, and application necessitate specialized training.
- It is important to recognize that the most effective use of chemical stabilizers is achieved when they are employed in combination, rather than depending solely on a single stabilizer.
- The effectiveness of these methods hinges on the establishment of techniques for the long-term monitoring of strength enhancement in the treated ground and the observation of any negative environmental impacts. Currently, long-term monitoring remains absent in the domain of ground stabilization.

The forthcoming research and practical experience, as mentioned above, will contribute significantly to the advancement of the ground improvement sub-discipline. Its evolution and significance are essential elements of effective geotechnical engineering and construction methodologies.

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