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Review Article

A comprehensive review on methods, agents and durability factors for stabilization of expansive soils

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ABSTRACT

Expansive soils cover a huge portion of the total land area in the world. They absorb water and expand, then shrink when they dry out. The volume change exerts pressure on engineering structures causing deformations, cracks, and movement of walls. This has a detrimental effect on serviceability and reduces the service life of structures constructed on expansive soil. Therefore, stabilizing expansive soil is important to lessen the negative characteristics of the soil and improve its general toughness and durability. This paper provides an overview of the methods of soil stabilization, stabilizing agents, testing of stabilized soil, and factors that have an impact on the durability of stabilized soil. The most common stabilizing agents which include lime and Ordinary Portland Cement (OPC) are studied. In addition, eco-friendly stabilizers like calcium chloride, sodium chloride, and modern stabilizers like geopolymers, zeolites, and nanomaterials are thoroughly discussed in the paper and potential areas for further research are also recommended. The study shows that the type and amount of stabilizer used, as well as the method of soil stabilization employed determines the extent of soil improvement.

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1. INTRODUCTION

A report by UN-HABITAT [1] on world cities, indicated that cities are home to half of the global population. According to the report, urban cities across the world are facing enormous challenges, especially in infrastructure, with only 13% of the cities having affordable housing. Around the world, 330 million reside in substandard houses, or were overstretched by housing costs by the year 2014, a number expected to rise to over 440 million households by the year 2025, and 2.5 billion by the year 2050 [2]. One of the factors that make housing unaffordable is the cost of construction as well as the availability of land for construction purposes [3].

For the creation of economic possibilities and the delivery of social services to the population, access to basic infrastructure services is essential. The economic growth of all the countries in the world is on a continuous rise, with African countries expected to experience a growth of at least 6% a year from 2022 to the year 2040 [4]. To achieve this growth, then infrastructural development and extension all over the world are inevitable. A report by African Center for Economic Transformation (ACET) (2020) and Organization for Economic Co-operation and Development (OECD) indicates that the population in Africa will grow by 70% in the next 25 years, with the urban population growing by 56%. 40% of the population in the world resides in developing nations with popu-

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lation growth being the fastest in these countries. In addition, 65% of the urban population in low-income countries live in slums. It is important, therefore, to scale up the investment in physical infrastructure to accommodate the fast-growing population. Extension of roads and housing projects should be done at the same rate as demographic growth.

According to Deloitte [5], about 60 billion US dollars are required annually for new physical infrastructure in sub-Saharan Africa, and about 30 billion US dollars for maintenance of the existing infrastructure. However, it is only about 25 billion US dollars are allocated for capital expenditure annually. This creates a huge shortage in the physical infrastructure in Africa, particularly in developing nations. It has been reported that the world would be excited to do business in Africa but it is difficult to access African markets, especially those in the interior due to poor access to roads [5]. Around 840 million people live more than two kilometers from all-weather roads worldwide [6]. For this reason, countries in Africa and the world at large need to invest in physical infrastructure especially the construction of roads and housing to meet the increasing demand. All physical infrastructures are founded on soil, and therefore, with the increase in demand for roads, pavements, housing, and other physical infrastructure, it is necessary to investigate the characteristics of soil as a foundation material before construction work begins on such soil. According to Sindelar [7], a lack of knowledge of soils can lead to catastrophic structural failure.

The stability of structures calls for suitable soil to ensure the foundation is sound. Roy & Kumar [8] stated that to determine the appropriateness of soil for foundation or as a construction material, an assessment of its properties should be done. Properties of soil such as plasticity index, compressibility, or bearing capacity determine the design that is suitable for construction on that soil. Geotechnical properties such as bulk density, specific gravity, compaction, consistency limits, permeability, consolidation, and shear strength determine the suitability of soil as the foundation surface for earth construction [9]. The interactions that happen between these properties help civil engineers in designing the foundations for different civil structures. Therefore, failure to put these properties under consideration when designing the foundation can lead to construction errors. Among the properties of good soil for construction is stability during wetting and drying seasons [7]. In addition, good soil should have pressure stability so that engineering structures do not sink when a huge load is applied to them.

It is important to carry out a site survey before construction work begins on any soil mass. The main properties considered during the survey are; project design, soil-bearing capacity, and swell-shrink behavior [10]. In most geotechnical works, a construction site will not satisfy the design requirement without alteration and this makes it a challenge for geotechnical engineering. Makusa (2012) reported that in the past, the options for unsuitable soil included changing the design of the project, removing the in-situ soil, and replacing it with a desirable soil type or abandoning the site. Abandoning the site led to a scarcity of land for construction purposes. In modern days, soil modification is being undertaken to improve the soil properties to make it suitable for the construction of the desired design [11]. Around the world, expansive soils are common, especially in arid and semi-arid areas [12]. According to Indiramma & Sudharani [13], expansive soils cover about 20% of the world's total land area. Numerous approaches have been used to address the issues related to expansive soils, owing to their widespread global distribution. This review article focuses on various methods of soil stabilization and soil stabilizers and their application in improving the properties of expansive soils. Mechanical stabilization and chemical stabilization (in-situ and ex-situ) have been discussed extensively in this paper. The performance of the unstabilized and stabilized soil has been evaluated majorly based on Plasticity Index (PI), California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), and comparison done.

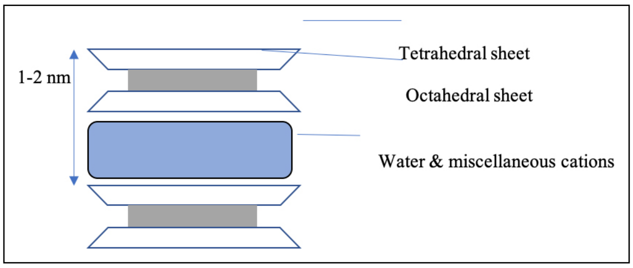

Figure 1. Montmorillonite chemical structure [21].

2. EXPANSIVE SOILS

An expansive soil is a type of soil that takes up water, expands, and then shrinks as it dries out. The unique swelling and shrinking of the soil is the primary engineering problem with expansive soils. The pressure from the volume change causes cracks on floors, pavements and roads, and wall movement as well as deformations in engineering constructions. This has a detrimental effect on serviceability and reduces the service life of structures constructed on expansive soil [12]. Shi et al. [14] state that cracking can either be vertical, where the crack continues to extend downward until a balance is achieved, or horizontal, produced by excessive water pressure from the exterior. Three primary traits of expansive soils include cracking, swelling, and over-consolidation [14].

The construction industry experience challenges working with expansive soils during construction as well as a structural failure after construction due to volume changes and low bearing capacity. According to Kerrane [15], the expansion in expansive clay soil can rise to about 10%. This volume change exerts pressure causing damages which include cracked floors, basement walls, and even damage to upper floors when there is a motion of the entire structure [16]. Therefore, expansive soils are one of the main concerns in the construction sector [17].

According to Osman [18], expansive soils contain up to 30% clay at a depth of 50 cm. They are composed of clay soil that contains expanding clay minerals, primarily the smectite group made of montmorillonite mineral, as shown in Figure 1 [19].

Montmorillonite belongs to the phyllosilicate class of minerals with a high SiO_2 to Al_2O_3 content in the ratio of 2:1 in the structure [20]. In the crystal structure, there are three sheets whereby one octahedral alumina sheet occurs between two tetrahedral sheets forming an interspace layer of about 0.96 nm wide [21]. The triple sheets are then connected by Van der Waals forces [22]. Krut & Yakushev [22] found out that between the layers there are several exchange monovalent cations especially Na+ trapped hence they suggested the formula of montmorillonite as $(Na, Ca)_{0.33}(Al, Mg)^2(Si_4O_{10})(OH)_2{\cdot}nH_2O)$. The presence of the exchange cations especially sodium in the interlayers of montmorillonite, increases the distance between the layers hence allowing entry of water and this phenomenon makes clay with montmorillonite minerals expansive in nature [23].

According to Antoni [24], montmorillonite clay surface is negatively charged. Kumari & Mohan [19] stated that the negative charge is a result of the isomorphous substitution of Si^{4+} by Al^{3+} in the tetrahedral unit and substitution of Al^{3+} by Mg^{2+} in the octahedral unit, and further that the magnitude of negative charge depends on the number of substituted atoms/ions. The authors also stated that the number of cations required to balance the charge deficiency caused by the isomorphous substitution is known as the Cation Exchange Capacity (CEC). Kinoti et al. [21] reported that of all the clay minerals, montmorillonite has the highest CEC ranging from 80 to 150 milliequivalent per 100 grams.

Expansive soils are distributed throughout the globe, with a world coverage of about 20% of the total land area [13]. Legros [25] estimates that expansive soils cover 335 million hectares of the planet. Arid and semi-arid regions have the highest concentration of expansive soils, with the problematic soils being common throughout North America and parts of Asia, including India, Northern Thailand, China, and Japan [26]. Sudan, Kenya, Ethiopia, and South Africa are the African nations having the largest fraction of expansive soils [18]. Furthermore, expansive soils can be found in abundance throughout Europe in countries like the UK, Germany, Greece, Romania, Spain, Sweden, Norway, Cyprus, and the Netherlands.

According to Jones [12], damages incurred annually in the US as a result of expansive soils are worth over $15 billion. A prediction by the America Society of Civil Engineers (ASCE) shows that damages caused by expansive soil are experienced in one out of every four homes. According to Jones [12], the loss experienced by property owners due to expansive soil is more than that of earthquakes, hurricanes, tornadoes, and floods combined. There is, therefore, a need to stabilize this type of soil to make it tolerable in construction and minimize the damages associated with it during and after construction.

3. SOIL STABILIZATION

To enhance one or more qualities of natural soil, special soil, cement, or other chemical components are typically added to it. This process is known as soil stabilization [27]. According to Negi et al. [28], soil stabilization is necessary for soil that has a minimum passage of 25% through a 75 mm sieve, sulfate composition of greater than 0.3%, plasticity index of above 10, and organic materials greater than 1%. Expansive soil must be stabilized before it may be utilized as a sub-base, sub-grade, or base for the construction of roads, bridges, and structures. Soil stabilization is mostly done to increase the stiffness and firmness of natural soil, and decrease its flexibility, and shrinkage/swelling potential [29]. According to Firoozi et al. [29], stabilized expansive clay soil has a higher bearing capacity when a heavy load is placed on it, as compared to unstabilized expansive soil.

For expansive soils to have less of a chance of expanding, soil stability is essential [30]. Chemical stabilization aims to provide additives that result in a lower liquid limit and a higher plastic limit, which together reduce the plasticity index overall [13]. As a result, the stabilized soil becomes more compressible, which improves the workability of the soil, moisture content, and maximum dry density.

Permeability affects soil consolidation when a load is applied [31]. It also affects the volume changes in the soil during wet and dry conditions. The permeability of the soil mostly determines the rate at which pore water pressure dissipates. With the use of soil stabilization, soil particles can be more tightly packed together, which lowers the void ratio and consequently reduces the permeability coefficient. Shil [32] examined how fly ash affected the permeability of stabilized soil and discovered that permeability reduces as fly ash content rises [33]. Therefore, soil permeability can be reduced by the introduction of a stabilizing agent which acts as a binder hence flocculating the soil particles as well as application of mechanical compaction [34]. In order to stabilize kaolinite soil, Ghavami et al. [35] employed cement and cement kiln dust; they reported a reduction in the volume of void spaces and an improvement in the compressive strength of the soil. Other researchers have used lime [36], nanocomposite [37], and granulated blast furnace slag [38] in the successful stabilization of clay soils.

In most cases, there is a reduction in the cost of construction where the properties of substandard, readily available materials are improved through stabilization. There is also a reduction in the cost of maintenance and repair since the swell-shrink potential of the expansive soil is mitigated through stabilization. The material may remain a granular type caused by an increase in cohesion, especially where cementation takes place or the bond between the fines improves [39].

4. METHODS OF SOIL STABILIZATION

In order to make soil useful for building, soil stabilization entails enhancing its engineering qualities. According to Obianigwe & Ngene [27], soil stabilization is the process of enhancing the natural qualities of soil so that it is acceptable for use in construction projects by adding a cementing material, a unique kind of soil, or a chemical additive. Soil stabilization is broadly categorized into mechanical and chemical methods. These two methods can be done using different approaches which can further be categorized as in-situ methods, ex-situ methods, wet-mixing stabilization, dry-mixing stabilization, and deep-mixing stabilization.

Table 1. Mechanical stabilization

Type of soil	Stabilizer used	Stabilizer dosage	Major property tested	Value before sta.	Value after sta.	Author
Marginal base material	Gravel with natural sand	20%	CBR	68%	85%	[45]
Clay soil	Fines from construction & demolition waste	10%	CBR	23%	50%	[46]
Black cotton soil	Quarry dust	10%	PI	39%	35%	[44]
Low plasticity clay	Stone dust & coarse aggregates	30%	CBR	32.4%	194.7%	[47]
Black cotton soil	Quarry dust	20%	UCS	0.88 MPa	1.88 MPa	[48]
High plasticity clay	Quarry dust	25%	PI	64%	29%	[13]
Black cotton soil	Recycled concrete aggregates	30%	CBR	3%	27%	[49]

sta.: Stabilization; CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive.

4.1. Mechanical Stabilization

This entails altering the gradation of expansive soils to stabilize them. To create a composite with distinct qualities from any of the separate soil ingredients, two or more soil materials of different gradations are combined. It includes the use of rammers, rollers, vibrators, and other mechanical energy to compact and densify the soil. Mechanical stabilization mainly applies compaction to get rid of the air voids present in the soil which leads to soil densification and hence, improves the ability of the soil to support loads [40]. Ikeagwuani & Nwonu [41] indicated that during compaction, it is important to know the relationship between moisture and density by observing the optimum moisture content (OMC) against the maximum dry density (MDD) for the soil being compacted. According to research by Huang et al. [42], an improvement in dry density at the ideal moisture content boosts the capacity of the soil to support loads because fewer air gaps bring soil particles closer together and reduce swelling potential. Similarly, the liquid limit rises as the optimum moisture content rises, but an increase in MDD lowers the plasticity index [43]. Table 1 discusses a few studies on the application of mechanical stabilization. Quarry dust has been extensively used in mechanical soil stabilization, resulting to a decrease in plasticity index and increase in UCS. According to the study by Kumar [44], the dosage of quarry dust has to be above 10% for a significant reduction in plasticity index.

From Table 1, it is evident that application of more coarse materials like quarry dust and aggregates improves the plasticity index and strength behaviour of clay soils. This is attributed to the decrease in fine content, resulting to an increase in load bearing capacity. Introduction of quarry dust and aggregates changes the gradation of the high plasticity clay soils. This results to reduction in the amount of water that can be absorbed by the clay particles, since the pores between the fine particles are filled by the coarser particles.

4.2. Chemical Stabilization

This involves the addition of chemically active additives to react with the natural soil hence changing its properties like swelling behavior and load-bearing capacity. To enhance soil qualities including strength, compressibility, and permeability, stabilizing chemicals are added. The interactions between the soil surface and water are what it seeks to alter. The geotechnical characteristics of soil have been chemically improved by the use of several additives. Khemissa & Mahamedi [50] state that the strength, volume stability, bearing capacity, permeability, and durability of soil can all be enhanced by the use of additives. The kind of soil, the surroundings, and the intended use of the soil all influence the additive that is chosen. Adding substances either in- or ex-situ is possible.

4.2.1. In-situ Stabilization

This method of soil stabilization involves the addition of stabilizing agents to the soil on-site without removing the bulk soil. Using augers, a cementitious substance, such as cement or lime, is injected into the soil either wet or dry. The number of holes to be drilled by the auger depends on the size of the auger and the area of stabilization. Factors such as the construction design to be done, the effectiveness of the stabilizing agents, in-situ soil conditions and the in-situ moisture content determine whether to use wet mixing or dry mixing methods. This method can be considered deep mixing or mass stabilization depending on the depth of stabilization [51].

The stability of soils at great depths is accomplished through deep soil mixing (DSM). A wet or dry binder is injected into the ground and blended with in situ soils using a mechanical or rotary mixing tool [51]. It blends existing soils with a stabilizer which is pumped to a soil mixing rig outfitted with a rotary head. As the rotary head is withdrawn the paddles achieve further mixing. The aim of deep mixing is not to produce a stabilized soil mass that is stiffy, but to produce one which may interact with natural soil. Therefore, effective interaction between the stabilized soil and natural soil should be maintained for effective stabilization. Ikeagwuani & Nwonu [41] stated that the auger-made hole is filled with calcium oxide during lime stabilization in-situ without the use of displaced soil. The research also indicated that the mechanism of stabilization in lime treatment entails calcium ions diffusion into the soil and eventually modifies the physicochemical properties through the ionic exchange.

According to Madhyannapu & Puppala [52], the following factors are considered when choosing the design for DSM;

Table 2. Application of deep soil mixing soil stabilization method

Deep soil mixing method	Type of soil	Stabilizer used	Major test parameter	Initial performance	Final performance	Author
Dry soil mixing	Clay	15% lime	UCS	–	6.5 to 10 times improvement	[52]
Wet soil mixing	Clayey silt soil	12% OPC	UCS	0.17 MPa	1.78 MPa	[58]
Dry soil mixing	Silty sand (SM)	6% OPC	CBR	5.07%	10.15%	[59]
Wet soil mixing	Clayey silt soil	250 kg/m^3 cement	UCS	1.2 MPa	7.0 MPa	[56]
Dry soil mixing	Peat soil (CH)	12% calcium carbide + 8% rice husks ash	Bearing capacity	5.274 kPa	32.44 kPa	[60]
Dry soil mixing	Organic soil	250 kg/m^3 cement	UCS	0.1 MPa	1.2 MPa	[53]
Dry soil mixing	Clayey-sand	120 kg/m^3	UCS	0.4 MPa	2.9 MPa	[61]

CBR: California Bearing Ratio; UCS: Unconfined compressive strength.

1. The best binder dose levels and stabilizer kind. Following laboratory mix design and further examination, this is carried out.
2. The water-to-binder ratio at which DSM columns work at their best.
3. The length, diameter, and spacing of DSM columns depend on the characteristics of treated and untreated soils discovered by laboratory research.

Deep soil mixing is further classified as either dry or wet mixing, as discussed and summarized in Table 2.

In dry mixing soil stabilization, dry stabilizing materials are injected into the soil and thoroughly mixed with wet soil. Dry powdered binder ingredient is injected into the soil using compressed air through perforations in a mixing tool positioned on a rotating Kelly bar. The inherent water content of the soil causes chemical changes that increase its shear strength by making the soil less compressible and porous [53]. According to Timoney et al. [53], in common European usage, columns have diameters ranging from 0.5 to 1.0 m, whereas they can reach 1.5 m in Japan. The soil is premixed as it descends using a specialized tool until the necessary depth is reached. The dry stabilizers are then injected and blended with the premixed soil when the mixing instrument is removed, leaving behind a mixed column of moist soil.

The dry mixing method was used by Timoney et al. [53] to explore the application of cement and Ground Granulated Blast Furnace Slag (GGBS) in soil stabilization and found that the usage of cement-GGBS mixture resulted in higher UCS values of over 1000 kPa at 28 days compared to cement alone. Additionally, according to this study, samples stabilized using fly ash and lime binders exhibit weaker strength improvements than samples stabilized with cement and GGBS binders. Quality assessment tests carried out by Pan et al. [54] discovered that the depth of the Dry Soil Mixing (DSM) column was inversely correlated with the number of unqualified DSM columns and the difficulty of controlling the quality of DSM columns.

The wet mixing method, on the other hand, involves turning a binder into slurry form, then after that, injecting it into the soil using the nozzles on the end of the soil auger. Transverse beams, a drilling rod, and a drill end with a head make up the mixing tool [55]. Grout is injected into the soil at high pressure while mixing continues. During penetration, 80–100% of the slurry is transferred to the ground, and the homogeneity of the soil-binder mixture depends on the soil properties, the type of rotating auger, and the time of mixing [56]. Wet soil mixing is the most common in-situ soil stabilization method in the world [57]. This is because it is easy and cost-effective for use in soil strengthening for diaphragm walls and deep foundation for buildings.

Table 2 shows the results for some of the research works that have applied deep soil mixing in soil stabilization.

From the table, a conclusion can be made that the application of DSM has successfully improved both index and mechanical soil properties in the past.

Another method of in-situ soil stabilization other than DSM is Mass Stabilization. It is used for both shallow and deep stabilization of expansive soils with a lot of moisture, as well as silty organic soils. Mass stabilization is a practical method for stabilizing soil, particularly in sites with a lot of water. The soil and stabilizing agents are mixed using excavators mounted with a mixing tool. The mixer rotates while simultaneously moving both vertically and horizontally to mix the soil. About 200 kg/m^3 of Portland cement is the ideal amount needed for mass stabilization using cement [62]. Table 3 displays some of the research projects that have been done on the applications of mass soil stabilization.

4.2.2. Ex-situ Stabilization

This method involves dislodging a soil material from its original site and treating it for use at a different construction site. It is most common where the depth of the expansive soil is shallow and hence, the excavation process is not complicated. The excavated soil is normally mixed with the stabilizers using backhoes or pug mills [66]. Factors to consider when choosing this method include removal method, cost of transportation, availability of the disposal location, and the treatment site. Table 4 shows some of the studies on soil stabilization that have been carried out in-situ.

According to Federal Remediation Technologies Roundtable [70], ex-situ stabilization achieves more uniform mixing compared to all methods of in-situ stabilization. The dis-

Table 3. Application of mass soil stabilization

Type of soil	Stabilizer	Test parameters	Initial performance	Performance after stabilization	Author
Soft peat & clay	200 kg/m^3 portland cement	Shear strength	30 kPa	500 kPa	[63]
High plasticity clay soil	Liquid ion soil stabilizer (LISS)	UCS	34.47 kPa	379.2 kPa	[64]
CH grey and CL red clayey soil	Lime	Plasticity index	52%	19.9%	[65]
Clayey soil (CH)	150 kg/m^3 OPC	UCS	20 kPa	600 kPa	[62]
Soft clay soil	6% OPC	UCS	20 kPa	160 kPa	[10]

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

Table 4. Application of ex-situ soil stabilization

Soil type	Test parameter	Stabilizer used	Stabilizer dosage	Initial per.	Final per.	Ref.
Soils with inorganic contaminants	UCS	Phosphate-based binder, KMP	6%	20 kPa	110 kPa	[67]
Pb-Zn contaminated soil	DCP Strength	Superphosphate	8%	1.55 kN	11.11 kN	[68]
Red mud	UCS	Fly ash	30%	300 kPa	2250 kPa	[69]

per.: Ref.: Reference; Performance; UCS: Unconfined compressive strength; DCP: Dynamic cone penetrometer.

advantages of in-situ stabilization over ex-situ stabilization include difficulties in ensuring uniform chemical reagent or additive dosages throughout the sediments to be treated, a lack of process control because of reliance on monitoring site conditions both before and after treatment, and a lack of process control [71]. On the other hand, in-situ soil stabilization is cheaper compared to ex-situ stabilization since it makes use of the natural existing soil material instead of the excavation process. Table 4 shows recent studies on the use of the ex-situ soil stabilization method.

Figure 2 gives a summary of the methods of soil stabilization and how they relate to each other.

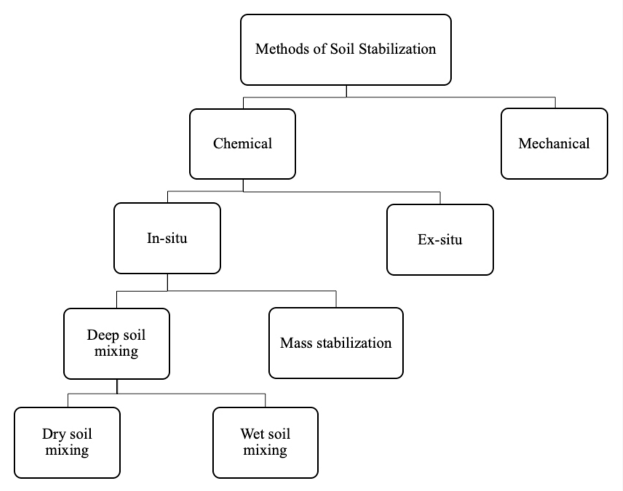

Figure 2. Methods of soil stabilization.

5. SOIL STABILIZERS

These are admixtures that are applied to stabilize soil both shallowly and deeply, enhancing the natural qualities of soil including strength and swelling behavior [72]. According to He [64], there are three different types of chemical stabilizers: traditional stabilizers (which include cement, lime, and fly ash), by-product stabilizers (which include coffee husk ash, blast furnace slag, lime kiln dust, cement kiln dust, and steel slag), and non-traditional stabilizers (which include ionic salts, enzymes, and geopolymers).

Geotechnical characteristics of expansive soils are improved by calcium-based additions like lime and cement. Their mechanism of stabilization depends on cation exchange between Ca^{2+} and other elements in the clay mineral like K^+ and Na^+ [73]. Jerod et al. [74] reported that the cement stabilization mechanism is divided into four; cation exchange, particle restructuring, cementitious hydration, and pozzolanic reactions.

In cation exchange, Ca^{2+} replaces the monovalent ions in the clay soil particles which leads to shrinkage of the water layer between the lay particles causing a reduction in soil plasticity. The introduction of Ca^{2+} decreases the distance between the layers as one divalent cation replaces two monovalent cations. Particle restructuring is the modification of soil also known as agglomeration and flocculation. It involves changing the texture of soil from plastic and fine to granular soil [74]. The production of calcium-aluminate-hydrate (CAH) and calcium-silicate-hydrate (CSH) as a result of cementitious hydration makes the soil more compact. Pozzolanic reactions, which increase the tensile strength of the soil, occur when calcium hydroxide $Ca(OH)_2$ reacts with the silica and alumina on the clay surface. Because the reactions can take months to complete, the soil must be continually strengthened [75].

5.1. Stabilization Using Lime

When quicklime is used, it reacts with the water in the expansive soil or added water and the process produces a lot of heat. The heat produced leads to the drying of the soil due to the evaporation of the moisture content, as illustrated in equation 1 [11].

Table 5. Soil stabilization using lime

Type of soil	Lime dosage	Properties studied	Initial performance	Performance after stabilization	Author (s)
Black cotton clay	6%	UCS	0.27 MPa	1.7 MPa	[76]
Low plasticity clay (CL)	15%	UCS	0.54Pa	2.54 MPa	[77]
High plasticity clay (CH)	4%	Swelling index	7%	0%	[17]
Clay soil	4%	CBR	1.17%	8.52%	[78]
Clay soil	6%	Swelling index	20%	1%	[79]

CBR: California Bearing Ratio; UCS: Unconfined compressive strength.

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} + \mathrm{Heat}\ (65\ \mathrm{kJ/mol}) \quad (1)$$

It is called the short-term treatment of the soil and usually takes place within the first few hours or days. The lime becomes hydrated after a reaction with water and forms Ca^{2+} and OH^{-}. The positively charged Ca^{2+} move to the surface of the negatively charged clay particles.

Additionally, calcium aluminate hydrate (CAH) and calcium silicate hydrate (CSH) cementitious byproducts, are created when calcium hydroxide combines with the soluble silica and alumina in the clay [29]. These reactions are summarized in Equations 2 and 3.

$$CH + S \rightarrow CSH \quad (2)$$

$$CH + A \rightarrow CAH \quad (3)$$

A force of attraction develops and therefore there is a decrease in the repulsion forces within the clay particles. The force of attraction strengthens the bond between soil particles changing the texture of the soil, a process known as agglomeration and flocculation [75]. The phenomenon produces friable and granular soil that is easy to compact [28].

According to Negi et al. [28], the reaction of lime with the expansive soil takes place immediately and an increase in carrying capacity, CBR, resistance to shrinkage, and reduction in plasticity index was observed within a few hours after the reaction started. However, when the soil goes through cycles of soaking and drying, using lime is ineffective because the cohesiveness between the soil grains and the lime weakens, finally increasing soil volume. When soil goes through cycles of soaking and drying, using lime is ineffective because the cohesiveness between the soil grains and the lime weakens, hence increasing soil volume [29]. Table 5 below shows a discussion of the application of lime in soil stabilization.

From Table 5, a conclusion can be made that lime has shown positive performance in increasing soil strength and workability, and also decreasing swelling characteristics. However, a study by He [64], demonstrates one of the major negative effects of lime-stabilized soils is the formation of ettringite which cause heaving in the stabilized soil according to equation 4.

$$\mathrm{2C_3A + C_3A.3C\bar{S}.32H} \rightarrow \mathrm{3[C_3A.3C\bar{S}.32}H\mathrm{]} \quad (4)$$

According to Equation 5, another problem with lime-stabilized soils is the production of calcium carbonate from the reaction of calcium hydroxide with atmospheric carbon (IV) oxide [80]. In this reaction, calcium ions are used up and negatively affect the pozzolanic reaction. In addition, the calcium carbonate formed is soluble and pulverizes with time leading to strength deterioration.

$$\mathrm{CH} + \mathrm{\bar{C}} \rightarrow \mathrm{C\bar{C}} + \mathrm{H} \quad (5)$$

Jawad et al. [75], proposed the replacement of lime with magnesium oxide or magnesium hydroxide as they pose similar chemical characteristics, and magnesium oxide or magnesium hydroxide do not undergo carbonation.

5.2. Stabilization Using Cement

Firoozi et al. [29] discussed the reactions in cement stabilization by use of chemical equations 6, 7, and 8. The belite (dicalcium silicates) and elite (tricalcium silicate) from the cement hydrate into cementitious calcium silicate and hydrated lime, as determined by equations 6 and 7, when it comes into contact with the water in the soil.

$$2C_2S + 6H \rightarrow C_3S_2H_3 + 3CH \quad (6)$$

$$2C_3S + 4H \rightarrow C_3S_2H_3 + 3CH \quad (7)$$

Tricalcium silicate hydrates and hardens very quickly causing early setting and strengthening of the stabilized soil. The early strengthening of stabilized soils increases as tricalcium silicate concentration increases. Contrarily, C_2S hydrates and hardens slowly; as a result, it is to blame for the increased strength of stabilized soil at later ages than 7 days.

The tricalcium aluminate phase undergoes hydration to form tricalcium aluminate hydrate according to Equation 8.

$$2C_3A + 4H \rightarrow C_3S_2H_3 + 3CH \quad (8)$$

Hydration of C_3A produces a lot of heat which results in rapid hardening. This reduces the workability of the soil being stabilized. The rapid hydration of C_3A is slowed down by gypsum which is normally added during the final grinding of cement. Cement that has C_3A would set rapidly if gypsum was not present. Low percentages of C_3A in cement make the cement resistant to waters and soils that contain sulfates (external sulfate attack).

In addition, calcium hydroxide produced in equations 6, 7, and 8 reacts with the alumina and silica present in the soil through a pozzolanic reaction according to equations 2 and 3. This result in bond formation between soil particles causing agglomeration and flocculation of the soil particles. Research by Solihu [59] concluded that Portland cement acts as an effective stabilizer by improving the Atterberg limits, unconfined compressive strength, and reducing the changes in volume. Use of cement has recently been the most common soil stabilization method and its mechanism is similar to lime addition. Both cement and lime help in reducing the plasticity of the soil by providing a strong matrix to the soil. A study by Abdelkrim & Mohamed [81] found out that increase in cement content decreases the pressure swelling as

Table 6. Soil stabilization using cement

Type of soil	Cement dosage	Properties studied	Initial performance	Performance after stabilization	References
High plasticity soil (CH)	8%	PI	57.8%	27.6%	[83]
		UCS	0.27 MPa	1.19 MPa	
–	5%	UCS	0.8 MPa	1.01 MPa	[85]
Medium plasticity soil	10%	PI	46.6%	26.6%	[86]
		UCS	1 MPa	6 MPa	
High plasticity clay	10%	UCS	1.5 MPa	3.8 MPa	[87]
Soft soil	6%	UCS	20 kPa	160 kPa	[10]
Clay soil	8%	CBR	7%	48%	[81]

CBR: California Bearing Ratio; PI: Plasticity index; UCS: Unconfined compressive strength.

well as the free swelling of expansive soil. In addition, both soaked and unsoaked California Bearing Ratio (CBR) increases linearly with increase in the cement content.

Cement-treated soils have enhanced shear strength and decreased liquid limit, plasticity index, and swelling potential [82]. Stabilizing granular soils with cement has proven to be more economical and efficient since a small cement dosage is required. Research has proven that soils with Plasticity Index, PI>30 are difficult to treat with cement hence lime is added before mixing to keep the soils workable [83]. This research also established that increased cement content leads to improvement in unconfined compressive strength (UCS) and a reduction in the plasticity of the soil from 57.81% to 27.57% when cement content was increased from 0% to 12%. In agreement with these findings, Khemissa & Mahamedi [50] found that the swell pressure of treated samples decreases with an increase in stabilizer dosage. They also concluded that hydration in cement occurs faster than in lime which allows an immediate gain of strength. Cement-stabilized soils continue to gain strength over time as curing continues. Table 6 shows some of the recent studies in soil-cement stabilization. In both studies, the performance of the stabilized soil satisfies the strength requirements, that the minimum CBR should be 15% and UCS should increase by at least 80% for cement stabilized soil [84].

From Table 6 above, all studies agree that cement stabilization provides an increase in the bearing capacity of the stabilized soil. This is due to the formation of CSH and CAH bonds. However, the durability of cement-stabilized soil is not long enough due to sulfate reactions which result to heave formation according to Equation 1. In addition, the cement production process emits a lot of CO_2 which is a chief greenhouse gas that is majorly responsible for climate change and global warming [88]. About 5–6% of global CO_2 emission is due to the manufacture of OPC [89]. The use of OPC in soil stabilization contribute greatly to CO_2 emission since a significant amount of cement is needed for effective soil stabilization [90].

5.3. Stabilization Using Chemicals

Calcium chloride is used as an additive for water retention in soil bases stabilized mechanically because it is hygroscopic and deliquescent. This lowers the vapor pressure and rate of evaporation as well as increases surface tension. There is also a lowering of the freezing point of pure water which causes a reduction of frost heave in the stabilized soil. The freezing point of pure water is lowered, preventing or reducing frost heave. For the salt to work, the relative humidity of the air must be greater than 30%. Calcium chloride facilitates compaction because it also causes soil flocculation. Sodium chloride can also be used in place of calcium chloride and it has similar stabilizing action to calcium chloride. Some of the studies on the application of calcium chloride and sodium chloride in soil stabilization are shown in Table 7. The CBR values after chemical stabilization did not meet the minimum requirements of 15% in the studies discussed. This can be attributed to the poor performance of the original soil samples, since the increase in CBR in all the studies was more than 100% after stabilization. The studies carried out indicates the potential of calcium chloride and sodium chloride in stabilization of clay soils.

It is clear from Table 7 that when salt concentration and soil strength increased, the plastic limit, liquid limit, and plasticity index decreased. Jafer [91] explained the decline in plasticity is caused by a decrease in the thickness of the diffused double layer with an increase in salt content. More flocculates were formed, which was also thought to be the cause of the rise in MDD, CBR, and UCS of unstabilized soil. While working with calcium chloride and sodium chloride, the fundamental difficulty is that regular application is required to replace the chemical loss caused by leaching.

5.4. Stabilization Using Fly Ash

In presence of water, the use of fly ash in the soil provides exchangeable cations of Al^{3+}, Ca^{2+}, and Fe^{3+}, which results in the flocculation of the soil particles [64]. Fly ash also serves as a source of silica that in an environment with a high pH, reacts with lime to form cementitious products according to equations 2 & 3. This is a pozzolanic reaction that occurs slower compared to cement hydration. According to Afrin [11], fly ash addition in the soil leads to a reduction in plasticity, and permeability and an increase in durability, strength, and stiffness. This conclusion was corroborated by

Table 7. Soil stabilization using sodium chloride and calcium chloride

Type of soil	Type of binder	Binder dosage	Properties studied	Initial performance	Performance after stabilization	References
High plasticity clay (CH)	$CaCl_2$	8%	PI	25%	18%	[91]
High plasticity clay (CH)	NaCl	8%	PI	23%	18.5%	[92]
			CBR	1.8%	3.1%	
Black cotton soil (CH)	NaCl	8%	PI	23%	16%	[93]
			CBR	1.82%	6.1%	
Clayey soil	NaCl	2%	CBR	4.75%	9.22%	[94]
High plasticity clay (CH)	$CaCl_2$	1 N	PI	46%	22%	[95]
			CBR	2.11%	8.32%	
High plasticity clay (CH)	$CaCl_2$	15%	PI	36%	14%	[96]
		5%	UCS	0.5 MPa	0.75 MPa	

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

Table 8. Use of fly ash in soil stabilization

Type of soil	Fly ash dosage	Properties studied	Initial performance	Performance after stabilization	References
Organic soil	15%	PI	22%	7%	[99]
Black cotton soil	6%	PI	28.32%	13.72%	[97]
		CBR	4.7%	8.05%	
Black cotton soil	6%	CBR	3.12%	4.82%	[100]
Black cotton soil	20%	PI	29.8%	22.9%	[101]
		CBR	6%	16.8%	
High plasticity clay	25%	PI	64%	31%	[13]
		UCS	10 kPa	43 kPa	
Low plasticity clay	20%	CBR	5%	45%	[102]

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

Kumar & Harika [97], who discovered that the maximum dry density and unconfined compressive strength of black cotton soil were both improved by the addition of fly ash. Afrin [11] however, noted the following as limitations of using fly ash in soil stabilization;

(a) It is effective in soil with less moisture content, which therefore may require dewatering of the soil to be stabilized.
(b) Slaking and strength loss may occur in a soil-fly ash mixture that has been cured below zero and subsequently submerged in water.
(c) It contains a lot of sulfur, which might cause expansive reactions in the soil-fly ash mixture and lower its strength and durability.

Some recent research on the use of fly ash in soil stabilization is shown in Table 8. From the studies on the table, it can be observed that the amount of Fly ash used determines the extent of soil stabilization. The recommendation by AASHTO for soil stabilization using Fly ash is that the dosage should be between 20 to 30 percent [98]. It is evident from the table, that only those studies that used Fly ash content above 20% recorded strength performance suitable for use as subgrade.

5.5. Stabilization Using Zeolites

In soil stabilization, zeolites act as aqueous aluminum silicate pozzolans containing alkali and alkaline earth metals. Their structures consist of frameworks of SiO_4 and AlO_4 tetrahedrons that are interconnected using oxygen atoms in such a way as to form pores of specific sizes and shapes [103]. The Si^{4+} is substituted by Al^{3+} in the tetrahedral structures which results in a structural negative charge and consequent high cation exchange capacity [104]. Silica and/or alumina interact with cement in zeolitic pozzolanic reactions, which are time- and lime-dependent, to produce cementitious compounds that stabilize soil [105]. Typically, the high specific surface area and porosity in zeolites, act as a bonus in the pozzolanic reaction when mixed with materials like cement to form CSH and CAH [106]. In addition, zeolites portray high ion exchange due to the exchangeable cations in the structural pores, providing sites for Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} catalysts [107].

In a study aimed to stabilize high-plasticity clayey soil, Yilmaz et al. [108] utilized a waste zeolite-lime mixture and reported a decrease in the swelling pressure exerted by the soil. Additionally, it was claimed that one-dimensional swelling of soil had boosted durability and unre-

Table 9. Soil stabilization using zeolites table

Type of soil	Zeolite used	Zeolite activator used	Zeolite dosage	Property studied	Initial performance	Performance after stabilization	References
Natural expansive clay	Natural clinoptilolite	Cement	30%	UCS	0.5 MPa	3.75 MPa	[111]
Clayey soil (with illite and smectite)	Natural phillipsite	Cement kiln dust	15%	UCS PI	250 kPa 66.5%	1200 kPa 31.9%	[112]
				CBR	1.73%	15.9%	
Gravel sand	–	Portland cement	10%	UCS	1.28 MPa	7.65 MPa	[113]
Expansive sand-Na-bentonite	Clinoptilolite zeolite	Cement	30%	UCS Swell potential	290 kPa 4.95%	394 kPa 0.35%	[114]
High plasticity clay	Zeolitic tuff (phillipsite and chabazite)	Lime	30% 25%	CBR UCS	1.6% 250 kPa	11% 500 kPa	[115]

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

stricted compressive strength on a small scale. Rajabi et al. [107] reported that increasing the content of zeolites in the stabilizer mixtures had a consequent increase in plastic and liquid limits and corresponding plasticity index. In the study, the problematic soil was mainly made up of illite clay mineral, which contained free lime that led to cation reactants diminishing the interlayer thickness of the soil structure, thus enhancing the water retaining capacity of the soil [109].

In some instances, cement on its own does not produce desired properties when utilized in soil stabilization. Shahriar Kian et al. [110] utilized zeolites in such a case to improve the qualities of soil that has been stabilized by cement. The authors reported improved mechanical properties for soils stabilized with cement-zeolite mixtures compared to cement-only stabilization. In addition, the soils showed improved freeze-thaw durability when zeolite was used. In agreement with this study, Muhiddin & Tangkeallo [109] reported improved unconfined compressive strength in the stabilization of laterite soils rich in brownish-red iron oxides. Table 9 displays some of the most recent research on the use of zeolites for soil stabilization. For all the cited studies, the strength performance met the set standards that the increase in UCS should be more than 50 psi (0.33 MPa) compared to the original soil material [98].

5.6. Stabilization Using Geopolymers

Geopolymers are amorphous inorganic polymers based on aluminosilicates that are cured under ambient temperatures, and synthesized from liquid precursors [116]. They are structurally nanoporous and nanoparticulate, exhibiting good mechanical properties, thermal resistivity, and ceramic-like brittle failure properties [117]. In their synthesis, compounds rich in Al^{3+} and Si^{4+} such as feldspar, industrial wastes, and kaolinite are utilized as precursors, activated by alkaline bases such as NaOH, KOH, Na_2SiO_3, and K_2SiO_3 under ambient temperatures [118]. Owing to their cementitious properties, geopolymers are seen to replace OPC with advantages such as over 80% carbon dioxide emission reduction, resistance to relatively high temperatures, and an aggressive environment [119]. They are therefore used to replace cement in soil stabilization to reduce the environmental toll of soil stabilization on the environment.

In a study by Ghadir & Ranjbar [120] comparing the effectiveness of clayey soil stabilization using volcanic ash-based geopolymer and OPC, it was found that with a 15% replacement of binder, the compressive strength of soil increased from 0.2–4 MPa in wet conditions to 2–12 MPa in dry conditions. It was observed that geopolymer treatment was most efficient under dry conditions due to the role of pH and water in the kinetics of geopolymerization. It was also observed that an increase in the molarity of the activating agent had a consequent improvement in the compressive strength of the geopolymer-treated soil. In a study examining the viability of using anhydrous sodium metasilicate as a geopolymer activator for soil stabilization, Yu et al. [121] reported a similar effect. To stabilize expansive soil, Baldovino et al. [122] employed a geopolymer based on recycled glass powder and reported that increasing the volume of glass content improved the microstructural and mechanical qualities of the soil. This was because an increased content of glass powder led to a higher Si/Al ratio and therefore a higher yield of cementitious gel. Table 10 shows recent studies in soil stabilization using geopolymers. Except for the study by Samuel et al. [123], all other studies cited on the table met the standard requirements, that the UCS of the stabilized soil should be more than 0.8 MPa for use as sub-grade [85].

5.7. Stabilization Using Nanomaterials

Nanomaterials are compounds with at least one dimension within the nanoscale. In soil stabilization, particles in the form of nanofibers, nanofilms, or nanopowders are dispersed in the soil matrix to form composites that exhibit improved structural properties for geotechnical applications [127]. Common nanomaterials utilized in soil stabilization include nanoclay, carbon nanorods, graphene oxides, SiO_2, TiO_2, and Al_2O_3.

Table 10. Soil stabilization using geopolymers

Type of soil	Precursors	Activators	Geopolymer dosage	Parameters studied	Performance before stabilization	Performance after stabilization	Ref.
High plasticity clay	Metakaolin and class C fly ash	Sodium hydroxide and sodium silicate with lime and gypsum modifiers	6%	Swell potential	16.2%	3.2%	[124]
Low plasticity clay	Metakaolin	Potassium hydroxide and amorphous silica fume	4%	UCS	103 kPa	310 kPa	[123]
				Free swell	15%	7.8%	
			15%	Linear	15.5% shrinkage	4%	
Coarse aggregate	Fly ash	High alkaline red mud	20%	UCS	10 MPa	16 MPa	[125]
High plasticity clay	Fly ash	Sodium thiosulphate and sodium hydroxide	20%	UCS	0.22 MPa	6.4 MPa	[126]

Ref.: Reference; UCS: Unconfined compressive strength.

Table 11. Soil stabilization using nanomaterials

Type of soil	Nanomaterial used	Dosage	Parameters studied	Performance before stabilization	Performance after stabilization	References
Kaolinite clay	Nano MgO		PI	38.06%	6.44%	[132]
	Nano Al_2O_3				9.14%	
	Nano MgO		Swelling	15.51%	0.2%	
	Nano Al_2O_3				0.47%	
Expansive clayey soil	Nano SiO_2	1.5%	UCS	235.2 kPa	333.2 kPa	[133]
	Nano Al_2O_3	1.2%		227.5 kPa	309.7 kPa	
Low plasticity clay soil	Nano $CaCO_3$ with carpet waste fibers as reinforcers	1.2%	UCS	250 kPa	450 kPa	[134]
Expansive clayey soil	Nano Al^2O_3 as an auxiliary additive to lime	2%	UCS	100 kPa	450 kPa	[135]
Clayey sand	Carbon nanotubes and nanofibers	1%	UCS	143 kPa	237.5 kPa	[136]
Soft clay	Nano SiO_2	2%	CBR	15%	31%	[34]
		7%	UCS	56 kPa	294.5 kPa	

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

In a study by Torabi-Kaveh & Heidari [128] nanoclay was comparatively used with lime in the stabilization of expansive marly soil. It was found that increasing the amount of nanoclay up to 4 percent improved the compressive strength of soil as a result of the nanocomposite particles filling the pore spaces of soil. Volumes of nanoclay beyond 4% exhibited increasing strength due to the flocculation of the particles. Similar findings were reported by Abisha & Jose [129] using nanoscales of clay, copper, and magnesium in the stabilization of soil, reporting improvement of dry density, linear shrinkage, and compressive strength with 1% nanomaterials.

In a study investigating the utilization of carbon nanomaterials in soil stabilization, Taha & Alsharef [130] used carbon nanotubes and nanofibers. Both were reported to improve dry density, specific gravity, and pH values slightly with maximum amounts of 0.2% dry weight of soil. The carbon nanotubes showed decreased hydraulic conductivity in comparison to the nanofibers. In a distinct study, nano-silica, lime, and vinyl acetate homopolymer coating were utilized to evaluate the mechanical behavior and physical features of soils in actual application in structural layers of rural roads [131]. The CBR and compressive strength were reported to considerably increase and thereby a possibility of reducing quicklime and mechanical means of preparing of sub-base layer was drawn. Table 11 lists some current studies on the application of nanomaterials to soil stabilization. However, the strength improvement in all the studies cited did not meet the minimum requirement. This can be attributed to the low dosages of nanoparticles used in the studies, which are below the recommended dosage of 4% for significant improvement in strength [128].

6. MICROSTRUCTURAL CHARACTERIZATION

Changes in the microparticles and micropores in a stabilized soil help to determine the overall changes in the stabilized soil. Chegenizadeh [137] indicated that SEM-EDS and XRD are important tools in the determination of microstructural development in stabilized soils. The physical properties of the microparticles are examined in SEM analysis, and their chemical composition is identified in XRD analysis. EDS is coupled with SEM to give details on the elements present in the soil material. Therefore, XRD and SEM-EDS are utilized to examine the chemical and physical properties of the soils, respectively.

6.1. X-Ray Diffraction

To determine the chemical composition of a material, XRD is used to analyze crystalline materials to pinpoint the crystalline phases that are present in a given substance [138]. The majority of soil particles are crystalline, and the crystals in those particles have distinctive geometries that can be used to identify the minerals that are present in soil material. A specific diffraction pattern is produced when an X-ray interacts with a crystallized specimen and is exclusive to the particular mineral and crystal structure it is found in. The diffraction pattern of the soil sample is analyzed for the qualitative and quantitative evaluation of minerals using powder diffraction or polycrystalline diffraction.

Due to the small size of soil particle sizes, it is not possible to investigate single crystals in soils; instead, powdered specimens are employed. The intensity of the diffracted beam as a function of range 2 Theta (2θ) is displayed on a chart after a small specimen containing particles in all possible orientations is placed in a collimated beam of parallel X-rays. Diffracted beams of various intensities are scanned and recorded automatically.

Horpibulsuk et al. [139] investigated the usage of cement for soil stabilization and reported that with an increase in cement dosage, soil particles and cement particles form clusters which decrease the number of voids in the soils and hence, increase the strength of the stabilized soil. Sekhar & Nayak [138] carried out a microstructural analysis on clay soil stabilized with Portland cement and BFS cement and reported that stabilization is due to the hydration process which leads to a reduction in the number of soil pores and voids that the hydration products fill. The XRD result also showed that the increase in strength was due to the formation of the CSH phase. According to Akula [140], XRD analysis can be used to quantitatively determine the reduction in the amount of quartz at different stabilizer dosages and different curing times, as well as an increase in CSH and CAH phases. This helps to account for the decrease in plasticity index, and an increase in maximum dry density and CBR at different stabilizer dosages and curing days. For instance, Sekhar & Nayak [138] carried out an XRD analysis for clay soil stabilized using Granulated blast furnace slag (GBFS) and associated the increase in the strength of stabilized soil with the formation of cementitious products CSH and CAH. Similarly, Mutaz & Dafalla [141] used XRD to account for higher strength in cement-stabilized clay soil in comparison to the one stabilized by lime. The authors observed higher amounts of CSH and CAH in cement-stabilized clay soil than when similar soil was stabilized using lime.

6.2. Scanning Electron Microscope with Energy Dispersive X-ray Spectroscopy

In the SEM examination, morphological changes are highlighted while interactions between the soil and stabilizing chemicals are visually displayed. Results from SEM and Energy-dispersive X-ray spectroscopy (EDS) are both semi-quantitative and qualitative. In SEM, the sample surface is scanned by an electron beam to provide a picture that depicts changes in the surface morphology of the material. The interactions between the stabilizing chemicals and the soil are displayed visually, and morphological changes are underlined. Additionally, SEM examinations are utilized to assess microstructural alterations in the examined specimens and examine the results of stabilizing soil additives. EDS is a commonly used elemental microanalysis technique that can identify and measure any element in the periodic table, except light elements up to Newbury & Ritchie [142]. Therefore, a combination of SEM coupled with an EDS detector helps to obtain information on the surface morphology of stabilized soil as well as the chemical composition of the products formed.

SEM studies carried out by Indiramma & Sudharani [143] indicated that the addition of fly ash causes the soil to assume a flocculated structure, which is responsible for the decrease in plasticity index and increase in strength of the stabilized soil.

According to Philip & Singh [144], sample preparation involves drying the soil sample for 1 hour at 50˚C–80˚C in an oven to remove any moisture present and then grinding the sample between two glass slides. The ground samples are then oven-dried again for one hour at the same oven temperature and then mounted in small amounts onto stubs. The sample is then fed into a scanning electron microscope machine for scanning and detection using EDS detector which gives a spectrum for all the elemental composition of the soil sample.

SEM-EDS shows reaction products and variations on stabilized soil microstructures due to pozzolanic reactions which result in the formation of CSH and CAH cementitious products. A study by Sekhar & Nayak [138], found that the natural clay soil SEM images show a smooth texture and larger void spaces as shown in Figure 3. After stabilization with cement and GBFS, the soil produced agglomerations; hence the particles were flocculated into friable granules and the pore or air spaces were reduced, causing strength gain to mixtures as shown in Figure 4.

The research also indicated that cement generates hydration products at higher curing periods, which helps to increase the strength of the stabilized soil with an increase in the curing period. In a study by Moretti et al. [145], EDS validated the XRD results on the chemical composition of the stabilized soil by showing a reduction in peak intensity of Al, Si, and K at 5% lime addition. According to Odeh & Rkaby [126], while geopolymer stabilized soil pores were filled with cementitious materials to generate a dense matrix

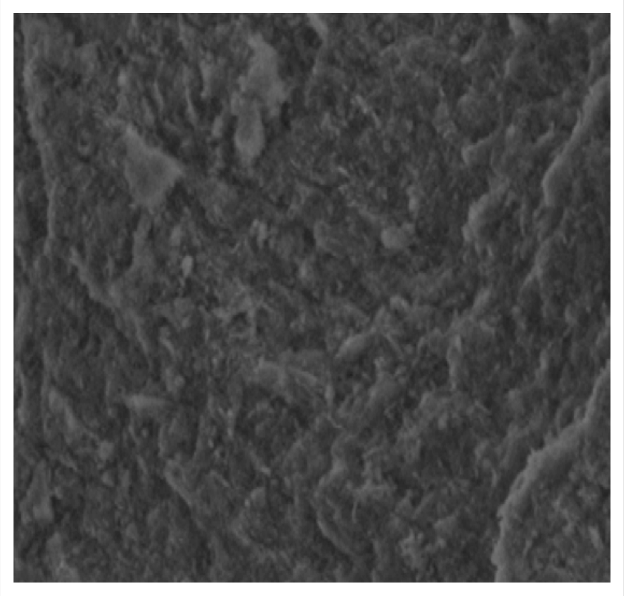

Figure 3. SEM image for neat clay soil [138].

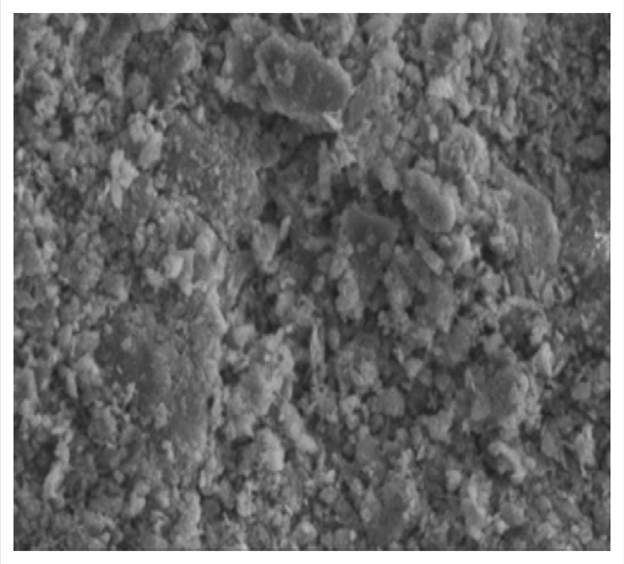

Figure 4. SEM image for GBFS & cement stabilized clay soil [138].

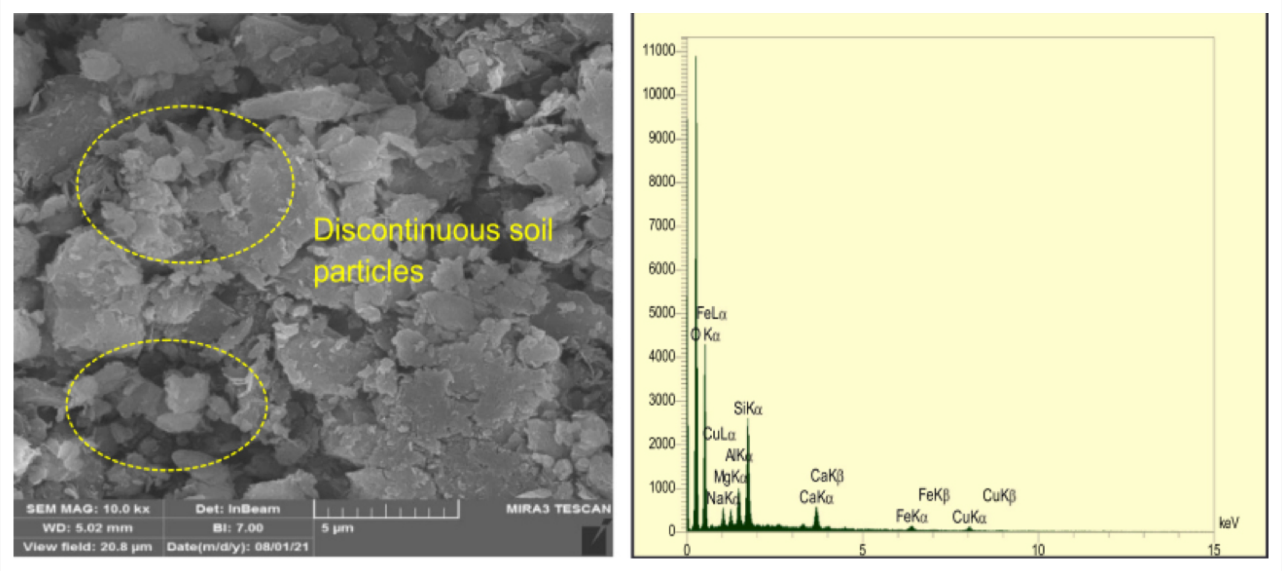

Figure 4. SEM-EDS analysis of untreated clay soil [126].

as seen in Figures 5 and 6, neat soil SEM pictures showed isolated soil particles with a weak, flaky structure and some arrangement between them. The geopolymer-treated samples EDS analysis revealed higher peaks and a higher fraction of O, Si, Al, Fe, and Na than in the clay that wasn't treated. It was clear that N-A-S-H, the main cementing element responsible for increasing strength, was at work.

6.3. Thermogravimetric Analysis and Differential Scanning Calorimetry

Thermogravimetric analysis (TGA) is performed in soil stabilization to ascertain the production of hydration products like CSH and CAH. With a rise in temperature, Weight loss for the samples with the temperature rise is measured by thermogravimetry [20]. TGA data is often converted to mass loss or gain peaks through differentiation in a technique known as Differential Thermogravimetric (DTG) Analysis, as an overlay over TGA data to ease interpretation. The amount of calcium consumed during hydration and pozzolanic reactions can be calculated using TGA in conjunction with Differential Scanning Calorimetry (DSC) [61]. According to Bandipally et al. [146], TGA can be used in soil stabilization using cement, to evaluate strength development during curing. The weight loss corresponds to decomposition of chemical phases formed during stabilization.

According to Scrivener et al. [147], the temperature range between 0 °C and 400 °C is where weight loss of water from smectite and other hydration products happens. Additionally, decarboxylation-related weight loss occurs above 700 °C. If the soil-cement sample TGA findings reveal little calcium consumption, there has been significant calcium

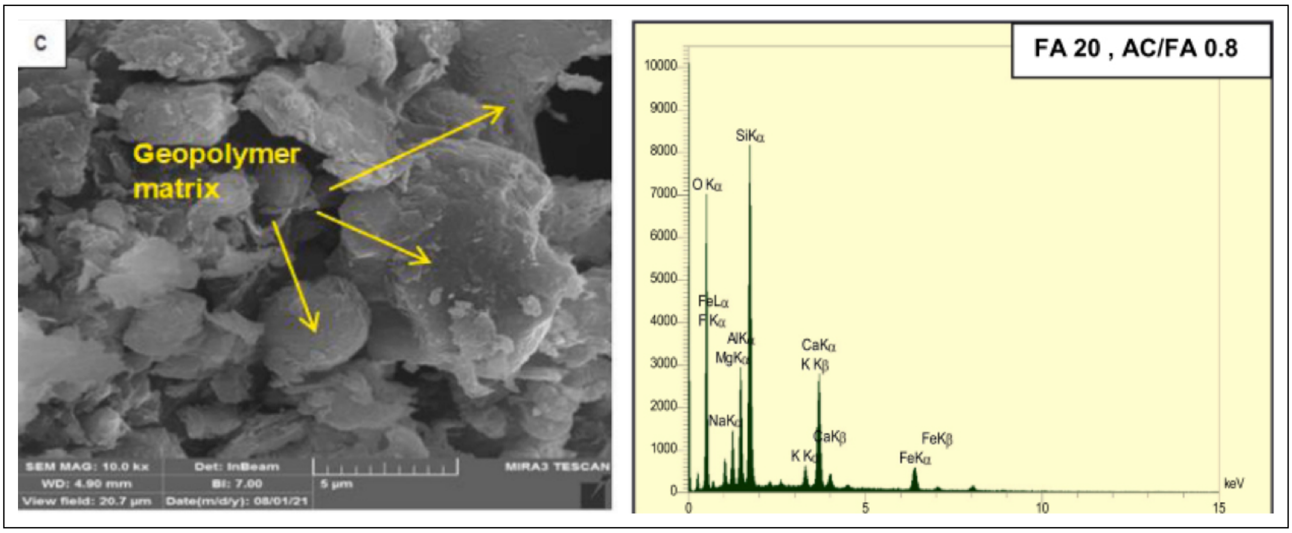

Figure 6. SEM-EDS analysis for geopolymer-treated clay soil [126].

leaching and a high level of degradation [148]. Pham et al. [61] observed degradation of portlandite at 400 ˚C 500 ˚C for cement-stabilized clay soil, which the authors attributed to the pozzolanic reaction to form CSH and CAH. A TGA analysis by Akula et al. [20] reported that lime-stabilized soil had a lower dehydration peak at 100 °C than virgin clay soil. This meant that there was less interlayer water for the treated soil sample compared to untreated soil.

6.4. Isothermal Calorimetry

Isothermal calorimetry can be used in soil stabilization to analyze the variations in reactivity between the employed binders to stabilize soil [149]. Thermal power displays the heat produced in real-time by a stabilized soil sample at a specific moment, whereas total heat displays the heat that has accumulated since the soil and binder were mixed at that specific moment. Thermal power displays the heat produced in real-time by a stabilized soil sample at a specific moment, whereas total heat displays the heat that has accumulated since the soil and binder were mixed at that specific moment [150].

Tran et al. [151] used Isothermal calorimetry to compare the heat of hydration at different water-binder ratios (w/b) and they found that a higher w/b ratio produces more heat compared to a lower w/b ratio. In addition, Wattez et al. [149] compared total heat flow when Portland cement, steel furnace slag, and alkali-activated slag were separately used to stabilize clay soil. They found that the total heat flow by pure Portland-treated soil was more than twice as when stabilized with BFS or with the sodium hydroxide-activated slag binder. This shows a higher reactivity of Portland cement binder in soil stabilization. Hu et al. [125] used isothermal calorimetry to investigate the effect of temperature on the stabilization of pavement base using geopolymer. When the temperature was elevated from 20 °C to 38 °C, both geopolymer base samples gained strength more quickly. This finding was in tandem with the study by Narmluk & Nawa [152] which reported an increase in pozzolanic activity with an increase in temperature.

7. FACTORS INFLUENCING SOIL STABILIZATION

7.1. Organic Matter

High organic content in soils results to lower gaining of strength [153]. This is explained by the fact that soil organic content prevents the formation of the hydration products by slowing down the pozzolanic reaction that leads to a gain of strength in stabilized soils. Firoozi et al. [29] stated that the amount of clay minerals are low in soils that have high organic content. They further added that organic contents have high water withholding capacity which results in less available water for the hydration process. Organic matter in soil also lowers the soil pH to about 9 because of the presence of humic acid which slows down the cementing reaction during cement stabilization [154].

Ling et al. [153] suggested the addition of kaolinite and zeolite to soils with organic matter that reacts with calcium hydroxide to form humic acid. This provides enough silica that is required for the pozzolanic reaction to occur in the soil. Also, the addition of bentonite to the soil during lime stabilization was found to reduce the negative effect of organic matter in the soil. Bentonite serves as a pozzolana material and also has a high water-retention capacity, which facilitates the hydration of cement and lime. Bentonite serves as a pozzolana material and also has a high water-retention capacity, which facilitates the hydration of cement and lime.

The presence of organic matter in soil increases its porosity thereby lowering the soil's strength as well as increasing its plasticity [155]. According to Pradeep & Vinu [156], the presence of organic matter in the soil increases the ability of the soil to hold onto water, raises the void ratio, and lowers the specific gravity of the soil because organic matter has a lower specific gravity. As a result, the maximum dry density of the soil decreases, increasing soil flexibility, and lowering CBR. Additionally, when the amount of organic material rises, the unconfined compressive strength decreases parabolically.

According to a study by Gui et al. [157], when the organic matter content of clay soils is above 7.5%, clay soils exhibit free organic matter properties. This increases the water adsorption capacity of the clay soil. In a clay sample containing 1.5 percent humic acid, cracks were noted by Wanatowski [158]. For clay containing 3% humic acid, the fissures were considerably more noticeable. This is due to the humic acid obstruction which retards particle flocculation when lime is added making the stabilization or modification process more difficult later. XRD analysis for lime-stabilized specimens with various humic acid contents indicated that the amount of silica and alumina decreases with increasing humic acid. This resulted in a decrease in the amount of CAH and CSH due to less pozzolanic reaction. Also, humic acid coats clay minerals (silica and alumina) making it difficult for them to be detected by EDX.

7.2. Sulphates

Sulphate ions in soil may originate from the presence of sulphate salts in soils or sulphides. Sulphides may be present in industrial by-products in form of Iron (II) sulphide (FeS_2). Once these industrial by-products are used in soil stabilization, FeS_2 may undergo oxidation to form sulphuric acid which then reacts with any calcium carbonate to form gypsum as shown in equations 11 and 12. In presence of excess moisture in the soil, the gypsum formed will lead to a degradation effect similar to sulphates [51].

$$FeS_2 + H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4 \tag{11}$$

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4.2H_2O + CO_2 \tag{12}$$

The presence of high sulphate content in the soil causes an expansive reaction when calcium-based stabilizers are used. This is because of the formation of ettringite according to equation 4, which is an expansive mineral that occupies a larger volume than the hydration products. Verástegui-Flores & Di Emidio [159] stated that degradation caused by sulphate attack affects parameters such as hydraulic conductivity, strength, and stiffness of calcium-based stabilized soils. According to Jha [160], sulphate increases the liquid limit of stabilized soil hence increasing its plasticity index. It also results in a decrease in maximum dry density and an increase in optimum moisture content due to the formation of ettringite which increases the pore size of stabilized soil. In addition, the presence of sulphate in large quantities decreases the strength of stabilized soil with longer curing time due to heave formation resulting from the ettringite compound. The type and amount of additives, the type of soil, the concentration and type of cation linked with the sulphate anion, and the extent of damage caused by ettringite are all factors that determine the durability of sulphate-rich stabilized soils [161].

7.3. Moisture Content

Calcium-based stabilizers and the reactive soil compounds (especially silica and alumina) dissolve in water and result in a soil-water-stabilizer reaction system which is a precipitation reaction according to equations 13 and 14 [162].

$$Ca^{2+} + SiO_2 + H_2O \rightarrow CaO.SiO_2.H_2O \tag{13}$$

$$Ca^{2+} + Al_2O_3 + H_2O \rightarrow CaO.Al_2O_3.H_2O \tag{14}$$

The reaction product precipitates on the surface of the soil and fills its micropores, strengthening the soil as a result. It is important, therefore, to have enough moisture content during stabilization for the hydration process as well as to enhance compaction. According to Afrin [11], cement takes 20% of its weight in water and is taken up by the environment, with quicklime absorbing roughly 32% of its weight in water. If the moisture content is not sufficient, the soil will compete for water with the stabilizing agent and if the soil has a high affinity for water like clay soil, the amount of moisture available for hydration will be less. This will result in a lower strength of the stabilized soil. Dahunsi [163] stated that when the natural moisture content of soil is higher than its optimum moisture content, the soil becomes saturated since the moisture content has moved to the wet side of the compaction curve. This reduces the density index of the soil hence, lowering the dry density of that soil. Similarly, Backiam [164] observed that strength of stabilized soil decreases with increase in moisture content.

According to a microstructural study conducted by Yin & Zhang [162] using SEM-EDS, the soil becomes finer and has few big aggregates and agglomerations as the NMC rises. Additionally, the hydration products were only discovered after 7 days of curing and are too little to be readily found in 1 day or 3 days. Because more free water converts into structural water during the hydration process, it was discovered by elemental analysis using EDS that at greater NMC, the percentage of oxygen element is a little higher.

7.4. Temperature

The pozzolanic reaction is sensitive to temperature changes and is favored by high temperatures. When temperatures are low the reaction is slow and this will lower the strength of the stabilized soil. Afrin [11] indicated that it is important to carry out calcium-based soil stabilization when the season is warm. According to [165], both liquid limit, plastic limit, and plasticity index decrease at high temperatures. This is because the kinetics of pozzolanic reaction involved in calcium-based stabilizers is slow at low temperatures [166]. With an increase in temperature, unconfined compressive strength also rises.

A study by Attah & Etim [167] reported that an increase in temperature results in a corresponding increase in the soaked CBR. In this study, SEM analysis was carried out and the soil at ambient temperature was found to have a different morphology from the one subjected to higher temperatures. This morphological change with temperature variation was due to the deformation or breakdown of soil fabrics, change in basic mineral composition as well as variations in the physicochemical and chemical processes that took place during heating.

7.5. Wet-dry Cycles

Cement-stabilized soils are prone to dry-wet cycles, which are typically brought up by daily temperature fluctuations and may generate stress inside a stabilized soil. Therefore, wet-dry cycles in soils stabilized by cement should be avoided. Wet-dry circumstances have a disorienting effect on lime-stabilized clayey soils [168]. A research by Consoli et al. [169] found that the strength of soil stabilized by Portland cement reduced after each wet-dry cycle. Each drying phase cycle causes the CBR to rise while the wetting phase causes it to fall. This outcome was in line with a study by Li et al. [170], which discovered that as the number of freeze-thaw cycles increased, the volume of mesopores grew and the volume of micropores dropped, lowering the CBR value. According to an SEM investigation, the porosity of the stabilized soil dramatically improved as the number of wet-dry cycles increased. Contrarily, Moayed et al. [171] found that after 5 wet-dry cycles, silty soil stabilized with lime-micro silica did not affect CBR. The majority of studies concur that a rise in wet-dry cycles reduces the stability of stabilized soil. According to James & Pandia [172], lime-stabilized soil is less effective under extreme wet-dry cycles. This finding was in tandem with the study by Kampala et al. [173] which found a significant decrease in the strength of clay soil stabilized using calcium carbide residue with increase in the number of wet-dry cycles.

7.6. Freeze-Thaw Cycles

Construction materials are frequently damaged by the freeze-thaw cycle. When water fills the spaces in a hard, porous material, it causes damage when it freezes and expands into a volume that is 9% larger than liquid water [174]. When surrounding material is under pressure from freezing water, cracks will appear because the pressure is greater than the tensile strength of the material [175]. The gaps are made larger during this process, allowing for the storage of more water during the subsequent thaw, which causes more cracking during the subsequent freeze. Camuffo [175] stated that the greater the pore size, the greater the force, so a material with high total porosity will be more exposed to risk. Duration and temperature range for the freeze-thaw cycle are the key determinants of the extent of damage to the physical and mechanical properties of a material [176]. The strength of stabilized soil decreases after cycles of freezing and thawing due to formation of microcracks on the stabilized soil particles, as was noted by de Jesús Arrieta Baldovino et al. [177]. Similarly, a research by Nguyen et al. [178] noted a significant decrease in the mechanical strength of lime-stabilized soil with increase in number of freeze-thaw cycles. This was attributed to the formation of ice lenses in the stabilized soil during freezing.

7.7. Curing Time

When calcium-based stabilizers especially lime and cementitious materials are used in soil stabilization, the strength of the stabilized soil increases with increased time. This can be attributed to the fact that the pozzolanic reaction is a slow reaction and therefore strength development is expected to continue for a long period [179]. According to Amadi & Osu [180], the pozzolanic reaction is time-dependent and cementitious products continue to form long after soil stabilization was carried out, causing a continuous increase in strength and maximum dry density of the stabilized soil. Horpibulsuk et al. [139] investigated the effect of curing time on the strength development in cement-stabilized soil and observed a decrease in pore volume with time. This was attributed to the continuous formation of hydration products which filled the pores between the soil particles. Athanasopoulou [181] observed a greater decrease in plasticity index for soil samples cured with lime and cement additives for 24 hours compared to those samples cured for half an hour. The author noted that an increase in curing time favors pozzolanic reaction, resulting in the formation of cementing compounds that bind the clay particles together to form large agglomerations.

7.8. Type of Soil and Minerals Present

Soil stabilization is greatly influenced by the type of soil and its mineralogical composition. This helps in choosing the most effective soil stabilizer for a given type of soil. According to James & Sivakumar [182], the effect of a given stabilizer on soil depends on the type of minerals present in the soil. Kaolinite is more effective in reducing plasticity and increasing strength using lime than illite and smectite [183]. Pedarla et al. [184] stated that soils with high content of montmorillonite failed in durability tests after stabilization with both cement and lime. The authors recommended that for effective stabilization, such soils should be stabilized with high dosages of lime and cement.

The difference in the effectiveness of soil stabilization for various types of soil is caused by the difference in cation exchange capacity and the type of cations present in the minerals [185]. For this reason, clay soil containing montmorillonite minerals is expected to have better improvement when stabilized with lime and cement than other clay minerals. This is because it has the highest CEC and a higher number of cations in the double-layer space [186].

7.9. Soil pH

Soil stabilization using lime and cement is influenced by changes in pH which determine the increase in strength of the stabilized soil. The pH value determines the extent of dissociation of silica and alumina in the soil during the pozzolanic reaction to form cementitious products (hydrates) of CAH and CSH [76]. Ghobadi et al. [187] stated that at low pH, alumina dissociates preferentially to form CAH, while at high pH, silica dissociates preferentially. However, the authors stated that for the dissociation of both alumina and silica, the pH value must be greater than 9.0. A study by Abdilor et al. [187] proposed the minimum pH value for soil stabilization using cement as 5.3. The study also stated that maximum soil stabilization using lime takes place at a pH value above 10.5.

Low pH value in soil consumes the alumina and silica content that should take place in the pozzolanic reaction. This causes a decrease in the strength of the stabilized soil from the expected value. Therefore, the pH value should be kept above 11 for the pozzolanic reaction to proceed effectively [182]. During lime stabilization, lime hydrates to produce calcium hydroxide which increases soil pH to above 12.4 and facilitates the pozzolanic reaction of Ca^{2+} with silica and alumina. Similarly, in soil stabilization using cement, pH increases as a result of calcium hydroxide which is produced as a by-product of the hydration of cement phases [188].

Table 12. Factors influencing soil stabilization

Factor	Soil stabilizer	Variation	Major geotechnical properties investigated	Initial value	Final value	Reference
Organic matter	Lime	15%	Shear strength	105.7 kPa	62.4 kPa	[157]
	–	1.5%	CBR	15.72%	4.75%	[155]
	5% lime	31%	CBR	12%	7.5%	[156]
Sulphate	10% OPC	20%	UCS	1.4 MPa	1 MPa	[191]
	6% lime	30,000 ppm	Shear strength	70 MPa	60.7 MPa	[192]
	15% OPC	1%	UCS	410 kPa	200 kPa	[193]
	4% lime	6%	PI	19%	60%	[161]
	5%	10,000 ppm	LS	5%	11%	[194]
Moisture content	4% OPC	15%–19%	UCS	2.9 MPa	2.4 MPa	[162]
Temperature	–	25 ˚C–100 ˚C	PI	44%	29%	[165]
	8% lime	23 ˚C–65 ˚C	Axial strain resistance	450%	950%	[195]
	–	25 ˚C–150 ˚C	CBR	6%	20%	[167]
	9% OPC	15 cycles	UCS	4.3 MPa	7.2 MPa	[196]
Wet-dry cycles	9% OPC	15 cycles	UCS	4.3 MPa	7.2 MPa	[196]
	4% lime	6 cycles	UCS	1.06 MPa	0 MPa	[197]
Freeze-Thaw cycles	6% lime	3 cycles	UCS	4 MPa	3.4 MPa	[198]
	12% OPC	10 cycles	UCS	1.05 MPa	0.5 MPa	[199]
Curing time	9% lime	7 days–28 days	UCS	0.8 MPa	2.3 MPa	[181]
	12% OPC	7 days–28 days	UCS	2 MPa	6 MPa	[180]
Quality of pulverization	6% lime	60% finer than 4.75 mm	UCS	0.06 MPa	0.65 MPa	[189]
		100% finer than 4.75 mm	UCS	0.06 MPa	1.43 MPa	

CBR: California Bearing Ratio; PI: Plasticity Index; UCS: Unconfined compressive strength.

7.10. Quality of Pulverization

Pulverization of soil before stabilization is one of the key factors that affects the extent of soil stabilization. It provides a surface for the reaction between the soil particles and the soil stabilizers. Good quality of pulverization ensures there is an increased surface area for uniform pozzolanic reaction throughout the soil particles. Bozbey et al. [189] observed that the most effective soil stabilization using lime is achieved for soil particles finer than 4.75 mm. Similarly, a study by Esan et al. [190] on soil stabilization using cement, noted a continuous increase in the strength of stabilized soil with a decrease in particle sizes for similar cement dosage. Therefore, it is important to ensure that the soil to be stabilized by cement or lime should be well graded with a higher percentage of fine particles after pulverization. According to James & Sivakumar [182], poor quality of pulverization results to slow rate of pozzolanic reaction, which leads to increased curing time to achieve the required strength of lime stabilized soil.

Quality of pulverization causes a difference between the laboratory performance of stabilized soil and performance in field application. This is because it is difficult to ensure similar pulverization in field application as in laboratory application. Researchers have recommended that large soil lamps should be broken and pulverized in the field to increase the performance of stabilized soils. This will also help in saving on the dosage of cement or lime needed to achieve the desired field performance. According to Bozbey et al. [189], higher fineness can be achieved in ex-situ soil stabilization than when soil stabilization is done in situ.

Table 12 summarizes some of the case studies on the parameters which influence soil stabilization.

8. CONCLUSIONS

The paper is a comprehensive review of the state of knowledge regarding expansive soils, and the different methods and agents (the traditional ones as well as the emerging techniques) that are used to stabilize expansive soils. From the review, the following conclusions were drawn.

1. Different stabilization methods can result in a comparable improvement on a given property of stabilized soil. Thus, it can be inferred that, the advantage of one stabilization method/ chemical over the other is highly dependent on the site's specific conditions.
2. Evaluation of the performance of the stabilized soil can be done majorly by comparing its PI, CBR and UCS with that of the original material before stabilization. The performance should also be compared with the set standards to determine the suitability of the stabilized material for field application.
3. Moisture content below or above the "optimum" amount is one of the main influential factors that affect soil stabilization using mechanical as well as

other stabilization methods. In relation to that, the moisture content of a given soil mass can be affected by the presence or absence of organic matter (because of their high water-holding capacity). Therefore, it can be understood that solely a single factor may not be the only influencing factor for the soil stabilization process. Multiple and interrelated factors can coexist together and affect the choice of stabilizers, stabilization methods, and the result.

4. Soil stabilization using cement is the most common among all the other methods of soil stabilization. However, it is deemed to contribute to about 6–8% of global CO2 emissions and bring a toll on the environment. On the contrary, the use of industrial wastes like fly ash is a sustainable and environmentally friendly solution for soil stabilization as well as waste management.
5. Methods such as SEM-EDS and XRD that are employed to study microstructural properties of materials are being used to examine microparticles and micropores of stabilized soils and it is helping to determine the overall changes in the stabilized soil.

8.1. Potential Areas For Future Research

1. Many studies have focused on the stabilization of expansive soil for application in roads, pavements, and highways. Soil stabilizers discussed in this review should be investigated for the stabilization of expansive soils to make them effective as construction materials in earthen construction.
2. Expansive soils stabilized with calcium-based stabilizers especially Portland cement and lime face problems of ettringite-based heaving which reduces durability. More studies should focus on suitable soil stabilizers which control the ettringite formation and offer similar performance as lime and cement.
3. Several chemical stabilizers have been used in improving the properties of expansive soils. More studies that focus on thermodynamic modeling of various reactions and/or processes between stabilizers and soil minerals to understand the reaction mechanism and/or solution chemistry are essential.
4. Studies show that an increase in temperature improves the properties of calcium-based stabilized soil, as it increases the rate of pozzolanic reaction. However, the optimum temperature for stabilization when different calcium-based soil stabilizers are used needs to be established. Further, more studies on the engineering performance of different stabilized soils should be conducted for different climatic conditions such as tropical and temperate climates.
5. The amount of stabilizer needed for optimum performance in soil stabilization depends on the type of soil. Further research should be carried out to determine the stabilizer dosage range for each type of soil according to different soil classification systems.
6. The strength of stabilized soil declines exponentially as soil organic content increases. Humic acid present in organic soils reduces soil pH and consumes calcium ions hence inhibiting stabilization. More research should, therefore, address stabilizers like bio-enzymes that can reduce the concentration of humic acid in organic soils and make stabilization effective.
7. OPC has been widely used in cement stabilization. However, its production process contributes to about 6–8% of global CO_2. Studies should focus on the applicability of new low-carbon cement for soil stabilization and any other environmentally friendly and sustainable solution. Also, sustainability studies on the use of OPC vis-à-vis other alternative soil stabilizers like zeolites, geopolymers, and nano-materials are required with the use of techniques such as Life Cycle Assessment and Cost Benefit Analysis.
8. A combination of different stabilization methods such as chemical and mechanical have been found to work in some case studies. However, a cost-benefit analysis should be conducted to evaluate the most feasible options for different applications and operating standards.
9. The durability of stabilized soil is affected by many factors like wet-dry cycles, chemical composition, and other external factors like temperature. Service life prediction models should be developed for the performance of stabilized expansive soils exposed to different conditions of temperature, moisture content, sulfates, and organic matter.
10. The effectiveness of soil stabilization using cement is determined by the hydration products of different types of cement. More studies on the hydration kinetics for OPC and blended cement when used as soil stabilizers should be conducted to predict strength development in cement-stabilized expansive soils.
11. Most of the common soil stabilizers reviewed are costly and unaffordable in most developing countries. There is, therefore, a need to explore on utilization of locally available raw materials such as bio-enzymes and geotextiles in soil stabilization.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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