

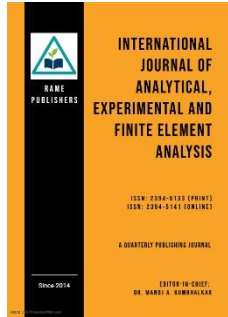


A Review of Expansive Soils in Geotechnical Engineering: Characterization and Mitigation Strategies

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Abstract- Expansive soils are a significant global engineering problem, resulting in approximately \$7–\$9 billion in annual economic losses per year in the United States and around \$73 million annually per year for India. This study is intended to review recent literatures on physical and chemical characterization of expansive soils as well as umbrella studies for analyzing the mechanistic and economic effectiveness of remediation techniques. All of these soils react primarily in a mineralogical sense, exhibiting montmorillonite activity and thus volumetric activity based on water content. Characterization was noted as the keystone of mitigation, relying on nanoscale sensing abilities to account for the physical-chemical deviations that generally known and combinatorial examples are suffering from (and in order to develop a definition of "active zone" (as in effective inhibitors) etc.) but following something close to the art of analysis - wherein there is no absolute predictivity without dealing with errors associated with samples whose integrity has been compromised. Hence, this review has attempted to summarize existing chemical stabilization methods utilizing lime, cement and fly ash whereby reduction of swelling potential was noted by the authors but determinable introduction of brittleness in soil structure can be another property introduced. The research also looks at structural and mechanical solutions based on under-reamed piles, waffle slab foundations, geosynthetics and geofoam. Case studies on India, Egypt and Australia demonstrate that a multi-faceted solution comprising moisture control, soil replacement (for instance the 1.5-meter sand cushion in Egypt) and adaptive foundation design lead to more successful renovation of infrastructure projects built in expansive soils over multinational regions. This research has resulted in a framework to assist practitioners in selecting mitigation strategies based on soil mineralogy, climatic conditions, and structural requirements.

Keywords: Expansive Soil; Soil Characterization; Geotechnical Mitigation; Chemical Stabilization; Lime; Cement; Montmorillonite; Foundation Engineering; Under-Reamed Piles; Geosynthetics; Soil Replacement; Swell Potential; Moisture Control; Active Zone; Infrastructure Resilience.

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1. Introduction

The expansive soils, also known as the shrink-swell soils is a geotechnical characteristic of soils when they tend to experience large volume changes because of the availability of moisture. These dry and semi-dry soils around the world are swelling soils or expansive soils that change in volume with change in moisture content as a result of its clay component, mostly montmorillonite, which absorbs water when moist, and releases it when dry. This may result in serious ground movement or repose resulting in instability of foundation differential settlement and damage to structures particularly on construction of buildings roads and infrastructure [1-5].

Characterizing expansive clay soil is important in order to ascertain its behavior and determine its influence on engineering structures. This is however a complicated task due to complicated, heterogeneous and in most cases unpredictable responses to changes of moisture, heterogeneity throughout a site and differences in their mechanical properties. The different mineral structure, plasticity and moisture content of expansive soils even within a single location is a big challenge to rightful characterization [5-10].

One of the most challenging geotechnical materials which is encountered in the civil engineering practice in the world is an expansive soil. Such soils have a reputation of being highly susceptible to changes in volume with moisture content that become very large when moist and contract when dry [15]. This abnormal behavior is primarily determined by their clay mineral composition, namely smectites-class minerals, and montmorillonite in particular [16]. Montmorillonite dominated soils are characterized by over volumetric changes on drying and wetting [13].

Expansive soils have a well-known and significant global effect on infrastructures. These problematic soils are related to extensive damage in onshore or offshore, sub-surface and mega infrastructure projects in 60+ countries from all continents except Antarctica [16]. The economic impact is also severe, with annual damage costs estimated at £150 million in the United Kingdom, \$1000 million in the USA and several billion pounds globally [14]. Types of infrastructure distress are: Infrastructure which is stable, its (look good), tilted structures, total and differential settlements of structures, cracking of building and basement walls/structural members/other components/upheaving in rigid/flexible pavements/cracking or failure utility lines etc. doors & windows damage [13] Factors Determining Behavior of Expansive Soils Expansion and compressibility behavior associated with expansive soils are influenced by some interlinked factors, namely mineralogical nature and quantity of clay minerals present in the soil, physical and chemical properties of the expansive clay being studied, density of the soil under scrutiny, moisture content, plasticity characteristics of the soil itself as well as temperature and time [20]. The degree of volumetric changes is dictated by the type and availability of clay minerals (exchangeable ions, internal microstructure) [13]. Although global investigations have focused on this domain for many decades, the informative and robust relationship between clayey mineral volume | mass ratio and expansive features still has not completed its conclusive formulation, yet behavior of such types of soils has only been partially unveiled and demonstrate unpredictable traits when wetting or drying [16].

The particularly salt-rich nature of expansive soils is common in arid and semi-arid zones, where these soils ultimately threaten the stability of structures as they swell and shrink [15]. One of the common soil problem in soil motion that can cause differential movement of structure foundations due to changes in moisture content under foundation [10]. Thus, accurate identification and understanding of such soil types are essential to prevent damages to structures that have already been erected or are yet to be constructed [10].

There are different mitigation strategies that have been devised to combat the issues caused by expansive soils. These methods are broadly classified as mechanical and chemical stabilization techniques [14]. The chemical stabilization using additives such as lime, cement and fly ash is a widely adopted method [9] The most commonly used stabilizing agents applied for the treatment of expansive soils are cement and lime which generate chemical reactions in the soil-water system to ensure long-term stabilization of soil [14]. Note that cement and lime treatments often make soils brittle, which might be undesirable in certain dynamic loading situations (for example, traffic loads on pavement systems) [11].

In addition to common cementitious additives, the wide variety of stabilizing agents that have been utilized by geotechnical engineers include non-cementitious (e.g., stone dust) and chemical additives (e.g., calcium chloride, magnesium hydroxide, sodium silicate), gypsum, biopolymers (e.g., guar gum), commercially available polymers as well as industrial waste materials, hydrophobic polyurethane foam and physical methods such as granulated tire rubber and pile anchoring systems [17]. There is a wide range of technical information available through research on how to improve expansive soils; however, this material can often vary and even complicate matters for construction engineers [12].

Therefore, efficient geotechnical characterization of expansive soils is important for selecting suitable mitigation techniques. Critical information would be required regarding cause and extent of damage, soil profile, and an indicator of the cycling potential of the clay [8]. For quantifying the swelling potential, oedometer test is the most common in engineering practice [8]. Thus, treating shrink-swell soils before construction is vital to avoid the loss of properties and lives [8]. Expansive soils, primarily composed of clays, constitute a challenging kind of soil. This occurs because they demonstrate swelling and shrinking events when exposed to wetting-drying cycles. The former frequently results in significant pathology of lightweight structures and subterranean systems. A comprehensive restoration of structures impacted by severe damage (macro-cracks, displacement of structural elements, heave, etc.) due to swelling-shrinkage cycles was documented following multiple case studies. The implementation of associated retrofit solutions incurs significant costs and necessitates the cessation of operations for the impacted structures.

The study of behaviour of foundations on expansive soils is therefore an issue of great interest in various regions around the world. The construction of foundations on swelling clays must be designed with a lot of attention, and it involves their characterization, measures to minimize the problems they generate, and suggestions regarding special design and construction process.

The special issue has three main elements. A comprehensive literature review will also be done to revise the characterization techniques of swelling soils. The latter product concerns the well-known methods of building to reduce the swelling issues, which leads many scientists to investigate the mechanisms behind it. What are the suitable methods of measuring swelling pressure? In this regard, a lot of contributions were made. One of the major issues is how to mitigate the swelling effects in foundation works on expansive soils. Alternative practices like use of granular materials and chemical treatment were tested. However, new opportunities can be also considered. The third one will focus on either advanced or updated recommendations of countermeasures and construction methods which can help civil engineers to design foundations successfully on expansive soils, thus avoiding the occurrence of illnesses throughout their lifetime.

In this paper, we will review the geotechnical characterization of expansive soils, their identification using laboratory testing, their behavior prediction in the field and available mitigation strategies to engineers. This paper seeks to summarize the issues in geotechnical characterization of expansive soils and examine the strategies employed for mitigating their negative influence on construction. It will look into the typical lab practices including Atterberg limits, shrinkage and swell tests, oedometer tests which can help understand the expansive nature of soils. It will discuss various methods of soil stabilization, techniques for moisture control, and foundation design approaches to minimize the hazards related to expansive soils. Familiarity with these practices and challenges allows engineers to make better decisions enhancing the safety, durability and cost of projects placed on expansive soils.

Commonly known as 'problematic soils', expansive soils display high degrees of volumetric change with variations in moisture content [15]. These soils show significant swelling with water uptake and drastic shrinkage upon drying [13]. The unique geotechnical behavior is mainly due to the presence of certain clay minerals, particularly from the smectite group, whose members have a very strong influence [16]. These minerals have strong affinity for water which leads to large volumetric changes during seasonal wetting and drying cycles which lead to cyclic soil expansion, contraction vertical and horizontal movements [13].

Expansive soil is a significant concern in geotechnical engineering, as it imposes serious threats to infrastructures with global distribution. Over 60 countries on nearly every continent have identified these soils [16]. The socioeconomic impact resulting from expansive soil types is extensive; for example, the annual cost of damage caused by such soils was estimated at approximately \$1,000 million in the USA and around £150 million in the UK [14]. The evidence of infrastructure distress manifests itself in the form of the tilting structures, fissures in building walls and foundation, upheaval on rigid and flexible pavements as well failures in underground utility lines [13]. Thus, ensuring the longevity and safety of civil engineering ventures depends considerably on its proper identification and characterization [10].

1.1 Purpose of the Paper

This paper aims to present a review of the current state-of-the-art on expansive soil treatment. Although current research has been conducted over several decades, the correlation between mineralogical composition and expansive characteristics appears to be complicated and soil practice tends to provide unexpected characteristics in various environmental conditions. E open up sources. The aims of this review are: 1. To identify the key issues related to the characterization of these materials, including effects of sample disturbance, and moisture sensitivity that lead to their detrimental effect on construction projects in general; and, 2. To evaluate the extensive range of mitigation measures as a transition between the theoretical approaches to soil mechanics-based systems and the geoenvironmental practice.

1.2 Scope of the Paper

This paper is divided into three key parts, each of which has a purpose of providing an underground to achieve this goal:

Characterization Techniques: An overview of the tools and techniques involved in the physical, chemical and mineralogical tests needed in expansive potential identification such as a review of oedometer testing and subsurface characterization.

The hurdles to understanding: discussion of the challenges of predicting soil behavior, including that a physicist can introduce errors due to sample disturbance, environmental variability and failure of existing models.

Mitigation: An exhaustive review of conventional as well as contemporary stabilization methods. These methods encompass: chemical additives such as cement and lime but there are also new experimental techniques that utilize industrial waste products or polymers along with physical anchoring systems with the aim of enhancing soil stability.



Figure 1. The flowchart of the geotechnical characterization of the expansive soils.

2. Geotechnical Characterization of Expansive Soils

2.1. Physical Properties

Expansive soils, compared to stable ones, have fundamentally different physical properties mainly because they are fine-grained and have an affinity for water. Key characteristics include:

Particle Size Distribution: Expansive soils are distinguished by a high percentage of clay-sized particles (usually mm) [15]. These properties have been shown to differ dramatically with particle size (down to nanoscale) [15]. In conversion tropical expansive clays, clay content can reach up to 42% of the total soil mass [19].

Plasticity: Such soils are generally of high plasticity (Table-1) often classified as "CH" (clay with high plasticity) according to Unified Soil Classification System [7]. The direct influence of high plasticity is reflected by soil volume changes [16].

2.2 Laboratory Tests for Characterization

Atterberg Limit: The most widely used index tests for classifying the consistency and swelling of clayey soils are Atterberg limits [16].

Liquid Limit: LL for expansive soils generally stands between 40% and 100%, however, it can be remarkably higher for certain clays such as bentonite [6]

Plasticity Index: The difference between the Liquid Limit and the Plastic Limit (, a high (eg.) is strongly correlated with high swelling potential [19]

Shrinkage and Swell Tests: These type of soil tests measure the volume change directly. The Shrinkage Limit for these soils [6] is usually between 6% and 18% as determined from shrinkage tests. The test involves inundation of the soil specimen with water, which is used to measure the swelling strain (the percentage increase height) or swelling pressure (the magnitude of pressure applied to prevent expansion) [16].

Oedometer Test: The oedometer is a standard laboratory apparatus which is used to perform one-dimensional consolidation and swell-compression test [7]. It helps engineers to assess the swelling potential and pressure in a controlled loading environment [8]. These may be done as both a “free swell” tests or a kind of “constant volume” tests to mimic different field conditions [16].

Free Swell Index: The Free Swell Index is a simple and swift method used to evaluate swelling potential by comparing its volume in water with that in a non-polar liquid (kerosene) [6]. The FSI varies from 20% for moderately expansive soils to more than 450% for highly reactive materials such as sodium bentonite [6], [7].

Hydraulic Conductivity Tests: Generally, expansive soils are characterized by low hydraulic/dehydration permeability [20]. Nevertheless, knowledge of permeability is important because permeability governs the rate at which water can enter or exit soil structure and ultimately dictates the speed of swelling/shrinkage cycles.

Mineralogical Characterization

X-ray Diffraction: XRD is primarily used to determine the mineralogical constituents of expansive soils [7]. The data is collected in diffraction (10° – 45° 2θ degrees) that enable the identification of the distinct d-spacing of individual mineral present [7]. This analysis is able to identify quartz, kaolinite and swellable minerals like montmorillonite [19].

Influence of the Mineral Composition: The swelling potential of these soils is mainly determined by the mineralogy of these soils. The main mineral responsible for the swelling and collapsing action is montmorillonite [6]. It is weakly bonded with its crystalline structure where the water molecules can quickly access inter-layer spaces leading to an enormous increase in the lattice [16]. The expansiveness degree is also modified by the type of exchangeable cations (caused by sodium or calcium) and the whole cation exchange capacity of the soil [18], [6].

Table 1. The mineralogical characterization of expansive soils.

Parameter	What It Is / Represents	How It Is Determined	Why It Matters
Sampling of Soils	Collecting disturbed and undisturbed soil samples from the site for laboratory testing.	Using standard sampling techniques (SPX, thin-walled tubes, shelly tubes) at different depths.	Ensures representative soil is tested so results reflect in-situ conditions.
Index Properties (LL, PL, PI, Gs)	Basic properties that indicate soil plasticity and general behavior.	Liquid Limit (LL), Plastic Limit (PL) and Plasticity Index (PI) by Atterberg limits tests; Specific Gravity (Gs) by pycnometer.	High PI values often indicate greater expansive potential.
Mineralogical Analysis (XRD, XRF)	Identifies clay minerals and chemical composition.	X-Ray Diffraction (XRD) for mineral identification; X-Ray Fluorescence (XRF) for elemental composition.	Presence of minerals like smectite indicates high expansiveness.

Swelling Characteristics (Free Swell, Oedometer)	Measures the tendency of soil to swell when in contact with water and under load.	Free Swell Test (volume increase in water); Oedometer Test to measure swelling pressure and strain.	Quantifies potential heave that can affect foundations and structures.
Strength Properties (UCS, Triaxial)	Determines the soil's resistance to loads.	Unconfined Compression Test (UCS) on cohesive samples; Triaxial Tests for shear strength parameters.	Expansive soils typically lose strength when wetted; needed for design safety.
Hydraulic Properties (Permeability, Suction)	Indicates how water moves through soil and how soil retains water.	Permeability Tests (constant/falling head); Suction measured using tensiometers or filter paper method.	Controls the rate of moisture change, which drives swelling and shrinking.
Moisture-Volume Relationship (Compaction)	Shows how soil density changes with water content.	Standard or Modified Proctor Compaction Tests to obtain maximum dry density and optimum moisture content (OMC).	Helps in specifying compaction requirements to reduce volume changes.

Figure 2 illustrates the Casagrande Plasticity Chart. This is a chart that has been in use to categorize soils on the basis of their plastic property traits. The chart is a 2-dimensional plot, where the Plasticity Index (PI) is plotted on y-axis and Liquid Limit (LL) is plotted on x-axis. The chart categorizes the soils based on their plasticity which is a property which defines how easily the soil can alter its shape without fracturing. There are two critical lines on the left upper hand of chart. The different types of soil are divided in these lines. A-line is denoted as (LL - 20) which is the demarcation of nonplastic and highly plastic soils. This line is quite crucial in distinguishing between high plastic and low plastic clays (CH, CL) since it is utilized in determining soil that is going to swell a lot should there be changes in moisture content. The other high plasticity silts (MH) threshold is the U-Line that is expressed by the formula of $PI = 0.9 (LL - 8)$.

These soils in this chart are known to be of a large size based on which they lie along the A-Line, and also along the 50% line, in case of LL. Soils with large plasticity index - those soils that normally swell and shrink significantly with changes in moisture level - are above the A-Line and to the right of the LL = 50% line. Expanding and contracting soils with change in moisture are an issue with construction. (Note that this area is indicated on the chart by a shaded area, in which the soils with high plasticity (i.e. those having expansive behavior) occur.) The given shaded area exemplifies an image of expansive soil and we can see that the data point of our sample is within the given area meaning that the sample in question still retains the characteristics that are normally present in high plasticity expansive soils. The figure 2 also identifies several soil categorize such as CH (high plasticity clay), CL (low plasticity clay), and ML (silt) with their accompanying regions in the chart. These are useful for engineers and geotechnical specialists to determine the class of soil based on its plasticity index and its liquid limit, giving insight into behavior at different moisture contents.

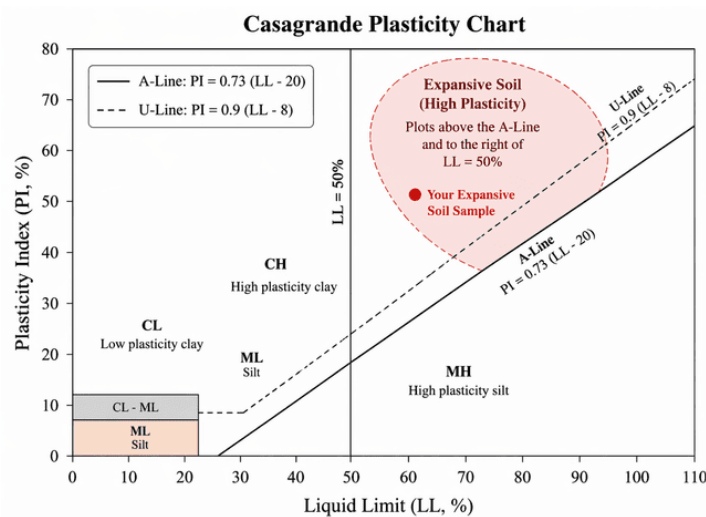


Figure 2. The classification of expansive soil samples on the Casagrande plasticity chart, indicating high plasticity characteristics.

The figure 2 caption indicates that the plot is a visual representation of soil classifications, also noting that the soil plotted above the A-Line has expansive properties. This means that these soils have high plasticity characteristics and can cause serious engineering difficulties in a construction site if they exist. It is thus a utility to help locate and comprehend soils for which engineering strategies would require special handling or remediation.

This figure 3 shows the X-ray Diffraction (XRD) pattern of expansive clay which is a sentiments in mineralogical characterization. In this graph, the intensity of X-ray diffractogram is represented on the vertical scale whereas 2 theta angle (10 o to 45 o) will be represented on the horizontal axis. The typical method of identifying and quantifying minerals in soils is X-ray diffraction (XRD), depending on the diffraction of X-rays within the mineral crystal lattice of a sample. The diffractogram has several sharp peaks at certain values of 2 theta, which can be identified as definite values of d-spacing and hence identify the various minerals available in the sample. The names of the minerals and the distance between the crystal planes in the structure of the mineral are attached to these peaks, in form of names and d-spacing. The d-spacing is known to determine the kind of minerals in the soil sample.

The highest peak is at approximately 14.3 on a 2 theta scale and this is in agreement with Montmorillonite a swelling clay mineral which can support this expansive nature of soils. The basal reflection of Montmorillonite is evident with the d-spacing of 14.3 Å; this peak is significant in the sense that it reveals the expansive characteristics of soil that is characteristic of a given mineral. Montmorillonite is a water absorber and when it absorbs, it swells hence the reason why Montmorillonite adds to the swelling behaviour of expansive soils. Along with the Montmorillonite high degree peaks at 7.17, 2, and 4.78, 2 theta, new lower degree peaks are also seen, which are at 7.17 2 theta (002) and 4.78 2 theta (003) with Montmorillonite respectively. This further supports the evidence that it is this mineral that gives expansive clays their swelling characteristics. The fact that there are many peaks that represent Montmorillonite, proves its dominant nature in the sample.

The chart further shows the existence of the other minerals within the larger clay sample, specifically quartz and kaolinite. The presence of Kaolinite (2:1 non sweller) indicated by the 7.15° 2θ (d = 7.15 Å) and a peak at around 3.57° 2θ (d = 3.57 Å), showing the abundance of this clay mineral, though it should also be noted that due to these minerals possessing different abilities they will vary in how swellable their structures are within soils similar to Montmorillonite but is significant as well. As the most abundant and stable mineral, quartz is characterized by peaks of 4.26° 2θ, 3.34° 2θ, and 2.28° 2θ (d-spacing of 4.26 Å, 3.34 Å, and 2.28 Å respectively). Quartz is present, meaning that that sample also includes non-swelling minerals contributing to the mineralogy of the soil. Montmorillonite is dominating in the sample. This is crucial as it is known that Montmorillonite takes the main control on swelling behavior of expansive soils. This figure visually illustrates the ability of XRD analyses to determine mineral content in soils and emphasize their key minerals causing expansive behavior. Knowing this data is critical in grasping the quality of the soil and its volume change due to moisture changes.

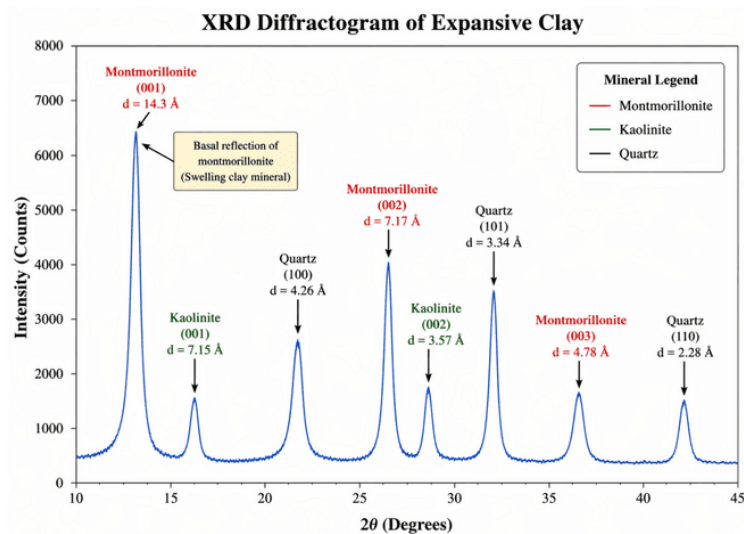


Figure 3. X-ray diffraction pattern of expansive clay showing dominant presence of montmorillonite minerals responsible for swelling behavior.

This is the Oedometer Swell-Compression Curve; a key graph that measures soil behavior, particularly in geotechnical engineering. This curve displays the relationship between the logarithm of pressure (x-axis, also referred to as Log Pressure, log P) and the void ratio (y-axis, also known as Void Ratio, e). The figure 3 shows that a soil acts in three primary phases when subjected to pressure changes: initial compression, swelling, and recompression. Dry samples upon application of a load are squeezed this decreases the void ratio from now we start to repeat 2 phases. This is the left-hand side of the graph, where we see a downward curve resulting from applied pressure.

Curve still increases in a swelling stage, during which there is a big and rapid increase in the ratio of voids. During this stage, the sample is continuously subjected to pressure of liquid (water). The soil swells with this water, and you may see that by a peculiar upward jump of the curve. The ratio of the void swells at an extremely high rate and this results in the swelling of the soil as water becomes absorbed in the soil.

The next stage after swelling is recompression which occurs when further load is imposed on soil. Then under pressure soil compresses (decreases the ratio of the voids) again, although not to this high ratio of voids as in pre-consolidation stage. The recompression phase of the process restores the soil to its previous state but at a greater pressure.

A notable attribute of this curve is the swelling pressure (ps) which is the pressure at which the ratio of void of a saturated soil goes back to the normal level. The graph indicates this pressure and it is important in finding the amount of pressure that must be applied to squeeze the soil to its pre-swelling position. It uses the potential swell pressure as a measure to approximate the required counteracting pressure caused by the absorption of water in soil which is important with expansive soils. The figure illustrates the normal swell-contract of a soil sample that was monitored in a test oedometer exercise, which is extremely prevalent in quantifying swelling pressure and determining the potential swelling of soils at different moisture content levels. It is an inseparable work in visualizing expansive soil behavior in relation to moisture and pressure that is critical in the design of the foundation and other systems in the regions where expansive soils are prevalent.

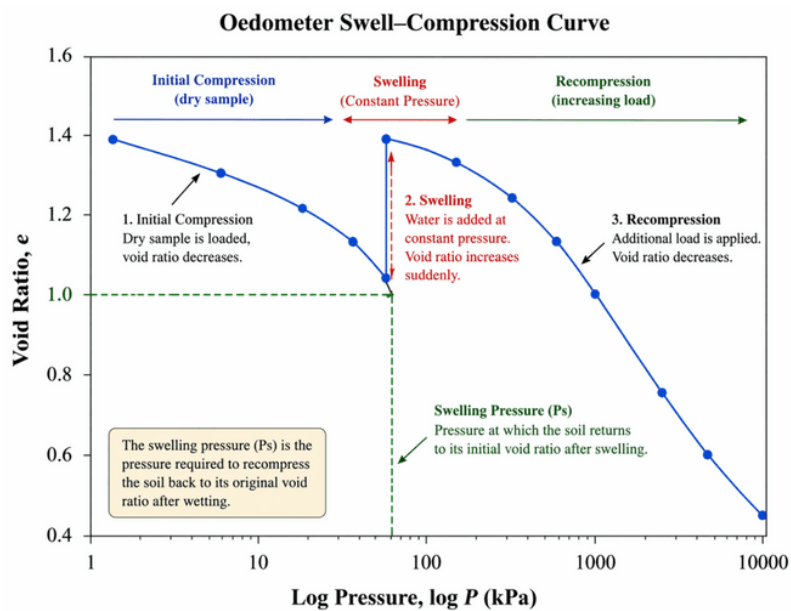


Figure 4. Typical swell-compression curve from an oedometer test used to determine swelling pressure and potential [5].

This figure 5 is more of a conceptual diagram about how Montmorillonite (2:1 clay mineral) expands. The mineral structure is illustrated as a "sandwich", two silica sheets (tetrahedral layers) sandwiching a central alumina sheet (octahedral layer), which gives rise to the defining 2:1 layer. This arrangement is responsible for the epsilon properties of Montmorillonite.

The image illustrates three states of Montmorillonite, dry state, hydration and swelled state. The interlayer space of the silica and alumina sheets are typically collapsed in the dry state, with weak van der Waals forces and cation bonding tightly holding the layers together. The proximities of the layers are better with the soil still in a compact form.

Water molecules penetrate into the interlayer space between silica and alumina sheets on hydration. The interlayer is subsequently occupied and "hydrated" by water molecules, which bind strongly to the exchangeable cations (e.g. Na^+ , Ca^{2+}) in a bid to insert themselves between the layers, thereby reducing attractive forces between them. This leads to an enlargement of interlayer space, denoted by a minor extension. When the foam expands, you can see that the water molecules keep pushing away from both layers, instigating more separation between them. This is the mechanism for soil swelling as clay expands considerably when water enters it, resulting in a macroscopic increase in volume of the soil. When cations are attracted to the negative particles of soil, they accumulate and form a layer, which has positive charges facing outward. In short, this scheme shows how the interlayer hydration of Montmorillonite leads to swell in soil due to two main factors, its mineralogical structure and water molecules. The process is represented at the molecular level by this diagram to best describe how soil may expand, a crucial concept in geotechnical applications for expansive soils.

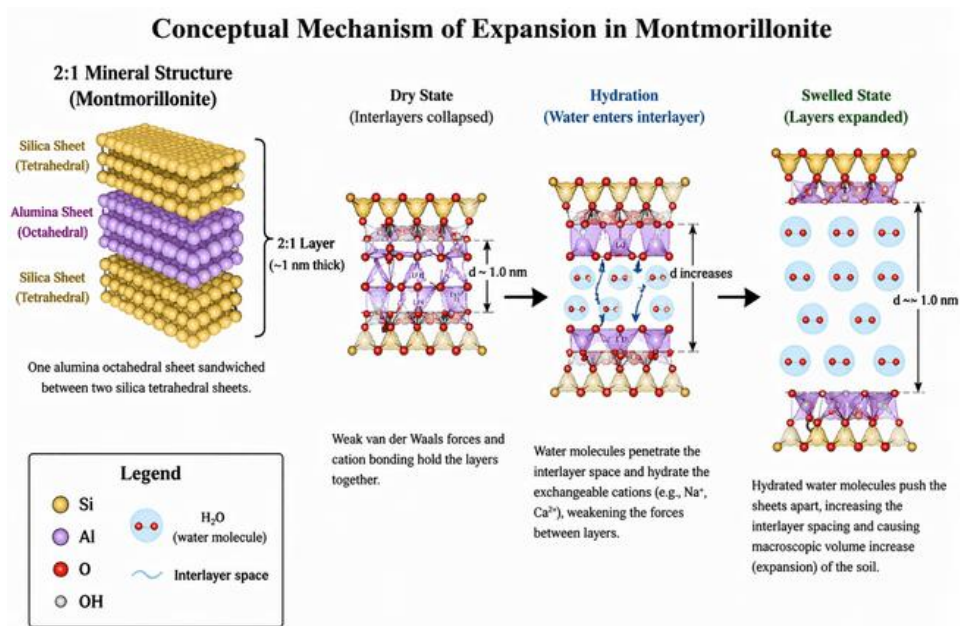


Figure 5. the schematic representation of the 2:1 mineral structure and the mechanism of interlayer hydration leading to soil expansion.

As Alsabhan et al. [6] point out, expansive soils are a serious geotechnical issue because their volume varies significantly with variations in moisture levels, which can have severe impact on infrastructure. This work is an investigation of the efficacy of thermal stabilization to lessen compressibility and swell potential of a kaolinite-rich, high-plasticity clay, of Al Ghat, Saudi Arabia. Also, we discussed and highlighted modifications in the basic parameters like the specific gravity, consistency constraints, and compaction properties. To capture the structural changes and comprehend the achieved improvement, microstructural analyses were conducted using X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX). Following heating to 200 °C, 400 °C, and 600 °C in two hours, soil samples were carefully analyzed in terms of geotechnical and microstructural properties. The research correlates expansion behavior declines with increases in temperature. After being treated at 600 °C, the plasticity index decreased dramatically by 27.00 to 2.94. The oedometer readings were in line with this; the free swell had decreased from 6% to almost nothing, and the swelling pressure had gone from 250 kPa to zero kPa. According to XRD analysis, metakaolin, with a lesser capacity to absorb water, was prepared through disintegration of kaolinite using dehydroxylation. The development of a coarser soil fabric and substantial particle aggregation were also shown by SEM. The findings indicate that kaolinitic expansive soils can be successfully stabilised and utilised in the construction industry by exposing the soils to heat treatment of 400 °C and above [6].

Figure 6 shows the distribution of particle sizes extracted from untreated expansive clay and clay heated to 600 °C using a laser diffraction particle size analyzer. Thermal treatment drastically changed the soil's particle size properties, as seen by the curves. The expanding clay that has been heated to 600 °C shows coarser particles, with around half of the particles smaller than 200 μm, in contrast to the untreated clay that has a finer gradation, with around half of the particles smaller than 12 μm. Findings

from earlier research on expansive soils [19], [25] are in agreement with the observed changes in particle size distribution after thermal treatment at 600 °C. Because soil particles aggregate and undergo structural changes, such as mineralogical transformations and dehydration, when exposed to high temperatures, the particle size distribution tends to become coarser after heating. The statement is from Alsabhan et al. [6].

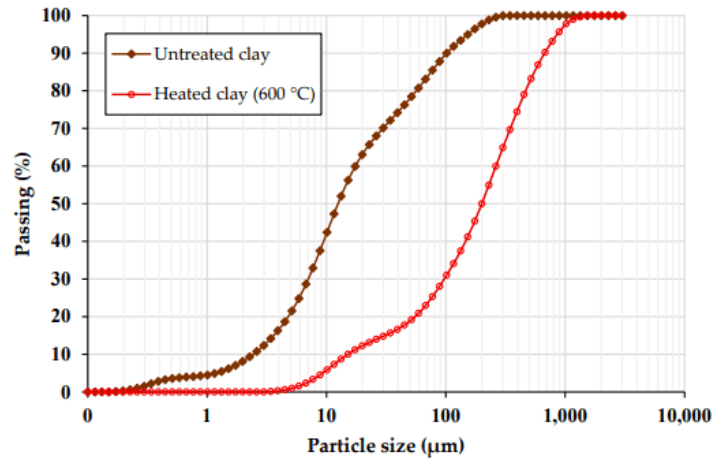


Figure 6. Particle size distribution curves for untreated and heat-treated expansive soil sample for 2 h at 600 °C. [6].

Figure 7 displays the outcomes of compaction tests conducted on both untreated and heated soil tested at 600 °C, 400 °C, and 200 °C. Thermal treatment drastically changes the compaction behavior of Al Ghat expansive soil, according to the results of the compaction test. The maximum MDD (around 1.63 g/cm³) was seen in the untreated soil at an OMC of roughly 26%. A little decrease in MDD was noted after 120 minutes of soil heating at 200 °C, but the compaction curve stayed quite close to the untreated soil's. Nevertheless, the MDD dropped even lower and the curve smoothed out around 400 °C, suggesting that compaction efficiency was lost. Soil MDD values were lowest across all water contents at 600 °C, and the nearly horizontal curve indicated that the soil structure had eroded due to severe heating. Thermochemical degradation of clay minerals and soil fabric disturbance are the causes of the decreasing MDD as temperature increases. Because of these alterations, the earth can no longer be compacted as tightly as before. In general, the findings show that expansive soil shows no change when heated to 200 °C, but its compactability is drastically reduced at 400 °C and 600 °C, which could jeopardize its engineering performance [6].

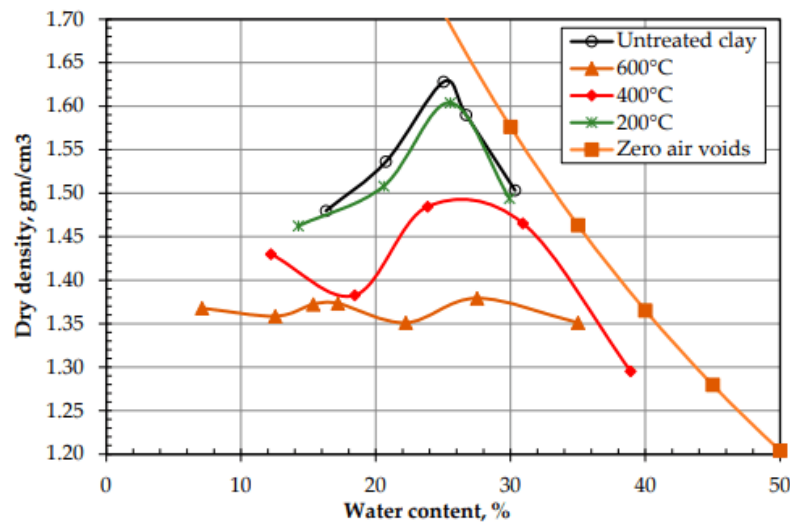


Figure 7. Compaction tests results for untreated expansive soil and heat-treated soil samples for at 600 °C, 400 °C, and 200 °C [6]

Figure 8 displays the axial strain (%) development with time (minutes) during the free swell oedometer test for both untreated expansive soil and soils treated with heat at 200 °C, 400 °C, and 600 °C for 2 hours. Before filling the samples with water to facilitate free swelling, they were subjected to a low seating load (7 kPa) for an extended duration; axial stresses were monitored during this time. An increase in axial strain to approximately 6% over time was indicative of substantial swelling behavior in the untreated soil. This reaction demonstrates its high expansive nature because its volume grows continually when exposed to moisture. Soil heated to 200 °C (G200) saw a considerable drop in axial strain, reaching approximately 3%, when subjected to water for a long time compared to untreated soil. Mild heating causes slight changes in soil structure and mineralogy, which in turn reduces edema, suggesting that soil expansiveness is greatly reduced. Further reductions in axial strain were detected at 400 °C (G400), which leveled out at around 2%. The thermally-induced alterations in soil particles are more pronounced, which improves structural stability and drastically decreases their swelling potential. During the whole testing period, the soil that was heated to 600 °C (G600) showed zero axial strain values and very no swelling. This phenomenon denotes a significant decrease or elimination of the soil's expansiveness, which is evidence of the substantial structural and mineralogical changes brought about by high-temperature thermal treatment, rendering the soil substantially less susceptible to swelling [6].

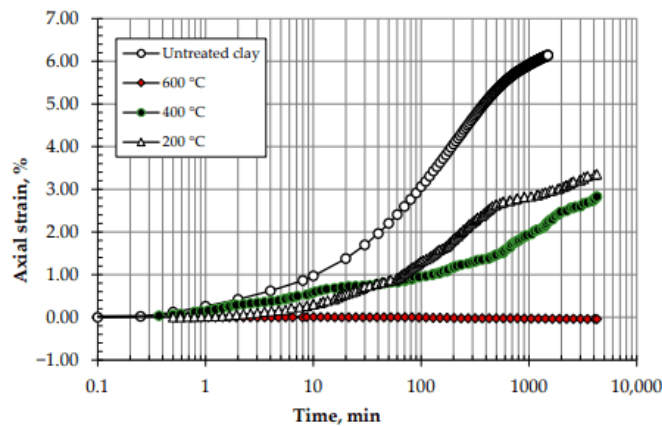


Figure 8. Free swelling versus vs. time for untreated expansive soil and heat-treated soil sample at 600 °C, 400 °C, and 200 °C [6]

Figure 5 illustrates the results of free swell oedometer experiments for both untreated expansive soil and soil heated at 200 °C, 400 °C, and 600 °C for 2 hours each. Figure 9 demonstrates the relationship between axial strain (%) and applied stress (kPa). A gentle seating load of 7 kPa was applied to the samples prior to the addition of water, ensuring that the ground could expand freely. Gradually raising the tension allowed us to calculate the swell pressure, swelling index (Cs), and compression index (Cc). The untreated soil exhibited swelling behavior of around 6% axial strain at the initial low load. Untreated expansive soils under incremental loading exhibit axial strain that changes from expansion to compression as stress increases. The statement is from Alsabhan et al. [6].

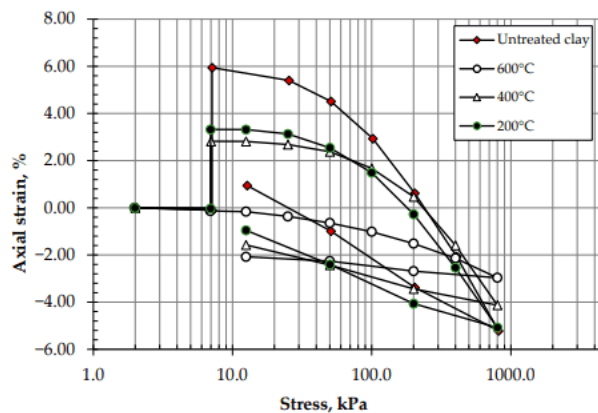


Figure 9. Free swell oedometer test results for expansive soil that has not been treated and for soil that has been heat treated at temperatures of 600 °C, 400 °C, and 200 °C [6]

The effects of heating on the compressive and expansionary characteristics of the expansive soil are illustrated in Figures 10 and 11, respectively. The compression index (C_c) and swelling index (C_s) of the soil samples relate to one another as a function of heating temperature in Figure 10. Clearly, when the temperature increases, both indices follow the usual trend of decreasing. The C_c shows a minor decrease, going from around 0.16 to 0.14, between 100 °C and 400 °C. However, between 400 °C and 600 °C, there is a much more noticeable drop in C_c , which drops sharply to about 0.045. The C_s is approximately 0.06 at 100 °C and declines to about 0.01 at 600 °C. As the treatment temperatures rise, particularly beyond 400 °C, the soil becomes less compressible under load and less likely to rebound or swell after unloading, indicating that this effect is becoming more pronounced.

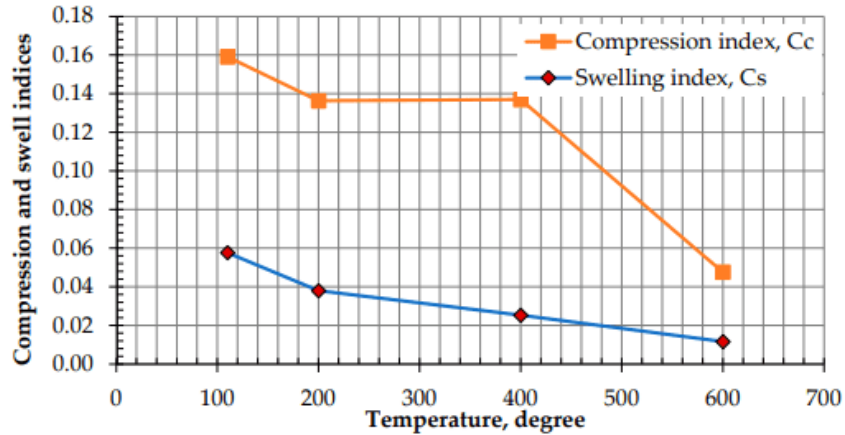


Figure 10. Variation between temperature, compressibility, and specific capacitance for heated expansive soil [6]

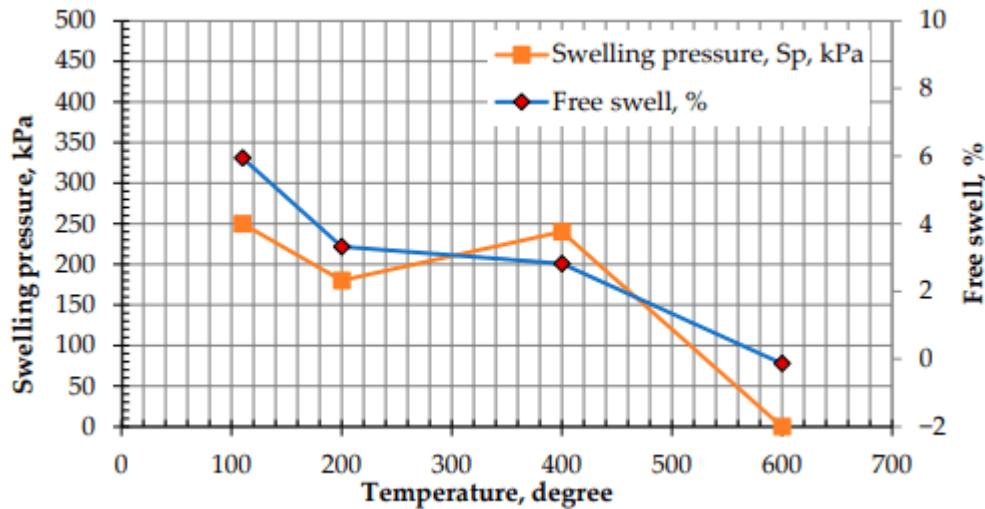


Figure 11. The relationship between temperature, swelling pressure, and free swell in heated expansive soil. As stated in the study of Alsabhan et al. [6]

Both the pre- and post-two-hour heating of the soil at 600 °C XRD patterns are displayed in Figure 12. The mineralogy of the soil was significantly changed by the heat treatment. Diffraction peaks between 10° and 12° 2θ can be seen in the raw material. The sample of kaolinite and illite is not included in the heated soil pattern. The decomposition of the clay minerals due to heat is shown by the disappearance of these peaks. The non-clay minerals were proven to be thermally resilient since the primary peaks for quartz at 26.7° 2 and calcite at 29.5° 2 remained at the tested temperature, despite alterations to the clay mineral structures. The diffractogram shows a decrease in the number of weak peaks as the heated sample undergoes a structural change from crystalline clay to an amorphous composition. When the kaolinite peaks vanish, it means that the mineral has been dehydroxylated

and converted to metakaolin. The dehydration and dehydroxylation processes, which are well-known in the thermal degradation of clay minerals, are compatible with this mineralogy.

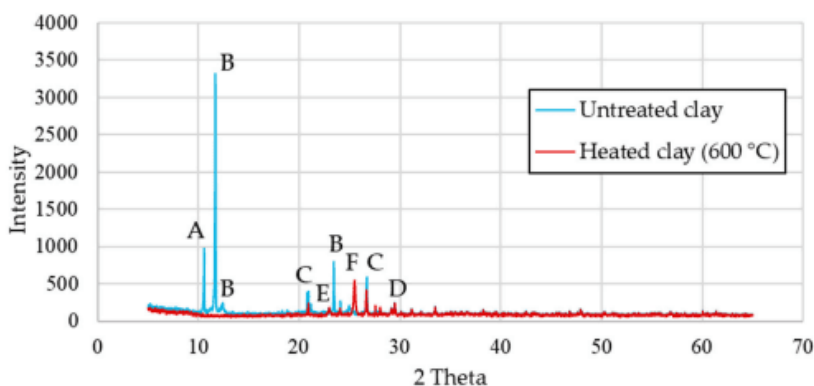


Figure 12. XRD analysis for untreated expansive soil and heat-treated soil sample for 2 h at 600 °C. (A = illite; B = kaolinite; C = Quartz; D = Calcite; E = Dehydrated clay phases; F = Transformed kaolinite) [6]

Because of the large volume changes that occur with changes in moisture, expansive soils create geotechnical issues [7]. Extensive deposits of expanding soils in the geographically and climatically diverse Kingdom of Saudi Arabia (KSA) necessitate methodical evaluation. In important areas such as Al-Ghatt, Tayma, Tabuk, Al-Madinah, Hofuf, Al-Qatif, and Sharorah, this study gathers and analyzes data on the distribution, geological origin, geotechnical behavior, and mineralogical composition of expansive soils. According to the results, expansive soils are present in nine out of Saudi Arabia's thirteen provinces and encompass over 37% of the country's overall landmass. Their development is the product of long-term geological events, sedimentary processes, and intense weathering in dry environments. Specific gravity (2.24–2.96), liquid limit (30–183.5%), and clay content (10–93%) are just a few of the parameters that show substantial geographical heterogeneity in geotechnical data. Limits of shrinkage (9 to 47.2%), as well as swelling pressure (14–1930 kN/m²), reflect variations in soil structure and minerals. Variations in geology and climate cause expanding soils in KSA to have different mineralogy. More mineralogical and geotechnical studies in uncharted areas should be the goal of future studies. In order to make data more consistent and easier to compare across regions, studies should use standardized testing methodologies. Expanded soil mapping and risk assessment throughout KSA will be improved by the integration of remote sensing and GIS.

Because of the expansive soils, it is crucial to conduct localized evaluations in order to use good geotechnical engineering procedures. Figure 13 shows the liquid limit of expansive soils in four regions of Saudi Arabia.

According to Chen's categorization [8], the extent of expansion is understood. There is a large expansion potential in the soil of the Eastern Province, especially in Al-Qatif, which has the highest liquid limits. Hofuf also shows high to extremely high levels of growth. Al-Ghatt soils are high to extremely high in the Central and Northern region, while Tayma soils are medium to very high. Tabuk, in contrast, contains both high- and low-expansion spots, with the former being more common. Soils of Al-Madinah have an expansion potential that ranges from medium to very high. The soils of the Sharorah region are known for their lower expansive tendency, with generally high expansion and a few medium values. Regional variances in mineralogy explain these discrepancies. In Figure 14, we can see the plasticity index values of expansive soils from four different places in KSA. The Eastern Province's Al-Qatif has the highest plasticity index and the greatest potential for expansion. On the other hand, Sharorah's low plasticity index indicates that she has little room to grow. Seed et al. (1962) [84] states that the majority of Al-Qatif and Al-Madinah samples are classified as having very significant expansion. There are very few low values among the soils of Al-Ghatt, Tayma, and Tabuk in the Northern and Central region, which exhibit medium to extremely high expansion. The samples from Hofuf go all the way up to very high, whereas the samples from Sharorah stay in the middle, with no extremes. Distinct geographical variations in mineralogy and clay composition account for these discrepancies [9]–[11].

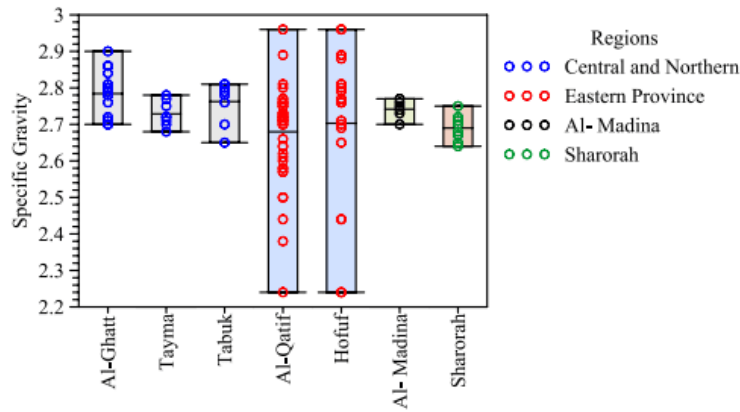


Figure 13. Studying the Variation in Specific Gravity of Expansive Soils in Saudi Arabia from One Region to Another [9]–[11].

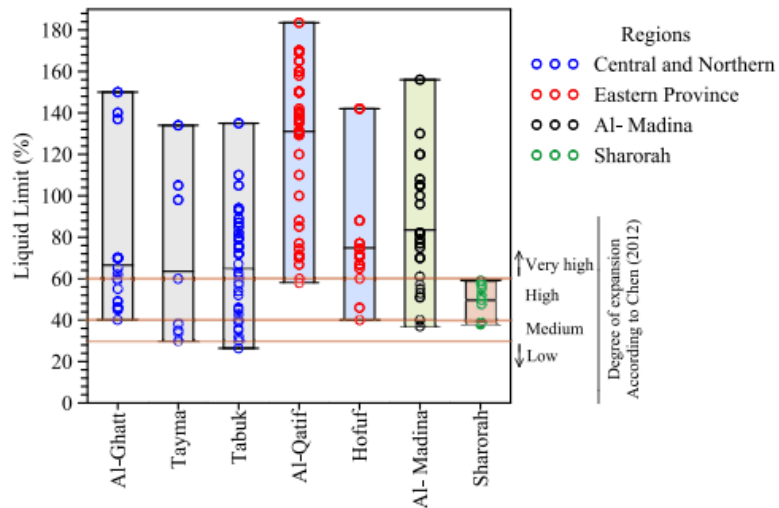


Figure 14. Different Regions of the Kingdom of Saudi Arabia Have Different Liquid Limits and Corresponding Degrees of Expansion [8], [10].

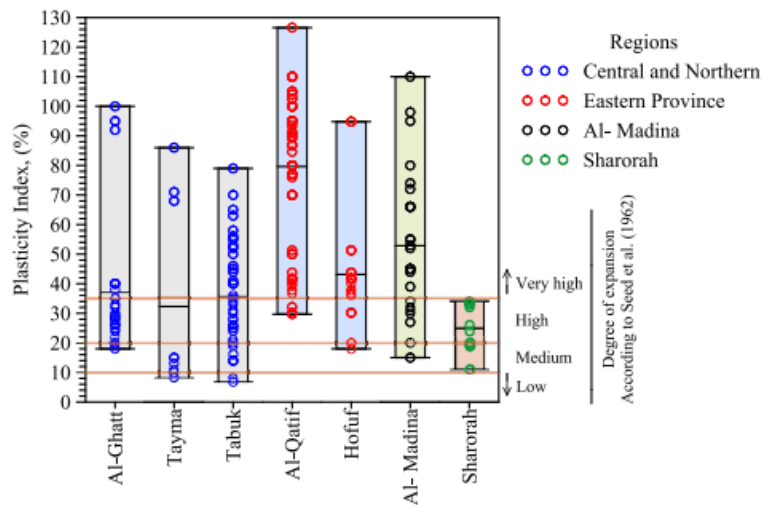


Figure 15. Dispersion of the Plasticity Index in Expansive Soils throughout Saudi Arabian Regions [7].

3. Challenges in Characterizing Expansive Soils

They also are known as shrink-swell soils) in geotechnical engineering. Examples are the Montmorillonites that are capable of forcing significant forces under saturation, producing unsafe straining and cracking of any type of infrastructure. The most important thing about these soils is to understand their behavior and a proper definition of these soils will help in alleviating the risks involved. The change behavior of expansive soils that is usually complicated and very sensitive to moisture content and the inhomogeneous character of the soils render it difficult to characterize them accurately. Additionally the strength and compressibility of expansive soils are not only variable but also cannot be unambiguously determined prior to their stabilization since they largely depend on the physical properties of the representative volume element (or RX) being compacted or stabilized.

3.1 Volume Change Behavior

The Volume change behaviour of expansive soils under various moisture conditions is one the most important aspect which needs to be characterized. Expansive soil experiences volumetric changes as a result of moisture content. When water is added to these soils, they swell (the volume of the soil increases) and when they dry out, they shrink. The ability of the soil mineralogy, in particular clay minerals such as Montmorillonite to absorb water in interlayer spaces between the layers of mineral leading to soil swelling controls this behavior. The level of swelling or shrinkage is greatly affected by the moisture content. Other variables in the environment can however influence the behaviour of the soil when the moisture conditions change as well temperature, soil texture and even existing organic matter can influence the behaviour of a given soils to the changes in moisture conditions. Therefore, the study and prediction of Volume Change Behaviour of expansive soils can only be reliably studied and forecasted in a consistent arrangement that is difficult to replicate in field research since natural changes in moisture vary naturally. The variability observed in literature poses difficulties in ascertaining the right magnitude of volume change capability of expansive soils thereby making it tough to analyse and design structures erected over them.

3.2 Moisture Sensitivity

Expansive soils are also sensitive to changes in moisture content that further complicates their characterisation. Such sensitivity means that the volume, strength, and the overall stability of the soil can change significantly when there is a minor change in moisture content. The response of soil to moisture changes can change significantly as time passes due to the influence of environmental factors like rainfall, change of seasons, irrigation practices or water supplied by underground factors. This end sensitivity demands a lot of testing and modeling of the soil moisture and suction properties to provide a broad image of the behavior of soil in different moisture regimes. The ability to reproduce what is happening in real life and imitate the speed of changes of moisture is a challenge that is hard to be recreated in the laboratory. Lab tests like the swelling pressure test or oedometer test will at least help foresee a behavior of a soil at a constant moisture level but they will not be able to explain precisely what will occur in the field where these complicated interactions of moisture occur. This means that, engineers will not easily predict the size of soils that they are supposed to be in field conditions; as a result, the construction and infrastructure projects are in danger.

3.3 Expansive Soils Inhomogeneity

There is one more challenge in defining the expansive soils which they are not homogeneous. The characteristics of expansive soils are not constant within a site, but can vary quite substantially with even very small distances. The differences in soil mineralogy, organic matter content, compaction history, and the occurrence of multiple soil types within a single location can be the cause of this heterogeneity. Call of Example, A site can have sections of Montmorillonite-rich soils and other areas that are Kaolinite or Quartz have a different type of swelling characteristics/trends. Such inhomogeneity makes soil testing a complicated affair, and introduces discrepancy among test findings. This is, the moisture sensitivity, property of strength or volume change can vary in the samples of soil collected in different places on the same site. It may result in a wrong depiction of the overall behaviour of soil. This means that to take into consideration the diversity and challenge of such differences within a site, engineers must carry out a large number of tests, increasing the time and cost of characterization activities.

3.4 Random Strength and Compressibility

Expansive soils are also known to be extremely difficult to predict in terms of their strength and compressibility especially in terms of moisture variations. The behavior of these soils can change radically, based on the moisture content at the time of the

test; resulting in incorrect predictions of the loads because of the change in soil behavior. Expansive soils are normally very weakly bonded when wet and become comparatively strong as they become drier and contract. However, when the soil is wet, strength is not only reduced drastically but compressibility is also high and that is proportional to the extent of load bearing.

Although the tests to describe these soils may be widespread and preserved on disturbed samples with varying levels of moisture, they are variable in nature. A soil which seems to be sufficient when dry might suffer greater compressibility and reduced shear strength when exposed to design conditions that involve moisture. This erratic behavior is a challenge to engineers especially when planning the foundation and other buildings that are reliant on the soil to act in a predictable manner when load is applied.

3.5 Compaction and Stabilization

Compaction and stabilization of expansive soils are yet another challenge. Very plastic soils which when moistened can expand are difficult to compact. On expansive soils, with the variation in moisture content, uniform densities cannot be got from compaction as they are sensitive to minor changes in moisture content and compacting when it is at wrong moisture level leads to low density /strength. This can be especially detrimental for construction projects that rely on uniformity of soil characteristics in order to maintain the establishments' structural integrity and lifespan.

Expansive soils are sometimes stabilized with Lime, Cement or Fly ash method to reduce the swelling potential. However, the above stabilization methods are intensive in nature, and might not yield stable performance benefits, particularly in soils with high swelling potential. Also, the difference in effectiveness of stabilization techniques contributes to the complexity of managing expansive soils further.

In conclusion, characterization of expansive soils is not easy due to the magnitude of the volume change behavior, moist sensitive nature, inhomogeneity, unpredictable strength and compressibility, compaction and stabilization difficult to achieve. To cope with these complications, it is essential to use a combination of advanced testing tools, careful site analysis, and the use of soil stabilization strategies that are consistent with the specifics of the soil under consideration.

The above diagram is a graphic representation of challenges of expansive soils whose five major types are grouped into. The former section is concerned with the behavior of expansive soils with regard to the volume change. It also demonstrates how such soils may undergo variations in their volume with respect to the amount of moisture. The diagram reflects the contraction of the soil when it is dry, when the soil is at an optimum state of moisture in the soil and when the soil swells up when water is absorbed by the soil. The characteristic of soil behavior is highly non-linear and unpredictable- even when the moisture content rises, the volume rises. The second section is concerned with moisture sensitivity of expansive soils, which are quite sensitive to changes in moisture content. The picture gives an insight into the influence of the moisture conditions on soil in a dry season (contraction) and wet season (water penetrating the layers of soil and resulting in expansion). This movement of swelling and shrinking of the soil leads to movement in the structures constructed over the expansive soil and makes any characterization of the soil either in the laboratory or in the field to be difficult since the behavior of the soil can change significantly with minimal changes in moisture.

The inhomogeneity of expansive soils is illustrated in the third section. It indicates these soils may differ greatly in composition and behavior over the course of a site. The 3D diagram subdivides the area into three zones, which have varying properties (e.g., varying Atterberg limits and swell potential). This variation renders large variations in test results making it difficult to characterize sites accurately and the need to conduct large test at multiple sites to gain a thorough picture of soil responses.

Section 4 deals with the variable strength and compressibility of expansive soils. It explicitly demonstrates the variability of both strength and compressibility of these soils with moisture content. According to the visual, the more the moisture, the lesser the strength of the soil and the more compressible. This doubt poses difficulties to engineers in planning the construction since it cannot be readily calculated accurately how well the soil would handle a load or whether it will settle.

In the last part, it discusses problems in compaction and stabilization of expansive soils. The graphics that large soils are prone to absorb water and expand, making it difficult to compact in a uniform manner. This results in uneven density and areas of weakness in the soil. The addition of stabilization methods (e.g. lime, cement additions) has proven to be an effort to reduce

the plasticity and swelling capability of these soils because they result in improved compaction, and will enhance the stability of the soil. Correct moisture control and mix design leads to uniform compaction and effective stabilization.

Overall, this figure illustrates the difficulties that engineers face when dealing with expansive soils because their behavior in changing their volume depends on the presence or absence of moisture, volatile compositional characteristics, and inaccurate values of strength and compressibility. It is important to control the amount of moisture present and appropriate and efficient stabilization on-site should we be interested in working with these more marginal materials.

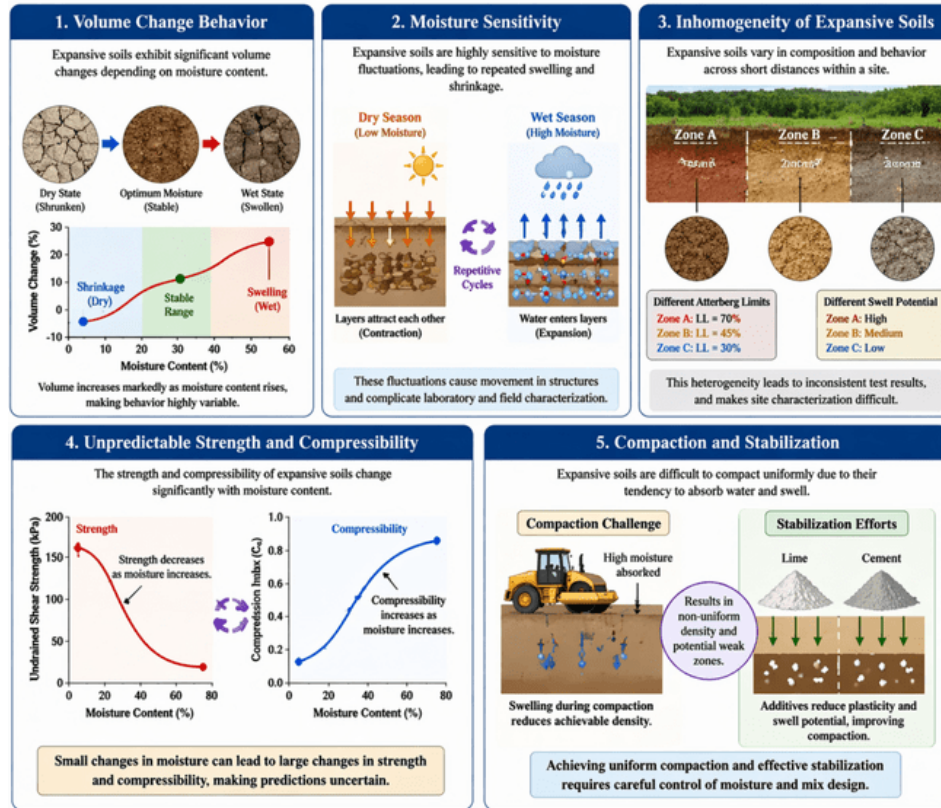


Figure 16. The Challenges in Characterizing Expansive Soils.

4. Mitigation Strategies for Expansive Soils

Such instability of expansive soil necessitates sound mitigation strategies to ensure infrastructure is not affected adversely by swelling and shrinkage during cycles. The annual cost of damage is in the billions of dollars all over the globe, with about 1,000 million dollars being spent by the United States alone; therefore, the strategy needs to be transformed into the choice of an adequate treatment approach [12]. So, mitigation steps can be broadly classified as chemical stabilization, mechanical reinforcement, moisture and structural amendments.

Soil Stabilization Techniques: Soil stabilization refers to modifying the physical and chemical properties of the soil to improve its engineering characteristics. This is usually accomplished by the incorporation of some chemical binders which react with clay minerals.

Lime Stabilization: Lime is the most conventional and efficient additives used for minimize expansive clays. In other words, when you add lime (calcium hydroxide or calcium oxide) to soil it starts many complicated chemical reactions. The cation exchange takes place first as all divalent calcium replaces monovalent ions (e.g., sodium) in the clay particle surface, which causes a reduction of the diffused double layer thickness [13]. Then combines with flocculation and agglomeration; therefore, this enhances the soil workability by reducing its plasticity index [13]. The lime reacts with clay minerals over time, resulting in pozzolanic activity of the silica and alumina derived from clay minerals which produces cementitious compounds including

calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) [13]. These reactions cause the soil to undergo significant reductions in swelling potential and increases in shear strength.

Cement Stabilization: The high strength realization and durability at a short time have found many applications in cement stabilization. The hydration of cement is not based on the minerals available in soil to undergo pozzolanic reactions like lime does but rather offers its own binding agents [12]. This group of hydration products subsequently forms a high rigidity skeleton whereby soil particles are enclosed and are essentially locked in position and are not as susceptible to moisture fluctuations [12]. Nevertheless, according to past studies, cement-stabilized soils are likely to become overly brittle, leading to fatigue cracking in dynamic loading structures commonly observed in pavement subgrades [14]. In addition, the grain size of the cement can also affect the stabilization process; low-grain cements often have better distribution and compressive strength in clays [12].

Fly Ash Stabilization: Fly ash, a waste product of coal-fired power plants is being increasingly used as an economic and environmentally friendly stabilizer. Class C fly ash has sufficient lime in its composition to produce self-cementing while Class F fly ash commonly requires the addition of lime or cementing materials to induce pozzolanic behavior [13]. Stabilization of soil by fly ash occurs mainly on the generally accepted basis of filling the pore spaces into soil and formation of cementitious bonds which ultimately is followed by decrease in the overall voids [13]. Currently, this significantly reduces the excess strain and enhances the California Bearing Ratio of the subgrade.

Moisture Control: Because the volume changes in expansive soils are fully driven by moisture, keeping a constant moisture regime in the substructure is one of the most basic mitigation measures.

Waterproofing and Drainage: The first step to good control of moisture is to ensure that water is not able to enter the dirt around your foundation. It consists of horizontal moisture barriers, such as polyethylene membranes or asphalt layers that are placed some meters beyond the boundaries of buildings to redirect surface runoff [5]. Moreover, subsurface drainage systems (like French or perforated pipes) are also needed to intercept laterally flowing groundwater and to avoid localized "wet spots" which might initiate differential swelling [5].

Landscape Management: Landscape management is a vital component of mitigation but one that receives little attention. Fully mature trees and shrubs, which consume more water than any other vegetation on a property line must also not be planted very close to the foundation — ideally at least as far away from the foundation as their mature height [15]. On the other hand, over-irrigation of gardens or lawns close to a structure can cause excessive swell. Keeping a "buffer zone" of non-expansive and well-drained material around the building periphery helps maintain isotropic moisture profile [15].

Soil Replacement: When the depth of any associated expansive soil layer is relatively shallow, the most straightforward remedy would be "remove & replace." A layer of non-expansive, granular material (sand or crushed stone) is compacted in place to replace the excavated, problematic clay [16]. The new, intermediary layer helps distribute load more evenly structurally and formed a flat formwork for construction on this level. The active zone—the depth at which moisture fluctuations take place—defines the depth of replacement and can be highly variable depending on local climatic conditions [16].

Foundation Design Modifications: Insufficient or uneconomical soil treatment means that foundations need to be designed to accommodate or bypass moving soil. Pile foundations like under-reamed piles or bored piles are almost always used to transfer the structural loads onto stable, non-expanding strata below the active moisture zone [15]. This is highly useful in the case of under-reamed piles since their bulbous bases can further anchor against upward "uplift" pressure induced by expanded soil [15].

Raft or Mat Foundations – A stiff raft or mat foundation can be applied for small structures don't require a proper sub-base. These foundations are rigid enough for them to "bridge" the localized soil movement, thereby preventing differential settlement and minimizing structural cracks [15].

Adaptable Slab Designs Flexible or "waffle" slabs are installed with built-in beams which provide the slab with rigidity but allow it to float on the soil that is moving. This is a practice where in the designs of buildings, void spaces underneath beams (whether formwork) may be left intentionally using collapsible forms made out of cardboard for the soil to swell upwards without pressing against the building [16].

Soil Reinforcement: Mechanical reinforcement, together with placement of fibers and grids, can significantly add to the tensile strength and stability of the soil mass.

Geogrid Reinforcement: Geogrids and other forms of geosynthetics impart lateral restraint to expansive soil subgrades, thus providing reinforcement. As the soil tries to expand, through the use of interface friction and interlocking, the geogrid forces a "confining" phenomenon that reduces vertical heave displacement while augmenting its overall bearing capacity [13], [16]. This is particularly common with road construction to control longitudinal cracking.

Geofoam and Lightweight Inclusions: Expanded Polystyrene geofoam is a lightweight fill replacement for heavy soil overburden. Geofoam can lower the total vertical stress on the underlying expansive clay, thus reducing the mean effective stress and its possibility to reach excessive consolidation or swelling [17]. Other innovative inclusions have been explored for their capacity to absorb some of the expansive energy from soil, reducing net swell pressure on foundations including recycled geobeads and granulated tire rubber [17], [3].

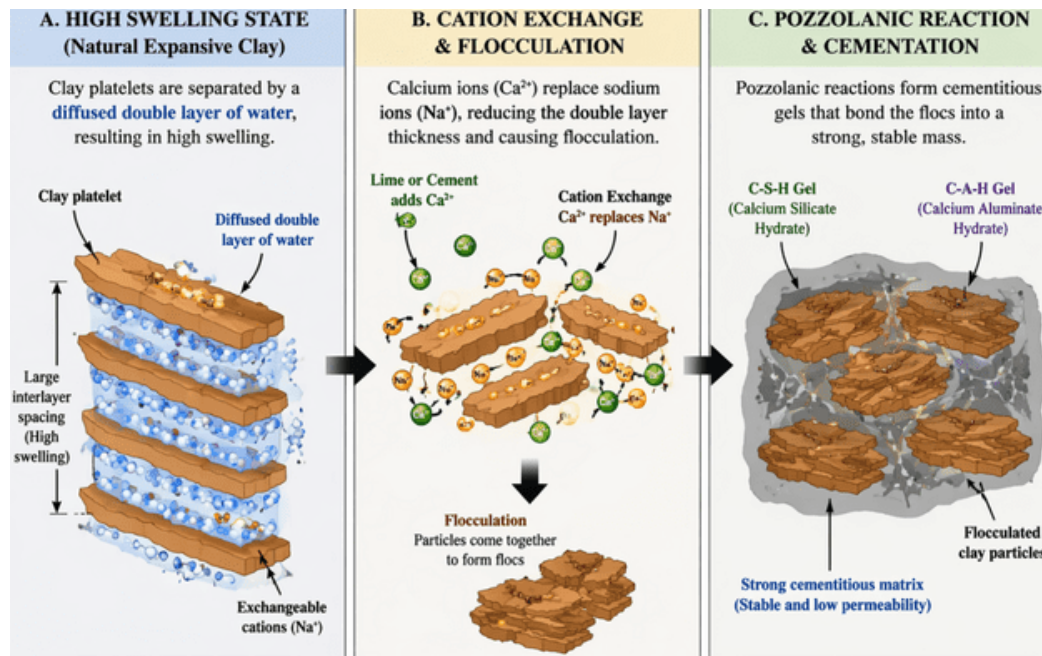


Figure 17. The schematic of the stabilization mechanism of expansive clay.

5. Case Studies

Case Studies- Effects of Expansive Soil and its Remedies

The wide occurrence of expansive soils create various engineering problems, leading to economic losses in the United States of \$7–\$9 billion per year [1] and \$73 million in India [2]. The below case studies demonstrate concrete applications of the mitigating strategies outlined earlier.

Case Study 1: Residential Impact in Pondicherry, India

Extensive areas of "black cotton" soils in numerous localities in Pondicherry and the central-southern regions of India have inflicted significant distress to low-rise residential structures [3], [4]. Conventional shallow footing structures displayed severe diagonal cracking in the monsoons along with a phenomenon known as "heaving" of floors, followed by settlement in dry seasons [4]. Geotechnical survey details suggest that under-reamed pile should be used [5]. By attaching the bulbous base of the pile into 3.5 to 4 meters deep, (well below the "active zone" of moisture change), it was possible to isolate these structures from surface level volumetric alterations [6], [5]. Results: Significantly greater stability and virtually no seasonal cracking were observed for structures retrofitted or newly designed with under-reamed piles than for those on shallow foundations [5].

Case study 2: (Case Study 2 - Egypt) Layered Mitigation for Utilities

Large-scale deposits of widespread shale are found in the Western Desert of Egypt and constitute a serious challenge to the construction of urban infrastructure and utility lines [7]. Over the past several years, rapid urbanization in the Assiut and Sohag regions led to the failure of a number of rigid pavements and buried water pipelines which ruptured because of high swelling pressure imposed by smectite-rich clay minerals [6], [7]. The topmost course was dug out and substituted with 1.5 m of compacted desert sand [7]. Utilizing lime stabilization to lessen the plasticity index and create a moisture-insensitive platform [8] for primary road subgrades. In terms of service life, the combination of both method, physical replacement and chemical modification worked to greatly extend the pavement service life while also lowering maintenance costs from pipe bursting [7].

Case study 3: Road Infrastructure Performance in Extreme Rainfall, Australia

Case studies conducted recently in Australia have contrasted traditional stabilization with contemporary geosynthetic solutions to extreme weather events [1]. Traditionally, lime-stabilized subgrades in regions of expansive clay experience failure after significant rain periods due to the "brittleness" of the stabilized section resulting in longitudinal cracking [1]. Engineers designed geosynthetic-stabilized base courses that restricted the lateral movement of the expansive soil [1]. Geogrids provide mechanical confinement, as opposed to lime that altered the chemistry of the soil [9]. Significant increases in effective longitudinal strength(s) of geosynthetic-reinforced sections observed with field observations during extreme rainfall events, while lime only performed worse than a soil without stabilization [1].

Case Study 4 | Louisiana, USA — Managing property risk

About 0.13 million square kilometers of expansive soils exists in the southern US including Louisiana, which causes extensive property damage [10], [2]. Louisiana’s floodplain alluvial clays are very sensitive to moisture variations, causing a widespread incidence of foundation failure in homes [10]. Current risk management emphasizes modified slab designs (waffle slabs) and landscape moisture control [10], [5]. Property owners are advised to maintain moisture around foundations by watering them from time to time and use lightweight inclusions such as geofoam in their new construction projects which can aid in reducing the total load on the subgrade [10].

Outcome: New residential developments have fared better than older ones due to the introduction of rigid, floating foundation designs that are harder to destroy [10].

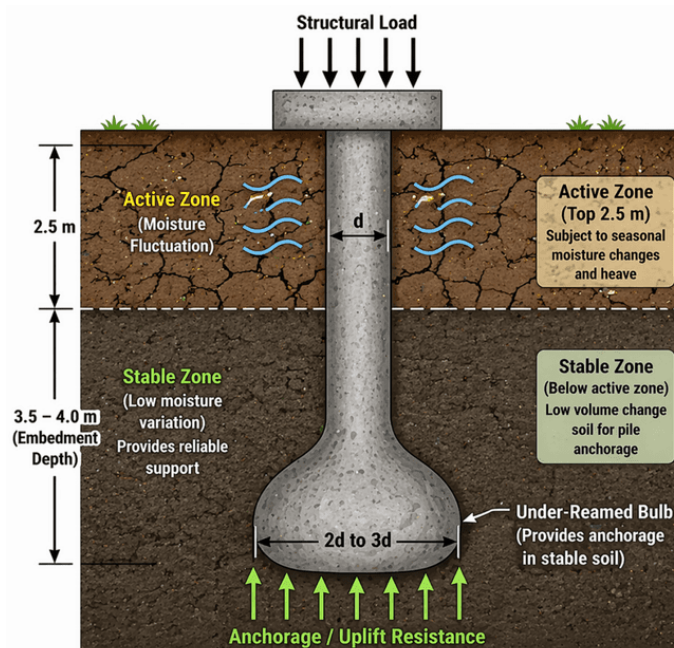


Figure 18. The schematic of an under-reamed pile foundation anchored below the active moisture zone to resist beave in indian expansive soils. (Case Study 1 - India) Under-Reamed Pile Foundation.

This figure 18 shows a schematic cross-section of an under-reamed pile foundation suitable for expansive soils eg the Black Cotton soils of India Hence it portrays that the pile is anchored below the active moisture zone to withstand soil heave tendency, a challenge of expansive soil.

In the diagram, a vertical concrete pile with diameter d is submerged in soil layers. There is an under-ream at the bottom of a pile, a bulbous expansion before the tip of the shaft, for further anchorage. The under-reamer diameter is about $2d$ to $3d$, it is much larger than pile main shaft. The diagram divides the nearby soil into a pair of layers. The Active Zone (top layer, down to 2.5 meters) is also labelled with wavy lines for falling and rising moisture levels. This layer experiences seasonal variations in moisture, which causes the soil to expand and contract potentially creating soil heave. Elongation and compression of soil are the major challenges and critical in structural design on expansive soils. Under this active zone is the Stable Zone, a 3.5 to 4.0 meter depth range. [CTA-ITEM] The stable area is clearly identified showing little to no moisture fluctuations and therefore much more consistent support as the pile will not be affected by any volumetric changes leading to potential foundation failure.

The under-reamed bulb provides resistance to anchorage (upward-pointing arrows beneath the pile base) and uplift (due to soil swelling causing upward movement of the pile). Downward arrows labelled "Structural Load" at the top of each pile indicate the pressure from structure that atrium piles must support. It helps visualize how the under-reamed pile foundations in expansive soils works; under-ream piles are again designed with a bulb under it which is anchored into the stable soil zone as the upper active zone undergoes seasonal swelling causing uplift forces. This approach is particularly effective against heave, which in turn is required to keep structures on swelling soil stable.

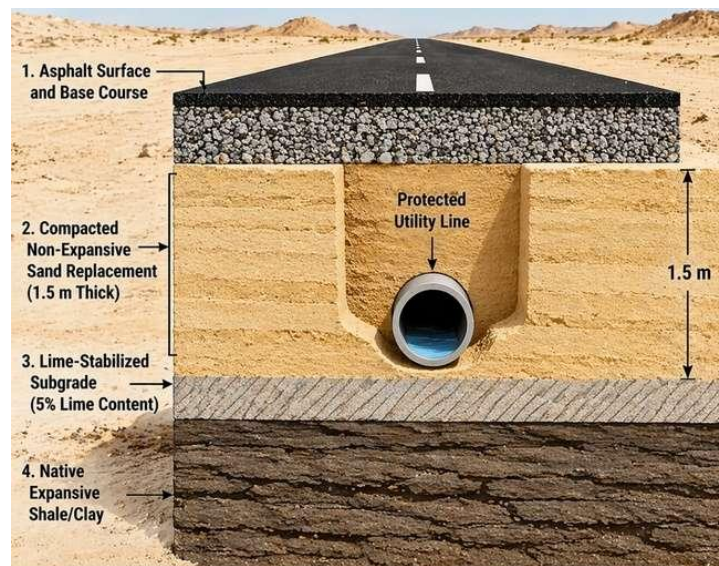


Figure 19: Infrastructure cross-section in Egypt’s Western Desert utilizing a 1.5m sand cushion and lime-stabilized subgrade to protect utility lines [7].

This represents a technical cross section through both a road and utility trench field application in the Western Desert of Egypt. This diagram illustrates the construction layers used in protecting utility lines, as a common example is enlarged soil. It clearly illustrates the various materials used to provide both structural integrity and safety of the underground utilities.

The Asphalt Surface and Base Course (top of the diagram) is what makes up the road surface. This being the first layer, it’s a stable, durable surface for your road. Under the asphalt it is 1.5 meters of Compacted Non-Expansive Sand Replacement. This layer is essential as it replaces expansive soils that may be problematic due to their tendency to expand and contract with moisture. Non-Expansive Sand to Minimize Soil Heave/Shrinkage The problem with expansive soils is they can lead to heave (hardening) or shrinkage of the soil beneath a road and negatively impact any underlying infrastructure.

The third layer (Lime-Stabilized Subgrade) consists of soil stabilized with 5% lime content. This soil replacement layer is not thicker than the sand replacement, but it is important for improving the moisture sensitivity and load-bearing capacity of the

underlying soil, compacted in place to provide strength and durability. In regions with expansive soils, lime stabilization is a widely practiced technique to control the degree of swelling and shrinkage due to moisture variations.

The Native Expansive Shale/Clay is at the bottom of the trench. However, this is the native soil in the region that usually undergoes high volumetric variations with moisture changes. These are expansive soils, and they can wreak havoc on infrastructure — the road surfaces heave, utility lines shift. The above layers are used to contain and shield from the effects of this vast material.

This figure 19 denotes a cross-section of said water pipe (Protected Utility Line) within the Compacted Non-Expansive Sand Replacement. A section of utility line lies embedded in the same sand layer designed to protect it from the overwhelming forces of the soil below. The design separates the utility line from the large expanse of shale/clay to isolate it from movement of soil that is subject to damage.

As noted in the caption, this infrastructure design is specifically intended to safeguard the utility line in Egypt's Western Desert region—where wide-reaching soils prevail. The alternative is a series of sand and lime-stabilized subgrade layers that provide a cushioned protection against the volume changes soil undergoes depending on moisture content, ensuring utility functions remain intact through time without interaction at all.

The basis of this figure is a bar graph showing the efficacy of three types of subgrade stabilization methods under conditions of extreme rainfall during Australian seasons on both longitudinal crack width and surface heave. Mitigation methods are represented along the x-axis and longitudinal crack width (mm) or surface heave (mm) are shown on the y-axis. This chart also shows a visual comparison between untreated soil, lime-stabilized soil and geosynthetic-reinforced soil. The Untreated soil has the tallest bar in this image as it experiences severe volume changes with moisture content, land cracking and heaving (aka failure-prone), signifying that expansive soils subjected to no form of stabilization can undergo extreme moisture-induced volume alterations. Lime-Stabilized soil has a moderately high bar indicating that lime stabilization minimizes cracking and heaving but keeps the soil brittle and prone to cracking under stress. The one that does the best, as can be seen from the shortest bar is the Geosynthetic-Reinforced soil, which shows crack and heave significantly lesser than all others. Soil swelling and shrinkage occurs and geosynthetics play a dominant role in controlling lateral restraint of soil due to which this result is achieved.

This point of care illustrates the reason why geosynthetics show better performance for expansive soil problem control, especially those highly sensitive areas with extreme rainy event fallen.

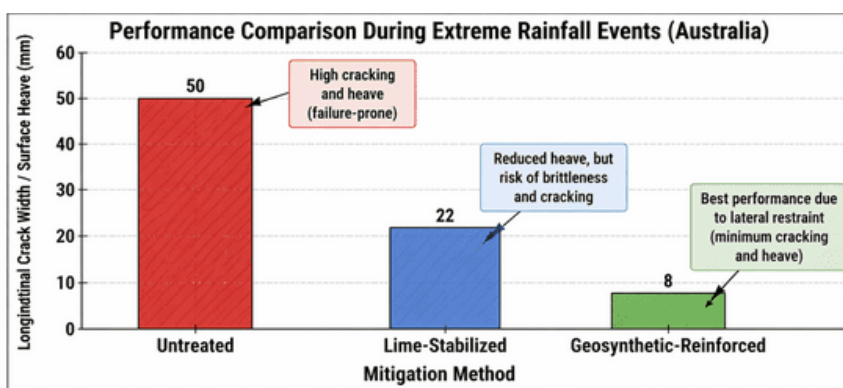


Figure 20. Comparative performance of subgrade stabilization techniques in Australia during extreme rainfall, demonstrating the superior lateral restraint of geosynthetics [1].

This figure 21 shows a schematic cross-section of a modern foundation approach employed in Louisiana residential properties, employing a waffle slab with geofoam inclusions to mitigate soil heaving experienced by expansive clay soil. The figure 21t here is a schematic of a concrete waffle slab, which shows thick, deep ribbing and looks like an upside-down waffle when viewed from the side. The ribs carry loads and clear the geometric voids (collapsible forms) between them. These spaces are meant to let dirt heave up and out without touch the slab, protecting it from damage caused by swelling expansive soils. Geofoam of expanded polystyrene has been placed under the foundation's edge in an effort to decrease the vertical stress held by the underlying

expansive clay. Because the geofoam is so light, it serves as a lightweight inclusion that reduces the total stress on the soil and therefore minimizes heave potential. The combination of void spaces to allow for soil expansion with geofoam to further reduce the compressive forces acting on the foundation allows for stability within soils that have a high swell potential.

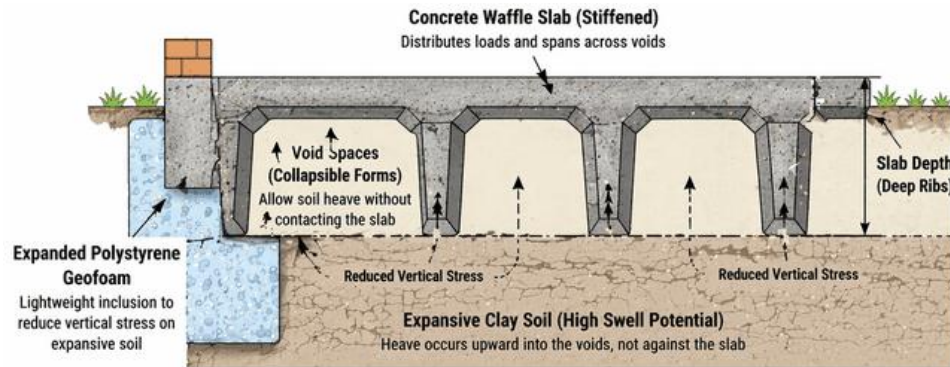


Figure 21. Alterations to the foundation in Louisiana, which include a stiffer waffle slab with voids and geofoam inclusions to reduce swell pressure [10][5].

6. Conclusion

The science of expansive soils is affirming that they have become one of the biggest and costly fly in the ointment of infrastructure in most parts of the world and they needed sophisticated ways of not only characterization but also alleviation. The petty patterns of behavior of these soils have been shown to be largely governed by their mineralogical character, the prime movers of such dramatic volume changes being the high-activity minerals, including montmorillonite, which are the major constituents of these soils. The mitigation strategy review showed that although traditional chemical stabilizers such as lime and cement are effective in decreasing plasticity and increasing strength, they need to be conducted with a specific knowledge of soil chemistry in order to avoid brittleness. Geogrids and lightweight geofoam inclusions are modern mechanical reinforcements that provide new ways of controlling soil movement, reducing vertical stress, without abusing chemical integrity of the soil. One of the most important findings made through this study is that the success of any engineering remediation project only relies on the accuracy of the results of the initial soil testing. A successful formulation needs to go beyond the simplest of macro-level observations and take into account the active zone and the microscopic fluctuations that drive expansion. This paper highlighted how traditional sampling methods may often manage to control to a “sample disturbance that introduces a bias to lab outcomes and that is the cause of the difference between predicted heave and field operation. Consequently, there can be no other way of making sure that the mitigation strategy adopted, which is the utilization of fill or replacement soil, chemical treatment, a special foundation, etc., will work as it was meant to work during the service life of the structure than by having an in-depth knowledge of how moisture and mineral activity take place on that particular site.

7. Recommendations and Final Thoughts

The fact that the physical sampling errors will be avoided is an encouragement to consider the technologies that enable in-situ and non-destructive soil testing. It is a chance whereby the industry contributes significantly and there is the possibility of substituting high-carbon binders such as cement with low carbon binders eliminating the industrial byproducts and recycling of materials that can be warms energy efficiency by providing sustainable warming of the "green" stabilization agents. In addition, civil engineers must also advocate multi-year monitoring of foundations in prone regions and more so as climate change produces more intense and repeated waves of rainfall and drought, which surpass the threshold defined by the existing metrics and design frameworks as safe. To design safe, sustainable and resilient urban environments, the identification and management of threats posed by expansive soils is one of the tasks that need to be performed. This versatile method enables complex geological knowledge to be combined with an assortment of adaptable engineering remedies - including the utilization of under-reamed piles to sophisticated moisture seals - cutting down the healing structural and economic expenses of the soil. This is the most

effective manner of dealing with the pervasive menace of wide spread clay by a multi-disciplinary approach that will be proactive and make the built environment globally sustainable over the long term.

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