



A State-of-the-Art Review on Sustainable Chemical Stabilizers for Expansive Soils

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Abstract Expansive soils are susceptible to significant volumetric changes due to the fluctuating moisture levels caused by the infiltration and evaporation of water. This has often resulted in destructive consequences for the structures they support. Various stabilization methods were developed and adopted to enhance their properties and make them suitable for construction purposes. Traditional stabilizers have an adverse impact on the ecosystem by releasing harmful greenhouse gases in the atmosphere and leaching of toxic chemical compounds into the groundwater. Hence, in the past few decades, research on soil stabilization has mainly focused on the utilization of various chemical additives that are environmentally friendly and durable for a longer period of time. This paper is aimed at providing a state-of-the-art review of some of the recent, emerging, and sustainable chemical additives for improving the engineering properties of expansive soil. The efficiency of various additives categorized under industrial by-products, synthetic polymers, biopolymers, geopolymers, and enzymes is discussed here. First, the interaction mechanism between different chemical additives and soil particles during the stabilization process is reviewed. Then, the effect of these additives on some of the crucial geotechnical parameters of expansive soils is discussed in detail. Emphasis is placed on the plasticity characteristics, swell–shrink behaviour, unconfined compressive strength, and compaction properties of expansive soils. The paper also comments on the challenges involved

in the utilization of these additives for practical applications. Laboratory test results for various stabilized soils are interpreted by understanding the stabilization mechanism for their successful field application in the future.

Keywords Expansive soil · Stabilization methods · Sustainable chemical additives · Swell–shrink behaviour · Stabilization mechanism

Introduction

Expansive soils, also known as swelling clays, pose a significant challenge in geotechnical engineering worldwide. They are widespread in Australia, the USA, the UK, China, Canada, South Africa, Israel, Iran, and India. In India, expansive soil covers nearly 20% of the total land area, mainly in the states of Madhya Pradesh, Maharashtra, Gujarat, Andhra Pradesh, Telangana, and Tamil Nadu. These soils have the ability to undergo volumetric changes upon wetting and drying, leading to extensive structural and geotechnical problems. The volume changes associated with expansive soils are primarily caused by the presence of the clay mineral montmorillonite, which, when exposed to water absorbs it into the crystal lattice, causing the soil to swell. Conversely, the absorbed water molecules are released upon drying, resulting in soil shrinkage. This swelling–shrinkage behaviour can put immense stress on surrounding structures, causing significant damage over time. Some of the severe structural damages caused by expansive soils include foundation cracks, cracking and heaving of pavements, deformation of railway lines, differential foundation settlement, rupturing of canal linings, underground pipeline cracks, and distortion of building members [1–5]. These damages result in substantial economic loss and pose serious safety

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hazards to the occupants. In the USA, damages incurred by the swell–shrink behaviour of expansive soils amount to several billions of dollars yearly, which is significantly higher than the damages incurred by natural calamities like earthquakes, floods, hurricanes, etc. [6]. This necessitates the improvement of such problematic soils to make them ideal for construction work. In this regard, soil stabilization is of great significance that aims to enhance physico-chemical and mechanical properties of problematic soils through various treatment techniques. Several stabilization methods were developed and practiced in the past decades that had various advantages and disadvantages.

Mechanical or physical stabilization was a commonly used technique in the earlier days of expansive soil treatment, which enhanced the behaviour of soils by altering their physical properties. Removal and replacement of expansive soil with non-problematic soil, pre-wetting the soil before construction, compaction, and soil reinforcement are some mechanical stabilization methods [2]. Chen [1] suggested that an expansive soil fill of 0.9–1.5 m can be removed and replaced by a non-expansive cushion layer. Though this method provides a simple technique for stabilization, it greatly depends on the availability of non-expansive soil nearby the site. The pre-wetting method is one of the oldest established techniques, which involves wetting soil and allowing it to swell before construction so that no more water can penetrate the swelled soil [2, 7, 8]. This method was proven to be successful only for expansive soils with high permeability so that they can be wetted in a short period of time, which is unlikely in most cases. Holtz and Gibbs [9] studied the influence of dry density and moisture content on the swelling behaviour of expansive soils. They showed that the soil swelled considerably low when compacted at a density less than the maximum dry density and a moisture content more than the optimum water content. Apart from these mechanical methods, there are a few moisture control techniques, such as providing horizontal and vertical moisture barriers and subsurface drainage systems that limit the increase in water levels in expansive soil layers [1, 2].

Evolution of Chemical Stabilization

In the later years, chemical stabilization of expansive soils gained interest among researchers with the introduction of calcium-based stabilizers. When added to soil in the presence of water, these calcium-based stabilizers initiate the following chemical reactions: Hydration, cation exchange, flocculation and agglomeration, pozzolanic reaction, and cementation [10–12]. Cement and lime are the two well-established calcium-based stabilizers that were popularly known as traditional stabilizers [13, 14]. Lime, when added to soil, reacts with water to form hydrated lime or calcium

hydroxide. This hydration product disintegrates into calcium ions (Ca^{2+}) and hydroxide ions (OH^-). The first stage involves the cation exchange process, where Ca^{2+} replaces the cations present on the surface of clay minerals. This results in a reduction of negative charges, thereby reducing the thickness of the diffuse double layer. The second stage involves the reaction of OH^- with silica and alumina present in the clay minerals to form cementitious compounds (calcium silicate hydrate and calcium alumina hydrate). These compounds act as binders and contribute to the agglomeration of soil particles, resulting in improved strength and volumetric stability.

Cement, on the other hand, with calcium silicates as a major constituent, reacts with water to form a binding agent called calcium silicate hydrate gel (C–S–H gel) and calcium hydroxide. The C–S–H gel is the primary binding agent that holds the soil particles together and contributes to the increased strength and stability of the stabilized soil. In addition to this, the calcium hydroxide that was formed as a hydration product disintegrates into Ca^{2+} and OH^- . Similar to lime-stabilized soil, these products undergo pozzolanic reactions to form additional cementitious compounds that result in enhanced strength. The effectiveness of lime and Portland cement in expansive soil stabilization was extensively studied [11–13, 15–17]. The studies revealed that the lime and cement stabilized expansive soil resulted in a reduction in liquid limit, an increase in plasticity index and shrinkage limit, increased unconfined compressive strength (UCS), and a considerable decrease in swell and shrinkage potential. However, the production of lime and cement has a severe negative impact on the environment. The production process releases significant amounts of carbon dioxide (CO_2) and other harmful greenhouse gases into the atmosphere [18–21]. In 2012, approximately 4 gigatonnes (Gt) of cement were produced globally, which emitted about 3 Gt of CO_2 into the atmosphere, nearly 8% of the total annual CO_2 emissions caused by human activities worldwide [22]. To solve the environmental concerns raised by traditional stabilizers, eco-friendly and sustainable chemical additives (commonly grouped as non-traditional stabilizers) have been diligently studied to improve the behaviour of expansive soils.

Non-traditional stabilizers include, but are not limited to, a wide variety of chemical additives: Industrial by-products, synthetic polymers, bio-polymers, geopolymers, enzymes, resins, salts, and ionic stabilizers [23, 24]. Unlike traditional stabilizers, the mechanism involved in each category and the specific chemical within the category vary considerably. Implementation of these non-traditional stabilizers, especially for expansive soils, has been a highly researched area in recent years [25–32].

There are several state-of-the-art review studies available currently that deals with soil stabilization using

non-traditional additives [24, 33–36]. Barman et al. [5] reviewed the stabilization mechanism of expansive soils using various chemical additives (traditional and non-traditional) and also discussed on the efficiency of the additives in improving the geotechnical characteristics of expansive soil. Chang et al. [37] provided a state-of-the-art review on biopolymer additives for soil stabilization. Their effect on various engineering behaviour of soil was discussed, considering their sustainability and commercial viability. Huang et al. 2021 [38] provided a detail review on the utilization of polymers in soil stabilization by discussing their interaction with soil particles and impact on geotechnical properties of soil. Still, a comprehensive review that focus solely on expansive soil stabilization using emerging, eco-friendly, and sustainable chemical additives are very limited. This paper provides a state-of-the-art review on sustainable chemical additives that are used currently for expansive soil stabilization. The effect of industrial by-products, synthetic polymers, biopolymers, geopolymers, and enzymes on the key engineering properties of expansive soil is discussed in detail through the results of state-of-the-art studies. The physico-chemical properties and the mechanism involved in the stabilization process of these additives is also explored. Finally, the overall efficiency and shortcomings of each stabilizer is analyzed, which will be beneficial for the engineers for better utilization in filed applications.

Expansive Soil Mechanism

Expansive soils are mainly characterized by clay minerals belonging to the smectite or vermiculate group that are particularly recognized for their interlayer expansion. Montmorillonite is one of the important members of smectite group that has a 2:1 layered structure (an octahedral alumina sheet sandwiched between two tetrahedral silica sheets). The two tetrahedral sheets are bonded by weak van der Waals force of attraction, thereby allowing the exchangeable cations and water molecules to enter the interlayer easily [2]. When isomorphous substitution takes place with replacement of cations with aluminum ions, a net negative charge is developed on the mineral surface. This negative charge is neutralized by the attraction of exchangeable cations, which is available within the clay-water network. The attraction of cations in turn, produces an irregular distribution of cations, with more concentration towards the clay surface and decreasing with distance from the clay surface. This redistribution of ions gives rise to the electrostatic property called diffuse double layer, and the quantity of cations needed to equalize this substitution is called the Cation Exchange Capacity (CEC) [1, 39, 40]. When in contact with water, the diffuse double layer expands, leading to the separation of clay minerals and consequent swelling of soil. Conversely, with the evaporation

of water, the diffuse double layer contracts resulting in soil shrinkage and cracking. This altering behaviour of diffuse double layer of the expansive clay minerals is the fundamental cause for the volumetric instability of soils [8, 40, 41].

Sustainable Stabilizers

Industrial by-Products

Industrial by-products (IBP), often regarded as industrial wastes or residues, are deposited in huge amounts as a result of various industrial processes. These by-products are often disposed in nearby fertile lands, thereby contaminating the land and ground water. Hence, studies were made on the utilization of the surplus waste generated in order to reduce the environmental damage. With both class F fly ash (FA-F) and class C fly ash (FA-C) gaining attention as an alternative additive over lime and cement, several researchers explored the possibility of utilizing other industrial wastes for stabilization of problematic soils—silica fume (SF), Bottom ash (BA), cement kiln dust (CKD), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), Bagasse ash (BAA), slag cement (SC), and copper slag (CS) are some of the commonly used industrial wastes in construction industry. With their excellent binding ability and chemical reactivity, they have been proved to enhance the hydro-mechanical characteristics of soils [37, 38, 42–46]. Lignosulfonate (LS), a by-product of paper industry, has got more attention in recent years because of its remarkable stabilization abilities [47–51].

Synthetic Polymers

Synthetic polymers are human-made organic polymers with basic constituents derived from petrochemical feedstocks. They are composed of repeating units called monomers, each having distinct physical and chemical properties. These are available in both solid (powder, fibres) and liquid forms. Some of the synthetic polymers used as expansive soil stabilizers are urea formaldehyde (UF), polyacrylamide (PAM), polyvinyl acetate (PVAc), polypropylene polymers (PP), polyvinyl alcohol (PVA), polymethylmethacrylate (PMMA), styrene co-butyl acrylate (SBA), and polyurethane. Table 1 shows the physico-chemical properties of some of the commonly used synthetic polymers in the field of geotechnical engineering. In addition, there are several copolymers that are formed by the polymerization of two or more different monomers, which have been utilized in expansive soil stabilization. Styrene acrylic is a widely used copolymer formed by the polymerization of styrene and acrylic monomers that offers excellent adhesion properties, rigidity, hardness, and flexibility. Al-Khanbashi and Abdalla [52] studied the

Table 1 General description and physio-chemical properties of common synthetic polymers used as soil stabilizers

| Synthetic polymer | General description | Physico-chemical characteristics | Influence as a soil stabilizer for non-expansive soils | References |
|--------------------------------|--|---|---|------------|
| Urea formaldehyde (UF) | Non-ionic polymer formed by a condensation reaction between urea and formaldehyde Composed of a mix of linear or branched oligomers and polymers with few monomers | Cross-linking ability to form strong three-dimensional networks, irreversible curing (thermosetting) when exposed to heat, excellent adhesive property, high reactivity, solubility, and dispersibility | Increase in unconfined compressive strength of clayey sand, better improvement for siliceous aggregates; increase in soil cohesion and bearing capacity; decrease in affinity for water; reduction in liquid limit and plasticity index | [48, 49] |
| Polyacrylamide (PAM) | Water-soluble organic polymer formed through the polymerization of acrylamide monomers High molecular weight polymers and are classified based on its charge as anionic, cationic and neutrally charged PAM Anionic type is most commonly used which is a group of linear polymers | Linear PAM is water soluble, while cross-linked PAM is only water absorbent. Remarkable binding ability, and flocculation property | Increased coefficient of consolidation, increase in structural yield stress, accelerating the consolidation process of high plastic clay; increase in failure strain of cemented soil; reduction in hydraulic conductivity of soil; increase in UCS for silty gravel, clayey gravel and clayey sand soil types; enhanced tensile strength | [50–52] |
| Polyvinyl Acetate (PVAc) | Amorphous, water-soluble emulsion belonging to the family of polyvinyl esters Formed through the polymerization of vinyl acetate monomers | Water-soluble and dispersible polymer with high adhesion property, biodegradation resistant, sensitive to moisture and humidity, | Without curing period PVAc addition had a negative impact on soil strength; increase in cohesion and friction angle; resistance to soil erosion; increase in UCS of silty soil; increase in shear modulus up to optimum dosage of coastal sand | [53–55] |
| Polyvinyl Alcohol (PVA) | Hydrophilic polymer formed by the hydrolysis of PVAc or other vinyl ester derivatives, where acetates groups are replaced by OH group Alcohol proportion is determined the degree of hydrolysis reaction | Solidified PVA forms strong films over the surface; high affinity to water; | Increase in UCS of soft clay stabilized with PVA and fly ash geopolymer; Increase in UCS of PVA-cement stabilized sandy soil; Reduction in cracks formation in lime-PVA treated soil; Significant increase in UCS of PVA-cement stabilized kaolinites | [56–58] |
| Polymethyl methacrylate (PMMA) | Thermoplastic polymer formed by the addition polymerization of methyl methacrylate monomers | High mechanical strength, resistant to chemical attacks, high impact resistance, good adhesion property | Increase in California bearing ratio (CBR) of dune sands; | [59, 60] |

performance of styrene acrylic emulsion as a stabilizer for sandy soil. Inclusion of styrene acrylic altered both hydraulic and mechanical characteristics of soil. Hydraulic conductivity was found to reduce with increasing SA content, while strength and stiffness increased considerably. Due to its broad applicability as a stabilizer for various soil types, as demonstrated in Table 1, synthetic polymers have emerged as a promising additive for the stabilization of expansive soils.

Biopolymers

Biopolymers are natural polymers that are produced either by living organisms like plants, animals, microorganisms (bio-based) or chemically synthesized from a biological matter. Bio-based polymers can be classified into various types depending on their origin, which include polysaccharides, starch, chitosan, alginates, chitin, casein, keratin, etc. They are widely used in the medical industries, agricultural fields, textile industries, water treatment plants, etc. Some of the important biopolymers, their characteristics, and state-of-the-art in soil stabilization is shown in Table 2.

Geopolymers

Unlike synthetic and biopolymers, geopolymers are inorganic polymers belonging to the group of alkali-activated binders which are primarily used in the construction industry. Extensive research on IBP as soil stabilizers revealed that many of the by-products were not able to exhibit binding characteristics without using a secondary activation additive such as cement, lime, or fly ash. This directed towards the introduction of using alkaline solutions to activate such binders. Geopolymers are formed by mixing aluminosilicate source materials with alkaline activators, causing polymerization of the aluminosilicate units to form a three-dimensional network structure. Various materials such as metakaolin, red mud, fly ash, ground granulated blast furnace slag, rice husk ash, volcanic ash, and bagasse ash have been used as potential aluminosilicate source in geopolymer production. Metal hydroxides such as sodium hydroxide and potassium hydroxide, along with sodium silicate, are the commonly used alkali activators. Geopolymers have emerged as an environment-friendly alternative to traditional calcium-based binders owing to its reduced carbon emissions and energy consumption. Davidovits [73] developed geopolymers initially as a new inorganic-polymer material to be applied in the fields of automobile, plastic, aerospace, metallurgy, and civil engineering. After that, over the last few years, various researchers studied the potential use of geopolymers for stabilization of soils [74–80]. It was used as a stabilizer for various soil types and was found to improve its engineering properties significantly, such as

shear strength, wet–dry and freeze–thaw durability behaviour, compressive strength, tensile strength, resilient modulus, and dynamic property.

Enzymes

Enzymes are natural organic molecules that act as catalysts for accelerating chemical reactions in all living organisms. Hence, they can be easily extracted from plants, animals, and other living beings using suitable technique. Typically, enzymes are composed of proteins, metal ions, and chains of amino acids. They are characterized by very specific functions, allowing them to perform certain reactions and ensure effective chemical alteration. The distinct chemical composition of the soil offers the necessary location for reaction to occur, while the pore water system in the soil-matrix facilitates the movement of enzyme. There are various enzymes that are commercially available (e.g., Terrazyme, Eko Soil, Earthzyme, Permazyme) to perform specific functions in soil stabilization, such as altering the compaction characteristics, workability, water-absorbing ability, mechanical behaviour, and chemical reactions of a soil. These synthesized enzymes are mostly supplied in liquid state with good solubility in water, which makes it easy to mix with soil. Enzymes are often added to soil in terms of application mass ratio (AMR) and dilution mass ratio (DMR), where AMR is the mass of enzyme to dry soil mass, and DMR is the ratio of mass of enzyme to mass of water. Several researchers studied the potential use of enzymes as a sustainable soil stabilizer for various types of soils [81–88].

Mechanism of Stabilization

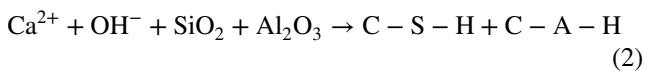
Industrial by-Products

Industrial by-products contain adequate sources of silica, alumina, calcium oxide, iron oxide, and magnesium oxide that actively react within the soil matrix. The composition of these elements can vary widely depending on the source material of the IBP and the process by which it is obtained. The interaction of IBP with expansive soil particles has similarities with certain mechanisms involved when using traditional calcium-based stabilizers. Upon introduction into the soil–water matrix, pozzolanic reactions take place between the calcium ions and silica or alumina present in the soil matrix. This results in the formation of cementitious products, such as calcium silicate hydrate (C–S–H) and/or calcium aluminate hydrate (C–A–H) [89–91]. Sharma and Sivapullaiah [90] observed distinctive peaks in x-ray diffraction (XRD) patterns that confirmed the formation of C–S–H and C–A–H compounds as a result of the pozzolanic

Table 2 General description and physio-chemical properties of common biopolymer used as soil stabilizers

| Biopolymer | General description | Physico-chemical characteristics | Influence as a soil stabilizer for non-expansive soils | References |
|-------------|---|--|--|-------------|
| Xanthan gum | Anionic polysaccharide derived from the microbial fermentation of carbohydrates by <i>Xanthomonas campestris</i> bacterium Has a unique structure made of glucose units with side chains composed of mannose and glucuronic acid | Highly viscous when dispersed in water; Fully soluble in water; pseudoplastic behaviour; pH stability; Formation of stable gels; | Decrease in optimum moisture content (OMC) and increase in liquid limit, plastic limit and maximum dry density (MDD) of sand lean clay soil; reduction in collapsible potential and permeability of a low-plasticity silty-clay soil; Increase in UCS of sandy soil | [61–63] |
| Guar gum | A polysaccharide extracted from guar beans (<i>Cyamopsis tetragonoloba</i>) Structure consists of linear chain of galactose and mannose units | Readily soluble in cold water; good thickening and gel forming property; high viscosity in solution form; | Increase in liquid limit, plastic limit, UCS and decrease in swell index of highly compressible silty-clay; greater resistance to freeze–thaw cycle in high plastic kaolin clay; Increase in shear strength of loess soil; durability against wet–dry cycles of silty sand | [52, 63–66] |
| Agar gum | A polysaccharide derived primarily from various species of red algae Consists of repeating units of agarose and agaropectin | Soluble in boiling water; forms gel on cooling; less reactivity due to its neutral network of chain; | Increase in UCS for air-dried and submerged conditions of sandy and clayey soils; | [67, 68] |
| Gellan gum | Anionic thermo-gelation biopolymer produced by microbial fermentation of <i>Spingomonas</i> elodea strains Composed of repeating units of glucose, glucuronic acid, and rhamnose monomers | Exceptional water-holding capacity; ability to form gel; resistant to pH changes; biodegradable; | Increase in drained shear strength parameters of sand-clay mixture; resistance to wet–dry cycles of poorly graded sandy soil | [69–72] |

reaction between GGBS-flyash stabilizer and clay particles as shown by the following equations:



where Ca(OH)_2 is a component in IBP; SiO_2 and Al_2O_3 are the components in clay mineral.

On the contrary, non-calcium IBP in reaction with soil containing a considerable amount of calcium compounds also leads to the formation of C–S–H gel compounds [92–94]. These cementitious products play a vital role in linking the soil particles together and improving their mechanical strength. Kalkan and Akbulut [95] demonstrated that the silica present in silica fume reacted with calcium and hydroxide ions in the soil and formed C–S–H that enhanced their engineering behaviour. In addition to this, the presence of certain minerals, such as alkaline oxides, can induce the cation exchange process by reacting with water to disintegrate into their respective alkali ions. These ions replace the cations present in the diffuse double layer, thereby reducing its thickness and improving its stability against swelling and shrinking [96, 97]. Furthermore, the ion exchange might cause flocculation and agglomeration in the soil matrix, which aids in improving soil strength [98]. Through a series of scanning electron microscope (SEM) and XRD studies, Ogila [99] reported that all the major stabilization mechanisms (hydration, cation exchange, pozzolanic reaction, flocculation, and agglomeration) had occurred in cement kiln dust stabilized expansive soil that caused the enhancement of its geotechnical properties.

Synthetic Polymers and Biopolymers

As discussed earlier, both synthetic polymers and naturally occurring biopolymers are composed of repeating monomer units that are basically organic in nature. These monomers are bonded by strong chemical bonds, resulting in long chains of polymers. Hence, the overall characteristics of a polymer are purely governed by the functional groups of the monomers. Still, the fundamental mechanism governing the interaction between these polymers and soil particles is similar to some extent due to the typical intermolecular forces in the polymer, the general physical and chemical properties of the polymer, and the presence of some common functional groups and their arrangement.

The net electrical charge of an organic polymer stabilizer can be positive (cationic), negative (anionic), or neutral, depending on the type and charges of the monomers in the polymeric chain. Montmorillonite clay mineral formed by the isomorphous substitution of aluminum

ions by silicon ions, carries a net negative charge [2]. Other minerals, such as illite, can carry a net positive charge and are capable of attracting negatively charged polymer units. Adsorption, electrostatic interaction, and hydrogen bonding are the major phenomena that govern the stabilization process of these polymers in expansive soils. When introduced into the soil matrix, the positively charged polymer gets adsorbed to the clay surface due to the complementary charges. Subsequently, the adsorbed polymers fill up the voids and interlock the soil particles through van der Waals bonding and/or hydrogen bonding. This alters the clay structure by providing a more stable diffuse double layer, thereby reducing the swell–shrink nature of expansive soils. Also, through further flocculation and agglomeration of soil particles, mechanical strength is improved considerably [100–103]. Similarly, when negatively charged polymers are added into the soil matrix, they get attracted to some positively charged soil particles and form bonds with them depending on the type of polymer functional group [104–111]. Soltani et al. [112] explains that negatively charged polymers like anionic PAM can be attracted to clay particles by the presence of some exchangeable cations (e.g., Ca^{2+} , Mg^{2+}). The strong bonds developed by the interaction of these ions lead to flocculation and agglomeration of soil particles, which in turn reduce the swell–shrink potential of the treated expansive soil. Hence, the efficiency of anionic polymer stabilizers depends on the presence of positive charges on the soil surface. The stabilization mechanism of neutrally charged polymers with expansive soils is basically driven more by physical interaction rather than electrostatic interaction.

Geopolymer

Geopolymer is synthesized through a chemical process called geopolymerization, which is a complex process and is still being studied. But commonly, the process involves three main stages: dissolution, polycondensation, and polymerization. Initially, when an alkali activator (NaOH or KOH with silicates) is mixed with a binder source material (e.g., slag, metakaolin, flyash, bagasse ash, rice husk ash, volcanic ash) in the presence of water, dissolution of alumina and silica occurs, leading to the formation of silicates and aluminates. This is followed by gel formation through the polycondensation reaction of the silicates and aluminates. In the case of expansive clay soils, silicates and aluminates inherently present in the minerals, such as montmorillonite, also take part in the polycondensation process [113]. Finally, continuous rearrangement of these monomers leads to the development of an amorphous, three-dimensional network of interconnected aluminosilicates, generally represented by the empirical relation (3):

$$M_n \left[-(\text{SiO}_2)_z - \text{AlO}_2 \right]_n \cdot w\text{H}_2\text{O} \quad (3)$$

where M , z , n , and w denote the alkali cations, polycondensation degree, Si/Al molar ratio, and molar water content, respectively [25, 114].

There are several studies in the literature that deal with the implementation of geopolymers in other construction materials such as concrete, bricks, and mortar. With the limited literature available currently for geopolymer-soil interaction, the basic mechanism involved in stabilization is discussed. Similar to IBP, the incorporation of geopolymer gel into expansive soils will initiate an ion exchange reaction with the cations in the interlayers, causing a reduction in swell potential. Cementitious products such as C–S–H and C–A–H may also be formed depending on the availability of calcium ions in the clay minerals. Further, the geopolymer gel infiltrates the pores, fills the voids, and finally wraps around the clay particles, making a strong interlock between them. This helps in improving the mechanical strength and overall volumetric stability of the expansive soil. Sahoo et al. [115] observed the presence of cementitious products (C–S–H, C–A–H, ettringite) in GGBS–NaOH-based geopolymer stabilized expansive soil from the XRD patterns. Miao et al. [116] observed peaks in XRD patterns of volcanic ash–KOH-based geopolymer stabilized soil that indicated the transformation of montmorillonite into illite (illitization), thereby reducing the swelling nature of the soil significantly. Samuel et al. [25] reported that the addition of MK–KOH-based geopolymer in the soil reduced the diffuse double layer thickness through ion exchange reactions, leading to further flocculation of particles.

Enzymes

Studies related to the potential usage of enzymes as expansive soil stabilizer are very limited, and this research area is still being explored. Also, the results of various laboratory tests from these studies are highly divergent owing to the unavailability of standardized testing methodology for enzyme stabilizers. A proper understanding on the interaction mechanism involved between soil–water system and enzyme is crucial to formulate a standard testing methodology for enzyme stabilizers. This has become a great challenge because of the various contradictory hypotheses on stabilization mechanism of enzymes that are available in the literature till date [87]. One of the first and widely accepted hypothesis is that once introduced into the soil-matrix, the enzyme binds with the adsorbed large organic molecules available on the surface of clay minerals. Then, these enzyme-encapsulated large positive molecules will surround the negatively charged clay minerals by displacing the diffuse double-layer water molecules. This results

in the neutralization of charge, reduction in diffuse double layer thickness, and thereby minimizing the affinity of clay mineral to water molecules [24, 85, 117]. Renjith [86] explains that the cation exchange process and alteration of diffuse double layer are highly dependent on the soil type. Soils with high swelling and plasticity characteristics have higher ability to undergo cation exchange reaction compared to soils with low plasticity and clay content. Another hypothesis suggests that the enzyme does not take part directly in the cation exchange process, rather simply acts as a catalyst in speeding up the cation exchange reaction between the organic molecules and clay minerals [118]. Few studies postulated that enzymes might behave as surfactants when added to soil-matrix, which reduces the water affinity of clay minerals by decreasing the surface tension [85]. Apart from these mechanisms, another hypothesis suggests that enzyme stabilizers might enhance the chemical bonding among particles, causing particle aggregation and reduction in porosity [87, 119]. This results in a denser soil structure, reduced water affinity, and thereby increased mechanical strength. Pooni et al. [119] performed various laboratory tests to study the chemical composition, microstructure, mechanical, and hydraulic behaviour of Eko Soil stabilized expansive soil. From the Fourier Transform Infrared Spectroscopy (FTIR) and XRD tests, it was showed that the enzyme stabilized soil did not have any new cementitious compounds or gels as observed in traditional stabilizers. Microstructural analyses confirmed the reduction in porosity because of the formation of aggregates. This change in the soil structure reduced the hydraulic behaviour and increased the mechanical behaviour of the treated expansive soil.

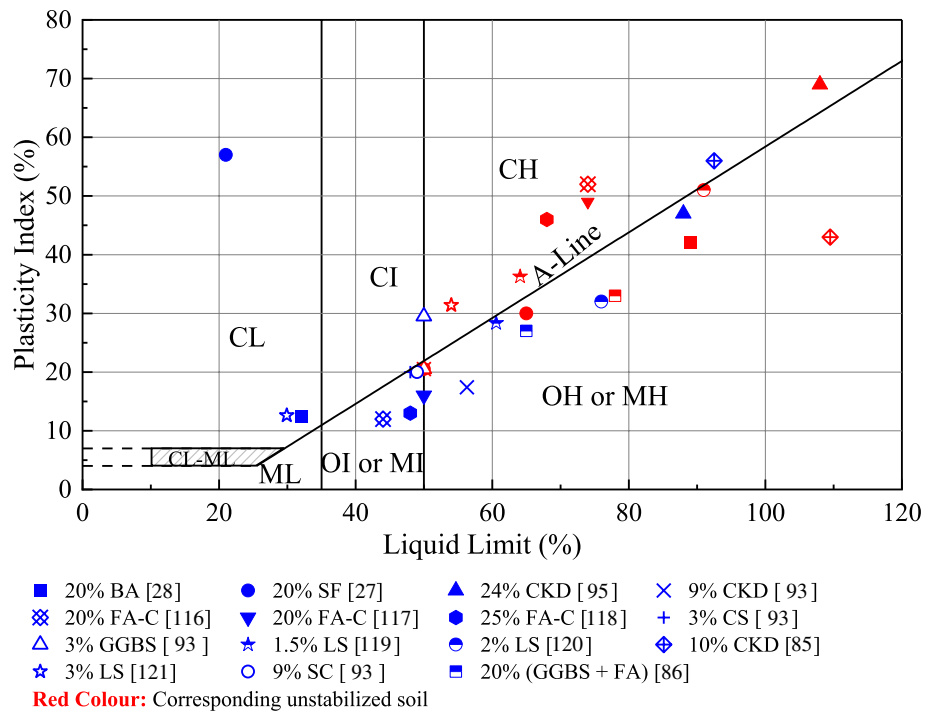
Effect on Engineering Properties of Expansive Soil

Consistency Limits

Atterberg liquid limit (LL), plastic limit (PL), and plasticity index (PI) are inherent characteristics of a soil that quantify its ease of deformation and volumetric change. Hence, changes in these parameters due to the addition of stabilizers directly reflect their resistance to swell/shrinkage and stability, especially for high swelling expansive soils.

The inclusion of IBP in expansive soils made noteworthy modifications to their soil behaviour in terms of consistency limits. Generally, both the liquid limit and plasticity index of expansive soils were found to decrease with increasing dosages of IBP. The addition of bottom ash to a highly plastic silt (MH) soil reduced the liquid limit from 89 to 32% and the plasticity index from 42 to 12.5% with increasing dosages (0–20%) [27]. Similarly, silica fume-treated MH soil decreased the LL and PI considerably, thereby changing the soil to low plastic clay (CL) soil [28]. Figure 1 shows

Fig. 1 Effect of IBP on liquid limit and plasticity index of expansive soils



the effect of various industrial-by-product stabilizers on the plasticity characteristics of expansive soil under optimum dosage conditions [27, 28, 89, 90, 97, 99, 120–125]. It is evident that, in most cases, the plasticity of the treated soils has been reduced, thereby improving their workability and water retention properties. Figure 1 also shows the comparison of the stabilizers with the most extensively used industrial waste, fly ash (often categorized as a traditional stabilizer). Even though the plasticity reduction capacity of the stabilizers in Fig. 1 could not match the effectiveness of fly ash-treated expansive soils, they could be considered a potential alternative to fly ash and other traditional stabilizers.

On the contrary, expansive soils treated with organic biopolymers show an increase in LL and PL with an increase in biopolymer content. The formation of viscous hydrogels by the biopolymers in reaction with the soil–water system led to an increase in the plasticity behaviour. For example, xanthan gum-treated expansive soil showed up to 117% and 127% increase in liquid limit and plasticity index, respectively, with increasing dosages (0–4%) [111]. Similarly, pectin-treated expansive soil had an increase in LL and PI of up to 45% and 102%, respectively, with increasing pectin content. Figure 2 shows the LL and PI of untreated and organic polymer-treated expansive soils in a plasticity chart [101, 104, 106, 108, 109, 111, 126–130]. The effect of synthetic polymers on the plasticity characteristics of expansive soils doesn't show a consistent pattern like that of biopolymers since it is highly dependent on the type of repeating monomer units and the net charge of the polymer. Soltani et al. [126] investigated the swell–shrink behaviour of a high

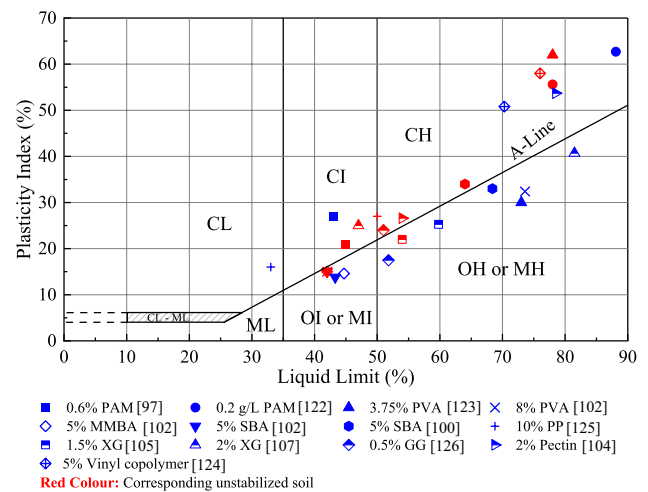


Fig. 2 Effect of synthetic polymer and biopolymer on liquid limit and plasticity index of expansive soils

swelling expansive soil treated with anionic PAM. Both LL and PI increased with PAM content up to an optimum dosage of 0.2 g/L, after which there was a marginal decrease in the water contents. The hydrophilic nature of the polymer and its ability to induce flocculation within the soil–water system are the primary causes for the increased plasticity behaviour of treated soils. While Zhou et al. [101] observed up to 4.7% and 50% decrease in LL and PI, respectively, for an expansive soil treated with cationic polyacrylamide.

Geopolymer, which is actually an IBP activated by an alkaline solution, was found to have an exceptional impact

on the consistency limits of expansive soils. Figure 3 shows the LL and PI of geopolymer-treated expansive soils for optimum dosage in a plasticity chart [115, 116, 116, 131] observed a clear decreasing trend in LL and PI of VA-treated expansive soil with increasing KOH content. For instance, the PI of VA-treated soil decreased by 14%, while the PI of geopolymer-treated soil decreased by about 59% when compared to the PI of untreated soil. A similar pattern was reported by several researchers using different source materials, alkaline solutions, and expansive soil.

From the limited studies available, enzymes are found to have a very minimal impact over the consistency limits of expansive soil. Rauch et al. [132] performed Atterberg limits tests to determine the effect of an enzyme stabilizer on the plasticity characteristics of an expansive soil and observed an insignificant decrease in its liquid limit. Whereas Kushwaha et al. [133] observed a 19% decrease in liquid limit for Eko Soil stabilized expansive soil. Reduction in adsorbed water surrounding the clay minerals due to the ion exchange process was believed to be the reason for decrease in plasticity.

Compaction

The mechanical and hydraulic behaviour of stabilized soil is highly dependent on its compaction characteristics: compaction energy, maximum dry density (MDD), and optimum moisture content (OMC). Depending on the type of IBP added, the MDD and OMC of IBP and geopolymer-treated expansive soils vary with increasing additive content. Sharo et al. [89] reported an increase in MDD and a reduction in OMC with increasing dosage of cement kiln dust. Similar behaviour was observed for GGBS and fly ash amended expansive soil [90]. Increase in MDD in these soils

is directly attributed to the high specific gravity of the IBP added. On the contrary, IBP with low specific gravity (e.g., silica fume, bagasse ash, rice husk ash, lignosulfonate) has caused a decrease in MDD, as reported by various studies [14, 27, 50, 94]. Also, the cation exchange reaction, followed by flocculation and agglomeration, results in the formation of coarse aggregates. These aggregates fill up only the large voids in the soil matrix, thereby increasing the soil porosity and reducing the dry density. Kishor et al. [134] showed that with increasing dosages of rice husk ash based geopolymer and sugarcane bagasse ash based geopolymer, maximum bulk density reduced up to 7.3% and 8.2%, respectively. Similarly, the inclusion of biopolymers has mostly resulted in the reduction of MDD and increase in OMC of expansive soils. Hamza et al. [135] observed a 25% decrease in MDD and a 14% increase in OMC with an addition of 5% xanthan gum. Vydehi et al. [111] and Sathyapriya [130] also observed a similar decreasing trend in MDD of expansive soils with increasing dosages of guar gum. High affinity for water and the viscous nature of biopolymers lead to the formation of coatings around the soil particles. This results in reduced particle–particle interaction, which causes separation between the soil particles and finally reduces the MDD, whereas expansive soils treated with synthetic polymers such as PAM have increased the MDD with increasing dosage [126]. For Eko Soil stabilized soil, MDD was found to increase with increasing dosage up to 4% (by volume of OMC), beyond which it decreased [133]. Pooni et al. [136] reported that the addition of 1% AMR Eko Soil increased the MDD by 3% and reduced the OMC by 7.4%.

Swell–Shrink Characteristics

The effectiveness of an expansive soil stabilizer greatly depends on its ability to restrain swelling and shrinkage. Swell potential, shrinkage strain, and swelling pressure are the critical parameters of an expansive soil that convey the susceptibility of soil to volumetric changes upon variations in moisture content. Swell potential and swelling pressure tests of a compacted soil specimen are often performed as per ASTM D4546 methodology. Several studies have consistently reported a gradual decreasing trend in both swell potential and swelling pressure when expansive soils are treated with IBP (Figs. 4, 5) [27, 28, 89, 92, 94, 97, 137, 138]. The addition of bagasse ash to a highly plastic clay soil, which was compacted at its OMC, reduced the swell potential from 10 to 0.8% with increasing ash content (0–25%) [94]. Al-Gharbawi et al. [138] observed a 62% and 78% decline in swell potential and swelling pressure for an expansive soil treated with 9% silica fume. Also, comparing the results with lime and cement stabilization for the same soil, silica fume was found to perform better than these traditional stabilizers. At a comparably low dosage,

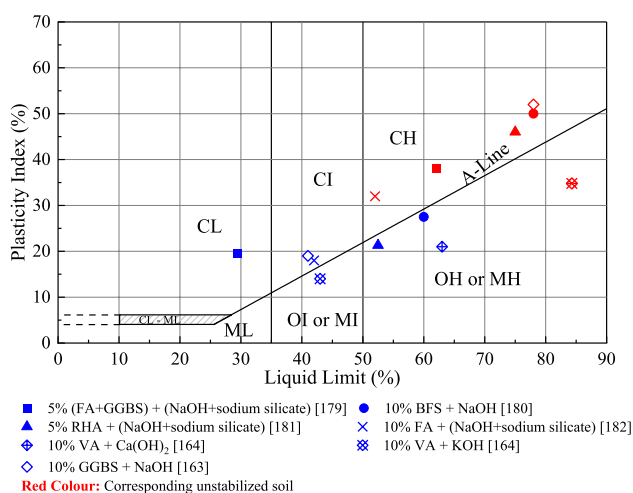


Fig. 3 Effect of geopolymer on liquid limit and plasticity index of expansive soils

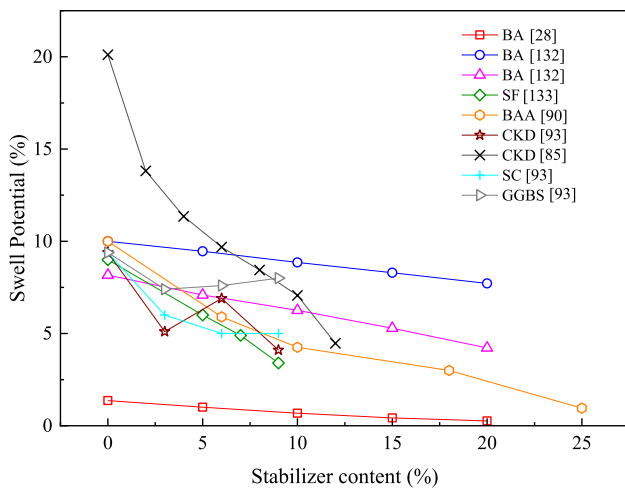


Fig. 4 Change in swell potential with increasing dosage of IBP stabilized expansive soils

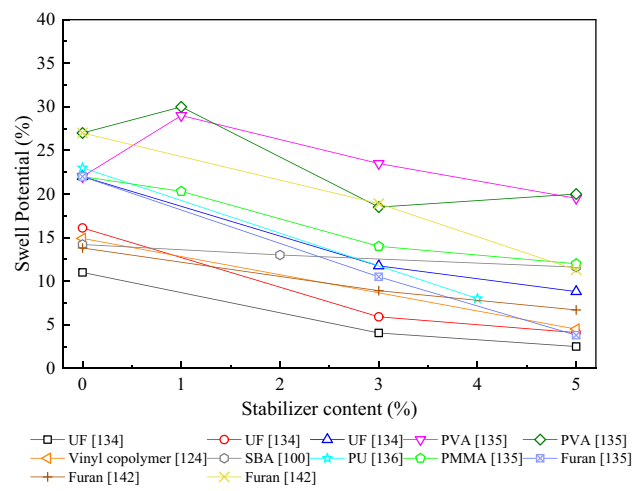


Fig. 6 Change in swell potential with increasing dosage of synthetic polymer stabilized expansive soils

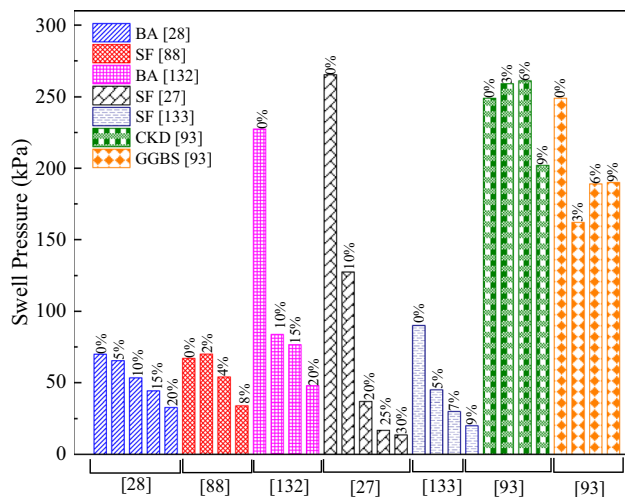


Fig. 5 Change in swell pressure with increasing dosage of IBP stabilized expansive soils

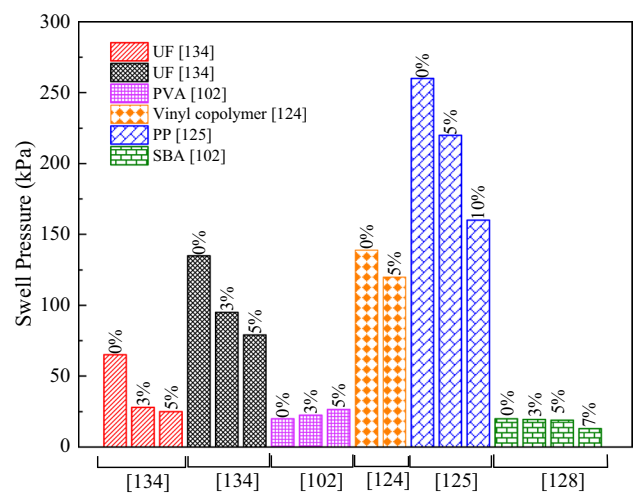


Fig. 7 Change in swell pressure with increasing dosage of synthetic polymer stabilized expansive soils

LS-stabilized soils have performed well in reducing swell potential and swell pressure. Fernandez et al. [31] observed a 44% decrease in swell potential at 5% LS content. LS-stabilized expansive soil also showed resistance to repeated wetting–drying cycles. According to Alazigha et al. [14], untreated specimens had a maximum swelling and shrinkage of 15.9% and 5.1%, respectively, in the third cycle. The addition of 2% LS reduced the swelling and shrinkage by 42% and 26%, respectively. The formation of cementitious products and flocculation as a result of pozzolanic reactions in the soil-matrix induced the reduction in swelling behaviour of IBP-stabilized expansive soils. A few IBP were found to rather increase the swell potential of expansive soils. A high plastic silty soil treated with 9% copper slag increased

the swell potential from 9.4 to 12% and the swell pressure by about 43%. A higher composition of sodium ions and a high cation exchange capacity of copper slag were reported as the primary reasons for such behaviour. Water content at which the soil was compacted for testing was found to have a notable impact on swell potential of soil. For instance, LS-treated expansive soil showed a progressive increase in swell potential with decreasing water content below its OMC [14]. Punthutaecha [137] also reported that bottom ash-treated soil specimen compacted on the dry side of OMC showed an increased swell potential when compared to that of soil compacted at OMC.

Figures 6 and 7 show the swell potential and swelling pressure for various synthetic polymer-treated expansive soils at varying additive contents [104, 106, 128, 129,

[139–141]. Vinyl copolymer, a liquid synthetic polymer, reduced the swell potential of a bentonite-clay mixture compacted at OMC from 14.9 to 4.5%, and the swell pressure from 139 to 120 kPa [128]. Similarly, urea formaldehyde was found to be effective for various types of soils with varying clay content and plasticity characteristics. For soils compacted at OMC with clay contents of 30%, 53%, and 73%, swell potential was reduced by 77%, 75%, and 60%, respectively, when treated with 5% UF [139]. Also, UF-stabilized soils were found to be effective under cyclic wetting and drying. At the end of the first cycle, shrinkage strain was reduced by 86% for the soil with a 30% clay content. PAM was also proven to be efficient against cycle wetting and drying [126]. An exponentially decreasing trend of swelling and shrinkage strain was observed with an increasing number of cycles for soil treated with 0.2 g/L PAM. Figure 8 shows the response of various synthetic polymer stabilized soils subjected to cyclic wetting and drying [126, 139]. As mentioned earlier, reduction in swelling behaviour is attributed to the formation of aggregates and thin film coats due to the electrostatic interaction between the polymer and charged soil minerals. Even though the consistency limits of soils treated with biopolymers increased substantially, a decrease in swell potential was observed with increasing biopolymer content, as shown in Fig. 9 [108, 109, 135, 142]. On the contrary, for a soil with very low clay content and high sand content, an increase in swell potential was also reported [142]. This behaviour is attributed to the creation of hydrogels within the soil structure and an insufficient curing period.

Geopolymer stabilized expansive soils were found to perform tremendously in terms of reducing swell potential, as shown in Fig. 10 [25, 116, 134, 143]. Samuel et al. [25] studied the stabilizing effect of metakaolin based geopolymer on

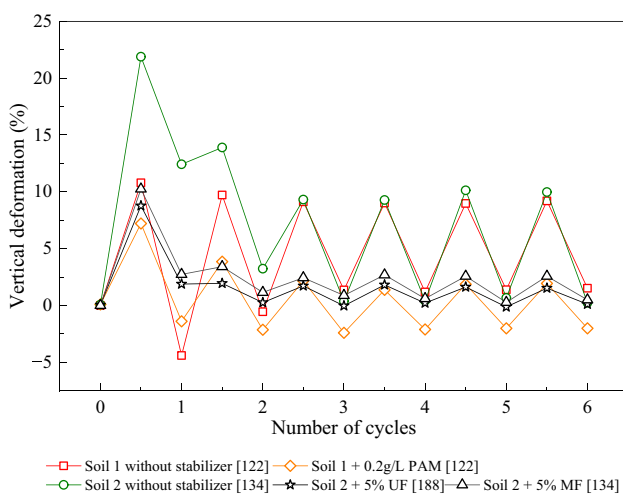


Fig. 8 Influence of enzyme on normalized UCS of expansive soil with increasing dosage Effect of synthetic polymer stabilized expansive soils subjected to W-D cycles

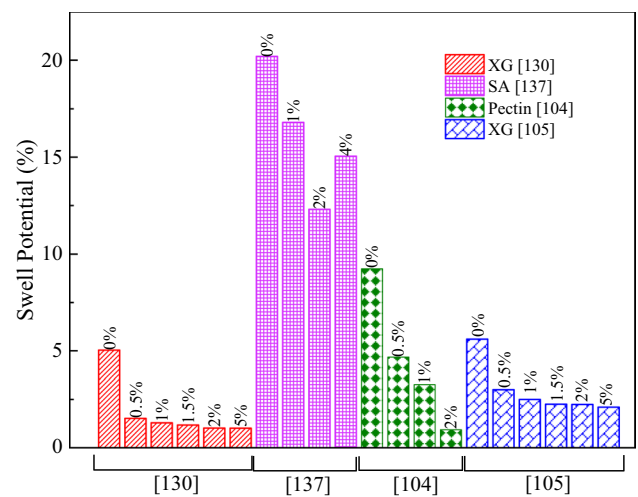


Fig. 9 Change in swell potential with increasing dosage of biopolymer stabilized expansive soils

expansive clays at varying dosages and curing periods. Even at a very low geopolymer content (4%), vertical swelling strain and shrinkage strain of specimens compacted on the dry side of OMC (95% of MDD) were reduced by about 83% and 30%, respectively, when tested immediately without curing. Further reduction was observed with increasing curing periods and geopolymer content. Very few research has been done to study the performance of bio-enzymes on the swelling characteristics of expansive soils [132, 136]. From the available studies, bio-enzymes were found to reduce the swell potential marginally. With Eko Soil, a commercially available enzyme as a stabilizer, swell potential was reduced by 24% for 1% dosage diluted at 1:500 (Pooni et al. [136]). The ability of enzymes to reduce the affinity of clay particles

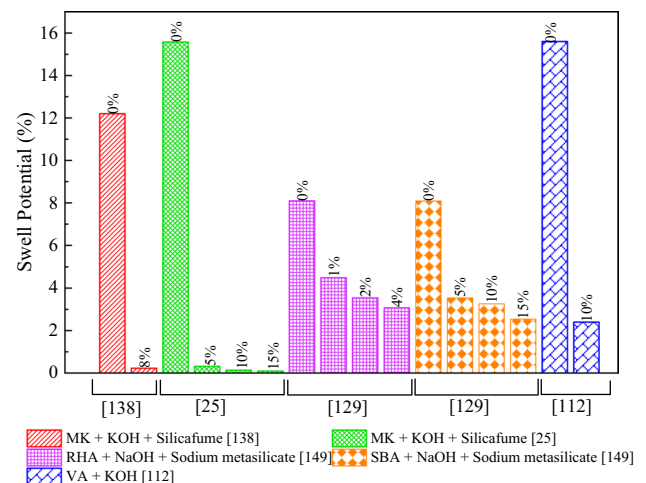


Fig. 10 Change in swell potential with increasing dosage of geopolymer stabilized expansive soils

for moisture absorption was reported as the major reason for such behaviour.

Unconfined Compressive Strength

The UCS of expansive soils stabilized with the chemical additives under consideration was found to improve significantly with an increase in stabilizer content and curing period. In the case of IBP, the C–S–H gels formed as a product of the pozzolanic reaction provide a strong bond between the clay particles, thereby improving their strength. Since the pozzolanic reaction progresses with time, the curing period has a notable influence on the UCS of stabilized soils. BA-stabilized expansive soil specimens compacted at OMC and cured for 28 days showed an increase in UCS of up to 173% with increasing BA content [28]. CKD-stabilized expansive soil showed a similar increasing trend until 10% CKD content, beyond which a reduction in UCS was observed [89]. The main reason for this reduction in UCS is the segregation of soil particles caused by the excessive CKD that has not reacted with clay particles yet. Synthetic polymers and biopolymers undergo ion exchange reactions with clay particles to form strong bonds that cause a notable increase in the soil strength. The effect of increasing stabilizer content and curing period on the normalized UCS of XG-treated expansive soils is shown in Fig. 11 [109, 111, 135, 144]. Normalized UCS is represented as a ratio of the UCS of treated soil at a particular dosage (q) to the UCS of untreated soil (q_0). The cation exchange reaction between the carboxylic group of XG and charged clay particles creates ionic bonds in the soil matrix, thereby improving the strength significantly. GG-treated expansive soils showed a considerable increase in UCS at a comparably low dosage.

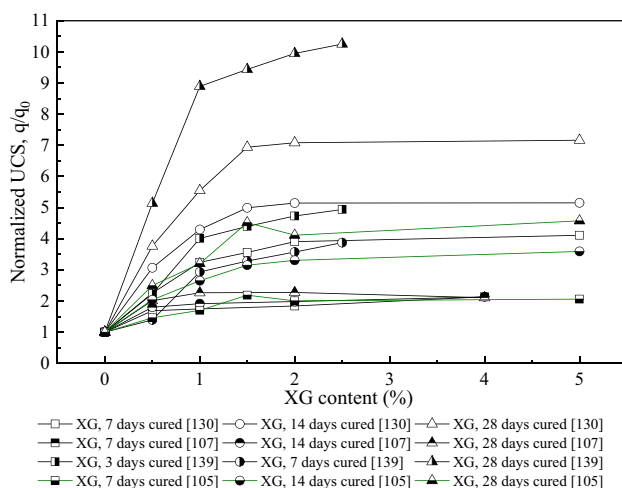


Fig. 11 Variation of normalized UCS of xanthan gum stabilized expansive soil with increasing dosage

Vydehi and Moghal [111] observed a 48% increase in UCS for 14 days cured GG-treated soil, and Acharya et al. [145] observed a 27.3% increase in UCS for 7 days cured GG-treated soil compacted on the dry side of OMC, both at a dosage of 0.5%. Similarly, the ion exchange reaction between synthetic polymers and clay particles has also led to an increase in UCS of expansive soils. PAM [101, 102], PVA [106, 127], PVAc [140], vinyl copolymer [128], and styrene acrylic [51] polymers have proven to considerably improve the UCS of expansive soils up to an optimum dosage level. The inclusion of geopolymers as chemical additives has also proven to improve the UCS of expansive soil with increasing dosage and curing periods, as shown in Fig. 12 [25, 114, 115, 131, 134]. For instance, GGBS when activated with sodium hydroxide (NaOH) alone, has increased the UCS from around 350 kPa to 5100 kPa when cured for 28 days [115]. Improved UCS of geopolymer-treated expansive soil is attributed to the dissolution of charged ions such as silicon, aluminium, calcium present in the IBP that form cementitious binding products. Also, compared to IBP-stabilized soil, geopolymer-stabilized soil showed a significant rise in UCS even when tested immediately without curing, mainly due to the quick reactive nature of geopolymers. Normalized UCS of enzyme-stabilized expansive soil is shown in Fig. 13 [118, 119, 133]. Pooni et al. [119] studied the stabilization effect of a commercially available enzyme, Eko Soil on expansive subgrade soil. They observed a maximum of 24% increase in UCS for samples mixed with enzyme of 1% AMR and 1:100 DMR, beyond which it had a negative impact.

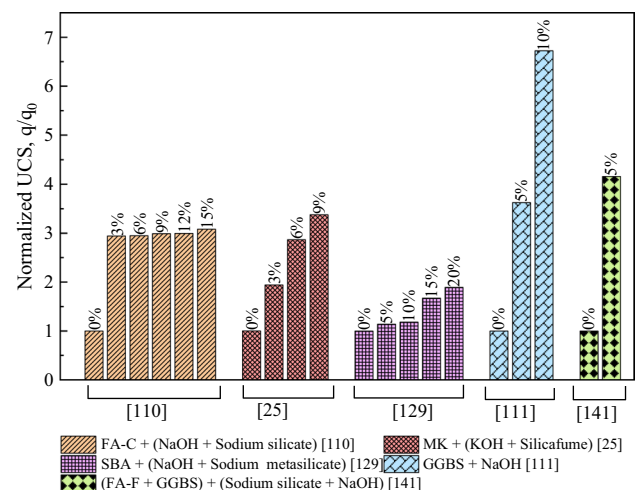


Fig. 12 Influence of geopolymer on normalized UCS of expansive soil with increasing dosage

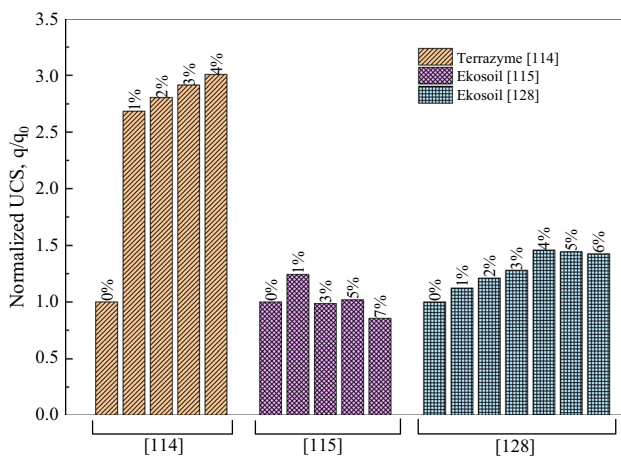


Fig. 13 Influence of enzyme on normalized UCS of expansive soil with increasing dosage

Challenges and Future Scope

Ensuring the long-term sustainability of the discussed chemical stabilizers is as important as their short-term performance. Some of the synthetic polymers and most of the biopolymers are biodegradable under certain environmental conditions [146]. The breaking down of polymer chains by microbial activity is termed biodegradation. There are some crucial parameters regarding the biodegradability of organic polymers that need extensive study: rate of degradation, toxicity of final degraded products, and the long-term impact of non-degraded polymer elements in soil. The degradation process occurs over a certain period of time for each polymer, depending on the type of monomer units, concentration of polymer in the soil, presence of organic elements in the soil, temperature, humidity, and pH of the soil. The final products of degradation are mostly non-toxic, although some polymers with toxic monomer units, such as acrylamide [147], might produce harmful chemicals in the soil–water ecosystem, which needs serious attention. When the degradation rate is very low, the long-term presence of a polymer in the soil matrix should be studied to ensure its sustainability [148]. Moreover, the improvement in expansive soil behaviour identified so far is based on only laboratory test results. For a successful field application, more large-scale and in-situ tests have to be carried out. In the case of enzyme stabilizers, very limited test data is currently available, which makes them an unpopular choice of stabilizer. Also, there isn't a standard procedure to test and use these emerging chemical additives as soil stabilizers in the field or in the lab, which is a serious problem for field application. Depending on the source material and manufacturing process, industrial by-products might contain traces of toxic elements. Though the major components of bottom ash are silica, calcium, and alumina, traces of heavy metals such as

lead, cadmium, zinc, and chromium could also be present [149]. Hence, it should be ensured that the quantity of these heavy metals in the stabilizer is insignificant to avoid any leaching into the groundwater table.

Expansive soils are more problematic in areas with extreme weather conditions that are subjected to rainfall–evaporation cycles, freeze–thaw cycles, erosion, etc. Hence, the durability of the stabilizers under such extreme environmental conditions is an important area that needs better focus. For a better understanding of the behaviour of stabilized soil under these varying climatic conditions, unsaturated parameters such as the soil–water retention curve (SWRC), hydraulic conductivity function, and unsaturated shear strength parameters must be studied, which is very limited currently.

Summary and Conclusions

This paper provides a detailed review on emerging chemical stabilizers for expansive soil treatment that ensures both sustainability and efficiency. Stabilization mechanism of various categories of stabilizers including industrial by-products, synthetic polymers, biopolymers, geopolymers, and enzymes, were discussed using the available literature. The influence of these stabilizers on the plasticity characteristics, swell–shrink behaviour, unconfined compressive strength, and compaction characteristics of soil was thoroughly explored. Some of the key conclusions that are drawn from this study are listed below:

1. Depending on the source material, industrial by-products are composed of varying quantities of calcium, silica, and alumina compounds. When mixed with expansive soils, pozzolanic reactions take place over time, resulting in the formation of cementitious compounds in the soil-matrix. This provided an improved cohesion and bond between the soil particles, thereby reducing the plasticity of IBP-treated soils considerably. Subsequently, the swelling and shrinkage of soil were controlled due to the strong interlocking provided by these cementitious products in most of the IBP (bottom ash, lignosulfonate, silica fume, blast furnace slag, and cement kiln dust) stabilized soil. IBP-stabilized soils also showed a significant increase in UCS with increasing curing periods and IBP content. The specific gravity of IBP was found to have a major influence on the compaction behaviour: for IBP with a high specific gravity, MDD was found to increase, while for IBP with a low specific gravity, MDD was reduced. Based on the experimental results, the optimum dosage of industrial by-products was found to be around 5–15%.

2. Synthetic polymers and biopolymers share some common stabilization mechanisms due to the similarities in their physico-chemical properties. The addition of these polymers to the soil-matrix triggers cation exchange reactions between the charged polymers and clay minerals. Both cationic and anionic-type polymers were found to be involved in this electrostatic interaction and form strong chemical bonds with soil particles. Most of the biopolymers (xanthan gum, guar gum, and pectin) were found to increase the plasticity of soil by increasing the liquid limit considerably. Still, they were found to be effective in reducing the swelling potential of soils with a high clay content. When added to expansive soils, certain synthetic polymers, like urea formaldehyde and vinyl copolymer, had a better effect than biopolymers on reducing the swelling potential and swelling pressure of the soil. The inclusion of xanthan gum has been found to increase the UCS of a wide variety of soils, with the optimum dosage mostly lying in the range of 1–2%. Synthetic polymers and biopolymers have opposite effects on the compaction characteristics of expansive soils. Synthetic polymers were found to increase the MDD, while biopolymers have mostly reduced it.
3. Polymerization of a binder material (mostly an industrial by-product) with alkali activators results in the formation of geopolymers. Geopolymer gels, on addition to the soil-matrix, fill up the micro-voids between particles, thereby reducing the porosity and increasing the density. Also, based on the binder material, geopolymers undergo ion exchange reactions with clay minerals and form cementitious compounds that provide additional mechanical strength to expansive soil. Hence, they were found to perform exceedingly well in reducing the plasticity and swelling-shrinkage strain of expansive soils. An increase in UCS was found to be better when compared to IBP-stabilized soil. GGBS, metakaolin, and bagasse-ash-based geopolymers at an optimum dosage of 5–10% are some of the noteworthy stabilizers to improve the engineering properties of expansive soils.
4. Enzymes are non-toxic, biodegradable compounds that act as catalysts for chemical reactions in all living organisms. Their eco-friendly chemical characteristics make them a great choice for expansive soil stabilization. With the available laboratory test results in the literature, they are found to reduce swell potential and increase the UCS of soil significantly at a very minimal dosage. It is found to have a minimal impact on modifying the plasticity of soil. Still, its influence on many other geotechnical properties (e.g., permeability, shrinkage strain, swelling pressure, and shear strength) remains largely unexplored. Also, different researchers have provided varying reasons for the stabilization mechanism of enzymes in soil.

Considering the aforementioned, industrial by-products, synthetic polymers, biopolymers, geopolymers, and enzymes, all have great potential for sustainable stabilization of expansive soils, more specifically in reducing their swell–shrink behaviour. However, further research is needed to overcome the various challenges mentioned earlier for successful field implementation.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest with this publication.

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