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Review article

Enhancing the properties of swelling soils with lime, fly ash, and expanded polystyrene -A review

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ABSTRACT

This paper discusses efforts made by past researchers to steady the expansive (problematic) soils using mechanical and chemical techniques - specifically with EPS beads, lime and fly ash. Administering swelling of problematic soils is critical for civil engineers to prevent structural distress. This paper summarizes studies on reduction of swelling potential using EPS, lime and fly ash individually. Chemical stabilization with lime and fly ash are conventional methods for expansive soil stabilization, with known merits and demerits. This paper explores the suitability of different materials under various conditions and stabilization mechanisms, including cation exchange, flocculation, and pozzolanic reactions. The degree of stabilization is influenced by various factors such as the type and amount of additives, soil mineralogy, curing temperature, moisture content during molding, and the presence of nano-silica, organic matter, and sulfates. Additionally, expanded polystyrene (EPS) improves structural integrity by compressing when surrounded clay swells, reducing overall swelling. Thus, EPS addresses limitations of chemicals by mechanical means. Combining EPS, lime and fly ash creates a customized system promoting efficient, long-lasting, cost-effective and eco-friendly soil stabilization. Chemicals address EPS limitations like poor stabilization. This paper benefits civil engineers seeking to control expansive soil swelling and prevent structural distress. It indicates potential of an EPS-lime-fly ash system and concludes by identifying research gaps for further work on such combinatorial stabilizer systems.

1. Introduction

Expansive and unsaturated soil, commonly known as swelling soil, has long been a concern due to its potential to damage structures built on top of it. Expansive soils are influenced by their soil science, particularly the composition of minerals and the interaction between clay and water [1,2]. Many expansive soils consist of smectite minerals, specifically dioctahedral Montmorillonite minerals. These minerals exhibit hygroscopic behavior, expanding upon contact with water and contracting and fracturing with desiccation. The soils undergo significant volumetric changes, exceeding 10 %. These substantial volume changes lead to differential movements, resulting in surface fractures that can ultimately damage foundations. This is particularly concerning for lightweight civil works such as expressway foundations and single-story structures. Yearly repairs to address foundation issues come with a hefty price tag, making them a global concern because of the widespread availability of expansive soils [3]. Such type of soil can be stabilized by the use of various stabilizers present in society/environment, out of which few can be noted down as expanded polystyrene, cement, lime,

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fly-ash, brick dust, fibers, organic matters etc. In addition to these stabilizers, waste iron tailings with cement-based inorganic binders have also been explored as an economical and sustainable highway engineering base material, with the potential to reduce iron tailings inventory and promote engineering applications [4]. Enhancing soil stability by employing mechanical techniques necessitates the utilization of fibrous substances. There is a wide range of materials available, including geosynthetics like geogrid, geotextile, geo-composite, geonet, and geocell, as well as independently dispersed fibers made from natural or synthetic sources [5]. Various types of natural and synthetic fibers have been utilized to reinforce expansive soils in different dosages and lengths. These include coir fiber, coir pith, sisal fiber, palm fiber, jute fiber, flax fiber, barley straw fiber, polypropylene fiber, carpet waste fiber, waste rubber fiber, polyester fiber, glass fiber, polyethylene fiber, and polyvinyl alcohol fiber [6–17]. Including of 20–40 % of compost material to the expansive soil shows better strength acquisition which went vice versa when the percentage was increased [18].

Chemical stabilization techniques have been extensively employed for enhancing the structural properties of various soils and aggregates. Lime, in particular, has emerged as one of the most ancient and highly regarded chemicals in this regard. Its widespread application and recognition further validate its effectiveness in achieving structural improvement. The neutralization of electrical imbalance in soil particles through the inclusion of lime involves the introduction of suitable ions [19]. The relationship between reduced soil plasticity and enhanced workability is well-documented, leading to notable improvements in both compressive strength and the capacity to bear loads. Another study focused on expansive soil from Nossa Senhora do Socorro, Sergipe, Brazil, the addition of 9 % lime resulted in a remarkable decrease in swell pressure by 88 % and free swell by 97 % [20]. Lime stabilization has emerged as a widely adopted technique in various construction projects, including highways, railroads, and airports, to enhance the performance of roadbeds and support layers of pavement. According to Ref. [21], the utilization of this technique has been observed to enhance the characteristics of both soft soils and dredged soils. Lime stabilization finds various specific applications in the field of construction. These applications involve the utilization of lime in various construction projects, such as strengthening soil beneath foundation slabs, building lime columns, and enhancing construction embankments [22]. [23] Performing a leaching cycle on chemically treated soils showed that clays with a high percentage of montmorillonite and a high plasticity index require a higher dosage percentage, as the lower percentage failed the leaching tests. Nevertheless, it is important to acknowledge that lime stabilization methods do possess certain limitations. The impact of leaching on lime stabilization methods is a significant factor to consider. According to Refs. [3,24], it was discovered that the swelling and plasticity index returned to levels comparable to those observed in untreated natural soils. In project sites where there is a need for significant strength improvements or when encountering granular deposits, it is not advisable to utilize these materials due to their lack of suitability. The lack of significant friction and cohesion in lime is the primary reason for this phenomenon. According to previous studies, it has been observed that there is a lack of strength gain in soils beyond a certain percentage of lime addition. According to Ref. [25] it has been observed that granular soils lack cations that can be substituted by lime ions. In addition, the result was noted that the utilization of lime in soils with high sulfate content can result to the occurrence of issues related to distress. The aggregation of ettringite as well its subsequent result on roads and structures has led to a phenomenon that is often referred to as a “roller coaster” effect [26,27]. Moreover, the inclusion of quick lime poses a potential risk to health and safety. Despite the limitations, lime remains the predominant chemical stabilizer employed for the treatment of expansive soils. Therefore, knowledge of proper dosage and type of soil is a must in such cases. Due to the environmental impact of greenhouse gas emissions during cement/lime production, there has been a growing interest in finding different substances that can substitute cement. These alternatives include agricultural wastes, pozzolanic minerals, and by-products from various industrial processes. This global trend focuses on reducing the harmful effects of cement production. There is a growing fascination with using waste or mineral materials to address greenhouse gas emissions, natural resource consumption, energy usage, and construction material costs [28].

Fly-Ash is another most common soil stabilizer worldwide. The research conducted by Refs. [29,30] highlights the potential stabilizing effects that can be achieved by incorporating fly ash into soil. These effects may be attributed to a pair of different kinds of reactions: quick or immediate reactions and over time reactions. The initial reactions lead to the origination of larger lump as the clay particles come in conjunction and exchange ions at the soil particle surface. This process enhances the workability properties of soils and leads to immediate enhancements in swell, shrinkage, and plasticity characteristics. The acquisition of additional strength can be achieved over time by the formation of cementitious materials [31]. Past research shows how Fly-Ash (FA) can efficiently decrease soil swelling while maintaining its structural integrity. Nevertheless, it may lack the necessary durability for roads that have finer layers of foundation and top materials, such as asphalt or concrete. This has the potential to significantly impact the overall construction costs [32,33].

[34] aimed to investigate the long-span stability of soft and problematic soil after being treated with numerous contents of Class C Fly-Ash (5 %, 10 %, as well 20 %). Furthermore, the influence of freeze-thaw cycles on the plasticity of soil was observed to be marginal, whereas a notable decrease in compressive strength was seen after several freeze-thaw cycles. Notably, the unconfined compressive strength (UCS) of soil treated with fly ash exhibited a threefold increase compared to untreated soil specimens [35]. found that for optimal long-term performance, the application of lime alongside FA (LFA) is more favorable than cement for stability purposes. The rate at which lime and fly ash react is comparatively slower when compared to the reaction rate of soil and cement. As a result, the subgrade stabilized with LFA gains strength over time and has a low risk of developing shrinkage cracks. Additionally, the self-repairing capability of pavements stabilized with Lime Fly Ash (LFA) mixtures is attributed to the continuous chemical interactions within the LFA compositions [36]. Addition of lime to a soil-FA blend, the liquid limit drops right away. However, after curing, it is observed to increase due to the process of flocculation.

Recent studies have explored the potential of expanded polystyrene (EPS) also known as thermocol in daily life as an innovative and rapidly spreading mechanical stabilizer for geotechnical engineering applications [37]. EPS beads are lightweight, spherical particles made from expanded polystyrene. They are produced by heating polystyrene beads containing a blowing agent, resulting in a closed-cell structure with low density and excellent insulation properties. EPS beads are widely used in construction, particularly as a lightweight aggregate in concrete and soil stabilization, due to their ability to reduce density, improve thermal insulation, and enhance drainage. The beads' versatility and unique properties also make them popular in packaging, insulation, and various consumer goods. EPS is valued for properties including light weight, low density, high compressibility, chemical and water resistance, suitable mechanical strength, and ease of construction use [38,39]. Prior research has investigated EPS blocks for stabilizing earthworks, with findings showing versatility across projects like compressible inclusions [40–42], durable embankments and pavements [38,39], mitigating problematic swelling subsoils [43,44], and reducing lateral pressures on retaining walls [40,45]. EPS applications have also been studied to address slope stability challenges in sandy soils [39,46].

While advantageous, EPS block use has limitations including lack of on-site fabrication demanding transport, uniform shapes poorly fitting irregular volumes, and difficulty adjusting properties to site conditions. An alternative approach utilizes mixtures combining soil with EPS beads as lightweight fill [47,48]. Prior testing found that crushed and heated EPS beads can reduce soil weight while increasing shear strength and permeability [49]. Cyclic triaxial experiments by Ref. [50] determined dynamic shear strength rises for cemented soil-EPS blends as stress increases. Cemented EPS soils also shared the same static and cyclic loading failure points. Though EPS-soil composite research has emphasized static loading scenarios, comprehensive dynamic parameter evaluation through cyclic or seismic loading tests is crucial for understanding total performance [41].

Lime and fly ash are widely used chemical stabilizers that have been extensively studied for their ability to improve the engineering properties of expansive soils. Lime stabilization is recognized for its effectiveness in reducing soil plasticity, increasing strength, and enhancing workability [19–22]. However, limitations such as leaching effects, lack of strength gain in certain soils, and potential health and safety risks have led to the exploration of alternative stabilizers [25–27].

Fly ash, a byproduct of coal combustion, has emerged as another common soil stabilizer worldwide. The stabilizing effects of fly ash on soil can be attributed to immediate reactions, such as flocculation and ion exchange, and long-term reactions, such as the formation of cementitious materials [29.30,31]. While fly ash can effectively reduce soil swelling, it may lack the necessary durability for roads with finer layers of foundation and top materials [32,33].

EPS beads, on the other hand, have gained attention as an innovative mechanical stabilizer for expansive soils. EPS is lightweight, compressible, chemically inert, and water-resistant, making it suitable for various geotechnical applications [37–39]. Moreover, the use of EPS beads can help reduce the environmental impact of EPS waste by recycling and reusing the material in soil stabilization [51,52].

While other materials such as cement, slag, and organic matter are also used in the solidification treatment of expansive soils, the authors chose to focus on lime, fly ash, and EPS due to their specific advantages and the need to explore alternative stabilizers that can address the limitations of traditional methods. Cement stabilization, for example, may lead to cracking due to high temperature and can be gradually removed from soils by water [27]. Lime stabilization, despite its effectiveness, can partially lose its favorable impact on soils due to cyclic wetting and drying [53]. By discussing lime, fly ash, and EPS, the present study aims to provide a comprehensive review of traditional chemical stabilizers and an innovative mechanical stabilizer, highlighting their potential for expansive soil stabilization while addressing the need for sustainable and environmentally friendly solutions.

The purpose of this review paper is to comprehensively examine the effects of expanded polystyrene (EPS), lime, and fly ash on the stabilization of expansive soils. The primary objectives are to discuss the individual effects of EPS, lime, and fly ash on the properties of expansive soils, explore the potential of combining these stabilizers for enhanced soil stabilization and identify research gaps and future directions in the field of expansive soil stabilization using EPS, lime, and fly ash.

By addressing these objectives, this review paper seeks to provide valuable insights for the development of effective and sustainable solutions for expansive soil stabilization. The significance of this research lies in its potential to contribute to the understanding of innovative stabilization methods and their applications in geotechnical engineering, ultimately leading to improved construction practices and reduced costs associated with expansive soil-related damages.

2. Characterization of expansive soil

2.1. Mechanics of swelling

Clay particles have a plate-like shape and a negative charge, which causes them to adsorb cations through isomorphous substitution. This process results in an overall negative charge for clay minerals. Cations become strongly attached to the clay surface through electrostatic force. The cation concentration is highest on the surface of the particle and drops as the distance from the particle surface increases. The cations and anions, along with water in the saturated state, form the diffused double layer (DDL). Clay is inherently negatively charged, and the equilibrium of positively charged ions on the surface of clay is maintained through the presence of exchangeable cations. However, due to the suspended clay, the cations tend to disperse from the clay surface and migrate into the surrounding liquid to balance the concentration disparity between the surface and the overall liquid phase. Nevertheless, a significant number of these ions, particularly those near the clay surface, have limited mobility due to the intense attraction resulting from the presence of a negative charge on the surface of the clay. The cations come together at the interface, creating an electric double layer that can have a thickness ranging from 50 to 300 Å [54,55].

As per [56], when clay particles come close together, repulsion occurs, preventing aggregate formation. This maintains suspension stability and prevents flocculation. The diffuse counterion atmospheres of the particles interfere with each other, creating repulsive energy. The size of the double layer regulates the repulsive potential. As the particles move apart, repulsion diminishes exponentially. van der Waals attraction occurs when particles are in close proximity but diminishes as they move apart. When particles are less than 20 Å apart, van der Waals force leads to clay particle aggregation and floc formation. Low electrolyte concentration leads to strong repulsion, while high concentration can lead to rapid coagulation or flocculation.

Clay structure- Isomorphous substitution taking place in a clay also depends upon the clay structure which is one of the important aspects which can't be left untouched by a researcher in-order to understand how the exchange of cation takes place and how the clay remains negative after the exchanging of cation is done which ultimately affects the swelling of soil. Clay minerals are classified as types 1:1 or 2:1 based on their layered structure. A clay mineral particle consists of individual layers composed of either one or two tetrahedral silicate (Si–O) sheets and one sheet of octahedral metal oxide/hydroxide (M-OH/M-O-H). A 1:1-type clay mineral consists of one tetrahedral sheet and one octahedral sheet. Kaolinite, serpentine, and halloysite are examples of clay with a 1:1-type structure. A clay mineral of the 2:1 type is characterized by an octahedral structure that is sandwiched between two tetrahedral silicate structures.

Diffuse double layer- DDL occurs when the soil is moist. When cations become adsorbed, they may attempt to move away from the surface as a result of their higher concentration near the surface. This movement is caused by Brownian motion. The phenomenon of Brownian movement can be described as the rapid and random motion exhibited by tiny particles. The cations in question attempt to disperse as a result of their random motion, which is when the diffuse double layer becomes relevant.

What is the reason behind this? The diffusive force, combined with the electrostatic forces from the negatively charged clay surface, leads to the dispersion of cations in the vicinity of the clay surface, forming a cloud-like distribution. The distribution of cations resembles the way air is distributed in the atmosphere, with the force of gravity preventing air from escaping into space. The "diffused double layer" refers to the combination of the charged clay layer as well as the scattered charge in the surrounding phase. The first layer consists of a surface with a negative charge, while the second layer contains distributed charges. The diffuse double layer consists of (i) Permanent negative charge of clay. (ii) Cations, which are diffused in soil solution that balances the negative charge of clay. (iii) The innermost film, which is tightly bound by clay, is referred to as the stern layer. (iv) The water present in this stern layer is referred to as adsorbed water and possesses a higher viscosity compared to free water. The layer that extends from the stern layer far from the clay surface is referred to as the diffuse layer. Diffused layer is a layer beyond stern layer which is diffused due to combined electrostatic force and diffusive force. There are three DDL models – Helmholtz model, Gou-Chapman model and Stern model. The Helmholtz model posits that counter ions are confined to a stationary layer situated between the clay surface and the soil solution. In contrast, the Gou-Chapman model suggests that the thermal energy of cations creates a diffuse double layer, resulting in an increase in concentration that leads to a state of optimum entropy or diffuse double layer. The Stern model is a composite of the two aforementioned models, consisting of a stiff zone next to the mineral surface and a diffuse layer connecting to the bulk solution. DDL thickness can be determined by the Boltzmann Equation which claims by the help of this relationship that there seems the direct influence of DDL on the expansion characteristics of expansive clays -

$$x = \frac{1}{k} = \left(\frac{\in_0 DkT}{2n_0 e^2 v^2}\right)^{1/2}$$

where x = count of thickness of diffused double layer, K = DDL parameter, $\in_0$ = permittivity on vacuum, k = Boltzmann constant, T = temperature, D = dielectric constant of bulk fluid, e = electronic charge, n_0 = ionic concentration, lastly v = valence of exchangeable cations [2]. assured the confirmation of achieving the swell potential as well the swell strains by the help of DDL swell prediction model and concluded with direct proportionality between the swell potential and swell strains.

Expansion in the soil occurs due to water retention occurring in soil matrix, which may occur due to capillary, osmotic and

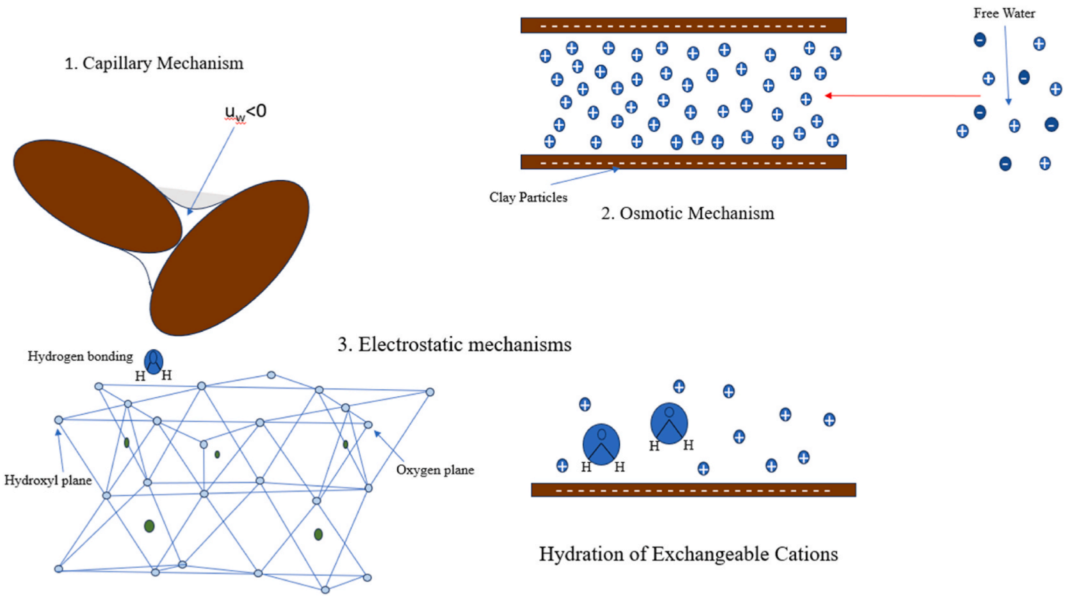

Fig. 1. Water retention mechanism related to the soil matrix (sourced by Ref. [57]).

electrostatic mechanism [57]. explained the mechanism better by Fig. 1 These mechanisms have been detailed up further in the paper.

2.2. Clay mineral identification

Various methods exist for identifying clay minerals within the ground, and a few of them are described below:

1. X-Ray diffraction (XRD)

X-ray diffraction (XRD) is a powerful technique for identifying and characterizing clay minerals, which are crystalline and have a repeating long-range structure [58]. XRD can be used to identify the mineralogical composition of clay minerals, including quartz, feldspar, and kaolinite [59] and to quantify mineral contents in different clays [60]. It has also been used to determine the mineralogy of residual clays, identifying kaolinite and nontronite as the major clay minerals [61]. XRD is particularly useful for clay minerals due to their layered structure and the presence of hydrogen bonding among the hydroxide ions of the octahedral sheet. The quantitative composition of a binary system can be calculated from the intensity ratio of the strongest diffraction scan [62], suggesting that the XRD method can be derived from the intensity ratios of the diffraction peaks of clay minerals. XRD patterns reveal the presence of different clay minerals based on their characteristic peak positions, shapes, and intensities, allowing for the identification and quantification of the proportions of different clay minerals in a sample [63–66]. The powder diffraction method is commonly used for studying clay minerals in soils due to the small size of clay particles [58]. XRD has been successfully employed to identify compounds formed when soil is treated with lime [67] and to measure clay mineral composition and smectite contents in swelling soils [68], making it a valuable tool for quickly and economically identifying expansive soils and their clay content.

2. Thermal analysis (TA)

Thermal analysis (TA) is a powerful technique for identifying and characterizing clay minerals based on their unique thermal reactions, such as dehydration, dehydroxylation, and phase transformations. The most common methods used in TA are thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). TGA measures the weight change of a sample as a function of temperature or time, while DSC measures the heat flow needed to maintain the same temperature between the sample and an inert reference material. The temperature and pattern of dehydroxylation in clay minerals, particularly in smectites, are influenced by factors such as octahedral occupancy, the type of octahedral cations, and the layer charge. Other thermal reactions, such as dehydrogenation in Fe(II)-bearing smectites and phase transformations at high temperatures, can provide valuable information about the composition and structure of clay minerals. Thermal analysis, in combination with evolved gas analysis techniques, has been widely used by researchers to identify and characterize clay minerals in soils [69,70].

3. X-Ray absorbance spectroscopy (XAS)

X-ray absorption spectroscopy (XAS) can be derived from various components of clay minerals, including iron (Fe), silicon (Si), magnesium (Mg), aluminum (Al), and calcium (Ca) [71–74]. XAS is a powerful technique that provides insights into the electronic structure, chemical environment, oxidation state, and coordination of specific atoms within clay minerals [73]. It has been extensively used to study the mineralogical composition, structure, and properties of clays, as well as their interactions with other materials like polymers [71–73]. Recent studies have employed XAS to characterize soils derived from basalt parent materials [71], investigate the fate of silicon in tropical agricultural soil clays using X-ray absorption near-edge structure (XANES) spectroscopy [72], and probe the structure of intercalated poly(aniline) in clay minerals [73]. XAS's ability to analyze heterogeneous samples, including whole soils and liquids, non-destructively and without long-range crystalline order requirements, makes it a versatile and valuable technique for studying clay minerals [64].

4. Scanning electron microscopy (SEM)

The scanning electron microscopy (SEM) technique can derive valuable information from the various components present in clay minerals. SEM enables the examination of the microstructural characteristics and morphological features of clay particles, such as kaolinite, montmorillonite, and illite [75]. Its high-resolution imaging capabilities facilitate the observation of the size, shape, and arrangement of these clay mineral constituents [76,77]. Moreover, SEM analysis can reveal the interactions between clay minerals and additive materials employed for soil improvement purposes, including lime, cement, fly ash, and industrial waste products [78,79]. The SEM images can provide visual evidence of the formation of new compounds, such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C-A-H), resulting from the pozzolanic reactions between clay minerals and additives [80,81]. Additionally, SEM analysis can be coupled with energy-dispersive X-ray spectroscopy (EDS) to obtain information about the elemental composition, allowing for the identification of specific mineral phases present in the clay samples [82,83].

2.3. Clay mineral quantification

The chemical properties of soil which helps to know about the influencing clay mineral can be determined by few of techniques enlisted blow-

1. Cation Exchange Capacity
2. Specific Surface Area
3. Total Potassium

Cation Exchange Capacity- The cation exchange capacity (CEC) of a soil measures the amount of readily interchangeable cations that balance out the soil's negativity. As per [84], Cation Exchange Capacity (CEC) refers to the total amount of negatively charged ions present on the outermost layers of clay and organic matter in soil. The presence of negative charges enables the attraction of positively charged ions or cations, which is why it is referred to as "cation exchange capability". Usually, soil CEC is denoted as the charge per unit weight of soil. Meq/100 g and $cmol_c$/kg are two different sets of units that have the same numerical value. CEC is a reliable indication of the chemical reactivity of soils. The soil's negative charges are derived by the sources and chemical processes mentioned ahead [85]:

a) Isomorphous replacement within layer silicate mineral structures.
b) Fractured links at the boundaries of minerals and outer surfaces.
c) Dissociation of acidic functional groups in organic compounds.
d) Selective binding of certain ions to particle surfaces.

There are various ways for estimating CEC, and many of them produce findings that vary considerably. According to Ref. [85], the summing method is a viable approach to calculate CEC. The cation exchange capacity (CEC) is calculated by calculating the total equivalent of exchangeable cations in the resulting "leachate" after replacing them with a saturated salt solution. In this process, the soil is completely saturated with a certain cation. Subsequently, the cation and the residual solution in the soil are replaced with a different salt solution, without requiring any more steps for the soil. The extract's cation and anion concentrations are computed, and the disparity between them is used to ascertain the soil's CEC.

Specific Surface Area (SSA)- SSA of a soil sample is the ratio of its entire surface area to its mass. Soils possessing a substantial specific surface area exhibit the capacity to retain a considerable quantity of water, efficiently absorb contaminants, and have an increased propensity for swelling. Therefore, surface type is an essential factor. The relationship between surface area and particle size distribution is tight [86]. Illustrate this process by conducting a straightforward mental exercise involving a 1 cm^3 cube with a density of 1 g/cm3. The cube has a specific surface area of 6 cm^2/g. When the cube is subdivided into tiny cubes measuring 1 mm on each side, the resulting 1000 cubes will possess an equivalent quantity of material. However, their specific surface area will be 60 cm^2/g. Similarly, if the cube were partitioned into 1012 cubes measuring 1 μm on each side, the total surface area would amount to 6 × 104 cm^2 per gram. Hence, the presence of smaller particles inside a given mass inevitably results to an increased specific surface area. A soil possessing a substantial specific surface area has an elevated capacity to retain water and a greater propensity for swelling. Soil water retention curve method provides a realistic values of specific surface area for the shell available to water [87].

At later stage [88] stated that SSA can basically be categorized in two parts external and internal where the researcher concluded that augmented Brunauer-Emmett-Teller (BET) equation can be modified to BET equation which will ultimately describe about the adsorption of external surface in a more accurate manner. Comprehensive research has demonstrated that the engineering characteristics of soils with small particles are significantly impacted by a specific element known as the specific surface area. This component has been identified as a fundamental determinant of soil behavior, as substantiated by extensive evidence in the literature. Several studies have demonstrated a strong association between the particular surface area of soil and its propensity to expand (e.g. Refs. [89–92]).

Total Potassium (TP)- The element used to identify the existence of the mineral illite is found to be as Potassium. As per periodic table, potassium is classified as an alkali metal due to its possession of one electron in the outermost layer. The formation of monovalent ions takes place due to the easily loss of electrons [93]. Several procedures are present in-order to analyze potassium levels in soils, although one developed by Ref. [93] which is broadly preferred and commonly employed. Illite, a clay mineral, contains potassium as its interlayer cation, distinguishing it from other minerals [56]. As a result, by measuring the amount of potassium ion in the soil, we can determine the presence of the mineral Illite. This technique employs a dual acid digestion procedure devised by Jackson [94], which entails the utilization of a couple of acids, hydrofluoric acid and perchloric acid, to disintegrate the mineral content of soil and extract the potassium ions. The content of potassium in the solution can be determined using a spectrophotometer or a suitable equipment after the process of extracting it. The concentration of potassium in the solution can be measured using a spectrophotometer or a suitable equipment after the extraction process.

2.4. Classification of problematic (expansive) soil

Such soil is classified with the help of the Free Swell Ratio (FSR), as there are more ways too. The free swell ratio refers to the proportion of the sediment amount of 10 g of soil that passes through a 425 mm screen after being dried in an oven and then immersed in fluid, compared to the volume in carbon tetrachloride/kerosene [95]. However, due to the composition of certain non-expandable and expansive soils, this is not always the case. The free swell ratio of kaolinitic clay material and montmorillonite is 0.4. The cone method liquid limit test was conducted using water and carbon tetrachloride for pore fluids to investigate the impact of clay mineral. The reason for this is the lack of polarity in carbon tetrachloride, which hinders the formation of the DDL and enables the formation of flocs. As a result, the liquid limit values of soils containing a significant amount of kaolinitic material increase [96]. Table .1 [97] describes FSR in a better way-

FSR in other words is the natural raise in soil amount unaccompanied to any outer or third-party stress as the soil gets flooded with fluid. It can be calculated as –

$$FSR = \frac{V_d - V_k}{V_k}$$

Vd and Vk represent the amount of a 10 g dirt specimen that has been dried in an oven and then passed through a 425-mm sieve. The specimen is then soaked in distilled water and kerosene oil for a period of 24 h. Soils having a Free Swell Index (FSR) of 1.5 or more are categorized as swelling soils. Additional essential laboratory tests for determining the engineering qualities of problematic soils include Atterberg's limits, compaction characteristics, and strength behavior (UCS and CBR) as outlined in Table 2 [97].

3. Soil stabilization

Soil modification is the predominant method for enhancing the geotechnical characteristics of weak and expansive soils through the use of stabilizing agents such as lime, cement, etc. This process is mostly used in typical engineering applications, such as sub-level or sub-base construction material in roads, railways, pavements, foundations, embankments, etc. This technique involves mixing many waste products with pozzolanic qualities with soil that lacks strength. The evaluation of various additives such as lime, EPS, concrete, sand, residues, and so on. Past scholars have made attempts at soil stabilization. Considering the cost factor, materials with no value are preferred. Mechanical stabilization involves the use of compaction, reinforcing, and the addition of aggregate materials. Chemical stabilization involves modifying the synthetic characteristics of soil structure using methods such as heating, employing polymers, introducing catalysts, or incorporating synthetic additives like lime, detritus, and Portland cement. The study of stabilization examines how additives affect the reaction mechanism, strength, moisture content, and provides recommendations for construction systems. There are multiple techniques available for soil stabilization. These approaches can be classified into two primary categories: mechanical stabilization and chemical stabilization. Mechanical stabilization refers to enhancing the characteristics of soil by altering its gradation, while chemical stabilization of expansive soil involves modifying the physico-synthetic properties of clay particles to reduce the amount of water needed to achieve static balance and impede water movement through the framework. This is done to facilitate specific road construction projects. Some more stabilization techniques can be listed as thermal stabilization, electrical stabilization and bituminous stabilization. Few other methods for soil stabilization are mentioned in Fig. 2.

3.1. Interplay and relative importance of factors influencing stabilization

The effectiveness of calcium-based chemical additives, such as lime and fly ash, in stabilizing expansive soils, is influenced by a complex interplay of multiple factors. Understanding the relative importance of these factors and their interactions is crucial for optimizing the stabilization process and achieving the desired soil properties.

Soil mineralogy and type play a significant role in determining the optimum amount of additive required for effective stabilization. Soils with higher clay content and specific surface area, such as montmorillonitic clays, typically require higher dosages of lime or fly ash than kaolinitic clays [98,99]. The presence of organic matter or sulfates in the soil can also hinder the stabilization process, even when other factors are favorable. Organic matter can adsorb calcium ions and reduce their availability for pozzolanic reactions [100], while sulfates can lead to the formation of expansive minerals like ettringite, causing swelling and damage to the stabilized soil [101].

The curing conditions, including temperature and duration, significantly influence the strength development and long-term performance of stabilized soils. Higher curing temperatures accelerate the pozzolanic reactions and lead to faster strength gain (102, 103). However, the optimum curing temperature and duration may vary depending on the soil type and additive used. Compaction delay can also affect the stabilization process, as forming cementitious bonds before compaction can hinder the achievement of the desired density and strength [100].

The water content of the soil during mixing and compaction is another critical factor influencing the effectiveness of stabilization. Excessive water content can dilute the additive and reduce its reactivity, while insufficient water content may hinder the hydration and pozzolanic reactions [100]. The optimum water content for stabilization depends on the soil type, additive used, and the desired properties of the stabilized soil.

The pH of the soil matrix also plays a significant role in the stabilization process. A high pH environment ($pH > 12$) is necessary for the dissolution of silica and alumina from the clay particles and their subsequent reaction with calcium ions to form cementitious compounds [100]. The presence of acidic substances, such as organic matter or sulfuric acid, can lower the pH and hinder the stabilization process [102].

Table 1
Overview of the classification of expansive soil [97].

Free Swell Ratio	Type of Soil	Degree of Expansiveness
<1	Non-Swelling	Negligible
1–1.5	Medium swelling	Low
1.5–2	Swelling	Medium
2–4	Swelling	High
>4	Swelling	Very high

Table 2
Overview on degree of expansiveness as per Atterberg's limit [97].

Degree of expansiveness	Liquid Limit %	Plastic Limit %	Shrinkage Limit %
Low	0–50	0–35	>17
Medium	40–60	25–50	8–18
High	50–75	35–65	6–12
Very High	>60	>45	<10

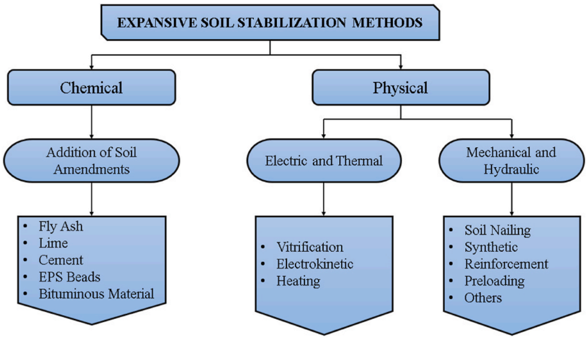

Fig. 2. Methods used in stabilization of expansive soil.

In summary, the effectiveness of calcium-based chemical additives in stabilizing expansive soils is influenced by a complex interplay of factors, including soil mineralogy and type, presence of deleterious substances, curing conditions, compaction delay, water content, and pH of the soil matrix. Understanding the relative importance of these factors and their interactions is crucial for optimizing the stabilization process and achieving the desired soil properties. Future research should focus on developing comprehensive models that consider the interplay of these factors and provide guidance for the selection and application of appropriate stabilizers based on site-specific conditions.

4. Lime

Limestone undergoes a process at higher temperatures that leads to the production of lime. When water, alumina, soluble silica, and lime are present in clay, a chemical reaction is initiated, creating distinct compounds. The primary purpose of adding water is to alter the particle composition and increase their resistance to shrink-swell and hygroscopic effects. The combination of particles, especially with clay, can have an additional impact on strength development due to the elevated concentration of electrolytes in the pore water and the interchange of cations between clay minerals and Ca^{2+} ions [103]. This allows for enduring pozzolanic reactions and the creation of cement-based substances. Three varieties of lime are employed to enhance soil parameters: hydrated lime ($Ca(OH)_2$), hydrated lime slurry, and quicklime (CaO). Quicklime and hydrated lime are widely used for soil stabilization due to their ability to produce sufficient calcium ions.

CaO has a higher reactivity compared to $Ca(OH)_2$ due to its smaller crystal size, lower apparent density, larger specific surface area, and narrower insulated pores [104]. The heat generated during the hydration of quicklime significantly decreases the soil's moisture content by around 32 % of the lime's weight and speeds up the pozzolanic reactions [100,105]. The fresh hydration product ($Ca(OH)_2$) has a higher solubility and reactivity with sediment pozzolans compared to commercially available hydrated lime. As a result, the lime requirement for a specific soil is slightly lower (1–2%) when using quicklime compared to hydrated lime [106]. Quicklime's increased reactivity results in a greater amount of cementitious gel and chemical bonds, enhancing resistance to compaction and leading to higher porosity [107]. Quicklime-treated soil exhibits reduced plasticity, increased CBR, and higher unconfined compressive strength (UCS), while hydrated lime-treated soil demonstrates enhanced compressibility and maximum dry density (MDD) [108,109].

When lime is added to clay, it sets off two different chemical reactions: one that occurs quickly and another that takes place over a longer period. As per [110], the short-term reaction encompasses a range of processes including cation exchange, flocculation, agglomeration, and lime carbonation. The cation exchange process observed at the clay particle surface is believed to be a result of the interaction between lime and water, which introduces Ca^{2+} and OH^{-1} ions into the soil-lime system. That is:

$$CaO + H_2O \Rightarrow Ca(OH)_2 \text{ and } Ca(OH)_2 \Rightarrow Ca^{2+} + 2(OH^{-1}).$$

The replacement of monovalent exchangeable cations by Ca^{2+} ions on the clay particle surface changes the valence, alters the electrical charge density surrounding the particles, and decreases the thickness of the diffused double layer. This leads to the formation of flocs and agglomerates within the soil system, reducing soil swelling [111]. Additionally, hydrated lime ($Ca(OH)_2$) can react with atmospheric carbon dioxide (CO_2) to form calcite crystals ($CaCO_3$) through lime carbonation. These calcite crystals exhibit a weak linkage with the clay particles. During this stage, the utilization of lime is restricted to a finite amount, regardless of the quantity introduced. The addition of lime effectively fulfills the soil's lime requirement until it reaches the point of lime fixation. According to Ref. [112], beyond a certain threshold, adding more lime to the soil does not result in further alterations in the plastic limit.

The long-term reaction resulting from the introduction of lime exhibits pozzolanic characteristics. The dissolution of silica and alumina in clay soil occurs gradually as a consequence of the introduction of hydroxyl ions into the system [113].

The reaction between calcium present in.

$$Ca^{2+} + 2(OH^{-}) + SiO_2(\text{clay silica}) \Rightarrow CSH$$

$$Ca^{2+} + 2(OH^{-}) + Al2O_3(\text{clay alumina}) \Rightarrow CAH$$

$$Ca^{2+} + 2(OH^{-}) + SiO_2(\text{clay silica})$$

$$+ Al_2O_3(\text{clay alumina}) \Rightarrow CASH$$

The inclusion of lime, silica, and alumina aids in the formation of binding substances like calcium silica-hydrates (CSH), calcium alumina-hydrates (CAH), and calcium-alumina-silicate hydrates (CASH). These compounds facilitate the bonding of soil particles [25, 114]. [115] explored the interaction between lime and the expansive FoCa clay found in France, involving pH assessments and various additional examinations. The study encompassed curing times from 1.5 h to 90 days and lime concentrations varying from 1 % to 7 %. The findings validated the previously discussed chemical reactions. However, lime stabilization may not be suitable for all cases, especially for soils with a plasticity index (PI) greater than 10 % and when more than 25 % of the soil particles can pass through a 0.075 mm sieve [116]. [117] further elaborate on the reactions, stating that the first reaction, which occurs immediately upon lime addition, is the replacement of adsorbed ions by calcium ions. The second reaction is the formation of a series of new minerals, and the third is the carbonation of hydrated lime. Their X-ray diffraction and differential thermal analysis studies provide evidence for these reactions and explain the different rates of reaction with various soils.

[118] also discuss the reaction mechanism, suggesting that the initial rapid reaction is chemically controlled, followed by a slower second stage controlled by diffusion in the product $CaCO_3$ layer. They propose that the high activation energy for product layer diffusion and low diffusivity values are indicative of solid-state diffusion processes.

In summary, the lime-clay reaction is a complex process involving short-term cation exchange and flocculation, followed by long-term pozzolanic reactions that form cementitious compounds. The reaction rates and products vary depending on the clay mineralogy, with kaolinite reacting more readily than illite and montmorillonite. The strength gains and structural changes in the clay minerals suggest that the improvements are relatively permanent.

The influence of grain size distribution on the expansion properties and plasticity characteristics of lime-treated soils is crucial. As the lime content in soil increases, the initial expansion capacity usually decreases. However, once the lime content exceeds a certain threshold, the expansion capacity starts to increase again. Soils with finer grains have a critical lime content level of around 5 %, whereas soils with coarser grains have a level of about 9 %. In soils with larger particles, the cementitious gel caused by lime remains trapped within the empty spaces without causing expansion. The gel expands and fills the spaces between grains, resulting in noticeable swelling when the lime concentration is high enough [100].

The optimum lime content for soil stabilization can be determined by the soil-lime mixture pH test [119] and the expression depicted by Ref. [112], relating the optimum lime content (OML) for achieving maximum increment in plastic limit and the percentage of clay content:

$$OML(\%) = \frac{Clay\ Content\ \%}{35} + 1.25$$

The lime fixation point, also known as the point of lime retention, corresponds to the maximum limit of plasticity [120,121]. The minimum plasticity index indicates the ideal level of lime application [122]. The lime fixation point represents the quantity of lime needed to replace the soil's exchangeable cations with calcium [123].

The strength of the soil can be influenced by the addition of lime, but the extent of this enhancement depends on whether the lime quantity is above or below a critical point. The enhancement of soil strength is believed to be caused by the clumping together of clay particles when the soil's single-charged exchangeable cations are replaced by double-charged calcium ions. At this stage, the surplus lime undergoes chemical reactions with the soil, resulting in the formation of pozzolanic, cement-like compounds that bind together the clay particles, greatly enhancing the overall strength and stability of the soil.

[102] examined the impact of different acid contaminations (hydrochloric, phosphoric, and sulfuric acids) on the unconfined compressive strength (UCS) of Suddha soil, a silty soil. The study involved analyzing the UCS of Suddha soil samples under different acid concentrations (2.5 %, 5 %, 10 %, and 15 %) and examining the UCS of untreated samples, acid-contaminated samples, samples treated with 3 % lime after contamination, and samples where acid effects were neutralized before a 3 % lime treatment. The lime

dosage for neutralization was determined based on the acid concentration. The samples were compressed at the OMC and cured for 14 days before testing.

Acid contamination significantly diminished the UCS of Suddha soil, with a 15 % acid concentration decreasing the UCS by up to 50 % compared to its uncontaminated condition. Adding 3 % lime to the soil without prior neutralization did not significantly improve its UCS. After neutralization, the soil showed significant improvement in UCS recovery, reaching levels comparable to clean soil when treated with 3 % lime. The effectiveness of lime treatment seemed to increase as calcium sulfate was used for neutralization. The strength of Suddha soil decreased under acidic conditions due to reduced cohesion, with the weakening effect beginning at acid concentrations as low as 2.5 % and becoming more severe with higher acidity levels. The inclusion of 3 % lime in acid-affected soil did not have a significant impact on UCS due to the lack of reactive silica necessary for pozzolanic reactions at the lower pH caused by acid. However, after adding lime to neutralize the acidic soil, a significant enhancement in UCS was observed, resulting in a comparable level to that of lime-treated uncontaminated soil. These observations emphasize the negative impact of acid contamination on soil strength and suggest that lime stabilization can improve soil strength once the acidic conditions are resolved. The improvement can be attributed to the pozzolanic reaction, which necessitates a higher pH for the interaction between lime and the silica/alumina content of the soil to take place.

Adding calcium to soil reduces its dry density, and the increase in soil strength depends significantly on soil density, which mainly depends upon compaction [36]. After the addition of lime into expansive soil, a decrement in the liquid limit (LL) was noticed, with further increases in LL observed at higher lime content and curing time. This is due to the flocculation that takes place, resulting in the enhancement of water holding capacity. Initially, the LL decreases due to the decrement in the thickness of the diffuse double layer (DDL) of clay particles as the electrolyte concentration increases because of the exchange of monovalent cations by divalent cations. The same reason applies to the plastic limit, which was noticed to increase with the addition of lime, although the LL increased more after curing. Moreover, when there is less availability of soil for lime effect, a decrease in plastic limit has been noticed. Several research studies have demonstrated the effectiveness, long-lasting effects, cost-effectiveness, and eco-friendliness of using lime for soil stabilization, particularly in the context of road and pavement construction [124]. investigated the mechanical performance of lateritic soil stabilized with lime for forest road construction in Niquelândia, Brazil. The study found that adding 2 % lime content significantly improved the soil's mechanical strength and load-carrying capacity. The best results were achieved with modified compaction effort and a 28-day curing period, making the lime-stabilized soil suitable for application as a subbase material in flexible road pavements. The authors concluded that using lime-stabilized local soils is a promising and cost-effective alternative for forest road construction.

[125] provided insights into the physico-chemical and micro-mechanistic aspects of lime stabilization in low plastic clay soil. The study demonstrated that the addition of lime leads to cation exchange, flocculation, and pozzolanic reactions, resulting in the formation of cementitious compounds (CSH, CAH, CASH) that bind soil particles and enhance strength. The unconfined compressive strength (UCS) of the soil increased by 211 % with 6 % lime addition and 28 days of curing. The authors also noted that the increased strength and stiffness of lime-stabilized soil could lead to a reduction in pavement layer thickness and construction costs [126]. studied the stabilization of gypsum clay soil using lime in Bechar, Algeria. The results showed that adding 6 % lime increased the UCS of the soil by 3.23 times and the modulus of elasticity by 2.58 times compared to the untreated soil after 28 days of curing. The authors concluded that lime stabilization is an effective and economical solution for improving the geotechnical properties of problematic soils, leading to better quality and strength parameters in earthwork construction and pavement design. Furthermore [127], investigated the influence of lime on low plastic clay soil used as a subgrade. The study found that the addition of lime reduced the plasticity index, increased the optimum moisture content (OMC), and decreased the maximum dry density (MDD) of the soil. The California Bearing Ratio (CBR) and UCS values improved significantly with the addition of lime, indicating that the soil can be satisfactorily stabilized with the addition of 6 % lime.

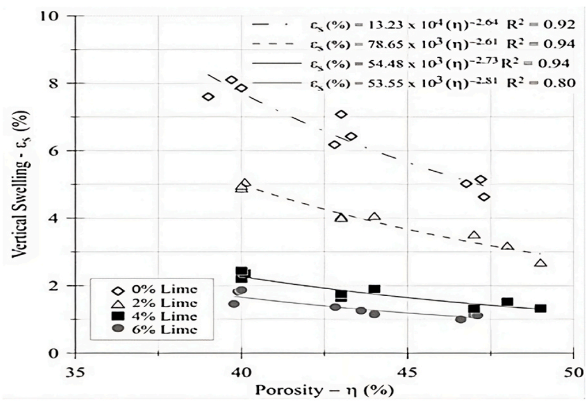

Fig. 3. Impact of porosity in 1D swelling [128].

4.1. Case study on lime treated soil

[128] investigated how 2 %, 4 %, and 6 % lime concentrations affect one-dimensional expansion of expansive soils. Soil-lime mixtures were compacted to 14, 15, and 16 kN/m^3 densities and swelling behavior evaluated after 3-h curing. Tests on compacted clay-lime combinations studied lime's impact on soil porosity and expansion ability through swelling pressure tests. The soil had LL = 49 %, PL = 21 %, OMC = 19 %, classified as highly clayey. Findings revealed decreased porosity linked to increased vertical expansion. Specimens with different lime percentages and dry unit weights were prepared. After 3-h curing, free swell tests gathered data. By Fig. 4 it can be noticed that swelling decreased with increasing lime content e.g., 0 % lime had 5–7% swelling while 6 % lime had ~1 % swelling. Swelling also decreased as dry unit weight increased due to denser packing restricting particle rearrangement (can be seen in Fig. 3). ANOVA confirmed lime content, dry unit weight, and their interaction as main factors influencing swelling. A porosity/lime index relating initial porosity and lime content was proposed. Adjusting the index with an exponent of −0.26 gave strong correlation (R^2 = 0.96) between swelling and porosity/lime index, verified using seven other studies.

The swelling decrease is attributed to clay particle clumping from cation exchange, with lime providing calcium ions displacing water between clay layers. Denser packing with higher dry unit weight restricts swelling. The porosity/lime index accounts for lime content and initial soil fabric in predicting swelling behavior, providing a rational method for estimating lime dosage to achieve target swelling reduction.

[129] investigated lime stabilization effects on a silty clay loam soil. The soil comprised 50–60 % fines with an initial high Plasticity Index (PI) of 25–35. Lime treatment significantly reduced PI to around 10 due to ion exchange. California Bearing Ratio (CBR) values showed 500–1500 % improvements through Dynamic Cone Penetrometer Test (DCPT), with variations across depth and location indicating inconsistent application quality. X-Ray Diffraction (XRD) and Thermogravimetric Analysis (TGA) confirmed lime presence in amended samples, absent in untreated samples, indicating lime retention within the treated layer. TGA revealed 1.2–17.5 % lime concentrations, frequently 5–7%. Higher lime levels generally corresponded to higher CBR values. XRD and TGA suggested uniform lime distribution within the treated layer. Treated soil pH of 10.5–12.5 was significantly higher than natural soil's pH of around 8, further confirming lime presence.

The study demonstrated lime stabilization improved soil engineering properties, resulting in higher dry density, lower plasticity, increased strength, and reduced swelling/shrinkage compared to untreated soil. Long-term treatment durability was confirmed, establishing lime stabilization as an effective viable option for soil stabilization in construction projects, especially with susceptible or unstable soil conditions.

[130] investigated lime treatment effects on compaction, strength, and stability of soils and aggregates to understand property improvements through lime stabilization. Unconfined compressive strength (UCS), tensile strength, California bearing ratio (CBR), and R-value tests evaluated strength. Natural soils showed 70–10,000 kPa UCS variability. Lime stabilization yielded typical 200–1000 %+ UCS increases over unstabilized soil, with strengths exceeding 1,000 kPa considered adequate for structural subbase/base layers. AASHTO T274 resilient modulus tests showed 10–25 times stiffness increase after lime stabilization. Back-calculated FWD tests gave 210–3,500 MPa lime-treated layer moduli versus 50–200 MPa for untreated soil. Field studies found 5–15 times higher moduli for treated versus untreated layers, increasing with curing time. Repeated load tests showed 4 times lower permanent strain accumulation after lime treatment. Soaked vs unsoaked CBR strength ratios around 0.7–0.85 indicated good durability. Lime treatment also improved freeze-thaw and wet-dry resistance. Results suggest lime addition greatly improves soils' and aggregates' structural properties through higher dry density, increased UCS, and greater CBR in treated materials, indicating stronger load-bearing capacity. Lime decreased plasticity index, lowering expansion/contraction tendency, effectively enhancing stability. Findings demonstrate lime treatment's practicality in improving load-bearing capabilities and durability, benefiting construction and infrastructure projects.

[131] evaluated how hydrated lime, Class C fly ash (CFA), and cement kiln dust (CKD) could improve clay subgrade resilient modulus (Mr) for potential pavement use. The study examined their impact on Mr in four clay subgrades through unconfined

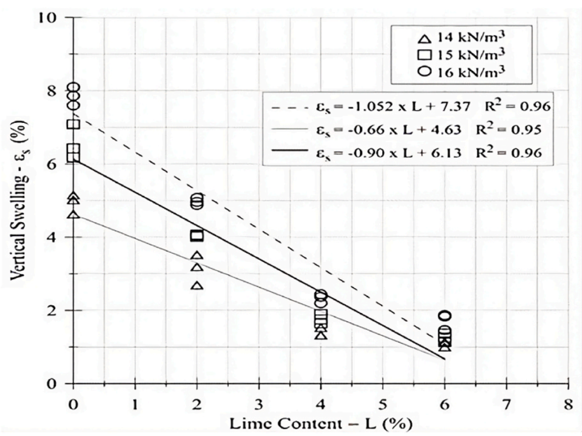

Fig. 4. Effect of Lime content in one dimensional swelling [128].

compressive strength (UCS) and Mr tests. Results showed UCS increase with stabilizing agents. Lime was most effective at 3–6% dosages, while CKD performed better at 10–15 %. Samples treated with varying lime, CFA, and CKD proportions were compacted and cured for 28 days under controlled conditions using a repeated load triaxial (RLT) apparatus for Mr determination. The study assessed stress-based models' effectiveness in predicting Mr and analyzed Mr's relationship with specimen characteristics, soil properties, and additives. Findings revealed substantial Mr increase with 3–6% lime, while CKD showed benefits at 10–15 %. A semi-logarithmic model considering deviatoric and confining stress provided accurate Mr predictions for stabilized subgrades. Mr values consistently increased with stabilizer amount until reaching a point where increments provided minimal advantages. Longer curing periods yielded higher Mr in treated subgrades. The study demonstrated lime, CFA, and CKD significantly improved clay subgrade Mr, indicating better deformation resistance and stronger pavement foundation. Results support using these stabilizers in construction projects involving clay subgrades, especially in areas prone to soil degradation or instability.

[132] investigated factors influencing lime treatment success, including lime quantity, soil composition, curing period, clay minerals, and soil pH through unconfined compressive strength (UCS), X-ray diffraction (XRD), and scanning electron microscopy (SEM) tests. The soil exhibited LL = 46.10 %, PL = 28.60 %, PI = 17.50 %, MDD = 1.58 Mg/m^3, OMC = 20.00 %, and initial UCS = 197 kPa. After 5 % phosphoric acid treatment and 8-month curing, UCS significantly increased to 1509 kPa, nearly sevenfold. XRD revealed the untreated soil mainly contained kaolinite clay, with new peaks indicating phosphate aluminate hydrate formation and reduced kaolinite intensity after acid treatment. SEM imaging showed fresh, pale, lump-like formations on acid-treated soil particles, indicating chemical reactions occurred. With 3 % acid and 8-month curing, the soil achieved 1017 kPa strength. The study found lime treatment suitable for improving Malaysian cohesive soils' physical and mechanical properties, potentially enhancing their performance and long-term durability in construction projects. The findings support lime utilization as a stabilizing agent for cohesive soils, especially in areas prone to soil degradation or instability.

[97] studied using sawdust ash (16 %) and lime (2–10 %) to improve black cotton soil characteristics. Optimal lime concentration was determined by the [119] soil-lime pH method. Combining sawdust ash and lime notably enhanced soil strength. Adding 4 % lime to the sawdust ash-clay mixture significantly improved California Bearing Ratio (CBR) by over 50 % compared to the unmixed soil. The liquid limit decreased 26.76 % with sawdust ash and further 49.15 % with lime due to cation exchange, flocculation, and agglomeration reducing soil particles' water absorption ability. Plasticity characteristics improved - plastic limit increased 8.90 % with 16 % sawdust ash and 18.49 % with 4 % lime addition, indicating easier workability and higher shear strength (aligning with Little's (1996) [119] findings). The plasticity index decreased to 28.7 % with sawdust ash and 7.4 % with lime, suggesting medium plasticity level. The study confirmed lime's potential as a stabilizing agent, improving properties like increased dry density, decreased water content, lower plasticity index, and enhanced strength (higher unconfined compressive strength and CBR) similar to Ref. [133]) observations on loess soil. Results indicate lime's effectiveness for soil stabilization in construction projects like road and embankment stabilization.

[134] found lime stabilization efficient for maintaining volumetric stability. Results indicated optimal lime percentage for volumetric stability may negatively impact repeated wetting and drying, while higher lime percentages showed positive effects on cyclic wetting and drying. Wet compaction effectively reduced swelling in clayey soil, though benefits were lost after drying-wetting cycles. Moreover [135], investigated freeze-thaw cycles' influence on the mechanical strength and permeability of high and low-plasticity clays stabilized with 6 % lime. 6 % lime initially increased hydraulic conductivity by ∼1000 times for both clays. After three freeze-thaw cycles, permeability further increased 10–20 times. High plasticity clay exhibited ∼15-fold strength increases after 28-day curing with 6 % lime, while low plasticity clay showed ∼3-fold increase. Freeze-thaw periods reduced lime-reinforced clays' strength by ∼10–15 %. Also [136], analyzed mechanical strength and shear stiffness variation in lime-stabilized clay with zeolite and EPS beads for artificially prepared soil (with different kaolinite and montmorillonite proportions) due to EPS beads. Tests included compaction, swelling pressure, UCS, and Blender Element Test.

4.2. Overview of findings confirming changes in texture, plasticity, and compaction resulting from the incorporation of lime

Lime treatment substantially impacts the soil plasticity index (PI), improving manageability through chemical reactions between lime and clay particles, related to soil mineralogy. High plasticity soils experience PI reduction and workability enhancement post-lime treatment. Extremely high PI soils (>50) can become non-plastic with lime application, supported by global studies [119,137–139].

Treatment with lime leads to a significant decrease in swell potential, with untreated soils experiencing an 8–10 % reduction, which can be further reduced to less than 0.1 % with lime treatment. The reduction in swell and plasticity index (PI) is immediate and continues to improve over time due to curing and pozzolanic reactions [139–141]. Lime-soil interaction affects the moisture-density relationship, influenced by soil properties, curing time, and lime amount. Density curves exhibit higher peaks at increased moisture content with lime, while density values are lower than without lime [139,142]. Enhanced compaction characteristics provide improved support for overlying layers, potentially addressable through resilient modulus enhancement. High PI clay exhibiting 2,600 kPa swell pressure saw a reduction to 1,700 kPa with 10 % hydrated lime, and 0 kPa after 28-day curing with 4 % lime, demonstrating lime's effectiveness in reducing expansion potential, especially with longer curing. Adding 3 % lime changed soil classification from CH to ML with decreased <2 μm particles from 56 % to 40 % without curing, 10 % after 7 days, and 2 % after 28 days, highlighting textural changes' importance for durability and strength [143]. [117] found lime-stabilized soil-maintained pH > 10 for over 3 years, indicating favorable pozzolanic reaction conditions [144]. suggested pH > 10 for 16 years post-lime stabilization, signifying potential for prolonged pozzolanic reactions and sustained plasticity modification and strength enhancement.

4.3. Summary of strength derived through lime stabilization

Numerous studies have investigated the effect of lime addition on the strength characteristics of stabilized soils [142]. found that lime can lead to immediate improvements in soil properties, including reduced plasticity and moisture retention, and improved compaction. This resulted in strength gains ranging from modest to several hundred percent. They reported many Illinois soils exhibiting unconfined compressive strengths (UCS) exceeding 700 kPa after 28 days of curing at 22 °C, and up to 4375 kPa with extended curing. AASHTO test embankment soil reached 11 MPa after 75 days of curing at 48.9 °C. Some soil-lime mixtures continued gaining strength for over 10 years under field conditions.

[117] studied the cured UCS of six mineralogically distinct soils and found that strength gain depended on both the quantity of lime added and soil mineralogy. Lime stabilization increased strengths by 200–1000 %. This highlights the importance of mixture design methods to determine optimal lime content.

Using the CALTRANS method [145], found 7-day curing at 38 °C produced comparable strength gains to 28-day curing at 23 °C for lime-stabilized California soils. Strength positively correlated with curing duration and some low plasticity soils also showed substantial improvements. All samples gained strength over 360 days, with some exceeding 10 MPa. Notable increases occurred between 180 and 360 days [146]. cured a plastic clay with 2.5–15 % lime for 180 days and observed significant strength gains from 60 to 180 days. The maximum improvement of 1100 % (11,050 kPa) was achieved at 10 % lime. Higher 15 % dosage reduced the gain, emphasizing the need to determine optimal lime content [147]. reported impressive strength results for lime stabilized Queensland black clays. Adding 8 % hydrated lime to high PI soils reduced the PI below 8 and increased 28-day strengths from 0.1 MPa to over 1.4 MPa. Cores at 26 weeks reached UCS values exceeding 4.5 MPa, indicating substantial long-term strength gain via pozzolanic reactions.

[148] studied the impact of mellowing period on ultimate strength and recommend shorter 12-h periods compared to 24 h or more. They noted significant increases in strength with lime, suggesting potential for structural applications.

[146] measured internal friction and cohesion of soils with 2.5–15 % lime over two months and found notable improvements in both parameters.

[137] observed that lime significantly enhances cohesive strength with a slight increase in internal friction. Shear strength improved considerably, even in uncured lime-soil mixtures, making lime-stabilized layers more resilient against shear failure and rutting damage. The indirect tensile strength of lime-stabilized soils was found to be approximately 0.13 times the UCS.

[140] estimates flexural tensile strength as 0.25 times the UCS. Lime incorporation in cured mixtures substantially improves UCS and consequently the tensile strengths. Tensile strength is an important consideration for evaluating shrinkage cracking and fatigue damage potential in lime-treated soils.

Several researchers, including [110,137,139,140,149–151] conducted CBR tests on uncured and cured lime-soil mixtures. They found that lime enhances the CBR of fine-grained Illinois soils, regardless of curing period and lime reactivity [137]. demonstrated significant property improvements in reactive soils with extended curing [139]. observed similar findings in soils from the southeastern, southwestern, and western US [117]. performed CBR tests on lime stabilized micaceous schist, plastic clay, and weathered granite from Virginia. Soaked CBR increased from less than 5 % to nearly 100 % following curing. XRD and SEM confirmed the presence of pozzolanic materials responsible for strength gain.

[152] modified natural clay silt soil at depths of 300 mm to 1 m and found that adding 3–4% hydrated lime increased initial CBR from 1-5% to 15–20 %. This efficient method provides a strong foundation for durable, high-quality pavements. Moreover, up to 2.5 % quicklime was also used as capping layers in Normandy. Adding 2.5 % quicklime to wet clayey silt (35–40 % moisture) effectively dried the soil and raised soaked CBR from 1.5 % to 30 % after 3 days dry and 25 days wet curing, demonstrating the potential of quicklime for soil improvement.

4.4. Overview of the properties of lime soil mixtures, specifically regarding stress-strain (stiffness) and resilience

The addition of lime to soils has been found to significantly improve their mechanical properties, particularly in terms of stress-strain behavior and stiffness [153]. reported that lime stabilization increased the resilient modulus of soil by 10 % or more and enhanced its shear strength by approximately 20 %. The stabilized soil also exhibited gradual improvement in stability over time, suggesting a natural ability to regenerate. Lime-stabilized soils demonstrated remarkable durability, maintaining their enhanced properties even under long-term loading and exposure to harsh environmental conditions, indicating their potential effectiveness for decades [153]. The immediate effects of lime treatment on stress-strain behavior are evident in the increased strength observed in uncured mixtures due to prompt lime-modification reactions [137,142]. These studies highlight noticeable improvements in soil stiffness or modulus [137]. investigated the stress-strain patterns of lime-stabilized soils and proposed a generalized plot to describe their mechanical response under various stress and strain conditions. By analyzing experimental data, a plot was created to showcase the typical responses of lime-stabilized soils under different loads. The results demonstrated a remarkable enhancement in soil stiffness, with the modulus increasing by at least a factor of 10. Additionally, lime stabilization significantly reduced the soil's failure strain to 1 % or lower [154].

[154] examined the impact of compaction and confining pressure on both lime-treated and untreated soils. After a brief curing period of three days, the resilient modulus of lime-stabilized soils exhibited notable enhancements ranging from 30 % to 50 % [137,140]. conducted studies on the behavior of lime-stabilized soils and proposed a generalized stress-strain plot to represent their mechanical response. Previous studies have shown that lime stabilization has a significant effect on soil stiffness, resulting in a tenfold or greater increase in modulus. Moreover, the failure strain of the soil is reduced from approximately 2-3%–1 % or less [137,140]. In these

studies, the researchers utilized Ultimate Compressive Crushing Strength (UCCS) and stress-strain data to estimate the elastic modulus. The approximation formula used for calculating the elastic modulus from UCCS is as follows: E (in ksi) = 9.98 + 0.124 (UCCS, in psi).

4.5. Summary of properties of lime-soil mixtures relating to durability

The impact of extended water exposure on lime-treated soils is found to have minimal negative consequences, with the ratio of soaked to unsoaked unconfined compressive strength (UCCS) being relatively high, ranging from approximately 0.7 to 0.85. According to research findings, it has been observed that lime-stabilized soils generally do not exceed a saturation level of approximately 90 %. In a study conducted by Refs. [155,156], the researchers investigated the chemical and physical properties of lime-stabilized soils. The study aimed to examine the effects of leaching with different water-salt solutions on these properties. Additionally [157], conducted a similar investigation to determine the impact of leaching on lime-stabilized soils. Their research focused on analyzing the chemical and physical characteristics of the soils after exposure to various water-salt solutions. The present study was conducted to investigate the effects of lime application on Texas clay soils. The findings of this research highlight the potential consequences of insufficient lime usage, which can lead to a reduction in stabilization effects. The reversibility of stabilization effects was frequently observed in cases where an insufficient amount of lime was utilized. In the study, it was observed that the stabilization effects exhibited a high level of resistance to leaching when an adequate amount of lime was utilized to achieve optimal property modifications. According to a study conducted by Ref. [141], it was found that the average rates of strength decrease for typical lime-soil mixtures were 60 kPa per cycle and 120 kPa per cycle for 48-h and 96-h (48.9 °C) curing, respectively.

4.6. Summary of lime case studies

Lime stabilization has proven to be an effective method for improving the engineering properties of expansive soils. The addition of lime, either in the form of quicklime (CaO) or hydrated lime ($Ca(OH)_2$), initiates a series of chemical reactions that alter the soil's characteristics. These reactions include cation exchange, flocculation, agglomeration, and pozzolanic reactions, which lead to the formation of cementitious compounds such as calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), and calcium aluminate silicate hydrates (CASH) [25,113].

The effectiveness of lime stabilization depends on various factors, such as the type and amount of lime used, soil mineralogy, plasticity, and environmental conditions. Quicklime is generally more reactive than hydrated lime due to its smaller crystal size, lower apparent density, and larger specific surface area [104]. The optimum lime content required for stabilization can be determined using the soil-lime pH test [119] or the expression proposed by Ref. [112]. Lime treatment has been shown to significantly reduce the plasticity index (PI) and swell potential of expansive soils [137–139]. It also improves soil workability, compaction characteristics, and strength [142,143]. The strength gains achieved through lime stabilization can range from modest to several hundred percent, depending on the soil type, lime content, and curing conditions [117,142,145].

The durability of lime-stabilized soils has been demonstrated through their resistance to water exposure and leaching [155,156]. However, the long-term effectiveness of lime stabilization may be compromised if insufficient lime is used or if the soil is exposed to severe environmental conditions [157]. In conclusion, lime stabilization is a viable technique for improving the engineering properties of expansive soils. By carefully considering factors such as soil type, lime content, and curing conditions, engineers can optimize the stabilization effects and enhance the performance of expansive soils in construction projects. The long-term durability of lime-stabilized soils, coupled with their improved strength and reduced swell potential, make this method an attractive option for addressing the challenges posed by expansive soils.

5. Fly-ash

Fly ash, a powdery residue, is primarily produced from the burning of coal in electric power plants. Its collection is typically achieved through the use of filtration systems or electrostatic precipitators. The properties of fly ash may differ based on the coal type used and the combustion process. Generally, fly ash particles are finer than 100 μm in size. This byproduct finds diverse uses, ranging from enhancing the quality of cement and concrete to soil amendment, thereby offering a sustainable option for handling the residuals from coal combustion. Fly ash is categorized into two principal classes: Class F and Class C, each defined by their distinct chemical compositions. Class F fly ash, generated from the combustion of anthracite or bituminous coal, is rich in silicates and aluminates but lacks inherent cementing capabilities. It undergoes a chemical reaction with calcium hydroxide and water to form cement-like compounds. Conversely, Class C fly ash, resulting from the combustion of lignite coal, is characterized by a higher calcium oxide content, enabling it to cement on its own. The significance of fly ash in producing cementitious materials lies in its high silica content and reactivity. Moreover, when fly ash interacts with soil, especially clay, it triggers complex chemical reactions that unfold over both short and long durations. At first, this interaction resembles the impact of lime. However, as time goes on, especially with Class C fly ash, the reaction between the ash's reactive silica and free lime leads to the formation of calcium-silica-hydrates (CSH), which act as a binding agent [123].

$$Ca^{2+} + 2(OH^{-}) + SiO_2 \text{ (clay silica)} \rightarrow CSH$$

The observed improvements in soil geotechnical properties due to fly ash treatment alone may not fulfill the criteria required for applications in road construction and foundation engineering [158,159]. Incorporating lime into the blend of clay and fly ash markedly increases the concentration of calcium ions (Ca^{2+}) within the mix. This rise in calcium ion concentration aids in generating substances akin to cement, mainly due to the reactions between calcium ions and the existing silica and alumina, particularly when the amount of added lime surpasses the threshold for lime fixation. The presence of these cement-like compounds plays a crucial role in binding together particles that have clustered, thus improving the material's structural integrity.

FA is currently being studied, and it is a fine-grained material with a lower density than regular soils [160]. FA has been widely utilized in various building and construction projects across different countries. Its applications range from compacted fills and concretes to bricks, liners, and embankment construction [161], and with the addition of cement as pavement material [162–164] that can be 1.5 times cheaper than conventional pavement material.

Numerous research studies have demonstrated the efficiency, long-lasting effects, cost-effectiveness, and eco-friendliness of using fly ash for soil stabilization, particularly in the context of pavement construction and foundation work [165]. investigated the effectiveness of fly ash and cement in stabilizing expansive soil for pavement and foundation work. The study found that the stability of subgrade soil can be significantly improved by adding fly ash and cement, providing a cost-effective and environmentally friendly alternative to traditional stabilization methods.

[166] studied the use of fly ash as a stabilizer in the presence of a strong binder like alccofine. The study showed that even a small percentage of fly ash can increase the strength and improve the engineering properties of expansive soils, making it suitable for construction purposes such as foundation and road pavement construction [167]. investigated the two-fold advantage of using fly ash for soil improvement. The study found that using fly ash not only helps avoid the environmental problems caused by large-scale dumping but also reduces the cost of stabilizing problematic soils and improving their engineering properties for the safe construction of engineering structures [168]. studied the effects of using fly ashes from Turkey in different proportions for the stabilization of clay soil samples. The study showed that the use of fly ashes in soil stabilization provides great benefits in contributing to the economy and decreasing environmental pollution.

[169] investigated the effectiveness of fly ash in improving the qualities of readily available local soils. The study found that the swelling nature of clay can be reduced up to 60 % after stabilization with fly ash, making it suitable for the construction of flexible pavements in rural areas with low traffic. Stabilization of problematic soils, such as loess, lakebed sediments, and expansive clays, is crucial for various construction applications, including road pavements. Traditional methods often involve the use of cement and lime, which can be costly and environmentally unfriendly. Recent studies have explored the potential of waste materials, such as fly ash and calcium carbide residue, as sustainable binders for soil stabilization [170]. investigated the use of calcium carbide residue and fly ash as binders for loess soil stabilization. They found that carefully designed mixtures of these waste materials, based on the Ca/(SiO2+Al2O3) ratio, can effectively improve the compressive strength and durability of loess soil under wet-dry cycles, offering an efficient and eco-friendly approach.

[171] explored the swell-shrink behavior of cement and fly ash-stabilized lakebed sediments. They introduced a digital imaging technique to measure volumetric shrinkage strain and demonstrated that the addition of fly ash reduces void spaces within the soil admixture, leading to decreased shrinkage and swelling compared to plain soil. Similarly [172], assessed the shrinkage characteristics of blended cement and fly ash admixed soft clay, finding that the addition of fly ash reduces void size within the soil matrix, resulting in decreased shrinkage. The study highlighted the importance of selecting the optimal fly ash content for maximum shrinkage reduction [173]. studied the stabilization of dredged lakebed sediments using ordinary Portland cement and fly ash for road pavement construction. They established empirical correlations between strength and stiffness parameters for the chemically stabilized sediments and determined the influence of curing period on strength development. The study identified optimized sediment/cement/fly ash mixtures for effective road construction applications [174]. investigated the macro-mechanical and micro-structural behaviors of dredged expansive clay treated with ordinary Portland cement or hydrated lime for potential reuse as pavement material. Their study confirmed the effectiveness of cement and lime in improving the swelling behavior and other engineering properties of expansive clay. They recommended correlations between mechanical properties and microstructures based on the results of mechanical testing and microstructural observations.

The case studies and research findings provide evidence of the long-term effectiveness, cost-efficiency, and sustainability of using fly ash for soil stabilization in various construction applications, especially in pavement construction and foundation work. By enhancing the engineering properties of soils and reducing the environmental impact of extensive fly ash dumping, fly ash stabilization can reduce construction costs and encourage the use of eco-friendly solutions in civil engineering projects.

5.1. Case study on fly-ash treated soil

Fly ash, a by-product of coal combustion in power plants, has gained significant attention as an effective and sustainable additive for soil stabilization. This paper explores the key factors influencing the performance of soil-fly ash mixtures, drawing insights from numerous research studies.

1. Fly ash content:

Numerous studies have explored the influence of fly ash content on the engineering properties of stabilized soils [36]. investigated the effects of fly ash on the liquid limit, plastic limit, and free swell properties of Indian black cotton soil. They observed that increasing fly ash content reduced the liquid limit and free swell of the soil, while increasing the plastic limit due to a reduction in the diffuse double layer's thickness and the addition of lime to the soil matrix. The replacement of finer soil particles with larger fly ash particles also contributed to this effect. However, higher fly ash proportions led to increased free swell due to the presence of pre-flocculated particles and the formation of gel-like substances from pozzolanic reactions.

[175,176] found that increasing fly ash content decreased soil plasticity, hydraulic conductivity, and swelling potential while improving dry unit weight and strength [177]. observed that the CBR of soil-fly ash mixtures increased with fly ash content and decreased with higher compaction water content, with wetter or more plastic fine-grained soils showing larger increases in resilient modulus (Mr) when stabilized with fly ash. Other researchers, such as [178,179], concluded that the free swell index value, swelling pressure, and volumetric shrinkage strain of expansive clay decreased with an increase in fly ash content, indicating that fly ash has a good potential to be used as an additive for improving the engineering properties of expansive soil.

Research has indicated that soils varying in their plasticity indices show enhanced physicochemical attributes upon treatment with an optimal quantity of Class C Fly Ash, which generally lies in the range of 15 %–20 % [180–183] while the suggested amount of Class F Fly Ash is higher, reaching levels in the range of 25 %–60 % [181,183,184]. As the fly ash content is raised, hydraulic conductivity (k) decreases and undrained cohesion (cu) increases [175,185], with the ideal proportion of fly ash to enhance performance effectively depending mainly on the unique properties of the soil and fly ash in question.

2. Lime content in fly ash:

The lime content in fly ash plays a crucial role in stabilizing soils [36]. noted that fly ash contains lime in both bound and unbound forms, with unbound lime being more reactive. An increase in unbound lime content positively influences the soil's engineering characteristics, although the enhancement may be constrained by the reduced availability of soil for lime reaction. The study also highlighted that the pozzolanic activity of fly ash is modifiable by altering the lime content [99]. suggested that the effectiveness of lime or fly ash containing lime in reducing shrinkage or increasing strength in clay soils might depend on the presence of pozzolanic materials that can react with lime. The absence of pozzolans in the soil-lime mix may not yield improvements in shrinkage properties. They also underscored a significant correlation between the reduction in shrinkage and the specific surface area of soils treated with lime and fly ash, suggesting that stabilization efficacy is linked to the extent of chemical reactions facilitated by the specific surface area [186]. attributed the improvements in soil properties to the pozzolanic reaction and pore refinement effect of fly ash as well as its high free-lime content, with the improvements being more pronounced with increasing fly ash content and lime content of the fly ash [187]. found that the presence of lime influenced the formation of hydration products like ettringite, C–S–H, and C-A-H gel, which reduced hydraulic conductivity, as confirmed by XRD and SEM analyses.

[188] found that the conversion rate of fly ash-lime to calcium sulfate was greater than that when using lime alone, with fly ash acting as a support medium for lime, thereby increasing its dispersion and extending its effective reaction surface area [189]. observed that leaching the raw fuels with water resulted in a significant reduction of the problematic elements in the fly ashes, indirectly impacting lime content by removing competing ions [190]. found that based on several tests conducted, the optimum lime contents for fly ash and soils are 5 % and 8 %, respectively, with the disposal of large quantities of fly ash posing a major environmental problem.

3. Curing time and temperature:

Several studies have investigated the effects of curing time and temperature on the performance of soil-fly ash mixtures for soil stabilization. The chemical reactions that occur during soil stabilization with fly ash are governed by curing conditions, which affect the formation of cementitious and pozzolanic compounds responsible for strength development. Proper control of curing time and temperature is crucial to achieve the desired levels of physical and mechanical characteristics in stabilized soils [191]. showed that increasing the curing time and temperature enhances the strength and durability of clayey soils stabilized with high-calcium fly ash and cement. Similarly [192], observed that the compressive strength of stabilized soils containing calcium carbide residue and fly ash increases with longer curing times. Moreover [193], noted that the shear strength and permeability of fly ash improve over time due to the pozzolanic reactions and self-cementing properties of the material.

The effects of curing temperature on the strength and microstructure of lime-amended fly ash have been studied by various researchers [194,195]. investigated the effects of curing temperature on strength and microstructure of lime-amended fly ash at different curing periods varying from 0 to 60 days, with curing temperature varying from 10 to 90 °C. The specimens were cured at different temperatures such as 10 °C, 25 °C, 45 °C, and 90 °C, and the unconfined compressive strength was determined after curing periods of 0, 7, 15, 30, and 60 days, demonstrating the importance of curing conditions in stabilization outcomes [196]. also evaluated the effect of curing temperature on the strength of lime-stabilized fly ash by curing UCS samples for 7, 15, 30, and 60 days with varying temperatures of 10 °C, 25 °C, 45 °C, and 90 °C. The influence of curing temperature on the compressive strength of fly ash-based mineral polymers has been investigated by Ref. [197]. The study observed that increasing the curing temperature could improve the compressive strength and shorten the curing time. The rate of improvement in strength differed with the type of activator solution, with 5 M K2SiO3 solutions achieving the highest improvement. The 7-day compressive strength curing at high temperature approached the 28-day compressive strength curing at normal temperature.

[198] systematically studied the problem of long standard curing age for lime-fly ash stabilized soil. By employing high-temperature curing and standard curing methods, the mechanical properties of lime-fly ash stabilized soil were researched through mix ratio test, compression rebound modulus test, and cleavage strength test. Comparative analysis of the microstructure of lime-fly ash stabilized soil cured by high temperature and standard temperature was carried out by electron microscope scanning. The results showed that by high-temperature curing, the microstructure of lime-fly ash stabilized soil could be ameliorated, early strength could be increased evidently, and curing age could be shortened [199]. assessed the effect of fly ash at different ranges (30 %–70 %) by

varying lime percentage (6 %–20 %) with thermodynamic parameters of their reaction in normal and raised temperature by curing compacted specimens in the laboratory. The compressive strength of the fly ash and lime mixture was determined for curing periods up to 28 days in normal state and one day in raised temperature. The result portrayed that raised temperature highly boosted the compressive strength of the mix from 30 % to 120 % at different ranges of fly ash mixture with lime.

4. Compaction energy and delay:

Compaction energy and delay significantly affect the performance of soil-fly ash mixtures [200]. mentioned that compaction energy and any compaction delays affect the performance of soil-fly ash mixtures [201]. found that the density decreases with an increase in compaction delay, and these delaying hours significantly affect the strength of stabilized soils. Most of the time, delay is unavoidable due to various factors, and these delaying hours significantly affect the strength of stabilized soils, as shown by compaction tests and unconfined compressive strength tests with time delays [202]. observed that adding lime affected the strength with delayed compaction, with the prepared samples tested to find out the effect of delayed compaction on strength, and curing periods increasing the strength considerably [203]. studied the effect of delay up to 7 days on compaction characteristics and unconfined compressive strength, showing that the delay in compaction has a significant effect on the compaction and strength characteristics of reactive fly ash and their mixture, but no practical effect on non-reactive fly ashes.

[204] found that to avoid swelling of soils stabilized with fly ash, the mixtures should be compacted at least 4 days after being maintained at a water content higher than optimum [205]. emphasized the importance of minimizing the delay between wet mixing and compaction of soil-lime-fly ash mixtures when the soil contains clay particles that can react with lime, lowering the density and strength for the same compaction effort [206]. found that the strength of soil-self-hardening fly ash develops rapidly when compacted immediately after mixing, with a time delay between mixing the fly ash with the soil and compaction of the mixture reducing the strength, and adequate mixing of the soil and fly ash and rapid compaction of the mixtures being important parameters in field construction of stabilized bases [207]. found that dry unit weight tended to drop when the mixed ratio of coal fly ash exceeded a certain percentage, with the optimum moisture ratio of coal fly ash shown to be approximately 23 %, and the study aimed at implementing a compaction test and examining the basic engineering property to explore the influence of crushing the particles through compacting the admixture of crushed stone and coal fly ash on its engineering property, and the impact of the admixture volume of each material on compaction property and material property.

5. Presence of sulfur:

The presence of sulfur in soil-fly ash mixtures has been found to have a significant impact on the long-term strength and durability of the stabilized soil [208]. conducted both indoor and outdoor experiments and found that the amount of sulfur in fly ash substantially influenced the intensity and stability of road base courses. High sulfur content fly ash was observed to cause expansion cracks, decrease in intensity, and ultimately lead to the destruction of the stabilized soil [209]. highlighted that the presence of sulfur-rich surface coatings on fly ash particles can affect the leachability of ash when it comes in contact with solutions. These coatings are highly soluble and, if present in sufficient quantities, can impart an acidic pH to the solutions initially in contact with the ash. This transient, acid-generating potential of some ash fractions should be considered when proposing the use of fly ash and predicting its behavior during disposal, as it may impact the initial ash leachability and alteration.

The formation of expansive minerals, such as ettringite and thaumasite, in lime-treated soils containing sulfate is detrimental to the soil's strength and durability [210]. [211] observed that the presence of sulfate increased the free swell volumes and oedometer swelling of lime-treated soils. However, the addition of barium chloride was found to prevent the formation of ettringite and thaumasite, restoring both deviator stress and strength parameters to their original levels [212]. noted that fly ashes with high sulfur content react with clay minerals and water in the soil to form expansive materials, which break up the mixture and result in no long-term strength gain. In contrast, low sulfur ashes have shown significant strength gain for two years, with the strength gain also being influenced by the curing temperature [213]. found that if the calcium oxide content in the mixture of raw materials is not beyond 12 % and the mixture is allowed to react before the manufacture of specimens, the formed ettringite does not cause crack formation. Instead, it fills the pores and contributes to strength development. However, if excessive ettringite is formed, the specimens may "explode" due to expansion, and over time, the ettringite can disintegrate due to carbon dioxide attack, resulting in a decrease in compressive strength.

While the presence of sulfate in fly ash may contribute to the formation of ettringite in lime-treated or cement-treated soils, potentially leading to swelling and stability issues [214–216], the addition of fly ash to these stabilized soils can help mitigate the adverse effects of sulfate-induced swelling to some extent [217]. The judicious use of fly ash in combination with lime or cement can be an effective strategy for reducing the detrimental impacts of sulfate on the stability and durability of treated soils [218–221].

6. Soil type and properties:

The type and properties of soil play a significant role in the effectiveness of fly ash stabilization [99]. found that the response of four different expansive soil samples to fly ash and lime varied, with one sample showing less shrinkage reduction when treated with both additives, which might be attributed to another soil constituent interfering with the pozzolanic reaction [222,223]. suggested that soils with high swell potential, particularly those with higher plasticity and specific surface area, generally show greater improvement upon fly ash treatment. Cation exchange capacity (CEC) values can be used to indicate the changes in the mineralogy of the fly ash treated soils and explain the reduction in plasticity and water absorption potential [177]. observed that wetter or more plastic fine-grained soils, which are generally considered poorer subgrades, tend to show larger increases in resilient modulus (Mr) when stabilized with fly ash. The final CBR and Mr values were found to be comparable irrespective of the soil type, but organic soil yielded the poorest results in both the CBR and resilient modulus tests [224]. investigated the impact of fly ash amendments on the plasticity, water retention, and penetration resistance-density-moisture relationships of three soils of different textures, finding that for all three soils, the addition of fly ash decreased the plasticity index but slightly increased the Proctor maximum density.

The presence of organic content in the soil has detrimental impacts on the physical and strength behavior of the soil [225]. studied the influence of fly ash as an additive to ordinary Portland cement for the stabilization of highly organic soils, finding that stabilization effects on the soil-cement admixture increased when fly ash additives were used even though the organic content was high [226]. investigated the effect of fly ash on the consistency, compactness, acidic properties, and strength of organic soil, using two types of fly ashes at different percentages, and found that fly ash significantly reduces the plasticity index of the organic soil, whereas the liquid and plastic limits increase [227]. compared the effect of different fly ash application rates on the soil physical properties and structure of sandy soil, finding that the bulk density of soil increases and the total porosity decreases with fly ash application, and soil hardness increases with high fly ash application, indicating that fly ash application could effectively improve soil properties and enhance water utilization efficiency [228]. observed that the addition of fly ash to highly expansive clays reduces cohesion and increases the friction angle, while in lean clays, both cohesion and friction angle values increase with the addition of fly ash. These findings highlight the importance of considering the type and properties of the soil when assessing the suitability and potential benefits of fly ash stabilization. The varying effects of fly ash on different soil types and the influence of clay content on the pozzolanic reactions underscore the need for a thorough understanding of the soil characteristics to optimize the stabilization process and achieve the desired improvements in soil properties.

7. Fly ash type:

The type of fly ash used in soil stabilization significantly influences the outcomes, as the chemical composition and reactivity of fly ash vary based on its classification. Fly ash is primarily categorized into two classes, Class C and Class F, with the key difference being the calcium content [229]. Class C fly ash, derived from the burning of sub-bituminous or lignite coal, contains higher levels of calcium oxide (CaO) and exhibits self-cementing properties when mixed with soil and water. In contrast, Class F fly ash, produced from burning anthracite or bituminous coal, has lower CaO content and requires an activator, such as lime or cement, to develop its cementitious properties [230,231]. Several studies have investigated the impact of fly ash type on the stabilization of various soils [99]. found that lime had a more pronounced effect on reducing linear shrinkage than an equivalent amount of Class C fly ash. A 5 % lime addition resulted in a significant decrease in shrinkage (4–7%), whereas a 5 % addition of Class C fly ash yielded a more modest reduction (1–2%) [180,181,232,233]. indicated that the optimal quantity of Class C fly ash for enhancing soil properties generally lies in the range of 15 %–20 %. The higher calcium content in Class C fly ash contributes to the formation of cementitious compounds, such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C-A-H), which bind the soil particles together, leading to improved strength, reduced plasticity, and decreased swell potential.

On the other hand [181,184,233], suggested that the optimal amount of Class F fly ash required for stabilization is higher than Class C fly ash, reaching levels in the range of 25 %–60 %. Class F fly ash exhibits pozzolanic properties and reacts with the available calcium hydroxide ($Ca(OH)_2$) in the soil or from added lime to form cementitious compounds. Due to its lower reactivity compared to Class C fly ash, Class F fly ash typically requires the addition of an activator to trigger the pozzolanic reactions and achieve desired stabilization effects [184]. observed that 10 % of Class C fly ash was sufficient to minimize the swelling potential of expansive soils, whereas 40 % of Class F fly ash was required to achieve the same effect [234]. noted that Class C fly ash, which contains more lime, is generally more effective than Class F fly ash in reducing shrinkage, plasticity, and swelling of expansive soils. However, when subjected to wet-dry cycles, the initial cementitious effect of the fly ash on controlling the swell was partially lost, leading to an increase in the volumetric deformation of the stabilized expansive soil.

[235] found that the addition of Class C fly ash was more effective than Class F fly ash when supplemented along with lime in improving the stability characteristics of clayey soil. The addition of fly ash in the clay soil mix containing lime decreased the plasticity of the soil and escalated the workability, resulting in a stronger and stiffer soil matrix by reducing the inter-particle spacing. These findings highlight the importance of considering the type of fly ash when selecting it for soil stabilization projects. The chemical and physical properties of fly ash, particularly its calcium content and reactivity, play a crucial role in determining its effectiveness in improving the engineering properties of treated soils.

5.2. Summary on fly-ash case studies

Fly ash, a byproduct of coal combustion in power plants, has been widely studied as a stabilizing agent for expansive soils. The effectiveness of fly ash in soil stabilization depends on various factors, including fly ash content, lime content in fly ash, curing time and temperature, compaction energy and delay, presence of sulfur, soil type and properties, and fly ash type.

Numerous studies have shown that increasing fly ash content generally reduces soil plasticity, hydraulic conductivity, and swelling potential while improving dry unit weight and strength [36,175,176]. The optimal quantity of fly ash for stabilization varies based on soil plasticity indices and fly ash type, with Class C fly ash requiring 15 %–20 % and Class F fly ash requiring 25 %–60 % [180,181,184,233]. The lime content in fly ash plays a crucial role in the pozzolanic reactions responsible for soil stabilization. Unbound lime in fly ash is more reactive and positively influences soil engineering characteristics [36]. The presence of pozzolanic materials in the soil-fly ash mix is essential for the effectiveness of lime in reducing shrinkage and increasing strength [99].

Curing time and temperature significantly affect the strength and durability of fly ash-stabilized soils. Longer curing times and higher temperatures generally enhance the formation of cementitious and pozzolanic compounds, leading to improved soil properties [191–193]. Compaction energy and delay also influence the performance of soil-fly ash mixtures. Delayed compaction can lead to reduced density and strength, emphasizing the importance of minimizing the time between mixing and compaction [200,201]. The presence of sulfur in soil-fly ash mixtures can have detrimental effects on the long-term strength and durability of stabilized soils. High sulfur content in fly ash can cause expansion cracks, decrease in intensity, and ultimately lead to the destruction of the stabilized soil [208]. Soil type and properties play a significant role in the effectiveness of fly ash stabilization. Soils with high swell potential, higher plasticity, and specific surface area generally show greater improvement upon fly ash treatment [223]. The presence of organic content in the soil can have detrimental impacts on the physical and strength behavior of the soil [225].

Fly ash type, classified as Class C or Class F based on calcium content, influences the stabilization outcomes. Class C fly ash exhibits self-cementing properties and is generally more effective than Class F fly ash in reducing shrinkage, plasticity, and swelling of expansive soils [234]. In conclusion, fly ash has demonstrated its potential as an effective stabilizing agent for expansive soils. By carefully considering the various factors that influence the stabilization process, such as fly ash content, lime content, curing conditions, compaction, soil properties, and fly ash type, engineers can optimize the use of fly ash to improve the engineering properties of expansive soils and enhance the performance of geotechnical structures.

5.3. Interplay and relative importance of factors influencing stabilization

The effectiveness of calcium-based chemical additives, such as lime and fly ash, in stabilizing expansive soils, is influenced by a complex interplay of multiple factors. Understanding the relative importance of these factors and their interactions is crucial for optimizing the stabilization process and achieving the desired soil properties. Soil mineralogy and type play a significant role in determining the optimum amount of additive required for effective stabilization. Soils with higher clay content and specific surface area, such as montmorillonitic clays, typically require higher dosages of lime or fly ash than kaolinitic clays [25,99]. The presence of organic matter or sulfates in the soil can also hinder the stabilization process, even when other factors are favorable. Organic matter can adsorb calcium ions and reduce their availability for pozzolanic reactions [100], while sulfates can lead to the formation of expansive minerals like ettringite, causing swelling and damage to the stabilized soil [215].

The curing conditions, including temperature and duration, significantly influence the strength development and long-term performance of stabilized soils. Higher curing temperatures accelerate the pozzolanic reactions and lead to faster strength gain [236,237]. However, the optimum curing temperature and duration may vary depending on the soil type and additive used. Compaction delay can also affect the stabilization process, as forming cementitious bonds before compaction can hinder the achievement of the desired density and strength [100]. The water content of the soil during mixing and compaction is another critical factor influencing the effectiveness of stabilization. Excessive water content can dilute the additive and reduce its reactivity, while insufficient water content may hinder the hydration and pozzolanic reactions [100]. The optimum water content for stabilization depends on the soil type, additive used, and the desired properties of the stabilized soil.

The pH of the soil matrix also plays a significant role in the stabilization process. A high pH environment ($pH > 12$) is necessary for the dissolution of silica and alumina from the clay particles and their subsequent reaction with calcium ions to form cementitious compounds [100]. The presence of acidic substances, such as organic matter or sulfuric acid, can lower the pH and hinder the stabilization process [102]. In summary, the effectiveness of calcium-based chemical additives in stabilizing expansive soils is influenced by a complex interplay of factors, including soil mineralogy and type, presence of deleterious substances, curing conditions, compaction delay, water content, and pH of the soil matrix. Understanding the relative importance of these factors and their interactions is crucial for optimizing the stabilization process and achieving the desired soil properties. Future research should focus on developing comprehensive models that consider the interplay of these factors and provide guidance for the selection and application of appropriate stabilizers based on site-specific conditions.

6. EPS expanded polystyrene

EPS which stands for expanded polystyrene. (EPS) is a white froth plastic material delivered from strong dots of polystyrene. In 1988 EPS was firstly applied for pipeline backfill [238] EPS essentially is outcome of a mixture of approx. 5–10 % of bombastic gusting agent, usually they are carbon dioxide or pentane as well 90–95 % polystyrene in its weight [239,240]. It is essentially utilized for packaging, protection, structural shock-resistant, material fillings in road embankment etc. It is a shut cell, inflexible froth material created from: Styrene - which shapes the cell structure. EPS possesses good thermal insulation behavior and also because of its enough availability and minimum cost, it has been in high demand.

As per [239], the main reason behind the supreme usage of EPS was due to big gap in the engineering properties when compared with other froths. Reasons presented by him were as follows-

1. It is accessible around the world;
2. It is the most affordable by a huge degree;
3. The main polymeric froth doesn't use as a blowing specialist CFC (chlorofluorocarbon), HCFC (Hydro-Chloro-Fluoro Carbon), or a comparable gas connected to the consumption of the Earth's upper-climate ozone layer.

4. It doesn't deliver formaldehyde, a poisonous gas created for expanded periods (years) by a few polymeric froths after their production.

The remarkable compressibility of Expanded Polystyrene allows it to be a perfect material for minimizing vertical and even pressure within its hollow microstructure, while maintaining minimal lateral deformation. According to the [241], the physical properties of rigid cellular polystyrene are presented in Table .3. EPS geofoam's incredibly light weight makes it an ideal choice for constructing banks and asphalts on unstable soil [242,243].

The utilization of soft portable EPS beads has significantly enhanced the engineering properties of the expansive soil. The soils that have been altered with varying levels of EPS have the potential to effectively control the expansion and contraction tendencies of the expansive soil subgrade [244]. The expense examination of development of road pavement showed that most extreme in general expense of EPS composite pavement is 12.87 % which is quite less than the traditional pavement execution [245].

Lately, there has been a growing issue with the increased use of EPS in building sectors. Expanded Polystyrene is a highly adaptable material that finds use in a wide range of applications. Its lightweight nature combined with its dense foam structure makes it an excellent choice. Additionally, EPS offers exceptional warmth properties and is highly resistant to impacts. The foam in EPS is a soft cellular plastic consisting of tiny spherical particles primarily made up of air. The exceptional protective and shock-absorbing qualities of EPS are a result of its microcellular shut cell structure. EPS consists of tiny polystyrene beads that are produced from styrene using a process known as polymerization. The distribution of droplet sizes can affect the foaminess of EPS. After the polymerization process, EPS is infused with specific blowing agents like pentane and hexane. The process of converting expandable polystyrene to EPS involves three stages: (1) pre-extension, (2) changing development and modification, and (3) extension and last trimming.

6.1. *Why EPS as a stabilizer?*

As we already know EPS is lightweight as well as bulky in nature and once its usage is over either being used for the safety of sensitive goods while transportation or any other, the EPS covers or packaging part is left away into dumping area or landfills which ultimately occupies considerable space of the dumping ground [51,52]. Which later on affects the capacity of landfill as a result harms the land as EPS is not a biodegradable or a decomposable one. In addition, several other additives can stabilize expansive soil, such as fly-ash, cement, lime, and calcium chloride. These additives have shown a high success rate in achieving stabilization [246–248]. Usually, cracking due to high temperature is seen in cement-stabilized soils, whereas lime-stabilized soils gain intermediate strength. Furthermore, water can gradually remove both stabilisers from soils [27]. Also, the favorable impact of lime stabilization on lime-treated soils is partially lost because of cyclic wetting and drying due to the biased breakage of cementation relationship as well loss in dry unit weight and moisture content [53]. In spite of these limitations, lime is commonly employed alongside other elements, like fibers, to strengthen expansive soils.

Lastly, EPS beads produced from EPS wastes helps in minimizing as well recycling the amount of EPS wastes being produced which ultimately promotes in saving land as EPS wastes is being dumped in land. Additional to it EPS usage as a stabilizer may result as a second option to chemical stabilization methods as well to other methods in-order to minimize the swell-shrink potential. EPS actually works as a partial soil exchanging technique wherein the recycled expanded polystyrene beads and in-situ soil are mingled up. This technique promotes to reuse the in-situ soil instead of replacing it. EPS beads help stabilize the expansive soil through decreasing the moisture content in the soil matrix, resulting in a decrease in swelling pressure. In addition, the incorporation of EPS beads results in the development of empty spaces within the soil structure, thereby enhancing its ability to withstand heavy loads.

Several factors can affect the performance of EPS beads as stabilizers. Various factors need to be considered, such as the beads' shape and dimensions, the soil type, and the percentage of beads utilized. Several research studies have demonstrated the effectiveness, long-lasting effects, cost-effectiveness, and eco-friendliness of using EPS beads for soil stabilization, particularly in the context of road construction and earthquake-prone areas [249]. investigated the performance of EPS geofoam as an infill and material for pavement construction. The study found that a combination of 0.5 % EPS beads with expansive soil significantly reduces swelling pressure and increases the unconfined compressive strength. The lightweight and compressible nature of EPS beads makes them suitable for use as

Table 3
Classes of EPS beads and their properties [241].

Physical Property	Unit	Class					
		L	SL	S	M	H	VH
Nominal Density (kg/m^3)		11	13.5	16	19	24	28
Compressive stress at 10 % deformation (min)	kPa	50	70	85	105	135	165
Cross-breaking strength (min)	kPa	95	135	165	200	260	320
Rate of water vapour transmission (max) measured parallel to rise at 23 °C	μg/m^{2}s	710	630	580	520	460	400
Dimensional stability of length, width, thickness (max) at 70 °C, dry condition 7 days	%	1.0	1.0	1.0	1.0	1.0	1.0
Thermal resistance (min) at a mean temperature of 25 °C (50 mm sample)	M^{2}K/W	1	1.13	1.17	1.20	1.25	1.28
Flame propagation characteristics:							
-median flame duration; max	S	2	2	2	2	2	2
-eighth value; max	S	3	3	3	3	3	3
-median volume retained;	%	15	18	22	30	40	50
-eighth value; min.	%	12	15	19	27	37	47

structural fill in earthquake-prone areas, reducing seismic forces on structures.

Furthermore [249] discussed the relevance of EPS geofoam for ground improvement and its field performance as infill and material for pavement construction. The study helps understand the behavior of EPS geofoam unit cells with fly ash embedded in the core, showcasing its potential as an efficient and eco-friendly construction material [250]. investigated the use of EPS beads in road embankment construction, addressing challenges such as bearing capacity failure, large total settlement, differential settlement, and slope instability. The study found that adding a small number of EPS to the mixture can significantly reduce the maximum dry density, demonstrating the material's efficiency in soil stabilization practices.

These case studies and research findings support the long-term effectiveness, cost-efficiency, and sustainability of using EPS beads for soil stabilization in various construction applications, particularly in the context of road construction and earthquake-prone areas. By improving the mechanical properties of soils and reducing the weight of embankments, EPS beads can minimize construction costs and promote the use of eco-friendly solutions in civil engineering projects.

6.2. Case study on EPS beads as a stabilizer

6.2.1. Effect of EPS beads diameters

[251] by the help of geofoam granules column (GGC) examined the swelling pressure, percentage of swell and the effect of number of GGC with different diameters in expansive soil (LL and PL was found to be 76 and 41 therefore the soil was classified as highly clayey). Swell tests were performed in large scale consolidation apparatus within which a setup of steel tank including steel tubes were placed in linear as well triangular positions. The results revealed a noticeable decrement in the percent swell, ranging between 74 % and 82 %, when two or three GGC were included. Additionally, the increase in number of GGC resulted to a decrement in vertical swelling. The larger diameter or lower l/d ratio gave maximum reduction in swelling pressure when compared with and without GGC involvement. Placing and designing of GGC in field up to an active depth was discussed as well recommended.

[252] has studied the impact of GGC inclusion in problematic soil using a large size 1D consolidation apparatus. The GGC columns of different diameters were made centrally in the soil specimen and were filled with geofoams at densities 15 kg/m^3 and 20 kg/m^3. The soil specimens were prepared at HMC and OMC moisture contents compacted statically to achieve MDD corresponding to the standard proctor value. The results of the test show that GGC inclusion reduce the vertical swell and the swelling pressure. The large diameter GGC with low geofoam density reduces percentage swelling and the swelling pressure more effectively than the opposite to this (can be seen in Table .4). Further at low initial moisture content corresponding to HMC at MDD resulted in higher swelling ability in terms of PS and SP in comparison to placement at OMC achieved for MDD. The CH type of soil with LL 76 and PI 35 having OMC 17 % at MDD 17.65 kN/m^3 was used. The HMC moisture content was approx. to 6 %. The waste geofoam of diameter between 2 and 6 mm were used in the study. Based on the model study the investigation recommended that the geofoam density of 15 kg/m^3 is optimal for reducing the percentage swell and the swelling pressure. This density is achieved by placing geofoam in layers without much compaction.

EPS bead size is to be kept under consideration while using it as stabilizing agent has been claimed by past studies. A narrow study on the group of limited bead size (0.3–1 mm, 1–2 mm, 2–3 mm) by Ref. [253] was done to analyze the impact of varying sizes of EPS beads on several properties of EPS clay blends. These properties include the optimal water content, highest dry density, unconfined compressive strength, ductility, coefficient of permeability, and compression index. The soil investigated was taken from Zhejiang, China which was classified as a low plasticity clay. EPS content of 1 % and 2 % were chosen to be mixed with clay in-order to prevent from segregation. Few tests like compaction, UCS, variable head parameter test, SEM were carried out. The OMC MDD of 0.3–1 mm, 1–2 mm and 2–3 mm was found to be 23.8 %, 23 %, 26.5 % and 0.87 g/cm^3, 0.9 g/cm^3,0.72 g/cm^3. The bead size ranging between 1 and 2 mm was found to be the best for the use as a stabilizing agent as it had highest MDD. UCS did not decrease with decreasing the EPS size rather the UCS for 1–2 mm group was found to be highest (95 kPa, 125 kPa and 80 kPa were found to the UCS value for EPS groups of 0.-1 mm, 1–2 mm and 2–3 mm). On the other hand, this group (1–2 mm) was noticed to be less ductile or brittle in comparison to other two as the other two groups of EPS beads had much more pores between the particles which when applied the shear stress helped in re-positioning to dissipate the energy. Hydraulic conductivity did not increase with EPS size. It was lowest for 1–2 mm group. 1–2 mm group had smallest void space due to highest density (Hydraulic conductivity for additive content of 1 % were found to be 60.9×10^{-6} cm/s, 9.0×10^{-6} cm/s and 710.6×10^{-6} cm/s, respectively, for the group 0.3–1 mm, 1–2 mm, and 2–3 mm) depicted in Table .5. Compression index did not increase with EPS size. It was lowest for 1–2 mm group (0.710, 0.500 and 0.780 for the group 0.3–1 mm, 1–2 mm, and 2–3 mm). 1–2 mm group had smallest compressibility due to highest MDD and lowest OWC. 2–3 mm group

Table 4
Variation in swell% and swell pressure kPa [252].

Test Identifier	Max Swell (%)	Swelling Pressure (kPa)
SA	5.8	
25D-20	4.79	165
25D-15	4.37	158
40D-20	4.56	105
40D-15	4.11	93
50D-20	4.45	87
50D-15	3.98	76
75D-20	3.53	72
75D-15	3.14	65

Table 5
Test results as per varying EPS beads size (mm) [252].

Sr. No.	EPS Bead size (Additive content 1 %)	OMC%, MDD (g/cm^3)	UCS (kPa)	Ductility	Hydraulic conductivity (cm/s)	Compression index
1.	0.3–1 mm	23.8, 0.87	95	2.7	60.9×10^{-6}	0.710
2.	1–2 mm	23, 0.9	125	1.8	9.0×10^{-6}	0.500
3.	2–3 mm	26.5, 0.72	80	3.3	710.6×10^{-6}	0.780

had more compression of EPS beads.

Discussion- OMC and MDD of different size beads vary according to its contact with the soil particles, if the size is too small (0.3–1 mm) The low pore volume of the material may result in a denser texture, making compaction more challenging. The small size of the EPS beads could also affect the adhesion between the material and soil particles. Consequently, when the pore size is reduced, there is a higher chance of water being absorbed, which in turn causes a rise in pore water pressure and a loss of energy compaction. Furthermore, when the beads are of a larger size, they can undergo deformation as a result of their elastic properties. This deformation occurs during compaction. Furthermore, larger beads also have a larger surface area, which shows decrement in adhesion behavior with the soil (bead size 2–3 mm). These findings can be attributed to the greatest maximum dry density as well as a minimal optimum moisture content. Additionally, the SEM study reveals that EPS beads with a smaller pore volume and a denser micro-structure exhibit superior strength and reduced ductility, hydraulic conductivity, and compression index.

[254] The size range and densities of EPS beads were found to have a significant effect on the engineering properties of the EPS-Fly Ash mixture (Class F). A variety of tests were carried out, such as the standard proctor test, direct shear test, California bearing ratio test, consolidated drained static triaxial test, permeability and consolidation test. The EPS content used for mixing remained steady at 0.6 %. The MDU experienced a decrease from 12.5 kN/m^3 to 10.38 kN/m^3 with the addition of 6 mm EPS beads. This decrease can be attributed to the lower density of EPS. There was no noticeable difference in OMC, which fluctuated from 29 % initially to 32 % at one point. The angle of friction was measured for different sizes of EPS beads, ranging from 1 mm to 6 mm. It was found that with larger beads, there was a corresponding increase in the angle of friction. This can be attributed to the improved intergranular friction and embedding of the larger beads. The cohesion values displayed a lack of consistency. By incorporating 1 mm EPS beads, a remarkable enhancement in CBR was observed, with the value rising from 4.9 % to 25.64 %. The reason behind this can be traced back to the greater density and heightened friction brought about by the beads. The reduction in bead size resulted in a boost in shear strength, which can be credited to the greater density. It has been found that beads measuring 1 mm in size exhibit exceptional strength. As the bead size increased, there was a noticeable increase in ductility. The stress-strain behavior observed in the 1–2 mm beads closely resembled that of EPS blocks. As the bead size decreased, the coefficient of consolidation exhibited an increasing pattern, reaching its maximum at a size of 4 mm. Perfect for 4 mm beads. There was a noticeable rise in permeability as the bead size increased. The size of EPS beads significantly affects the geotechnical properties of fly ash. The highest density, strength, CBR, and consolidation coefficient were achieved using 1 mm beads. Using larger beads resulted in a decrease in density and strength, while enhancing ductility and permeability. Small beads measuring 1–2 mm can be used as a lightweight fill material instead of EPS blocks. Utilizing a combination of fly ash and 0.6 % EPS beads measuring 1–2 mm in size can prove advantageous for construction projects involving unstable soil.

Discussion- The reduction in Maximum Dry Density (MDD) can be primarily linked to the lower density of Expanded Polystyrene (EPS) compared to Fly-Ash. With the enlargement of EPS bead dimensions, there is an increased volumetric occupation, leading to a diminished dry unit weight. The research indicates that selecting an appropriate EPS bead size for use in the backfill of retaining structures can effectively mitigate wall pressure. Observations from the study also revealed variations in the angle of internal friction contingent upon the size of the beads. In particular, the internal friction angle saw an augmentation with bead sizes in the range of 1–2 mm, whereas it witnessed a decline with the use of larger bead sizes, indicating enhanced inter-particle friction among the smaller beads. The reduction in bead size within the mixture was found to correlate with a denser composition, thereby facilitating a more integrated incorporation of beads within the fly ash matrix, which is likely to augment the internal friction angle. Further analysis through Scanning Electron Microscopy (SEM) images highlighted that EPS beads are characterized by the presence of surface pores, in contrast to the small spherical particles that constitute Fly-Ash. These particles have the potential to lodge within the EPS bead pores, thereby bolstering the frictional interaction between the Fly-Ash particles and EPS beads. The strength of the mixture has significantly increased, resulting in a notable improvement in the CBR. The CBR value has risen from 4.9 initially to 25.64 %, showcasing the positive effects of the research.

[255] by the use of dynamic triaxial test and numerical simulation (PFC3D software) explained the effectiveness of EPS beads size (range – 1,3,5,6 mm) on the dynamic strength of light weight soil mixed with 50 % of EPS and 15 % of cement. Density of EPS beads taken were 31.8, 13.8, 9.4 kg/m^3. The soil was taken from China with LL 37.43 % and PL 21.30 %, therefore considered as a low silt clay. Initially the OMC and MDD of loess found by standard compaction test was 20.51 % and 1.69 g/cm^3. Accordingly, the loess-cement mix samples were prepared by addition of different EPS bead sizes and were compacted properly in-order to perform dynamic triaxial test. Dynamic triaxial tests conducted on samples at confining pressures of 50, 100, 150, 200 kPa. Dynamic strength decreased with increasing EPS size. For 150 kPa confinement:

1–3 mm: 103 kPa, 3–5 mm: 86 kPa (−15.53 kPa, −15.29 %), 5–6 mm: 69 kPa (−33.27 kPa, −32.76 %) was noticed, which ultimately states that as the particle size was increasing there was the increase in im-proper contact between the soil particles and EPS beads. PFC3D discrete element modelling was also done to simulate tests. Where PFC3D simulation matched well with lab tests. Contact force between EPS-soil particles lower than soil-soil due to lower EPS stiffness. With increasing EPS size, contact forces became more uneven, causing stress concentration. Displacement fields showed particles moved from ends to middle. Interface shifted downwards initially for 5–6 mm EPS, then moved to middle. Finally concluded that dynamic strength decreased with increasing EPS size from 1-3 mm to 3–5 mm and 5–6 mm. PFC3D simulation explained this through increased weak contact area, uneven contact forces and displacement interface movement. 1–3 mm EPS gives highest strength due to uniform contact forces and symmetric displacement fields.

Discussion-Therefore, introduced the uneven distribution of forces, as a result, samples were destroyed easily while the test and resulted in biased displacement. This would be due to the decrease of normal and tangential stiffness with the increment of EPS beads. Variations of size of EPS particles have an impact on their rigidity and the contact area they have with soil particles. It's interesting to note that the axial strain associated with the highest dynamic stress value in the numerical simulation doesn't show a noticeable increase. As the size of the EPS beads increased from 1 to 3 mm, 3–5 mm, and 5–6 mm, a noticeable decrease in dynamic strength was observed.

[256] explored the EPS beads size ranging from 3 to 10 mm incorporated to enhance the engineering properties of expansive soil to replace lime or cement, where EPS beads in different proportions (0.5 %, 0.75 %, 1 %) were used. Where liquid and the plastic limit of the soil was reported to be 83 % and 35 %, which accordingly was reported as a highly clayey soil. Additional to it 17.9 kN/m^3 and 11 % was noted as the MDD and the OWC of the soil. Compaction and Oedometer test on samples prepared at different EPS bead content were performed. Respectively, optimum moisture content (OMC) increased (11 %, 13 %, 13 %, 15 %) with increase in EPS content (0 %, 0.5 %, 0.75 %, 1 %) and therefore increased the plasticity of soil. It is possible that the dry unit weight would decrease when EPS beads are added to soil, due to their extremely light weight. The findings indicate a notable trend where the increase in EPS bead proportion (from 0 % to 1 %) led to a reduction in the maximum dry unit weight, which dropped from 18 kN/m^2 at 0 % to 13.8 kN/m^2 at 1 %. Additionally, the incorporation of EPS beads into the soil resulted in a marked decrease in swelling pressure. The most substantial decline, approximately 37 %, was recorded at the 1 % EPS bead concentration. Lesser declines of 9 % and 22 % were observed when the EPS bead concentrations were 0.5 % and 0.75 %, respectively.

Furthermore, the increment in OMC can be credit to the compressibility characteristics of EPS beads. At lower proportions, EPS beads can be easily compressed. However, as the proportion increases, compaction becomes more challenging. This is because the increased proportion leads to a larger surface area of the beads, which in turn requires more water for soil particles to adhere to.

6.2.2. Effect of different EPS beads content

EPS content is another factor being highlighted for achieving optimum reduction in swelling.

Study of [257] approves the decrease in percent swell (PS) when increased the EPS content while reinforcing the BC soil with EPS beads. The percent swell is calculated by dividing the ultimate change in thickness of the soil by the actual thickness of the soil sample. The analysis revealed that the soil had a high clay content, with a plastic limit (PL) of 276 % and a liquid limit (LL) of 33 %. In addition, the MDD was recorded at 1.38 g/cm^3, while the OMC was found to be 38 %. A thorough consolidation test was carried out, adhering to the test procedure laid out in ASTM D4546 [258]. The table below shows the results of increasing the EPS content from 0.25 % to 1 %, which helps prevent soil swelling. Additionally, it is worth noting that the pressure reduction increases as the EPS content is increased. The study further analyzed additional parameters to support the approval of adding EPS beads, as shown in Table 6. This phenomenon occurs because when the collapsible EPS beads are mixed in a random manner, they can either facilitate or hinder the flow of water into the soil. Consequently, the swelling strain in black cotton soil experiences a decrease.

Use of recycled EPS beads as admixture blended with sand has were taken into consideration as replacement layer in expansive soil wherein the ratios of sand and EPS beads content (beads variation- 0.3 %, 0.6 %, 0.9 % and 1.2 %) were kept varying. The study by Ref. [259] stated that not only the EPS content and the density but also the thickness of the new replaced layer had a strong impact on the reduction of swelling as well in the decrease in the settlement. Recycled geofoam beads were mixed with the replaced soils at OMC. Study on the highly clayey soil (soil to be replaced) was performed wherein the LL, PL, OMC and MDD was noted as 143 %, 47.6 %, 24 % and 14 kN/m^3. Whereas the OMC and MDD of poorly graded fine sand (replacing soil) was 9 % and 19.2 kN/m^3. The compaction test gave the OMC and MDD as 24 % and 14 kN/m^3. Additionally, by performing Standard proctor compaction test on circular footings of varying diameter (5 cm, 7 cm, 10 cm and 12 cm) where the sand-EPS mix replacement layer above the bentonite layer were packed at their OMC and the vertical loading of 30 kN/m^2 was applied, it was noticed that as the breadth of footing was increased there was increase in settlement too whereas decrease in settlement and reduction in swelling of about 60 % was noticed in the presence of EPS beads. Moreover, the study also signified that as the beads content increased accordingly the swelling and settlement decreased, as the beads density increases vice versa was the effect on the swelling, lastly as the replacement layer thickness was increasing more it restricted the swelling and settlement as depicted in Fig. 5. Therefore, EPS as a admixture along with a replaced layer proves to be

Table 6
Test results as per different geo-bed content [257].

TI	Ps (%)	Sp (kPa)	Psr	Spr
Soil Alone	14.69	530	1.00	1.00
g_c = 0.25 %	13.23	452	0.90	0.85
g_c = 0.5 %	11.87	328	0.81	0.62
g_c = 0.75 %	9.44	273	0.64	0.52
g_c = 1 %	8.09	210	0.55	0.40

Where, gc = geo-bead content, TI = Test Identifier, Ps = Percent Swell, Sp = Swelling pressure, Psr = Percent swell reduction factor, Spr = Swelling pressure reduction factor.

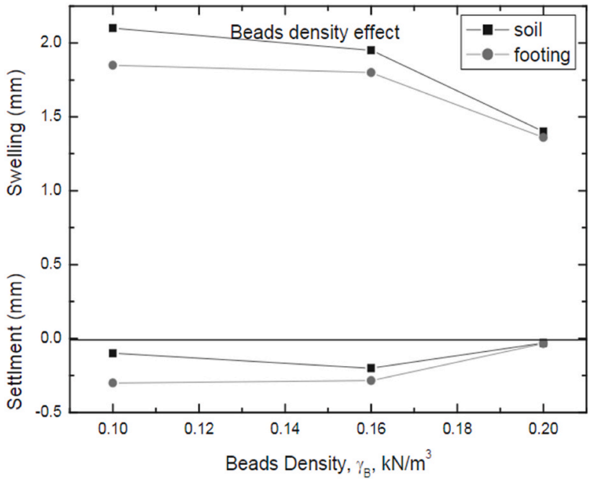

Fig. 5. Increasing Beads density on settlement and swelling for soil and footing [257].

beneficial to restrict and minimize the expansion and settlement of expansive soil.

[260] examined the deformation percentage of EPS beads at different diameter (3 mm and 4 mm) by performing laboratory consolidation compression test as well as simulating the same through FE-based ABAQUS software. The study involved conducting both lab-based consolidation compression experiments and computational modeling through ABAQUS to investigate the deformation behaviors and dynamics of EPS silt lightweight soil when subjected to repetitive stress. A variety of enhanced consolidation experiments were performed to assess the impact of numerous variables on the peak dynamic shear modulus and the baseline shear strain. The research examined how several factors, such as the proportion of EPS beads, the initial mean effective consolidation pressure, and the initial stress ratio of consolidation, influence the outcomes. Furthermore, the research delves into experimental methods, detailing the physical attributes of the base soil, the makeup of the binding agent, and the experimental arrangement. In these experiments, the team employed cyclic loads in the shape of trapezoidal waves and developed a medium-sized model for osmotic consolidation testing to record the EPS beads' deformation. The findings revealed that with an increase in the EPS beads' diameter, their volumetric deformation's contribution to the overall volumetric change diminished. Furthermore, the investigation uncovered that a higher EPS content led to a larger specific surface area and enhanced soil deformation. The research includes mesoscopic finite element numerical simulations of typical mixture ratio samples and compares the simulation results with experimental and theoretical calculations. The result shows (Fig. 6- where A_c, A_e,$V_{EPS,}$ V_t is the cement content, EPS content, volume of EPS beads and the total volume) The deformation of EPS particles plays a crucial role in the overall deformation of silt lightweight soil. In fact, the EPS deformation contributes significantly to the total volume deformation. Through extensive investigation, it was discovered that there was a significant decrease in the ratio of volumetric deformation as the diameter of EPS beads was enlarged during cyclic loading, as depicted in

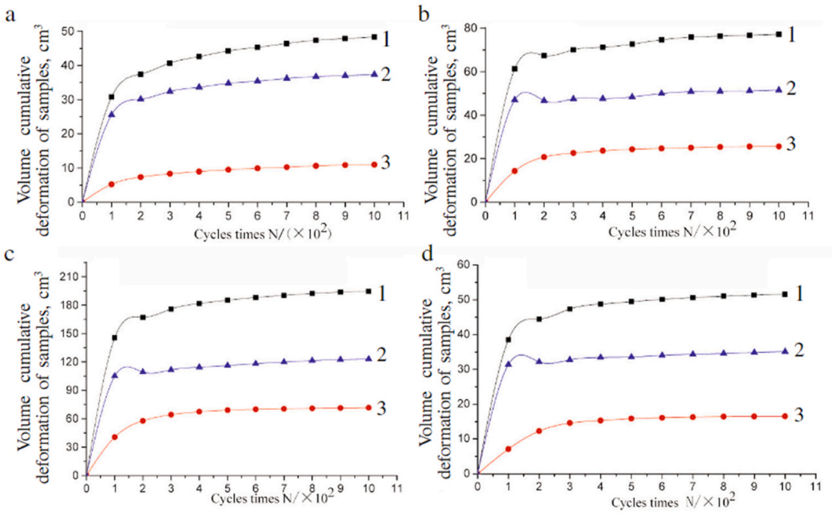

Fig. 6. Cumulative deformation relation curve of samples with different proportioning ratio: a) $A_c = 10$ %, $A_e = 3$ %, d = 3 mm; b) $A_c = 10$ %, $A_e = 3$ %, d = 4 mm; c) $A_c = 15$ %, $A_e = 4$ %, d = 4 mm; d) $A_c = 15$ %, $A_e = 2$ %, d = 4 mm; 1) V_t, 2) the drainage amount, 3) V_{EPS}t [260].

Fig. 6.

6.2.3. Effect of different EPS beads densities

[261] explored the mechanical characteristics of three distinct soil types: colluvial clayey soil, sandy soil, and bentonite. Conducted compaction tests, direct shear and drained triaxial tests to analyze their behavior. Additionally, explored the effects of reinforcing the soils with EPS beads at varying proportions (0.25, 0.5, 0.75, 1). All three types of soil have their respective Atterberg limits listed in Table .7. EPS beads have a low apparent density and do not absorb much moisture. Clayey soil when added up with EPS beads to a noticeable amount, decrement was seen in both the optimum moisture content and the maximum specific dried mass of the material. Observations were made regarding the design behavior of materials under different initial effective confining stresses. It was discovered that both sandy and clayey soil displayed a shift in stress compared with deformation behavior when subjected to higher initial effective confining stress. Similarly, bentonite showed a reduction in materials stiffness as the residual resistance increased, while still maintaining a constant peak resistance value at high initial effective confining stress. Studies on the impact of EPS bead addition on the expansiveness of clayey, sandy, and bentonite soils have shown a consistent reduction in expansion and contraction tendencies. It is worth noting that the integration of EPS into bentonite consistently enhanced its expansiveness. The study discovered that the addition of EPS had no negative effects on soil behavior, regardless of the different compositions used. In addition, the presence of EPS consistently improved one of the main measures of resistance, either cohesion or the internal friction angle. This highlights the positive impact of EPS in soil stabilization projects.

[262] performed a series of test on three artificial clays along within the mixture of EPS granules (EPS content mixed 0.9 %). The artificial clay included of sand-bentonite (where the bentonite content mixed were in the range of 16 %, 24 % and 32 %) in it whose properties are mentioned in the table. Several tests were conducted, including free swell, compaction, swell pressure, and volumetric shrinkage tests. Table 8 shows that the compaction test revealed a minimal change in the OMC, while a significant decrement was observed in the MDD. Fig. 7 demonstrates a noticeable reduction in swell pressure, with a range of 20–50 %, as the EPS content increases from 0 to 0.9 %. In addition, the observer observed a decrease in volumetric shrinkage and crack intensity with the introduction of EPS beads. The determination of volumetric shrinkage required the utilization of Proctor molds, while the assessment of crack intensity was conducted by measuring the crack intensity factor (CIF), which offers a measurement of subsurface cracking in the soil concentration [263–265].

$CIF = \Delta A/A = A_C/A$.

ΔA = Difference in area.

A_c = Area of cracks.

A = Actual area of soil sample.

[266] investigated the impact of freeze-thaw cycles on the characteristics of EPS particle lightweight soil. The researchers examined a specific type of clay, with a liquid limit of 31 %, a plastic limit of 17.1 %, a plasticity index of 13.9 %, and a maximum dry density of 1.8 g/cm^3. To evaluate the soil's response, tests were conducted including frost heave rate, mass loss rate, unconfined compressive strength, direct shear strength, and scanning electron microscopy. The key finding was that adding EPS particles significantly enhanced the soil's resistance to damage from repetitive freezing and thawing. Compared to untreated soil, samples with 2.5 % EPS showed lower frost heave and mass loss after 9 cycles. The EPS also helped preserve strength - the soil alone lost 75 % of its unconfined compressive strength through freeze-thaw cycling, whereas losses dropped to just 22.6 % with 2 % EPS content. Shear strength losses were also cut from 67.1 % to 31.8 % with 2 % EPS. The improvements stem from EPS's low density, thermal insulation, and elasticity to absorb strains. Cement hydration products also bolster particle bonding. Incorporating an optimal concentration of EPS beads counteracts freeze-thaw degradation of soil physical, mechanical, and microstructural properties. After undergoing 9 freeze-thaw cycles, the soil with 2.5 % EPS experienced a significant reduction in frost heave rate compared to the natural soil. The mass loss rate also decreased from 1.25 % to 0.42 % with EPS addition. Furthermore, the unconfined compressive strength loss was lowered from 75 % for the plain soil to 22.6 % for the soil with 2 % EPS. The shear strength loss rate also reduced from 67.1 % to 31.8 % with 2 % EPS content. Concept behind such enhancement would be due to - The advancements can be credited to the unique properties of EPS, such as its low density and thermal conductivity, which offer excellent insulation. Additionally, its elastic nature allows it to absorb frost heave deformations and minimize structural damage caused by freeze-thaw cycling. Cement hydration products also assist by enhancing strength and connectivity between the soil and EPS particles. An optimum EPS content balances the stiffness reduction and damping improvement effects. Excess EPS reduces the cement bonding capability. SEM observation showed that the EPS maintained soil integrity after freeze-thaw cycles by absorbing expansive forces. In general, incorporating EPS beads into the mixture helps counteract the adverse result of F-T cycles on soil characteristics. This can be achieved by leveraging the insulation properties of the beads and maintaining a cohesive structure with the cement binder.

Table 7
Test results of soil as different soil [261].

Sr No.	Name of soil	Liquid Limit	Plastic Limit	USCS Classification	Min-Max Void Ratio
1.	Colluvial clayey soil	53	39	CH	–
2.	Bentonite	368.4	53.7	CH	–
3.	Sandy soil	–	–	SP	0.51–0.74

Table 8
Liquid limit and compaction results of different mixtures [262].

Mix	LL %	PL%	OMC %	MDD g/cc
SB16	43	21	13.5	1.73
SB24	60	22	12	1.74
SB32	77	24	14	1.71

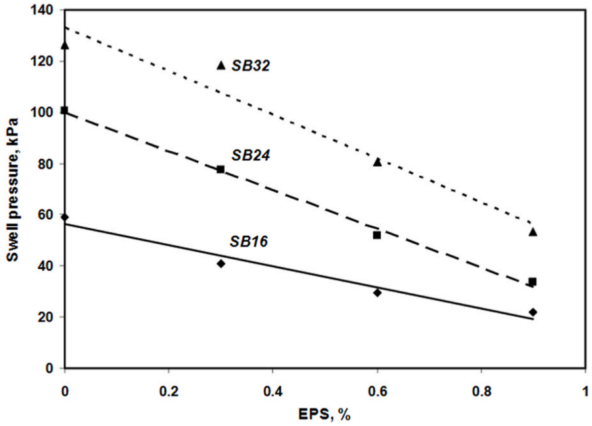

Fig. 7. Swell pressure of soil mixed with EPS [262].

6.2.4. Summary of EPS case studies

The use of EPS beads as a stabilizer for expansive soils has shown promising results in reducing swelling, improving strength, and enhancing overall soil behavior. The effectiveness of EPS stabilization depends on various factors, such as bead size, content, and density. Studies have shown that EPS bead sizes in the range of 1–3 mm generally provide the optimal stabilization effects, exhibiting higher density, strength, and lower hydraulic conductivity. Smaller beads tend to have better bonding with soil particles, leading to improved strength and reduced compressibility [251,253–255].

Increasing EPS bead content in the soil mixture has been found to decrease swelling pressure and percent swell significantly. The collapsible nature of EPS beads and their ability to absorb volumetric deformations contribute to the reduction in swelling behavior [257,259,260]. The density of EPS beads also plays a role in their stabilization efficacy. Lower density beads provide better insulation and elastic properties, helping to absorb strains and minimize damage from freeze-thaw cycles [261,262,266]. In conclusion, the incorporation of EPS beads as a stabilizer for expansive soils offers a promising alternative to traditional stabilization methods. By carefully considering factors such as bead size, content, and density, engineers can optimize the stabilization effects and improve the performance of expansive soils in construction projects.

7. Discussion

In the current review of soil stabilization techniques for problematic soils, various indicators of engineering performance have been thoroughly discussed to evaluate the effectiveness of different stabilization methods. The study emphasizes key parameters such as resilient modulus, swelling behavior, strength, specific surface area (SSA), and cation exchange capacity (CEC) as crucial indicators of soil performance.

The resilient modulus, a measure of soil stiffness and load-bearing capacity, has been shown to improve significantly with the addition of stabilizing agents like lime, fly ash, and cement kiln dust. This enhancement in resilient modulus indicates improved structural support and resistance to deformation under repeated loading conditions. Swelling behavior, which refers to the tendency of soils to expand when exposed to water, is another critical indicator addressed in the study. The incorporation of materials such as expanded polystyrene (EPS) beads has been investigated for its potential to mitigate the swelling potential of expansive soils, thereby enhancing soil stability and reducing the risk of structural distress.

Soil strength plays a crucial role in determining the load-bearing capacity and resistance to deformation. The research highlights the importance of reinforcing soils with fibers, such as palm fibers, to enhance their mechanical properties and ductility. Improved strength characteristics are essential for ensuring the long-term performance of stabilized soils in various construction applications. The specific surface area (SSA) of soil particles is identified as a critical factor influencing soil behavior. The study recognizes that soils with smaller particles and higher SSA exhibit notable changes in engineering characteristics. Therefore, understanding and controlling the SSA is crucial for predicting and optimizing soil performance. Furthermore, the study explores the role of lime treatment in altering the cation exchange capacity (CEC) of marine clay. CEC is a measure of a soil's ability to retain and exchange cations, affecting its nutrient availability and stability. By addressing the impact of lime treatment on CEC, the study provides insights into soil improvement practices.

By considering these key indicators of engineering performance, the reviewed manuscript offers valuable insights for engineers seeking effective and sustainable soil stabilization solutions for infrastructure development. The comprehensive evaluation of these parameters enables a deeper understanding of soil behavior and facilitates the selection of appropriate stabilization techniques tailored to specific project requirements and soil conditions. Additionally, the efficient role of lime and FA in stabilizing various soils relies upon the unique physicochemical properties of both the soil as well as its additives. Where lime and FA are additives that contain calcium.; however, their calcium oxide content differs. Consequently, their application frequently results in fluctuation in the strength, durability as well as on the performance of treated soils. When it comes to lime and FA stabilization, all three treatment processes are involved: pozzolanic reactions, flocculation-agglomeration, and cation exchange. In comparison to cement or FA, lime exhibits a higher reactivity with clay and exerts a more notable impact on the plasticity of soil [267,268]. Since multiple F-T cycles, the efficacy of cement-treated soil under dynamic loading is superior to that of lime-treated soil [269]. Because of its low lime content, FA does not offer the same level of strength or durability as other materials In contrast, clay treated with FA has a lower occurrence of sulfate-induced heave in-respect to cement or lime [219].

The efficient role of lime and fly ash in stabilizing various soils relies upon their unique physicochemical properties and their interaction with the soil. Lime and fly ash both contain calcium, but their calcium oxide content differs, leading to variations in the strength, durability, and performance of treated soils [267,268]. Lime exhibits higher reactivity with clay and has a more significant impact on soil plasticity compared to cement or fly ash. However, the efficacy of cement-treated soil under dynamic loading after multiple freeze-thaw cycles is superior to that of lime-treated soil [269]. Fly ash, due to its low lime content, does not offer the same level of strength or durability as other materials, but clay treated with fly ash has a lower occurrence of sulfate-induced heave compared to cement or lime [219].

EPS beads, on the other hand, have been shown to improve the engineering properties of expansive soils by reducing swelling pressure, decreasing volumetric shrinkage, and increasing strength [256,257]. The effectiveness of EPS beads depends on factors such as bead size, content, and density [253–255].

Combining EPS beads with lime and fly ash could potentially lead to a synergistic effect, where the unique properties of each stabilizer complement each other. The pozzolanic reactions, flocculation-agglomeration, and cation exchange processes associated with lime and fly ash treatment, coupled with the mechanical stabilization provided by EPS beads, could result in improved soil properties. However, research on the combined use of these stabilizers is limited, and further studies are needed to understand the interaction between EPS beads, lime, and fly ash in soil stabilization.

Research gaps that need to be addressed for EPS-lime-fly ash systems include:

1. Optimizing the proportions of EPS beads, lime, and fly ash for different soil types and conditions.
2. Investigating the long-term durability and performance of soils treated with EPS-lime-fly ash systems under various environmental conditions, such as freeze-thaw cycles and wet-dry cycles.
3. Examining the microstructural changes and chemical interactions in soils stabilized with EPS-lime-fly ash systems.
4. Evaluating the environmental impact and sustainability of using EPS-lime-fly ash systems for soil stabilization.

8. Conclusion

This paper offers a thorough examination on the impact of many add-ons, inclusive of lime, EPS beads and Fly-Ash on the stabilization of expansive soils. The present review focusses on deep understanding of the transformation that occur in expansive soils when subjected to various additives, their characteristics, both physical and chemical, along with their microstructural characteristics, undergo changes. By the above-mentioned research's, it can be concluded that –

1. Incorporating calcium-based chemical additives enhances the dimensional stability and mechanical robustness of clay materials. The efficacy of this stabilization technique is contingent upon multiple variables such as the dosage of the stabilizer, the mineral composition of the clay, the nature of the soil, the soil's pH balance, the duration of curing, freeze-thaw cycles, the temperature during curing, and the existence of deleterious substances like organic matter and sulfates.
2. Fly-Ash with the combination of lime can give better results instead of being used alone, although after certain drying-wetting cycles the binding and the strength enhancing effect may get reduced.
3. EPS beads with the combination of other additives in order to reduce swelling are resulting more efficient, more economical and long lasting. Although further study on EPS beads with more such additives are required which would ultimately pave the path for re-using of such world-wide waste in a fruitful manner and can be used at many places such as back fill of retaining wall, under light weight structures, bridge abutments etc.
4. EPS beads with moderate density and small sizes have gained the most efficient results in order to reduce swelling. Although content, density and size determination will purely depend on the soil particle size or type. Therefore, a study from this aspect is needed in-order to draw a proper relation between EPS beads parameters and soil properties in respect to use beads accordingly. Generally, EPS content with a broad range of between 0.5 and 1% with densities varying between 13 and 25 kg/m^3 have yet shown the better results.
5. The combination of lime fly ash and EPS beads can result more efficiently to not only reduce the swelling in the soil but would also withstand the flaws of fly-ash and lime wherever needed, especially in freezing and thawing or wetting and drying cycles.

6. More studies on local lime should be proposed in-respect to get better engineering characteristics of expansive soil as the quick or hydrated limes are not easily available at remote places.
7. Studies on reduction of specific surface area with the involvement of EPS beads is another aspect to be looked into as the swelling of soil is directly linked to specific surface area.

CRediT authorship contribution statement

Utkarsh: Writing – review & editing, Writing – original draft, Visualization. **Pradeep Kumar Jain:** Supervision, Investigation.

Declaration of competing interest

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

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References

[1] B.C.S. Chittoori, A.J. Puppala, A. Pedarla, Addressing clay mineralogy effects on performance of chemically stabilized expansive soils subjected to seasonal wetting and drying, J. Geotech. Geoenviron. Eng. 144 (1) (2018), https://doi.org/10.1061/(asce)gt.1943-5606.0001796.
[2] A.J. Puppala, F. Asce, A. Pedarla, M. Asce, A. Pino, A.M. Asce, L.R. Hoyos, Diffused double-layer swell prediction model to better characterize natural expansive clays. https://doi.org/10.1061/(ASCE, 2017.
[3] A. Puppala, A. Cerato, Heave distress problems in chemically-treated sulfate-laden materials ODOT: validation and refinement of chemical stabilization procedures for pavement subgrade soil in Oklahoma view project ODOT: realtime monitoring of slope stability in eastern Oklahoma view project. https://www.researchgate.net/publication/290487635, 2009.
[4] P. Jiang, Y. Chen, W. Wang, J. Yang, H. Wang, N. Li, W. Wang, Flexural behavior evaluation and energy dissipation mechanisms of modified iron tailings powder incorporating cement and fibers subjected to freeze-thaw cycles, J. Clean. Prod. 351 (2022) 131527, https://doi.org/10.1016/j.jclepro.2022.131527.
[5] S.M. Hejazi, M. Sheikhzadeh, S.M. Abtahi, A. Zadhoush, A simple review of soil reinforcement by using natural and synthetic fibres, Construct. Build. Mater. 30 (2012) 100–116.
[6] M. Bouhicha, F. Aouissi, S. Kenai, Performance of composite soil reinforced with barley straw, Cement Concr. Compos. 27 (5) (2005) 617–621, https://doi.org/10.1016/j.cemconcomp.2004.09.013.
[7] A.K. Choudhary, J.N. Jha, K.S. Gill, A study on CBR behavior of waste plastic strip reinforced soil, Emirates Journal for Engineering Research 15 (Issue 1) (2010).
[8] A.R. Estabragh, H. Rafatjo, A.A. Javadi, Treatment of an expansive soil by mechanical and chemical techniques, Geosynth. Int. 21 (3) (2014) 233–243, https://doi.org/10.1680/gein.14.00011.
[9] P.K. Jayasree, K. Balan, L. Peter, K.K. Nisha, Volume change behavior of expansive soil stabilized with coir waste, J. Mater. Civ. Eng. 27 (6) (2015), https://doi.org/10.1061/(asce)mt.1943-5533.0001153.
[10] S.M. Marandi, A. Prof, M.H. Bagheripour, R. Rahgozar, H. Zare, Strength and ductility of randomly distributed palm fibers reinforced silty-sand soils 1, Am. J. Appl. Sci. 5 (3) (2008) 209–220.
[11] M. Mirzababaei, M. Miraftab, M. Mohamed, P. McMahon, Impact of carpet waste fibre addition on swelling properties of compacted clays, Geotech. Geol. Eng. 31 (1) (2013) 173–182, https://doi.org/10.1007/s10706-012-9578-2.
[12] S.S. Park, Unconfined compressive strength and ductility of fiber-reinforced cemented sand, Construct. Build. Mater. 25 (2) (2011) 1134–1138, https://doi.org/10.1016/j.conbuildmat.2010.07.017.
[13] S.K. Patel, B. Singh, Effect of fibre reinforcement on strength and stiffness improvement of cohesive soil, Infrastructure Development for Environmental Conservation & Sustenance 137 (2015) 2–7, 28-30 October, 2015.
[14] J. Prabakar, R.S. Sridhar, Effect of random inclusion of sisal fibre on strength behaviour of soil, Construct. Build. Mater. 16 (2002).
[15] M. Segetin, K. Jayaraman, X. Xu, Harakeke reinforcement of soil-cement building materials: manufacturability and properties, Build. Environ. 42 (8) (2007) 3066–3079, https://doi.org/10.1016/j.buildenv.2006.07.033.
[16] Y.-X. Wang, P.-P. Guo, W.-X. Ren, B.-X. Yuan, H.-P. Yuan, Y.-L. Zhao, S.-B. Shan, P. Cao, Laboratory investigation on strength characteristics of expansive soil treated with jute fiber reinforcement, Int. J. GeoMech. 17 (11) (2017), https://doi.org/10.1061/(asce)gm.1943-5622.0000998.
[17] J.S. Yadav, S.K. Tiwari, Effect of waste rubber fibres on the geotechnical properties of clay stabilized with cement, Appl. Clay Sci. 149 (2017) 97–110, https://doi.org/10.1016/j.clay.2017.07.037.
[18] A.J. Puppala, S.P. Pokala, N. Intharasombat, R. Williammee, Effects of organic matter on physical, strength, and volume change properties of compost amended expansive clay, J. Geotech. Geoenviron. Eng. 133 (11) (2007) 1449–1461, https://doi.org/10.1061/ASCE1090-02412007133:111449.
[19] S. Bhattacharja, J.I. Bhatty, Comparative performance of Portland cement and lime stabilization of moderate to high plasticity clay soils. www.cement.org, 2003.
[20] R. Leite, R. Cardoso, C. Cardoso, E. Cavalcante, O. De Freitas, Lime stabilization of expansive soil from Sergipe-Brazil. https://doi.org/10.1051/e3sconf/20160914005, 2016.
[21] D.T. Bergado, L.R. Anderson, N. Miura, A.S. Balasubramaniam, Soft Ground Improvement in Lowland and Other Environments, ASCE Press, 1996.
[22] H. Brandl, Alteration of soil parameters by stabilization with lime, in: Proceedings of the 10th International Conference on Soil, vol 3, Mechanics and Foundation Engineering, Stockholm, 1981.
[23] B.C.S. Chittoori, A.J. Puppala, T. Wejrungsikul, L.R. Hoyos, Experimental studies on stabilized clays at various leaching cycles, J. Geotech. Geoenviron. Eng. 139 (10) (2013) 1665–1675, https://doi.org/10.1061/(asce)gt.1943-5606.0000920.
[24] M.F.R. Hasan, I.Z. Utama, A.F.A. Razzak, A. Salimah, P.A.M. Agung, Clayshale stabilization using active natural lime to increase the shear strength of soil, in: IOP Conference Series: Earth and Environmental Science, vol 1173, IOP Publishing, 2023, May 012025, https://doi.org/10.1088/1755-1315/1173/1/012025, 1.
[25] F.G. Bell, Lime stabilization of clay minerals and soils, Eng. Geol. 42 (4) (1996) 223–237, https://doi.org/10.1016/0013-7952(96)00028-2.
[26] S. Hanchanloet, Evaluation of a New Chemical Stabilization Method on Physical and Strength Properties of Cohesive Soils, The University of Texas at Arlington, 1999.
[27] A.J. Puppala, E. Wattanasanticharoen, K. Punthutaecha, Experimental evaluations of stabilisation methods for sulphate-rich expansive soils, Proceedings of the Institution of Civil Engineers-Ground Improvement 7 (1) (2003) 25–35, https://doi.org/10.1680/grim.2003.7.1.25.

[28] H. Mola-Abasi, A. Eslami, Prediction of drained soil shear strength parameters of marine deposit from CPTu data using GMDH-type neural network, Mar. Georesour. Geotechnol. 37 (2) (2019) 180–189.
[29] S. Diamond, E.B. Kinter, Mechanisms of soil-lime stabilization, Highw. Res. Rec. 92 (303) (1965) 83–102.
[30] M.A. Usmen, J.J. Bowders Jr, Stabilization characteristics of class F fly ash, Transport. Res. Rec. 1288 (1990).
[31] P.G. Nicholson, V. kashyap, C.F. Fujii, Transportation Research Record No. 1440, Design and Performance of Stabilized Bases, and Lime and Fly Ash Stabilization, 1994.
[32] S. Pavan, S.K. Rao, Effect of fly ash on strength characteristics of roller compacted concrete pavement, IOSR J. Mech. Civ. Eng. 11 (6) (2014), https://doi.org/10.9790/1684-11620408, 04–08.
[33] A. Puppala, L. Hoyos, C. Viyanant, C. Musenda, Fiber and Fly Ash Stabilization Methods to Treat Soft Expansive Soils, 2001.
[34] S. Bin-Shafique, K. Rahman, M. Yaykiran, I. Azfar, The long-term performance of two fly ash stabilized fine-grained soil subbases, Resour. Conserv. Recycl. 54 (10) (2010) 666–672, https://doi.org/10.1016/j.resconrec.2009.11.007.
[35] W.F. Barstis, Long-term Effect of Lime-Fly Ash Treated Soils (No. FHWA/MS-DOT-RD-03-147), Dept. of Transportation, Mississippi, 2003. Sivapullaiah, P. V., Prashanth, J. P., & Sridharan, A. (1996). Effect of fly ash on index properties.
[36] P.V. Sivapullaiah, J.P. Prashanth, A. Sridharan, Effect of fly ash on the index properties of black cotton soil, Soils Found. 36 (1) (1996) 97–103.
[37] A.H. Padade, J.N. Mandal, Expanded polystyrene-based geomaterial with fly ash, Int. J. GeoMech. 14 (6) (2014) 06014013.
[38] T.D. Stark, Guideline and Recommended Standard for Geofoam Applications in Highway Embankments, vol 529, Transportation Research Board, 2004.
[39] A.T. Özer, O. Akay, G.A. Fox, S.F. Bartlett, D. Arellano, A new method for remediation of sandy slopes susceptible to seepage flow using EPS-block geofoam, Geotext. Geomembranes 42 (2) (2014) 166–180.
[40] J.S. Horvath, The compressible inclusion function of EPS geofoam, Geotext. Geomembranes 15 (1–3) (1997) 77–120.
[41] A. Khajeh, R. Jamshidi Chenari, M. Payan, A review of the studies on soil-EPS composites: beads and blocks, Geotech. Geol. Eng. 38 (2020) 3363–3383, https://doi.org/10.1007/s10706-020-01252-2.
[42] G.P. Murphy, The influence of geofoam creep on the performance of a compressible inclusion, Geotext. Geomembranes 15 (1–3) (1997) 121–131, https://doi.org/10.1016/S0266-1144(97)00009-5.
[43] M. Aytekin, Numerical modeling of EPS geofoam used with swelling soil, Geotext. Geomembranes 15 (1–3) (1997) 133–146, https://doi.org/10.1016/S0266-1144(97)00010-1.
[44] S.B. Ikizler, M. Aytekin, E. Nas, Laboratory study of expanded polystyrene (EPS) geofoam used with expansive soils, Geotext. Geomembranes 26 (2) (2008) 189–195, https://doi.org/10.1016/j.geotexmem.2007.05.005.
[45] O.L. Ertugrul, A.C. Trandafir, Reduction of lateral earth forces acting on rigid nonyielding retaining walls by EPS geofoam inclusions, J. Mater. Civ. Eng. 23 (12) (2011) 1711–1718, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000348.
[46] O. Akay, A.T. Özer, G.A. Fox, S.F. Bartlett, D. Arellano, Behavior of sandy slopes remediated by EPS-block geofoam under seepage flow, Geotext. Geomembranes 37 (2013) 81–98, https://doi.org/10.1016/j.geotexmem.2013.02.005.
[47] H.L. Liu, A. Deng, J. Chu, Effect of different mixing ratios of polystyrene pre-puff beads and cement on the mechanical behaviour of lightweight fill, Geotext. Geomembranes 24 (6) (2006) 331–338, https://doi.org/10.1016/j.geotexmem.2006.05.002.
[48] T. Tsuchida, A. Porbaha, N. Yamane, Development of a geomaterial from dredged bay mud, J. Mater. Civ. Eng. 13 (2) (2001) 152–160, https://doi.org/10.1061/(ASCE)0899-1561(2001)13:2(152).
[49] N. Yasufuku, Geotechnical reuse of waste expanded polystyrene as a light-weight geomaterial, in: Proc. 4th Int Congr Environ Geotechnics., vol 1, 2002, pp. 603–608, 2002.
[50] K. Minegishi, K. Makiuchi, R.J. Takahashi, Strength-deformational characteristics of EPS beads-Mixed lightweight geomaterial subjected to cyclic loadings, in: Proceeding of the International Workshop on Lightweight Geo-Materials, 2002, March.
[51] S.W. Lye, H.S. Aw, S.G. Lee, Adhesives for bead fusion of recycled expandable polystyrene, J. Appl. Polym. Sci. 86 (2) (2002) 456–462, https://doi.org/10.1002/app.11004.
[52] C. Shin, G.G. Chase, D.H. Reneker, Recycled expanded polystyrene nanofibers applied in filter media, Colloids Surf. A Physicochem. Eng. Asp. 262 (1–3) (2005) 211–215, https://doi.org/10.1016/j.colsurfa.2005.04.034.
[53] S.M. Rao, B.V.V. Reddy, M. Muttharam, The impact of cyclic wetting and drying on the swelling behaviour of stabilized expansive soils, Eng. Geol. 60 (1–4) (2001) 223–233, https://doi.org/10.1016/S0013-7952(00)00106-5.
[54] M.B. McBride, A critique of diffuse double layer models applied to colloid and surface chemistry, Clay Clay Miner. 45 (4) (1997) 598–608.
[55] N.V. Nayak, R.W. Christensen, Swelling characteristics of compacted, expansive soils, Clay Clay Miner. 19 (1971), https://doi.org/10.1346/CCMN.1971.0190406. Pergamon Press.
[56] J.K. Mitchell, K. Soga, Fundamentals of Soil Behavior, vol 3, John Wiley & Sons, New York, 2005. USA.
[57] A. Tarantino, Basic Concepts in the Mechanics and Hydraulics of Unsaturated Geomaterials, 2010, https://doi.org/10.1002/9781118616871.ch1.
[58] L.D. Whittig, W.R. Allardice, X-ray diffraction techniques, Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods 5 (1986) 331–362, https://doi.org/10.2136/sssabookser5.1.2ed.c12.
[59] R.A. Osemenam, T.B. Afeni, V.A. Alfred, J.N. Onwualu-John, Evaluation of Some Ceramic Properties of Gadabiu Clay Deposit (Kwali Area Council, Abuja, Nigeria), Mining of Mineral Deposits, 2019, https://doi.org/10.33271/mining13.01.009.
[60] S. Vahur, L. Kiudorv, P. Somelar, J.M. Cayme, M.D.C. Retrato, R.J. Remigio, I. Leito, Quantitative mineralogical analysis of clay-containing materials using ATR-FT-IR spectroscopy with PLS method, Anal. Bioanal. Chem. 413 (26) (2021) 6535–6550, https://doi.org/10.1007/s00216-021-03617-9.
[61] A.A. Adebowale, B.T. Anthony, Rare earth and trace elements composition of a residual clay from Sosan Akoko, southwestern Nigeria: implications for weathering and provenance, Environmental & Earth Sciences Research Journal 9 (2) (2022), https://doi.org/10.18280/eesrj.090201.
[62] X. Zhou, D. Liu, H. Bu, L. Deng, H. Liu, P. Yuan, H. Song, XRD-based quantitative analysis of clay minerals using reference intensity ratios, mineral intensity factors, Rietveld, and full pattern summation methods: a critical review, Solid Earth Sciences 3 (1) (2018) 16–29, https://doi.org/10.1016/j.sesci.2017.12.002.
[63] B.D. Cullity, Elements of X-Ray Diffraction, Addison-Wesley Publishing, 1956.
[64] J.E. Amonette, Methods for determination of mineralogy and environmental availability, Soil mineralogy with environmental applications 7 (2002) 153–197, https://doi.org/10.2136/sssabookser7.c5.
[65] R.E. Grim, Clay mineralogy McGraw Hill Book Company, JOUR GEOL SOC INDIA 66 (2005), 179-1.
[66] D.M. Moore, R.J. Reynolds, X-Ray Diffraction and the Identification and Analysis of Clay Minerals, 1989, p. 332.
[67] S. Narasimha Rao, K.V. Subba Rao, G. Rajasekaran, Microstructure studies of lime treated marine clays, in: Proceedings of the international conference on offshore mechanics and Arctic engineering, American Society of Mechanical Engineers, 1993, p. 425, https://doi.org/10.1016/S0029-8018%2896%2900041-8, 425.
[68] Y. Shouxun, P. Jin, A study on the correlation relationships between smectite contents and spectral absorption indices of swelling soils, in: IGARSS 2004. 2004 IEEE International Geoscience and Remote Sensing Symposium, vol 7, Ieee, 2004, September, pp. 4674–4677, https://doi.org/10.1109/IGARSS.2004.
[69] K. Emmerich, Thermal Analysis in the Characterization and Processing of Industrial Minerals, 2010, https://doi.org/10.1180/EMU-notes.9.5.
[70] A. Derkowski, A. Kuligiewicz, Thermal analysis and thermal reactions of smectites: a review of methodology, mechanisms, and kinetics, Clay Clay Miner. 70 (6) (2022) 946–972, https://doi.org/10.1007/s42860-023-00222-y.
[71] L.L. Baker, D.G. Strawn, K.L. Vaughan, P.A. McDaniel, XAS study of Fe mineralogy in a chronosequence of soil clays formed in basaltic cinders, Clay Clay Miner. 58 (6) (2010) 772–782, https://doi.org/10.1346/CCMN.2010.0580605.
[72] A. Saentho, C. Sjöstedt, N. Prakongkep, W. Klysubun, J.P. Gustafsson, W. Wisawapipat, Fate of silicon in tropical agricultural soil clays using XANES spectroscopy, Appl. Clay Sci. 245 (2023) 107145, https://doi.org/10.1016/j.clay.2023.107145.

[73] G.M. Do Nascimento, Structure of clays and polymer-clay composites studied by X-ray absorption spectroscopies, in: J.N. Govil, G.V. Gajewicz (Eds.), Clays, Clay Minerals and Ceramic Materials Based on Clay Minerals, CRC Press, 2016, pp. 137–174.
[74] N. Finck, Iron speciation in Opalinus clay minerals, Appl. Clay Sci. 193 (2020) 105679, https://doi.org/10.1016/j.clay.2020.105679.
[75] N. Ural, The significance of scanning electron microscopy (SEM) analysis on the microstructure of improved clay: an overview, Open Geosci. 13 (1) (2020) 197–218, https://doi.org/10.1515/geo-2020-0145.
[76] R.D. Holtz, W.D. Kovacs, An Introduction to Geotechnical Engineering, Prentice-Hall, 1981.
[77] T.W. Lambe, The structure of inorganic soil, Proc. Am. Soc. Civ. Eng. 79 (10) (1953) 1–49.
[78] B. Behera, M.K. Mishra, Effect of lime on the California bearing ratio behaviour of fly ash-mine overburden mixes, World Academy of Science, Engineering and Technology 75 (2011) 161–166.
[79] M.A.M. Al-Bared, A. Marto, N. Latifi, S. Horpibulsuk, Sustainable improvement of marine clay using recycled blended tiles, Geotech. Geol. Eng. 36 (5) (2018) 3135–3147, https://doi.org/10.1007/s10706-018-0525-8.
[80] Y. Millogo, J.C. Morel, K. Traoré, R. Ouedraogo, Microstructure, geotechnical and mechanical characteristics of quicklime-lateritic gravels mixtures used in road construction, Construct. Build. Mater. 26 (1) (2012) 663–669, https://doi.org/10.1016/j.conbuildmat.2011.06.069.
[81] F. Zhu, Z. Li, W. Dong, Y. Ou, Geotechnical properties and microstructure of lime-stabilized silt clay, Bull. Eng. Geol. Environ. 78 (4) (2019) 2345–2354, https://doi.org/10.1007/s10064-018-1307-5.
[82] A. Fauzi, Z. Djauhari, U.J. Fauzi, Soil engineering properties improvement by utilization of cut waste plastic and crushed waste glass as additive, Int. J. Eng. Technol. 8 (1) (2016) 1–5, https://doi.org/10.7763/IJET.2016.V8.855.
[83] M. Keramatikerman, A. Chegenizadeh, H. Nikraz, A.S. Sabbar, Effect of flyash on liquefaction behaviour of sand-bentonite mixture, Soils Found. 58 (5) (2018) 1288–1296, https://doi.org/10.1016/j.sandf.2018.06.007.
[84] J.J. Camberato, Cation exchange capacity-everything you want to know and much more, SC Turfgrass Found. News (2001). Mitchell, J. K. (2005). Fundamentals of soil behavior (3rd ed.). John Wiley & Sons.
[85] J.D. Rhoades, Cation exchange capacity, in: A.L. Page, R.H. Miller, D.R. Keeney (Eds.), Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, second ed., American Society of Agronomy, 1982, pp. 149–157, https://doi.org/10.2134/agronmonogr9.2.2ed.c8.
[86] J.A. Campbell, Soil and soil physical properties, in: M. Crummy (Ed.), Encyclopedia of Earth Sciences Series - Soil Mineralogy, Springer, 2005, pp. 44–47.
[87] M. Khorshidi, N. Lu, I.D. Akin, W.J. Likos, Intrinsic relationship between specific surface area and soil water retention, J. Geotech. Geoenviron. Eng. 143 (1) (2017) 04016086, 0.1061/(ASCE)GT.1943-5606.0001572.
[88] N. Lu, C. Zhang, Separating external and internal surface areas of soil particles, J. Geotech. Geoenviron. Eng. 146 (2) (2020) 06020001, https://doi.org/10.1061/(ASCE)GT.1943-5606.0002198.
[89] G.S. Dasog, D.F. Acton, A.R. Mermut, E. De Jong, Shrink-swell potential and cracking in clay soils of Saskatchewan, Can. J. Soil Sci. 68 (2) (1988) 251–260, https://doi.org/10.4141/cjss88-025.
[90] Amaral Dos, Effect of Temperature on the Unconfined Shear Strength Behavior of a Saturated Remolded Clay, Master's thesis, University of California, Berkeley, 1965. ProQuest Dissertations and Theses database.
[91] P.F. Low, The swelling of clay: II. Montmorillonites, Soil Sci. Soc. Am. J. 44 (4) (1980) 667–676.
[92] C.J. Ross, Relationships of specific surface area and clay content to shrink, Swell Potential of Soils Having Different Clay Mineralogical Compositions, Master's thesis 58, University of Saskatchewan, 1978, pp. 159–166, https://harvest.usask.ca/handle/10388/etd-07092010-103531.
[93] D. Knudsen, G.A. Peterson, P.F. Pratt, Lithium, sodium, and potassium, in: A.L. Page, R.H. Miller, D.R. Keeney (Eds.), Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, second ed., American Society of Agronomy, 1982, pp. 225–246.
[94] M.L. Jackson, Soil Chemical Analysis-Advanced Course, 1969.
[95] A. Sridharan, K. Prakash, Classification procedures for expansive soils, Proceedings of the Institution of Civil Engineers-Geotechnical Engineering 143 (4) (2000) 235–240, https://doi.org/10.1680/geng.2000.143.4.235.
[96] K. Prakash, A. Sridharan, Free swell ratio and clay mineralogy of fine-grained soils, Geotech. Test J. 27 (2) (2004) 220–225, https://doi.org/10.1520/GTJ10860.
[97] C.C. Ikeagwuani, D.C. Nwonu, Emerging trends in expansive soil stabilisation: a review, J. Rock Mech. Geotech. Eng. 11 (2) (2019) 423–440, https://doi.org/10.1016/j.jrmge.2018.08.013.
[98] F.G. Bell, Lime stabilization of clay minerals and soils, Eng. Geol. 42 (4) (1996) 223–237.
[99] R.L. Buhler, A.B. Cerato, Stabilization of Oklahoma expansive soils using lime and class C fly ash. https://doi.org/10.1061/40906(225, 2007.
[100] S.K. Dash, M. Hussain, Lime stabilization of soils: reappraisal, J. Mater. Civ. Eng. 24 (6) (2012) 707–714, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000431.
[101] A.J. Puppala, N. Intharasombat, R.K. Vempati, Experimental studies on ettringite-induced heaving in soils, J. Geotech. Geoenviron. Eng. 131 (3) (2005) 325–337, https://doi.org/10.1061/ASCE1090-02412005131:3325.
[102] T.S. Umesha, S.V. Dinesh, P.V. Sivapullaiah, Effects of acids on geotechnical properties of black cotton soil, International Journal of Geology 6 (3) (2013) 75–84.
[103] A. Herzog, J.K. Mitchell, Reactions accompanying the heat-curing of lime-soil mixtures, Highw. Res. Rec. (29) (1963).
[104] S.H. Gallala, A. Awad, M. Ayoub, Evaluation of municipal solid waste incineration bottom ash for replacements of cement, J. Eng. Sci. 36 (4) (2008) 957–970. Assiut University.
[105] C. Shi, Formation and Stability of 3:1 Chloride Minerals in Thermal Environment (No. DOE/ER/14795–1T; BNL-68213-2001), Brookhaven National Lab., Upton, NY (US), 2001.
[106] E.B. Nelson, G.A. Miller, Fabric Characteristics of Lime Soil Mixtures and Their Relation to Strength: A Literature Review, Transportation Research Board, 1997.
[107] M. Di Sante, E. Fratalocchi, F. Mazzieri, E. Pasqualini, Time of setting and demolding of a pozzolanic lime–cement brick material with castor oil, Mater. Des. 63 (2015) 512–521.
[108] T.M. Petry, T.R. Lee, Quality control for a lime-treated urban soil base, Transport. Res. Rec. 1192 (1988) 275–281.
[109] A.A. Amadi, A. Okeiyi, Use of quick and hydrated lime in strength improvement of expansive soils: a comparative study, J. Civ. Eng. Construct. Technol. 8 (1) (2017) 1–11.
[110] D.N. Little, The Fundamentals of the Stabilization of Soil with Lime, National Lime Association, 1996.
[111] F.G. Bell, Engineering Treatment of Soils, CRC Press, 1993.
[112] G.H. Hilt, D.T. Davidson, Lime fixation in clayey soils, Highway Research Board Bulletin 262 (1960).
[113] P.K. Mathew, S.N. Rao, Effect of lime on cation exchange capacity of marine clay, J. Geotech. Geoenviron. Eng. 123 (2) (1997) 183–185.
[114] M. Arabi, S. Wild, Fabric and strength of lime-treated soils, in: Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering, vol 2, Balkema, 1989, pp. 915–918.
[115] M. Al-Mukhtar, A. Lasledj, J.F. Alcover, Lime consumption of different clayey soils, Appl. Clay Sci. 50 (2) (2012) 191–198, https://doi.org/10.1016/j.clay.2014.03.024.
[116] National Lime Association, Lime-treated soil construction manual: lime stabilization & lime modification (No. 4331.2), Bulletin (2004) 326.
[117] J.L. Eades, R.E. Grim, The reaction of hydrated lime with pure clay minerals in soil stabilization, Highw. Res. Rec. (29) (1963) 474–492.
[118] S.K. Bhatia, D.D. Perlmutter, Effect of the product layer on the kinetics of the CO2-lime reaction, AIChE J. 29 (1) (1983) 79–86, https://doi.org/10.1002/aic.690290111.
[119] J.L. Eades, F.P. Nichols, R.E. Grim, Formation of new minerals with lime stabilization as proven by field experiments in Virginia, Highw. Res. Rec. (139) (1966) 31–39.
[120] K. Bergrade, G.W. McAlpin, D.L. Newman, Soil stabilization: a bedrock solution, Civil Engineering News (1996) 54–59.

[121] F.G. Bell, Stabilisation and treatment of clay soils with lime. Part 1-basic principles, Ground Eng. 21 (1) (1988).
[122] M. Mateos, Soil lime research at Iowa State University, J. Soil Mech. Found Div. 90 (2) (1964) 127–153.
[123] P.V. Sivapullaiah, J.P. Prashanth, A. Sridharan, Lime stabilization of expansive soils: issues and remedies, Compression and Consolidation of Clayey Soils: IS Shamsher Prakash Festschrift (1998) 573–602.
[124] R.S. Pereira, F. Emmert, E.P. Miguel, A. Gatto, Soil stabilization with lime for the construction of forest roads, Floresta e Ambiente 25 (2) (2018) e20150077, https://doi.org/10.1590/2179-8087.007715.
[125] A.K. Jha, P.V. Sivapullaiah, Lime stabilization of soil: a physico-chemical and micro-mechanistic perspective, Indian Geotech. J. 50 (3) (2020) 339–347, https://doi.org/10.1007/s40098-019-00371-9.
[126] I. Saidate, A.E. Berga, T. Rikioui, Stabilization of gypsum clay soil by adding lime, Civil Engineering Journal 8 (11) (2022) 2511–2520, https://doi.org/10.28991/CEJ-2022-08-11-010.
[127] A. Asad, A. Hussain, A. Farhan, A.A. Bhatti, M. Munir, Influence of lime on low plastic clay soil used as subgrade, Journal of Mechanics of Continua and Mathematical Sciences 14 (1) (2019) 69–77.
[128] C. Silvani, G. Barchi, M. Ventola, Soil engineering properties and volumetric behavior of a compacted expansive clay-lime mixture, Appl. Clay Sci. 195 (2020) 105718.
[129] C. Jung, A. Bobet, Post-Construction Evaluation of Lime-Treated Soils. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, 2008.
[130] D.N. Little, Evaluation of Structural Properties of Lime-Stabilized Soils and Aggregates, vol 1, National Lime Association, 1999.
[131] P. Solanki, M.M. Zaman, J. Dean, Resilient modulus of clay subgrades stabilized with lime, class C fly ash, and cement kiln dust for pavement design, Transport. Res. Rec. 2186 (1) (2010) 101–110, https://doi.org/10.3141/2186-11.
[132] K.A. Kassim, A. Eisazadeh, H. Nur, Micro-structural characteristics of a phosphoric acid stabilized soil, in: International Conference on Construction and Building Technology, 2010, pp. 167–174.
[133] J.B. Croft, The influence of soil mineralogical composition on cement stabilization, Geotechnique 17 (2) (1967) 119–135, https://doi.org/10.1680/geot.1967.17.2.119.
[134] P.A. Gilbert, M. Asce, C.M. Oldfield, V.M. Schroeder, Effectiveness of lime-treatment of expansive clays in changing wetting-drying cycles, in: Proceedings of the 2009 World of Coal Ash (WOCA) Conference, 2009.
[135] M. Yildis, The Effect of Freezing and Thawing on the Mechanical Characteristics of the Lime and Lime-Cement Stabilised Clays, Doctoral dissertation, Dokuz Eylul University), 2012, https://doi.org/10.1016/j.scient.2012.06.003.
[136] A. Khajeh, S.M.M. Hosseini, K. Fakharian, Mechanical strength and shear stiffness of lime-stabilized clay with zeolite and EPS beads: empirical formula and numerical simulation, J. Rock Mech. Geotech. Eng. (2023), https://doi.org/10.1155/2024/6613742.
[137] M.R. Thompson, Soil mechanics and foundations division proceedings of the American society of civil engineers lime reactivity of Illinois soils, J. Soil Mech. Found Div. 92 (5) (1966) 67–88.
[138] W.G. Holtz, Volume change in expansive clay soils and controlby lime treatment, Highway Research Board (1969) 157–174.
[139] D.N. Little, Stabilization of Pavement Subgrades and Base Courses with Lime, Kendall/Hunt Publishing Company, 1995.
[140] M.R. Thompson, Engineering properties of lime-soil mixtures, J. Mater. 4 (4) (1969) 821–835.
[141] B.J. Dempsey, M.R. Thompson, Durability properties of lime-soil mixtures, Highw. Res. Rec. (235) (1968) 61–75.
[142] R.H. Neubauer, M.R. Thompson, Stability properties of uncured lime-treated fine-grained soils, Highw. Res. Rec. 381 (1972) 39–53.
[143] A.A. Basma, E.R. Tuncer, Effect of lime on volume change and compressibility of expansive clays, Transport. Res. Rec. 1295 (1991) 52–61.
[144] L. Bicysko, Lime stabilization of expansive soils. Strength and volume change with variations in temperature and clay mineralogy, J. Cold Reg. Eng. 10 (1) (1996) 39–50.
[145] R. Doty, M.L. Alexander, Determination of strength equivalency for design of lime-stabilized roadways, Rep (1968). *No. FHWA-CA-TL-78-37*.
[146] K. Uddin, A.S. Balasubramaniam, D.T. Bergado, Engineering behavior of cement-treated Bangkok soft clay, Geotech. Eng. 28 (1997) 89–119.
[147] P. Evans, Lime stabilization of black clay soils in Queensland, Australia, in: Presentation to the National Lime Association Convention, San Diego, California, 1998.
[148] C.C. Holt, J. Freer-Hewish, Lime treatment of capping layers in accordance with the current specification for highway works, in: Lime Stabilisation: Proceedings of the Seminar Held at Loughborough University Civil & Building Engineering Department on 25 September 1996, Thomas Telford Publishing, 1996, pp. 51–61.
[149] S.P. Miller, T.W. Kennedy, W.R. Hudson, *Evaluation of Factors Affecting the Tensile Properties of Lime-Treated Materials* (Master's Thesis, University of Texas at Austin), 1970.
[150] W.S. Tulloch, W.R. Hudson, T.W. Kennedy, *Evaluation and Prediction of the Tensile Properties of Lime-Treated Materials* (No. 3-8-66-98), University of Texas at Austin, 1970.
[151] D.N. Little, Evaluation of Structural Properties of Lime Stabilized Soils and Aggregates, National lime association, 1998, pp. 1–97. Arlington.
[152] F. Puatti, Use of lime for the stabilisation of road foundations, in: Proceedings of 11th IRF World Meeting, 1998. Budapest, Hungary.
[153] B. Wibawa, Swelling Clay Stabilized with Lime, Civil Engineering Research, 2003, pp. 47–48.
[154] A.J. Puppala, L.N. Mohammad, A. Allen, Engineering behavior of lime-treated Louisiana subgrade soil, Transport. Res. Rec. 1546 (1) (1996) 24–31, https://doi.org/10.3141/1546-03.
[155] M.R. Thompson, Soil stabilization for pavement systems–state of the art, Technical Rep. Prepared for Construction Engineering Research Laboratory (1970).
[156] M.J. Dumbleton, Investigations to Assess the Potentialities of Lime for Soil Stabilization in the United Kingdom, HM Stationery Office, 1962.
[157] L.D. McCallister, The Effects of Leaching on Lime-Treated Expansive Clays, The University of Texas at Arlington, 1990.
[158] B.R. Christopher, C.W. Schwartz, R.L. Boudreau, Geotechnical Aspects of Pavements: Reference Manual, US Department of Transportation, Federal Highway Administration, 2010.
[159] K. Marg, R. Puram, Quality Assurance Handbook for Rural Roads Volume-II EQUIPMENT and TEST PROCEDURES Indian Roads Congress, 2007.
[160] T. Chompoorat, T. Thepumong, A. Khamplod, S. Likitlersuang, Improving mechanical properties and shrinkage cracking characteristics of soft clay in deep soil mixing, Construct. Build. Mater. 316 (2022) 125858, https://doi.org/10.1016/j.conbuildmat.2021.125858.
[161] R. Sharma, Laboratory study on sustainable use of cement–fly ash–polypropylene fiber-stabilized dredged material, Environ. Dev. Sustain. 20 (5) (2018) 2139–2159, https://doi.org/10.1007/s10668-017-9982-0.
[162] T. Chompoorat, T. Thepumong, S. Taesinlapachai, S. Likitlersuang, Repurposing of stabilised dredged lakebed sediment in road base construction, J. Soils Sediments 21 (7) (2021) 2719–2730, https://doi.org/10.1007/s11368-021-02974-3.
[163] P. Jamsawang, S. Charoensil, T. Namjan, P. Jongpradist, S. Likitlersuang, Mechanical and microstructural properties of dredged sediments treated with cement and fly ash for use as road materials, Road Mater. Pavement Des. 22 (11) (2021) 2498–2522, https://doi.org/10.1080/14680629.2020.1772349.
[164] N. Yoobanpot, P. Jamsawang, P. Simarat, P. Jongpradist, S. Likitlersuang, Sustainable reuse of dredged sediments as pavement materials by cement and fly ash stabilization, J. Soils Sediments 20 (2020) 3807–3823, https://doi.org/10.1007/s11368-020-02635-x.
[165] P. Rai, W. Qiu, H. Pei, J. Chen, X. Ai, Y. Liu, M. Ahmad, Effect of fly ash and cement on the engineering characteristic of stabilized subgrade soil: an experimental study, Geofluids (2021), https://doi.org/10.1155/2021/1368194.
[166] L.S. Sambyal, N. Sharma, Utilizing fly ash and alccofine for efficient soil stabilization, International Journal of Science and Engineering Research 9 (3) (2018).
[167] B.A. Mir, Some studies on the effect of fly ash and lime on physical and mechanical properties of expansive clay, Int. J. Civ. Eng. 13 (3) (2015) 203–212, https://doi.org/10.22068/IJCE.13.3.203.
[168] E. Seyrek, Engineering behavior of clay soils stabilized with class C and class F fly ashes, Sci. Eng. Compos. Mater. 25 (2) (2018) 273–287, https://doi.org/10.1515/secm-2016-0084.
[169] C.R.V. Prasad, R.K. Sharma, Influence of sand and fly ash on clayey soil stabilization, IOSR J. Mech. Civ. Eng. 334 (2014) 36–40.

[170] P. Julphunthong, P. Joyklad, P. Manprom, T. Chompoorat, M.T. Palou, T. Suriwong, Evaluation of calcium carbide residue and fly ash as sustainable binders for environmentally friendly loess soil stabilization, Sci. Rep. 14 (1) (2024) 671, https://doi.org/10.1038/s41598-024-51326-x.
[171] T. Chompoorat, S. Likitlersuang, T. Thepumong, W. Tanapalungkorn, P. Jamsawang, P. Jongpradist, Solidification of sediments deposited in reservoirs with cement and fly ash for road construction, International Journal of Geosynthetics and Ground Engineering 7 (4) (2021) 85, https://doi.org/10.1007/s40891-021-00328-0.
[172] T. Chompoorat, S. Likitlersuang, Assessment of shrinkage characteristic in blended cement and fly ash admixed soft clay, Japanese Geotechnical Society Special Publication 2 (6) (2016) 311–316, https://doi.org/10.3208/jgssp.THA-01.
[173] T. Chompoorat, S. Likitlersuang, S. Sitthiawiruth, V. Komolvilas, P. Jamsawang, P. Jongpradist, Mechanical properties and microstructures of stabilised dredged expansive soil from coal mine, Geomechanics and Engineering 25 (2) (2021) 143–157, https://doi.org/10.12989/gae.2021.25.2.143.
[174] T. Chompoorat, K. Thanawong, S. Likitlersuang, Swell-shrink behaviour of cement with fly ash-stabilised lakebed sediment, Bull. Eng. Geol. Environ. 80 (2023) 2617–2628, https://doi.org/10.1007/s10064-020-02069-2.
[175] B.R. Phani Kumar, R.S. Sharma, Effect of fly ash on engineering properties of expansive soils, J. Geotech. Geoenviron. Eng. 130 (7) (2004) 764–767, https://doi.org/10.1061/(ASCE)1090-0241(2004)130:7(764.
[176] P.G. Kumar, S. Harika, Stabilization of expansive subgrade soil by using fly ash, Mater. Today: Proc. 45 (2021) 6558–6562, https://doi.org/10.1016/j.matpr.2020.11.469.
[177] T.B. Edil, H.A. Acosta, C.H. Benson, Stabilizing soft fine-grained soils with fly ash, J. Mater. Civ. Eng. 18 (2) (2006) 283–294, https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(283).
[178] B. Bose, Geo engineering properties of expansive soil stabilized with fly ash, Electron. J. Geotech. Eng. 17 (1) (2012) 1339–1353.
[179] A.A. Amadi, A. Okeiyi, Use of quick and hydrated lime in stabilization of lateritic soil: comparative analysis of laboratory data, International Journal of Geo-Engineering 8 (2017) 1–13, https://doi.org/10.1186/s40703-017-0041-3.
[180] A. Misra, Stabilization characteristics of clays using class C fly ash, Transport. Res. Rec. 1611 (1) (1998) 46–54, https://doi.org/10.3141/1611-06.
[181] E. Cokca, Use of class c fly ashes for the stabilizationof an expansive soil, J. Geotech. Geoenviron. Eng. 127 (7) (2001) 568–573, https://doi.org/10.1061/(ASCE)1090-0241(2001)127:7(568.
[182] P. Solanki, N. Khoury, M.M. Zaman, Engineering properties and moisture susceptibility of silty clay stabilized with lime, class C fly ash, and cement kiln dust, J. Mater. Civ. Eng. 21 (12) (2009) 749–757, https://doi.org/10.1061/(ASCE)0899-1561(2009)21:12(749).
[183] B.A. Mir, A. Sridharan, Mechanical behaviour of fly-ash-treated expansive soil, Proceedings of the institution of civil engineers-ground improvement 172 (1) (2019) 12–24, https://doi.org/10.1680/jgrim.16.00024.
[184] B.A. Mir, A. Sridharan, Physical and compaction behaviour of clay soil–fly ash mixtures, Geotech. Geol. Eng. 31 (2013) 1059–1072, https://doi.org/10.1007/s40098-013-0035-4.
[185] A.R. Katti, R.K. Katti, Procedure for design and construction of shallow foundations in expansive clayey soils with CNS and MSM technology, in: Proceedings of National Seminar on Partially Saturated Soils and Expansive Soils. Kakinada, 1996, pp. 5–14.
[186] A. Sezer, G. İnan, H.R. Yılmaz, K. Ramyar, Utilization of a very high lime fly ash for improvement of Izmir clay, Build. Environ. 41 (2) (2006) 150–155, https://doi.org/10.1016/j.buildenv.2004.12.009.
[187] S. Sangita, Strength and Microstructure of Lime-Fly Ash Stabilized Expansive Soil (Doctoral Dissertation, National Institute of Technology Rourkela), 2015.
[188] C. Shi, X. Xu, Formation and Stability of 3: 1 Chloride Minerals in Thermal Environment (No. DOE/ER/14795–1T; BNL-68213-2001), Brookhaven National Lab., Upton, NY, 2001 (US).
[189] D. Vamvuka, Leaching behaviour of elements from fly ash, in: Encyclopedia of Environmental Health, Elsevier, 2008, pp. 807–809.
[190] P.V. Sivapullaiah, Disposal of fly ash: challenges and opportunities, Geosynthetics India 7 (2007) 18.
[191] S. Kolias, V. Kasselouri-Rigopoulou, A. Karahalios, Stabilisation of clayey soils with high calcium fly ash and cement, Cement Concr. Compos. 27 (2) (2005) 301–313, https://doi.org/10.1016/j.cemconcomp.2004.02.019.
[192] S. Horpibulsuk, C. Phetchuay, A. Chinkulkijniwat, Soil stabilization by calcium carbide residue and fly ash, J. Mater. Civ. Eng. 24 (2) (2012) 184–193, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000370.
[193] A. Porbaha, S. Shibuya, T. Kishida, State of the art in deep mixing technology. Part III: geomaterial characterization, Proceedings of the Institution of Civil Engineers-Ground Improvement 4 (3) (2000) 91–110, https://doi.org/10.1680/grim.2000.4.3.91.
[194] A. Pani, S.P. Singh, Effect of curing temperature on the strength and microstructure of lime-amended fly ash, Indian Geotech. J. 47 (3) (2017) 249–257.
[195] A. Pani, S. Prasad, Effect of curing temperature on strength and microstructure of lime-amended fly ash, International Journal of Geosynthetics and Ground Engineering 4 (4) (2018) 1–8.
[196] A. Pani, Effect of Curing Temperature on Strength of Lime Stabilized Fly Ash (Doctoral Dissertation, National Institute of Technology Rourkela), 2014.
[197] L. Qiao, The effect of curing temperature on the compressive strength of fly ash based mineral polymers, Front. Chem. Eng. China 1 (4) (2007) 493–496.
[198] X.Z. Wang, Amelioration of microstructure and early strength of lime-fly ash stabilized soil by high temperature curing, J. Wuhan Univ. Technol.-Materials Sci. Ed. 23 (4) (2008) 503–507.
[199] A. Ghaffari, A. Ghaffari, Effect of fly ash and lime on the compressive strength of a silty soil, in: Geo-Congress 2013: Geo-Characterization and Modeling for Sustainability, ASCE, 2013, pp. 105–114.
[200] D.J. White, D. Harrington, Z. Thomas, Fly ash soil stabilization for non-uniform subgrade soils, in: Engineering Properties and Construction Guidelines, vol I, 2005. No. IHRB Project TR-461, FHWA Project 4).
[201] S.R. Joshi, V. Sharma, Effect of compaction delay on fly ash stabilized black cotton soil effect of compaction delay on fly ash stabilized black cotton soil, International Journal of Engineering Innovation and Scientific Research 1 (1) (2015) 45–51.
[202] S.S. Vincy, Delayed compaction effects on the behaviour of stabilized soils, in: Indian Geotechnical Society, 2009, pp. 419–423.
[203] P.V. Sivapullaiah, Delay in compaction and importance of the lime fixation point on the strength and compaction characteristics of soil, Ground Improv. 2 (1) (1998) 1–9, https://doi.org/10.1680/gi.1998.020105.
[204] V.A. Tkachev, V.P. Mel'nichenko, L.V. Goncharova, Soil stabilisation with fly ash, Avtomob. Dorogi (12) (1977) 15–17.
[205] M. Mateos, D.T. Davidson, Compaction characteristics of soil-lime-fly ash mixtures, Highw. Res. Rec. 29 (1963).
[206] S.I. Thornton, D.G. Parker, Construction procedures using self hardening fly ash, NASA STI/Recon Technical Report N 81 (1980) 23334.
[207] L. Han-su, K. Seon-gon, L. Joo-ho, C. Byeong-sik, Experimental study to derive the appropriate mixing ratio of crushed stone and bottom ash as a compaction pile material, Journal of the Korean Society of Geotechnical and Environmental Engineering 13 (9) (2012) 5–16.
[208] Feng Liu, The Influence and Analyse of Fly Ash with High Sulphur Content on Expansion Cracks of Lime-Fly Ash Base, Journal of Chongqing Jiaotong University, 2005.
[209] N.S. Fishman, C.A. Rice, G.N. Breit, R.D. Johnson, Sulfur-bearing coatings on fly ash from a coal-fired power plant: composition, origin, and influence on ash alteration, Fuel 78 (2) (1999) 187–196, https://doi.org/10.1016/S0016-2361(98)00146-X.
[210] A.J. Puppala, N. Intharasombat, R.K. Vempati, Ettringite and its effects in expansive soils, in: Geo-Trans 2004, 2004, pp. 1–10.
[211] H.N. Ramesh, Effect of sulphate content in soils as a potential geohazard, in: Indian Geotechnical Conference (IGC-2009), 2009.
[212] Z. Thomas, Engineering properties of soil-fly ash subgrade mixtures, in: 2002 Transportation Scholars Conference, Iowa State University, Ames, 2002, November.
[213] E. Mulder, A mixture of fly ashes as road base construction material, Waste Manag. 16 (1–3) (1996) 15–20, https://doi.org/10.1016/S0956-053X(96)00026-8.
[214] P.T. Sherwood, Effect of sulfates on cement-stabilized clay, Highway Research Board Bulletin 198 (1958).
[215] A.J. Puppala, N. Intharasombat, R.K. Vempati, Experimental studies on ettringite-induced heaving in soils, J. Geotech. Geoenviron. Eng. 131 (3) (2005) 325–337, https://doi.org/10.1061/(ASCE)1090-0241(2005)131:3(325).
[216] I. Kalıpcılar, A. Mardani-Aghabaglou, G.İ. Sezer, S. Altun, A. Sezer, Assessment of the effect of sulfate attack on cement stabilized montmorillonite, Geomechanics and Engineering 10 (6) (2016) 807–826.

[217] M.J. McCarthy, L.J. Csetenyi, A. Sachdeva, R.K. Dhir, Identifying the role of fly ash properties for minimizing sulfate-heave in lime-stabilized soils, Fuel 92 (1) (2012) 27–36, https://doi.org/10.1016/j.fuel.2011.07.026.
[218] A. Bhatt, S. Priyadarshini, A.A. Mohanakrishnan, A. Abri, M. Sattler, S. Techapaphawit, Physical, chemical, and geotechnical properties of coal fly ash: a global review, Case Stud. Constr. Mater. 11 (2019) e00263, https://doi.org/10.1016/j.cscm.2019.e00263.
[219] J.K. Tishmack, J. Olek, S. Diamond, Characterization of high-calcium fly ashes and their potential influence on ettringite formation in cementitious systems, Cem. Concr. Aggregates 21 (1) (1999) 82–92, https://doi.org/10.1520/CCA10512J.
[220] D. Dermatas, X. Meng, Utilization of fly ash for stabilization/solidification of heavy metal contaminated soils, Eng. Geol. 70 (3–4) (2003) 377–394, https://doi.org/10.1016/S0013-7952(03)00105-7.
[221] M.J. McCarthy, L.J. Csetenyi, A. Sachdeva, R.K. Dhir, Fly ash influences on sulfate-heave in lime-stabilised soils, Proceedings of the Institution of Civil Engineers-Ground Improvement 165 (3) (2012) 147–158, https://doi.org/10.1680/grim.11.00026.
[222] R.L. Buhler, A.B. Cerato, Stabilization of Oklahoma expansive soils using lime and class C fly ash. https://www.researchgate.net/publication/290487635, 2007.
[223] Z. Nalbantoglu, Effectiveness of Class C fly ash as an expansive soil stabilizer, Construct. Build. Mater. 18 (6) (2004) 377–381, https://doi.org/10.1016/j.conbuildmat.2004.03.011.
[224] E. Mapfumo, D.S. Chanasyk, Modifying soil properties and plant responses with selected fly ash materials, Can. J. Soil Sci. 78 (4) (1998) 641–651, https://doi.org/10.4141/S97-081.
[225] L. Shao, The stabilization of highly organic soils using cement and fly ash, in: GeoCongress 2008: Geosustainability and Geohazard Mitigation, 2008, pp. 657–662, https://doi.org/10.1061/40971(310)84.
[226] B.D. Nath, Effect of fly ash on improvement of engineering properties of organic soil, Geotech. Geol. Eng. 35 (5) (2017) 1963–1978, https://doi.org/10.1007/s10706-017-0217-y.
[227] Z.J. Tang, Effect of fly ash on soil physical properties and structure, Trans. Chin. Soc. Agric. Eng. 25 (8) (2009) 92–97.
[228] J. Prabakar, R.S. Sridhar, A. Sridharan, Effect of random inclusion of fly ash on strength behavior of soil, Construct. Build. Mater. 18 (7) (2004) 507–521, https://doi.org/10.1016/j.conbuildmat.2004.03.008.
[229] ASTM C618-17, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, 2017, https://doi.org/10.1520/C0618-17A.
[230] J.G. Cabrera, C. Woolley, Engineering properties of a special waste, in: Environmental Geotechnology, Springer, Dordrecht, 1994, pp. 123–128, https://doi.org/10.1007/978-94-011-1420-9_13.
[231] R.C. Joshi, Fly ash in construction materials, in: Fly Ash in Construction Materials, Nova Science Publishers, Inc, 2000, pp. 1–14.
[232] P. Solanki, M. Zaman, J. Dean, Resilient modulus of clay subgrades stabilized with lime, class C fly ash, and cement kiln dust for pavement design, Transport. Res. Rec. 2186 (1) (2009) 101–110, https://doi.org/10.3141/2186-11.
[233] B.A. Mir, A. Sridharan, Optimum utilization of Class F fly ash (FA) for stabilizing expansive soil, International Journal of Geosynthetics and Ground Engineering 5 (3) (2019) 1–12, https://doi.org/10.1007/s40891-019-0173-5.
[234] T.A. Kumar, Effect of Class C and Class F fly ash on shrinkage, plasticity and swelling of expansive soil, CTCCE (2022) 441–445, https://doi.org/10.1063/5.0113540, 2022.
[235] M.S. Deepak, Strength characteristics of clayey soil stabilised with lime and fly ash, Mater. Today: Proc. 43 (2020) 2600–2604, https://doi.org/10.1016/j.matpr.2020.11.640.
[236] M. Al-Mukhtar, A. Lasledj, J.F. Alcover, Behaviour and mineralogy changes in lime-treated expansive soil at 20°C, Appl. Clay Sci. 50 (2) (2010) 191–198, https://doi.org/10.1016/j.clay.2010.07.023.
[237] M. Al-Mukhtar, A. Lasledj, J.F. Alcover, Behaviour and mineralogy changes in lime-treated expansive soil at 50°C, Appl. Clay Sci. 50 (2) (2010) 199–203, https://doi.org/10.1016/j.clay.2010.07.022.
[238] H. Yamada, N. Kuribara, K. Ishizuka, EPS geofoam application for pipeline backfill, in: Soil and Rock America 1989, AA Balkema, 1989, pp. 299–301.
[239] J.S. Horvath, Geofoam Geosynthetic, Scripta Book Company, 1994.
[240] J. Scheirs, Characterization of polymers and their composites, in: Polymer Recycling, John Wiley & Sons, Inc, 1998, pp. 51–71, https://doi.org/10.1002/9783527615865.ch4.
[241] Australian Standard ® Rigid Cellular Plastics Sheets for Thermal Insulation Part 3: Rigid Cellular Polystyrene-Moulded (RC/PS-M), Standards Australia, 1992.
[242] V.V. Dugkov, EPS as a lightweight fill for road construction, in: Proceedings of the International Symposium on EPS Construction Method, EPS Construction Method Development Organization, Tokyo, Japan, 1997. Tokyo.
[243] F. Wang, L. Miao, Application of expanded polystyrene in transportation engineering, in: Proceedings of the 8th International Conference on Testing and Design Methods for Deep Foundations, 2009, pp. 491–496.
[244] B. Tiwari, K. Ajmani, S. Pandey, Soil stabilization using EPS beads, Mater. Today: Proc. 26 (2020) 1422–1426, https://doi.org/10.1016/j.matpr.2019.12.131.
[245] R. Deshmukh, S. Iyer, P. Bhangare, Geotechnical characterization of Expanded polystyrene (EPS) beads with industrial waste and its utilization in flexible pavement, Mater. Today: Proc. 61 (2022) 187–196, https://doi.org/10.1016/j.matpr.2021.07.462.
[246] I.D. Desai, B.N. Oza, Influence of anhydrous calcium chloride on shear strength of clays, Symposium on expansive soils 1 (1997) 17–25.
[247] A.Ö.Ö.Ü. Okça, Experimental Study on Stabilization of Black Sea Littoral Sea Clay with Cement in Black Sea Coastal Road Province [Master's Thesis, Uludag University, Bursa, 2001.
[248] K. Punthutaecha, Anand, J. Puppala, Sai, K. Vanapalli, H. Inyang, Volume Change Behaviors of Expansive Soils Stabilized with Recycled Ashes and Fibers, Geotechnical Special Publication, 2006, pp. 2295–2306, https://doi.org/10.1061/ASCE0899-1561200618:2295.
[249] R. Deshmukh, S. Iyer, P. Bhangare, M. Bhat, S. Upadhyay, The relevance of expanded polystyrene beads for ground improvement: a review, in: Advances in Geo-Science and Geo-Structures: Select Proceedings of GSGS 2020, Springer, 2022, pp. 181–188, https://doi.org/10.1007/978-981-16-1993-9_19.
[250] A. Syahril, A. Krisnandi, A. Febriansya, The effect of EPS addition to soil stabilized with fly ash as lightweight fill materials for embankment construction, J. Phys. Conf. 1364 (2019) 012015, https://doi.org/10.1088/1742-6596/1364/1/012015.
[251] M. Selvakumar, V. Vignesh, S. Jebasing, P.V. Sivapullaiah, Effect of geofoam granular columns on swelling behaviour of expansive soil, Geotech. Geol. Eng. 40 (2) (2022) 1069–1083, https://doi.org/10.1007/s10706-021-01955-6.
[252] M. Selvakumar, B. Soundara, Reduction in swelling behaviour of expansive soil with EPS waste inclusion, Innovative Infrastructure Solutions 4 (2) (2019) 1–17, https://doi.org/10.1007/s41062-019-0218-7.
[253] C. Liang, Y. Wu, J. Liu, H. Wu, D. Chen, H. Liu, Y. Song, Effect of expanded polystyrene particle size on engineering properties of clayey soil, Adv. Civ. Eng. 2021 (2021) 9951915, https://doi.org/10.1155/2021/9951915.
[254] S.M. Nawghare, J.N. Mandal, Effectiveness of expanded polystyrene (EPS) beads size on fly ash properties, International Journal of Geosynthetics and Ground Engineering 6 (1) (2020) 1–13, https://doi.org/10.1007/s40891-020-0189-3.
[255] X. Lan, T.S. Hou, Y. Yang, Y.F. Zhang, X.D. Jiang, Numerical simulation on dynamic deformation characteristics of light weight soil with different EPS particle sizes by discrete element method, Journal of GeoEngineering 16 (3) (2021) 111–120, https://doi.org/10.6310/jog.202109_16(3).4.
[256] S. Selvakumar, A. Suganya, B. Soundara, R. Scholar, A. Professor, A. Professor, Improvement in swelling properties of expansive soil. https://www.researchgate.net/publication/360412995, 2017.
[257] B. Soundara, M. Selvakumar, Swelling behaviour of expansive soils randomly mixed with recycled geobeads inclusion, SN Appl. Sci. 1 (10) (2019) 1–17, https://doi.org/10.1007/s42452-019-1324-4.
[258] ASTM D4546-14e1, Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils, ASTM International, 2014, https://doi.org/10.1520/D4546-14E01.
[259] G.E. Abdelrahman, H.K. Mohamed, H.M. Ahmed, New replacement formations on expansive soils using recycled EPS beads, International Journal of Engineering and Innovative Technology 3 (2) (2013) 316–328.

[260] Y. Feng, Y. Chao, P. Zhang, Meso-structure deformation mechanism of EPS silt mixed lightweight soil material under cyclic loading, Soil Mech. Found. Eng. 57 (3) (2020) 237–243, https://doi.org/10.1007/s11204-020-09660-5.
[261] M.V. Silveira, A.V. Calheiros, M.D.T. Casagrande, Applicability of the expanded polystyrene as a soil improvement tool, J. Mater. Civ. Eng. 30 (10) (2018) 04018256, https://doi.org/10.1061/(ASCE)MT.1943-5533.0002494.
[262] H.K. Illuri, A. Nataatmadja, Reduction of shrink-swell potential with EPS inclusion, in: GeoDenver 2007: New Peaks in Geotechnics, 2007, pp. 1–11, https://doi.org/10.1061/40917(236)18.
[263] C.J. Miller, S. Rifai, R. Ferakovich, Moisture retention curve modelling for nontreatment liner material, in: Proceedings of the Specialty Conference, Geotechnical Earthquake Engineering and Soil Dynamics III, ASCE, 1998, pp. 1598–1609.
[264] N. Yesiller, C.J. Miller, G. Inci, K. Yaldo, Desiccation and cracking behavior of three compacted landfill liner soils, Eng. Geol. 57 (1–2) (2000) 105–121, https://doi.org/10.1016/S0013-7952(00)00023-6.
[265] C.J. Miller, N. Yesiller, K. Yaldo, S. Merayyan, Impact of soil type and compaction conditions on soil water characteristic, J. Geotech. Geoenviron. Eng. 128 (9) (2002) 733–742, https://doi.org/10.1061/(ASCE)1090-0241(2002)128:9(733.
[266] Z. Mei, G. Zhang, S. Zhang, X. Li, Z. Wu, Effect of freeze-thaw cycles on soil microstructure and properties of cement-EPS stabilized dredged clay with high water content, Construct. Build. Mater. 368 (2023) 130521, https://doi.org/10.1016/j.conbuildmat.2022.130521.
[267] C.W. Jones, Stabilization of expansive clay with hydrated lime and with Portland cement, Highway Research Board Bulletin 193 (1958).
[268] A.R. Estabragh, M.R.S. Pereshkafti, B. Parsaei, A.A. Javadi, Stabilised expansive soil behaviour during wetting and drying, Int. J. Pavement Eng. 14 (4) (2013) 418–427, https://doi.org/10.1080/10298436.2012.746688.
[269] J. Liu, T. Wang, Y. Tian, Experimental study of the dynamic properties of cement- and lime-modified clay soils subjected to freeze-thaw cycles, Cold Reg. Sci. Technol. 61 (1) (2010) 29–33, https://doi.org/10.1016/j.coldregions.2010.01.002.