The Influence of Percentage of Clayey Size Material Soil and Loading on Expansive Behavior of Soils

Soil Investigation Study

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1. Introduction

1.1 General

Expansive soils exhibit significant volume changes; they shrink upon drying and swell when wet. These volume changes can exert substantial pressure, sufficient to damage sidewalks, driveways, basement floors, pipelines, and even building foundations. Notably, the swell potential varies among different expansive soils. Specific tests are designed to evaluate a soil's swell potential and assess the likelihood of structural damage. Globally, problems associated with soil volume changes are predominantly observed in arid and semi-arid climates, similar to conditions found in certain regions of our country. Here, variations in moisture content significantly influence the soil's expansiveness.

In the realm of geotechnical engineering, a mixture of bentonite and sand offers a viable solution to mitigate issues such as heaves, cracks, and other damage induced by soil swelling and shrinkage. Utilizing a bentonite/sand mixture can:

I. Decrease the settlement time of structures,

II. Enhance soil permeability.

In Iraq, expansive soils are widespread across extensive areas in the northern, southern, and central regions. Numerous studies have been undertaken to explore the swelling characteristics of these soils, aiming to better understand and mitigate their impact on construction and infrastructure.

1.2 Objective of the Study

The primary aim of this study is to elucidate the impact of sand addition on the behavior of expansive soils, specifically bentonite. This investigation focuses on how varying sand grain sizes influence the physical properties of the soil matrix. Additionally, the study examines the effects of temperature variations on expansive soil behaviors. A significant aspect of the research also involves exploring how the inclusion of sand in different proportions and particle sizes can mitigate swelling and reduce swelling pressure in expansive soils. This comprehensive analysis aims to enhance our understanding of soil modification techniques, contributing to more effective management of soil expansion in civil engineering applications.

1.3 **Objectives**

The need for this study is driven by several critical factors, which can be summarized as follows

I. Reducing Free Swell and Swelling Pressure: To alleviate the detrimental effects of soil expansion on construction and civil engineering projects by reducing both the free swell and swelling pressures of expansive soils.

II. Optimizing Grain Size for Sand: To identify the optimal grain size of sand that effectively reduces the free swell of expansive soils under varied environmental conditions.

III. Mitigating Swell Under Temperature Variations: To explore how changes in temperature impact the swelling behavior of soils and to determine strategies for reducing swell in response to different temperature degrees.

These objectives underscore the practical implications of understanding and manipulating the physical properties of expansive soils to enhance construction safety and efficiency.

1.4 Layout of the Study

The study is structured into five distinct chapters, as outlined below:

Chapter One: Introduction

This opening chapter sets the stage for the research by providing an overview of the study's scope and objectives.

Chapter Two: Literature Review

This chapter presents a comprehensive review of the unique properties of expansive soils, including the factors influencing their swelling characteristics. It also covers theoretical approaches for measuring free swell and various treatment methods for expansive soils.

Chapter Three: Materials and Methods

This section details the materials and testing equipment utilized in the study. It describes the experimental program and outlines the physical and chemical tests performed to evaluate the impact of sand on expansive soil.

Chapter Four: Results and Discussion

Results from the physical tests on both treated and untreated soil samples are presented in this chapter. It includes a comparative analysis of the data obtained from tests using an oedometer cell for both treated and untreated samples, highlighting key findings and insights.

Chapter Five: Conclusion

The final chapter synthesizes the findings from the research, drawing conclusions regarding the effects of sand (both percentage and grain size) on expansive soils. This section also discusses the implications of the study and potential areas for future research.

2. Literature Review

2.1 Introduction

In the region under study, three primary types of soil are naturally present: sand, silt, and clay. Among these, clay soils are predominantly classified as "expansive." This classification is due to their characteristic behavior of expanding (increasing in volume) when they absorb water and contracting (decreasing in volume) when they lose moisture.

One of the most notably expansive types of clay soils is referred to as "adobe," as identified by Lerot and Low (1999). The significant variability in the behavior of expansive soils in response to moisture or temperature changes poses a myriad of complex challenges for geotechnical engineers. Expansive soils located above the water table are particularly prone to volumetric changes contingent upon fluctuations in moisture levels. An increase in moisture content typically results in soil swelling, which can lead to heaving of foundations—a severe issue for structures built on such soils, as documented by Sivapullaiah et al. (1996).

Concerning the management of expansive soil, numerous interrelated factors must be considered to control its behavior effectively. The interaction of these factors can lead to significant perils for structural integrity, potentially resulting in extensive damage and substantial repair costs, as observed by Al-Dahlaggi (2001).

The physical and environmental factors contributing to the behavior of expansive soils include the composition of clay minerals, soil density, natural water content, plasticity indices, surcharge pressure, temperature, and the duration of exposure to these environmental factors.

2.2 Expansive Soils

The term "expansive soil" typically refers to those clay minerals that exhibit a reversible behavior—swelling and shrinking—in response to changes in moisture content over time. The primary cause of such behavior is the environmental conditions that accompany its geological formation, as noted by Al-Dahlaggi (2001).

Structural damage is most pronounced when the foundation experiences uneven settling or "oozing" at varying rates across different areas of the structure. This can result in visible cracks, sticking windows and doors, and sloping floors, as the foundation becomes increasingly unlevel. Such differential movements may be triggered by factors like improper drainage, plumbing leaks, and even the water uptake by nearby vegetation, as documented by Mitchell (1993).

The specific type of clay mineral plays a crucial role in determining the extent of heave in expansive soils. Among the three common types of clay minerals—illite, kaolinite, and montmorillonite—the latter is known to have the highest swelling potential. The swelling behavior of these clay minerals is influenced by several factors, including the crystal lattice structure, the structural arrangement of the clay mass, and the cation exchange capacity of the minerals, as detailed in studies by Lamb (1959) and Gramko (1974).

2.2.1 Montmorilonite Clays

Montmorillonite Clays

The term "montmorillonite" for this group of clay minerals was first introduced in 1847 by Damoure and Salvetat, referencing a mineral discovered in Montmorillon, France. Montmorillonite clay minerals are characterized by the general formula $[M(Al,Fe,Mg)_4, (Al,Si)_8, O_{20}, (OH)_4 \cdot nH_2O]$, where the ratios of Al, Fe, and Mg are fixed, M denotes exchangeable cations such as Ca, Mg, Na, K, and H, and nH_2O represents the hygroscopic water content (Grim, 1959).

The swelling response of montmorillonite clay and the development of swelling pressure, when swelling is restrained, result from complex interactions between clay particles and within the particles themselves. Understanding and quantitatively modeling these fundamental interactions are crucial for effectively managing these systems (Katti & Katti, 2005).

Expansive soils, such as those containing montmorillonite, typically shrink when dry and swell when wet, exerting enough pressure to cause damage to sidewalks, driveways, basement floors, pipelines, and even foundations. It's important to note that not all expansive soils exhibit the same swell potential. Specific tests can determine the swell potential of a given soil and assess the likelihood of structural damage.

Moreover, the residual expansive soil profiles that develop over basic igneous rocks or montmorillonite sedimentary rocks are often accompanied by transported materials derived from these parent rocks, known as alluvial, colluvial, and loess-trim deposits (Mohan, 1957).

2.1.1.1 Bentonite

Bentonite is a type of geologic clay that is part of a rock formation widely recognized for its ultra-fine quality. Both bentonite clay and black cotton soil are classified under the montmorillonite clays, a categorization supported by findings in the literature (Jumics, 1962; Morthy, 1989). Predominantly, there are two main types of bentonite: sodium and calcium bentonite. Of these, sodium bentonite is known for its superior swelling capabilities, making it particularly significant in various industrial applications. Table 2-1 below outlines some of the common variants of bentonite clay, detailing their specific properties and uses.

Table 2-1: Varieties of Bentonite Clay with Swelling Characteristics*

No.	Name	Free Swell % Range
1	Sodium montmorillonite	1400-2000
2	Calcium montmorillonite	45-150
3	Halloysite	70-100
4	Indian Bentonite	300-1000

* It is based on research originally documented by Holtz and Gibb in 1956 and later cited by Ibrahim A. in 1989.

Wyoming bentonite, predominantly composed of sodium montmorillonite, was selected for these studies due to its high swelling capacity. To prepare deuterated bentonite for experimental analysis, 500 mg of Wyoming bentonite was dispersed in 5 ml of deuterium oxide (D_2O), sourced from Aldrich Chemical Co. with a purity of 99.9%. This mixture was then stirred under dry nitrogen for a period of four days to ensure full saturation and uniform distribution of the deuterium oxide within the clay structure. For all swelling experiments, double deionized water was utilized to maintain consistency and control experimental variables, as documented by Katti and Shanmughasundaram in 2001. This methodological approach ensures that the swelling behavior of the bentonite is accurately assessed under controlled laboratory conditions.

2.3 Free Swell

Free swell is characterized as the change in volume of a soil specimen when it is inundated with water, under minimal applied pressure. Shreif et al. (1982) noted that the surcharge pressure, which should be applied prior to the inundation of the sample, is approximately 7 kPa. This initial pressure is critical in standardizing the conditions under which the free swell is measured, ensuring that the volume change is due solely to water absorption and not to external pressures.

2.4 Methods of Predicting Free Swell

There are several methods available for predicting the free swell of soils, which can broadly be categorized into two main groups: laboratory test methods and empirical methods.

2.4.1 Laboratory Methods

2.4.1.1 Direct Method

I. Modified Free Sell Index Test

Developed and refined by Sivapullaiah et al. in 1987, the Modified Free Swell Index Test is designed to quantitatively assess the swelling potential of soil. The procedure begins by obtaining an oven-dried soil sample with an approximate mass of 10 grams. This sample is thoroughly pulverized to ensure uniform particle size and consistency.

The pulverized soil is then transferred into a 100-milliliter graduated jar filled with distilled water. The soil is allowed to soak and interact with the water undisturbed for a period of 24 hours, facilitating maximum absorption and expansion. After this period, the volume of the swollen sediment is carefully measured from the graduation marks on the jar.

The modified free swell index is calculated based on the change in volume, providing a numerical value that represents the soil's swelling potential under controlled conditions. This index is crucial for predicting the behavior of expansive soils in engineering applications, ensuring appropriate measures are taken to mitigate potential issues related to soil expansion.

$$Modified\ free\ swell\ index = \frac{v - v_s}{v_s}$$

Where:

V = Soil volume after swelling,

v_s = Volume of soil solid = $\frac{ws}{G_s \gamma_w}$

ws = Weight of oven dried soil, and

G_s = Specific gravity of soil solids

γ_w= Unit weight of water.

Table 2-2, provides a classification of the swelling potential of soils as determined by their modified free swell index values:

Table 2-2: Qualitative Classification of Expansive Soils Based on the Modified Free Swell Index

Modified Free Swell Index	**Swelling Potential**
Less than 2.5	Negligible
2.5 to 10	Moderate
10 to 20	High
Greater than 20	Very High

This classification helps in assessing the potential risk and impact of soil expansion on construction and civil engineering projects. Understanding these categories is crucial for effective soil management and mitigation strategies in areas with expansive soils.

II. Consolidation Method:

The Consolidation Method is a widely recognized procedure used to assess the swelling properties of soil samples. In this method, the soil specimen is saturated with water and allowed to swell under a nominal load. The process continues until no further swelling is observed. The extent of swelling is quantitatively determined using the following formula:

$$S\% = \frac{\Delta H - H}{H} \times 100$$

Where:

S = Swelling percent

ΔH = Final height of the sample, and

H = Initial sample height

This method provides valuable insights into the behavior of expansive soils when subjected to moisture changes under load, crucial for designing foundations and other structures on such soils.

2.4.1.2 Indirect Method

I. Index Properties

Holtz & Gibbs (1956) demonstrated the efficacy of simple identification tests that rely on colloid content and consistency limits to satisfactorily predict the expansive characteristics of clays. These tests are based on the premise that high colloid content is indicative of the most active part of any soil material, primarily contributing to its expansion potential. Additionally, high plasticity indices serve as another crucial indicator; they reflect the volumetric changes a soil undergoes when transitioning from a semi-solid to a liquid phase. Conversely, a low shrinkage limit suggests that the soil changes volume at relatively low moisture content, making it a reliable indicator of expansive properties.

The relationships between these indices and the soil's expansion potential are summarized in the following table:

Table 2-3: For Index Properties

<table>
<tr><th colspan="3">Data from Index Test</th><th rowspan="2">Estimated Probable Expansion (%) (dry to saturated)</th><th rowspan="2">Degree of Expansion</th></tr>
<tr><th>Colloid Content %<0.00lmm</th><th>Plasticity Index</th><th>Shrinkage Limit%</th></tr>
<tr><td>>37</td><td>>32</td><td><10</td><td>>30</td><td>Very high</td></tr>
<tr><td>18-37</td><td>23-45</td><td>6-12</td><td>20-30</td><td>High</td></tr>
<tr><td>12-27</td><td>12-34</td><td>8-18</td><td>10-20</td><td>Medium</td></tr>
<tr><td><17</td><td><20</td><td>>13</td><td><10</td><td>Low</td></tr>
</table>

2.4.2 Theoretical Method

I. Holtz Method

Developed by Holtz in 1959 and later discussed by Gramko in 1974, the Holtz Method provides an empirical formula for estimating the swelling potential of soils. This method utilizes the shrinkage index (S.I) as a predictive tool, applying the following equation:

$$S\% = B(S.I)^P$$

Where:

S% = Swelling as percent

B = Constant = 1/6.3

P = Constant = 1.17

Holtz proposed that the shrinkage index not only measures soil shrinkage but also serves as a qualitative indicator for assessing the degree of soil expansion. This relationship between the shrinkage index and the swelling potential is summarized in the table below, facilitating a straightforward interpretation of potential expansion risks based on empirical data.

Table 2-4: Shrinkage Index and Degree of Expansion

Shrinkage index %	Swelling of exopansion
0.0-20	Low
20-30	Medium
30-60	High
> 60	Very high

This method is particularly useful in preliminary soil assessments where direct measurement methods might not be feasible, allowing engineers to estimate swelling potential from existing soil data effectively.

II. Seed, Woodward & Lundgren Model

The Seed, Woodward & Lundgren model, established through the work of Seed et al. (1962), examines swelling potential in artificially-prepared compacted soils, which vary in their properties. This model posits that the swelling potential of a given soil type is empirically related to the activity of the soil and its clay content. The relationship is defined by the following equation:

$$S\% = K\,A^{2.44}C^{3.44}$$

Where:

S% = Swelling as percent

K = constant for all types of clay minerals = 3.6×10^{-5}

A = activity of the soil = $\frac{P.I}{C-n}$

Where:

P.I = The plasticity index

N = Constant = 5 for natural soils

= 10 for artificial soils

C= Clay content (% < 0.002 mm)

Additionally, another empirical equation provided by Seed et al. relates the swelling percentage to the shrinkage index:

$$S\% = 41.13 \times 10^{-5}(S.I)^{2.67}$$

Where:

S% = Swelling as percentage

S.I = Shrinkage index = L.L – S.L, as percent

These models are instrumental for predicting the swelling behavior of soils, particularly in the context of civil engineering and geotechnical applications, where understanding soil expansion due to moisture changes is crucial for designing stable structures.

III. Chen Method

The Chen Method, developed by Chen in 1975, offers an indirect approach to estimating the swell potential of soil based on its plasticity index. This method is derived from the empirical analysis of 321 undisturbed soil samples, which led to the formulation of a predictive equation:

$$\%S = Qe^{N(P.I)}$$

Where:

S% = Swelling as percent

N = Constant = 0.0838

Q = Constant = 0.2558

P.I = Plastic Index

This equation quantifies the relationship between the plasticity index and the swelling potential, providing a valuable tool for geotechnical engineers to predict soil behavior without extensive laboratory testing. This method is particularly useful in preliminary site assessments where direct soil testing is not feasible.

V. Sherif, Ishibashi and Medhin Method

In 1982, Sherif et al. introduced a novel formula that establishes a relationship between the percentage of swelling and the liquid limit for disturbed soil samples. These samples are characterized by a natural water content equal to the plastic limit and a density of 1.85 g/cm³. The researchers conducted experiments at various temperatures—24°C, 38°C, and 66°C—and developed a diagram that plots the relationship between the liquid limit, maximum swelling as a percentage, and temperature, as illustrated in Figure (2-2).

$$S\% = \frac{\Delta H}{H} = B \log \frac{L.L}{35}$$

Where:

$S\% = \frac{\Delta H}{H}$ = Swelling as a percent

L.L = Liquid limit, and

B = slope of the straight line as shown in Figure (2-2)

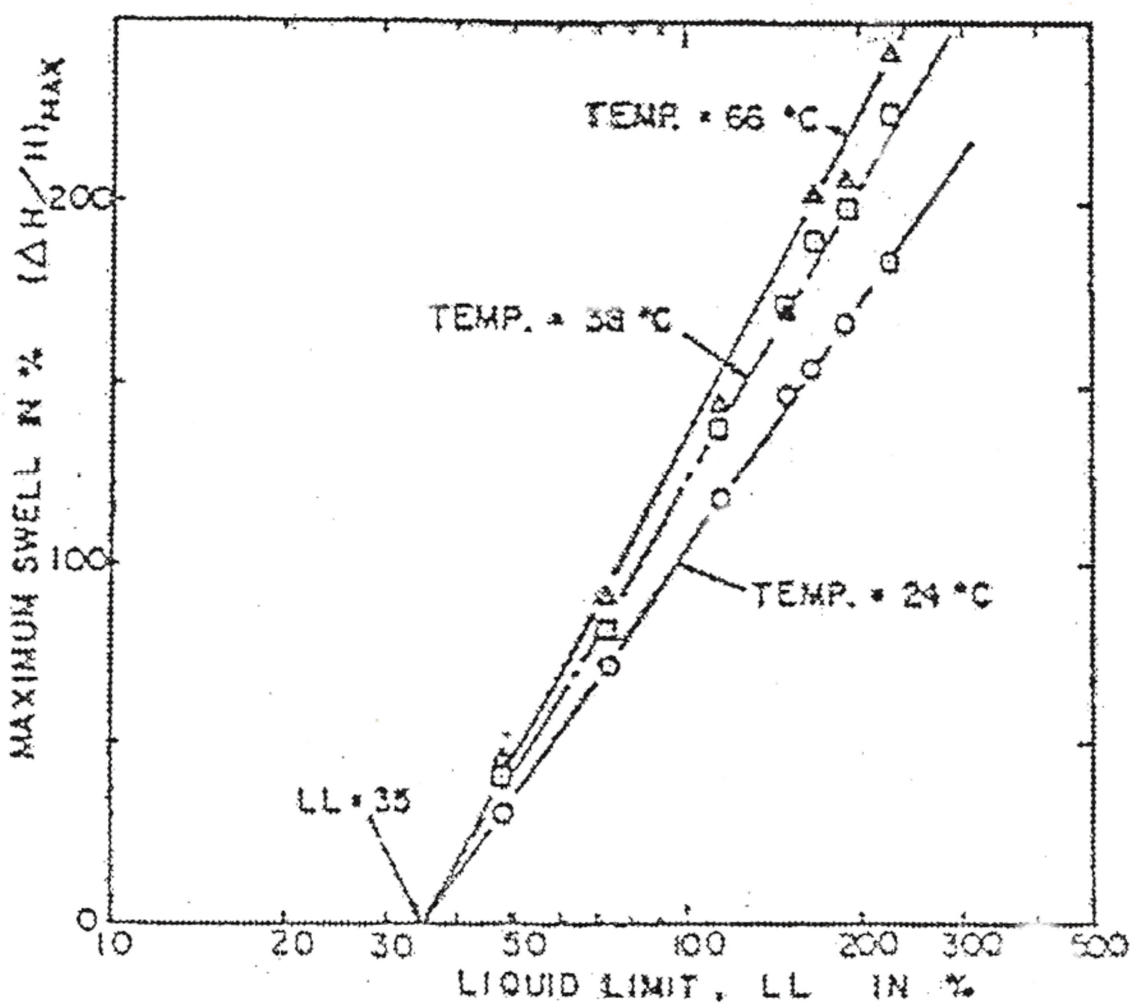

Figure 2-2: Maximum Swelling Vs. Liquid Limit (After Sherif et. al.)

This method provides a critical tool for predicting the swelling behavior of soils under specific conditions, helping engineers assess potential ground movement and its impact on structures. Figure (2-2) illustrates the maximum swelling versus liquid limit, providing a visual representation of the data after Sherif et al.

2.5 Causes of swell and swell pressure in Compacted Clays

Numerous studies have been conducted to investigate the underlying factors contributing to the swelling of compacted clays. The role of mechanical factors in swelling has been well-documented over the years, with significant contributions from researchers like Terzaghi (1931), While (1956), Ladd (1959), Lamb and Whitman (1959), Nobel (1966), Gramko (1974), Shreif et al. (1982), and Jones and Jones (1987). It is widely accepted that the expansion of soil upon exposure to water and/or the reaction to external loads is due to a combination of several factors.

The propensity of soil to absorb water upon exposure to free water or upon the release of load is fundamentally a result of the water pressure differential inside and outside the soil sample. The entry of free water is facilitated by a hydraulic gradient, with factors leading to a water pressure less than that of the free water being pivotal in controlling both swelling and the development of swell pressure conditions within fine-grained soils. These contributory factors have been classified into three general categories by Seed et al. (1962):

I. Physical factors: These involve the inherent physical properties of the soil, such as density, porosity, and aggregate size.

II. Environmental factors: These include external conditions such as temperature, humidity, and the hydraulic conditions surrounding the soil.

III. Physico-Chemical factors: These refer to the chemical composition of the soil and the ionic interactions within the soil matrix.

Further, many researchers have noted that results from swelling tests often exceed those observed in the field. This discrepancy is attributed to the difficulty in obtaining undisturbed soil samples and the common practice of using remolded samples in tests (Gramko, 1974; Nobel, 1966). The use of distilled water in laboratory tests has also been cited as a contributing factor to these differences. Jones and Jones (1987) pointed out additional factors such as expansive characteristics and overburden pressure that limit swell in practical settings. They noted that the actual shrink/swell behavior in the field typically ranges from 10% to 80% of the theoretically possible swell, as further supported by Al-Dahlaggi (2001). This insight emphasizes the complexity of predicting soil behavior accurately in natural conditions and underscores the importance of considering a wide range of factors in soil mechanics studies.

2.5.1 Physical Factors

2.5.1.1 Effect of non-Swelling Materials

Sivapullaiah et al. (1996) explored the influence of size, shape, and quantity of non-clay materials on the swelling behavior of soils. The study found that the time to reach an asymptotic swelling value varies significantly with the non-swelling fraction present. Generally, the maximum amount of swelling increases with the addition of bentonite content, indicating that the rate of swell follows different paths depending on the non-swelling fractions in the mixture.

2.5.1.2 Mineral Type and amount

Lambe and Whitman (1959) demonstrated that swellability varies with the type of clay mineral; it decreases in the order Montmorillonite, Illite, Attapulgite, and Kaolinite. A smaller particle size allows for more water adsorption per unit volume of clay particle, enhancing swell potential.

Mitchell (1976) found that soils containing montmorillonite and vermiculite are the most expansive. El-Sohby (1985) reported that both swell and swelling pressure increase with the increase in clay content, particularly with smaller particles of montmorillonite.

2.5.1.3 Initial Moisture Content

Initial moisture content is a crucial factor affecting the swelling potential of soils, particularly in remolded states. Krebs and Walker (1971) noted that higher initial moisture content satisfies the soil's natural desire for adsorbed water. Chen (1975) observed that swelling pressure is unaffected by changes in moisture content in soils with identical dry density if allowed to soak adequately. Al-Layla and Al-Ashou (1985) found that increasing natural water content in Mousil's clays above the plastic limit results in a loss of their swelling ability.

2.5.1.4 Dry Density

According to Gramko (1974), dense clays swell more when wet compared to the same clay at a lower density and the same initial water content. Ganeshan and Al Naqshabandy (1988) discovered that swelling characteristics increase with dry density. Brackely (1975) found that free swell without load primarily depends on moisture content and dry density, whereas swell pressure in a constant volume method depends on dry density.

2.5.1.5 Soil Structure

Seed and Chen (1959), showed that the soils of flocculated particles swell more than that of dispersed particles, Moreover, they found that soil compacted by kneading or impact method will swell less than that compacted by static method for the same soil properties.

2.5.1.6 Time

Ladd (1959) emphasized that expansive soils require a long time to complete the swelling process. The time factor also depends on permeability, layer thickness, initial moisture content, and dry density. Seed et al. (1962) stated that the swell pressure developed after 7 days of soaking was at least 100 percent greater than that developed after 1 day. Gramko (1974) pointed out that moisture transmission is slow and may require weeks or even years to saturate, depending on permeability and layer thickness.

2.5.1.7 Thickness of Clay Layer

Chen (1975) reported that the amount of swell increases with the thickness of the expansive clay layer. Conversely, the swelling percent and swell pressure decrease with the increase in overburden pressure.

2-5-1-8 Degree of saturation

Chen (1975) also noted that the volume change is directly proportional to the degree of saturation at the end of a standard oedometer test. Al-Saoudi et al. (1986) observed that the final degree of saturation at the end of the swelling process is less than 100%, while Al-Dahlaggi (2001) demonstrated that swelling continues beyond 100% saturation. Variations in soil profile properties, such as layer thickness and the depth of the swelling layer below the ground surface, significantly influence total volume change (Senthaen 1975).

2.5.2 Environmental Factors

2.5.2.2 Depth of Seasonal of Moisture Variation

One of the predominant factors affecting swelling in clays is the variation in water content, where increases in moisture typically lead to enhanced swelling. The depth at which soil moisture content changes in response to environmental factors is referred to as the "active zone." This depth can be determined by plotting the liquidity index against the soil profile depth over several seasons, as depicted in Figure (2-3).

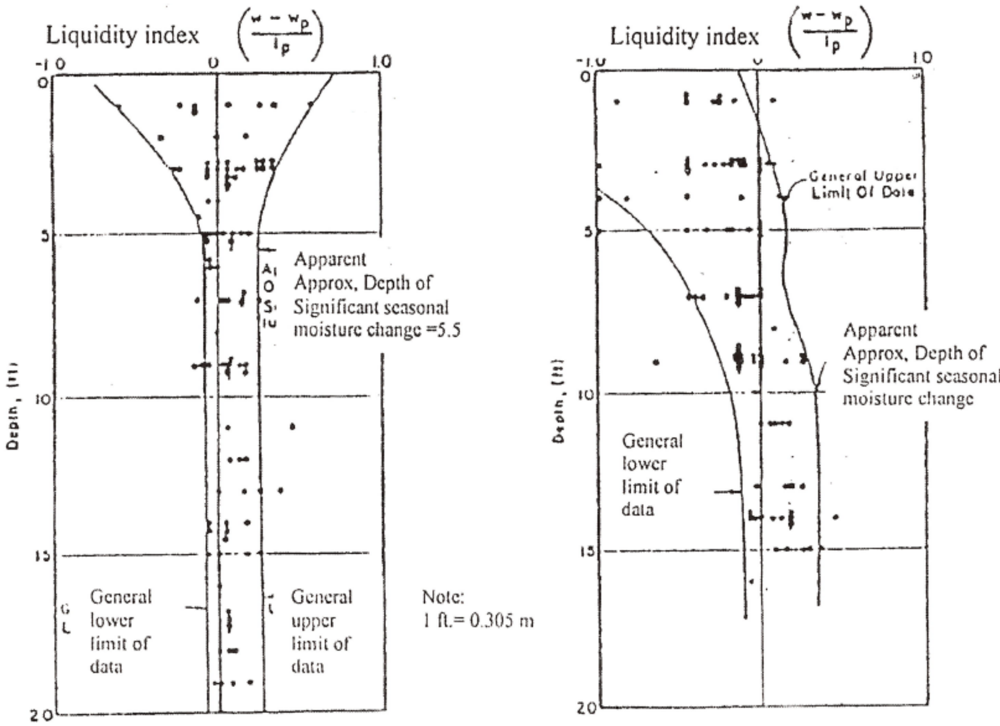

Figure 2-3: Liquidity Index vs. Depth for Samples Taken Over Several Seasons in the Houston, Texas area (Data Courtesy Southwestern Laboratories): (a) Beaumont Formation; (b) Montgomery Formation.

The data from the Beaumont and Montgomery formations in Houston, Texas, illustrate how formation characteristics can influence the depth of the active zone. In regions like the Southern and Western United States, where some moisture-deficient clays and shales are found, evidence suggests that swelling can occur at depths ranging from 30-50 feet (9-15 meters), especially when moisture content is artificially increased by methods such as placing a membrane over the site to impede evaporation (Holtz, 1969; Johnson, 1979).

Table 2-5: Active Zones in Various U.S. Cities

City	Depth of active zone	
	(ft.)	(m)
Houston	5-10	1.5-3
Dallas	7-15	2.1-4.6
San Antonio	10-30	3-9
Denver	10-15	3-4.6
Texas gulf	5-15	1.5-4.6
San lewis	4-10	1.2-3

Table 2-5: Active Zones in Some Iraqi Cities

City	Active Zone (m)
Sallah Aldden	1-5
Anber	1-10
Dylla	2-7
Wassite	8.5-19
Babylon	2-5
Karballa	6-20
Al-Qadissia	4-24
Al-Najaf	2-13

2.5.2.3 Climate

Thornthwaite (1948) discussed the impact of climate on the swelling behavior of soils. Soils that undergo a long dry period followed by heavy rainfall are more susceptible to swelling. The distance of the water table from the surface also influences the moisture content, affecting the equilibrium between rainfall and evaporation. The Thornthwaite Moisture Index (T.M.I) is used to evaluate the climate's effect on swelling soils:

$$T.M.I = I_r - I_c$$

Where,

T.M.I = Thornthwite moisture index

I_r = Average annual rainfall in (inch)

I_c = Evaporation water in (inch)

In locations where the T.M.I varies between +20 and -20, soils exhibit significant swelling issues.

2.5.2.4 Temperature

Research by Shreif et al. (1982) indicates that the test temperature significantly affects the amount of soil swell. Higher temperatures increase swelling due to decreased plasticity, reduced water attraction, and increased permeability from soil shrinkage and crack formation. Flaherty (1988) noted that both soaked and unsoaked compressibility is reduced due to decreased water sensitivity. Temperature variations from 10°F to 15°F can change the observed swell by up to 0.5 percent for samples of 0.5 thicknesses, emphasizing the temperature's physico-chemical impact on swell and swell pressure.

2.5.3 Physico-Chemical Factors

Research has established that the physico-chemical factors significantly influence the volume change characteristics of dry soils upon swelling at lower stresses, while mechanical effects become more dominant at higher stresses (Mitchell, 1976; Rao and Reddy, 1998).

2.5.3.1 Pore Fluid

The swelling behavior of soils is greatly affected by the electrolyte concentration and the valence of the ions in the pore fluid. High concentrations of ions can significantly reduce, or even completely nullify, soil swelling. Maximum swelling occurs when the soil is exposed to electrolyte-free (distilled) water (Katti, 1972). Gramko (1974) noted that the degree of swelling varies depending on the type of fluid present in the soil's pores, with higher salt concentrations in free water resulting in less water absorption and subsequently less swelling.

2.5.3.2 Cation Exchange

Barnes (2000) described the base exchange, or cation exchange capacity, as the ability of clay minerals to swap cations within their structure with other cations, measured in milliequivalents per 100 grams of dry soil. El-Sohby et al. (1983) observed that the swelling percent and swelling pressure are significantly influenced by the type of cation present. Positively charged ions (cations) are more readily adsorbed than negatively charged ions (anions), indicating a predominance of negative charge on the clay surface (Mitchell, 1976).

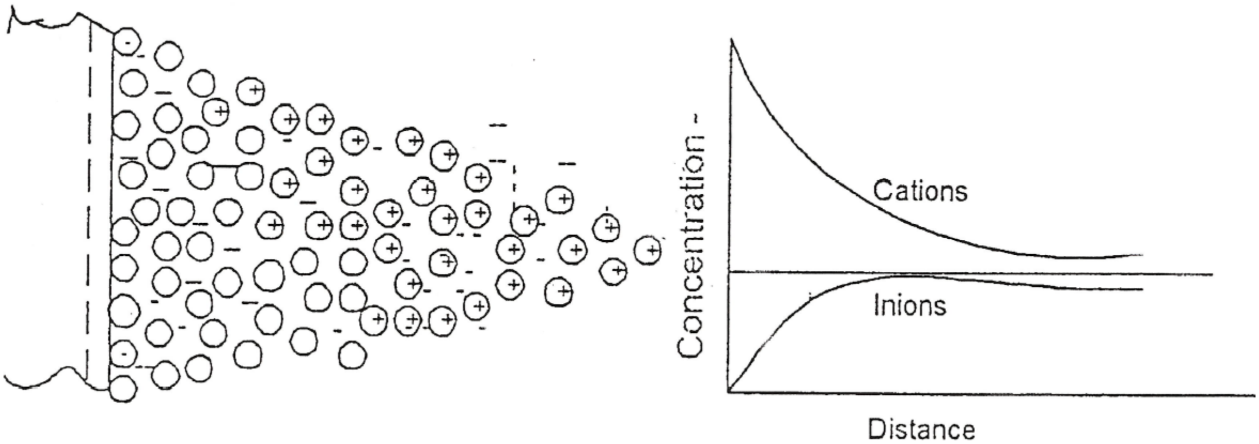

Figure 2-4: illustrates the distribution of ions adjacent to a clay surface, conceptualized as the diffuse double layer, based on the work of Mitchell (1976).

Table 2-7: demonstrates the relationships between adsorbed cations and soil properties, such as Atterberg limits and the type of clay mineral. For example, different cations, including Na+, K+, Ca+, and Mg+, show varied impacts on the Liquid Limit (L.L.) and Plasticity Index (P.I.) across different types of clay minerals such as kaolinite, illite, and montmorillonite. This table provides a comprehensive view of how cations interact with specific clay minerals, influencing the soil's physical properties and its potential for swelling.

Clay Mineral	**Cation**	**Na+**		**K+**		**Ca+**		**Mg+**	
		L.L.	**P.I.**	**L.L.**	**P.I.**	**L.L.**	**P.I.**	**L.L.**	**P.I.**
Kaolinite		29	1	35	7	34	8	39	1 1
Illite		61	27	81	38	90	50	83	44
Montmorillonite		344	251	161	104	166	101	158	99

This detailed analysis helps in understanding the complex interactions between clay minerals and the surrounding environment, providing crucial insights for addressing challenges related to soil swelling in geotechnical engineering.

2.6 Stabilization of expansive clayey soils

The stabilization of expansive clayey soils is crucial due to the significant structural challenges they pose. Various methods have been developed to mitigate the heave of these soils, based on economic feasibility and practical application. These methods can be broadly categorized into compaction control, prewetting, maintaining constant water content, and chemical and electro-osmotic stabilization techniques. The choice of a suitable stabilization method depends on site-specific conditions and a comprehensive understanding of the limitations and applications of each technique (Gramko, 1974).

2.6.1 Compaction control

As noted by Shanker et al. (1982), expansive soils exhibit minimal expansion when compacted at low densities with high moisture but expand substantially under high density and low moisture conditions. Chen (1975) highlighted the advantages of this method, particularly its ability to reduce swelling potential without the adverse effects of excessive moisture introduction.

2.6.2 Pre wetting

Chen (1975) also discussed the benefits of prewetting expansive soils before construction. By allowing the soil to swell by wetting prior to construction and maintaining high moisture content thereafter, the soil volume remains essentially constant, thus preventing structural damage.

2-6-3 Constant Water Content

This method involves moisture control techniques around the perimeter of structures to minimize edge wetting or drying, which can affect the foundation. O'Neil (1980) noted that horizontal barriers are generally less effective than vertical barriers, as they can act as wicks, drawing moisture out of the soil.

2-6-4 Soil reinforcement

Al-Omari and Hamodi (1991) attempted to reinforce expansive soil using high-stiffness geogrids oriented in the direction of swell. Al-Murshdi (2001) advocated for the use of reinforced granular trenches under continuous footings to support lightweight structures, achieving significant improvements with strategic placement of reinforcement layers.

2-6-5 Chemical Stabilization

This method involves the addition of chemical additives like lime and cement to expansive soils, which has been practiced with varying degrees of success (Gramko, 1974). McDowell (1959), Thompson (1965), and Bell (1988) documented that small amounts (3 to 8 percent by weight) of these additives significantly improve the soil's plasticity, workability, and strength properties.

2.6.6 Soil Replacement

Jones and Jones (1987) proposed replacing the foundation soil with non-swelling soil to manage expansive soils effectively, a method that is particularly feasible where the expansive soil layer is three feet deep or less.

2-6-7 7-Electro-Osmotic Stabilization

Al-Bayati (2001) described the use of direct current to induce water movement towards a cathode in the soil, reducing soil volume by the amount of water removed, thus stabilizing the soil.

2-6-8 Thermal Stabilization

Jha and Sinha (1981) reported that heat treatment could transform expansive clay into non-expansive material, a method used successfully in various large-scale projects in the USSR (Al-Bayati, 2001).

2-6-9 Sand Bentonite Mixture

Research by Shreif et al. (1982) and Al-Ashou et al. (1997) has shown that mixing bentonite with sand can significantly reduce the free swell of the soil. A 20% sand mixture is recommended for construction purposes as it effectively reduces both swelling potential and pressure.

These stabilization techniques provide a range of options for managing the challenges posed by expansive soils, each with its own set of considerations and applicable scenarios.

3. Experimental Work

3.1 Introduction

This chapter details the experimental laboratory work conducted to evaluate the effectiveness of using sand to mitigate the free swelling characteristics of expansive soils.

3.2 Materials

3.2.1 Bentonite

Ca-based bentonite sourced from AL-Faluja Cement Factory was utilized as the expansive soil for all tests described in this chapter. Following recommendations by Spangler and Handy (1982), all bentonite specimens were oven-dried, as montmorillonite soils should be air-dried prior to engineering tests to ensure they re-wet properly.

3.2.2 Sand

The study employed commercially available fire sand from the city, characterized by a well-graded, fine, crushed silica composition. The grain size distribution of the sand, specifically retained between 0.2 mm and 1.0 mm at 60% with a uniformity coefficient of 4.0, is depicted in an accompanying figure (Graham et al., 1989).

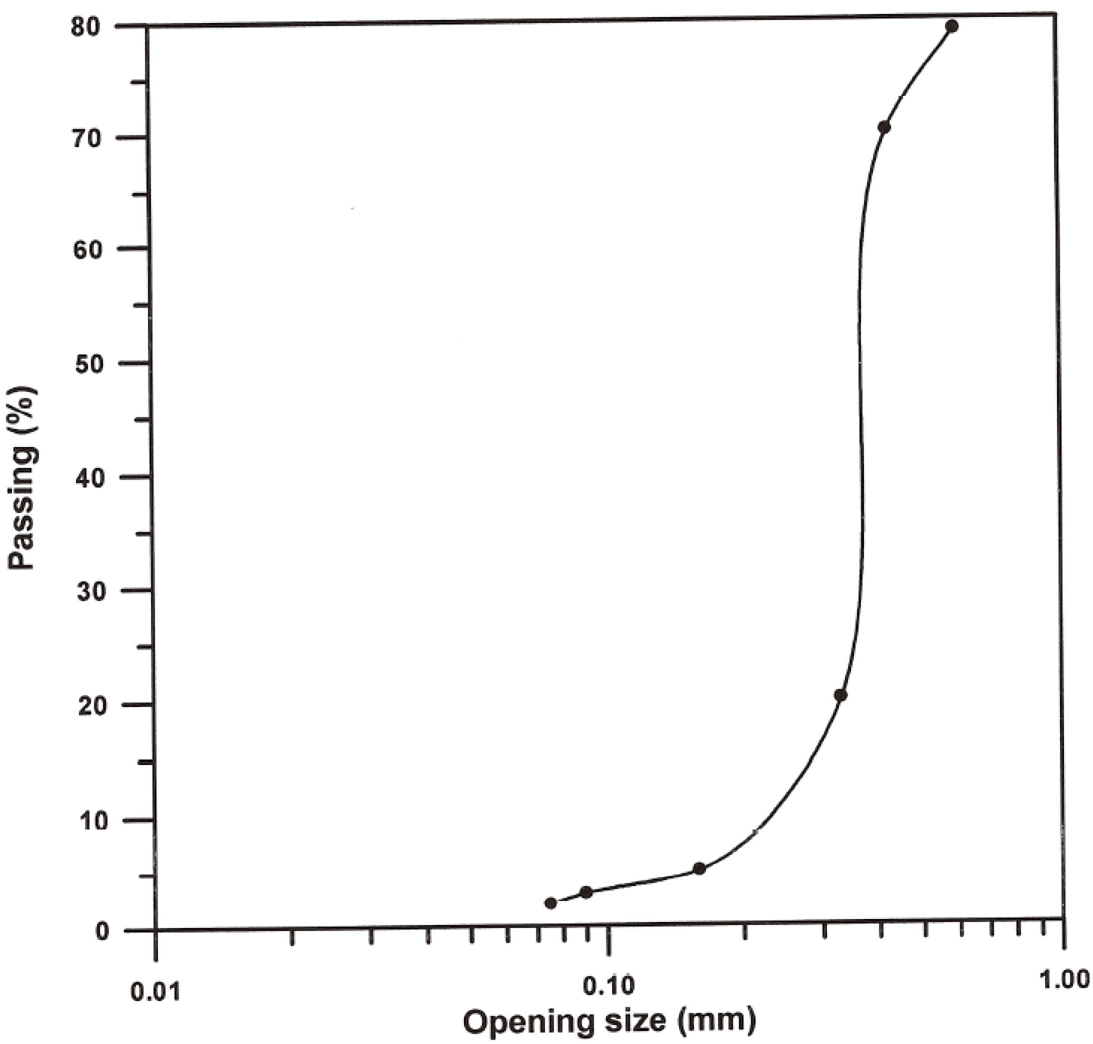

Figure 2-5: Graham et.al. (1989) pointed that the sand used in Bentonitel sand soil mixture is : well graded ,fine ,crashed silica sand (percentage retained 0.2 mm -l.0mm=60% uniformity coefficient =4.0).

3.3 Physical properties of the Bentonite /sand soil mixtures

The physical properties of the bentonite/sand soil mixtures were determined in the laboratory as follows:

3.3.1 The specific Gravity

The specific gravity of all mixing ratios is listed in Table 4.3 for all specimens. This was determined using a 50 ml capacity density bottle in accordance with BS 1377-1975, Test No. 6.

3.3.2 Atterberg limits

3.3.2.1 liquid limit

The liquid limit was measured using a cone penetrometer apparatus (BS 1377-1975, Test 2A). Venkatappa Rao and Rekhi (1977) highlighted the cone penetrometer's widespread success in determining the liquid limit due to its simplicity and minimal human error. The method is particularly accurate for high plasticity soils compared to the Casagrande device (Head, 1984).

3.3.2.2 Plastic Limit

Tests were carried out on all specimens in accordance with BS 1377-1975, Test 3.

3.3.3 Compaction Tests

The relationship between dry density and moisture content for all Bentonite/Sand mixtures was established using the standard compaction test (BS 1377-1975, Test 12), with results presented in Chapter Four.

3.4 Preparation of Compacted Specimens

To conduct the experimental work, numerous test specimens were meticulously prepared in the laboratory. Sherif et al. (1982) recommended drying the commercial bentonite in an oven to a constant weight at 105°C ± 5°C, as the material may contain numerous rolled soil balls distributed throughout the sample. The preparation process involved:

I. Mechanical compaction (dynamic compaction) for oedometer test specimens using a timber rod to achieve a specified density (15 kN/m^3).

II. Static compaction for CBR mold specimens to achieve the same specified density (15 kN/m^3).

3.4.1 Mixing with water

For oedometer specimens, sand was mixed with bentonite without water addition. In contrast, for the CBR mold specimens, 10% water was added and mixed manually, then left to equilibrate for

24 hours to ensure uniform moisture distribution. Bentonite was oven-dried at 105-110°C as per BS 1377-1975, Test A.

3.5 Swelling Tests

3.5.1 Free Swell and Swelling Pressure Tests Using Oedometer Cells

The standard oedometer apparatus was used to determine the swelling behavior of oven-dried Bentonite/Sand soil mixtures. Required quantities of bentonite mixed with non-swelling material (silica sand) were transferred to a consolidation ring with a 75mm internal diameter and 20mm height. Silicon grease was applied to the inner surface of the ring to minimize friction. Specimens were dynamically compacted to a density of 15 kN/m^3 using a timber rod with a diameter of 40mm and height of 150mm. Specimens of 10mm height were prepared using brass molds of 10mm height and 74mm diameter, then loaded incrementally until the specimen returned to its initial height. The final swell (Free swell (%) = [(LiH/H0) * 100]) and the pressure required to restore the specimen to its original height were defined as the swelling pressure.

4. Results and Discussions

4.1 Introduction

In this study, test results are analyzed to explore the advantages of utilizing fine sand in treating expansive bentonite clays. The focus is on understanding how fine sand can mitigate the expansive properties of bentonite, a significant concern in geotechnical engineering.

4.2 Physical Analysis

4.2.1 Grain Size Distribution

The grain size distribution of the fine sand is documented in Figure (3-1), showing a coefficient of curvature (Cc) of 1.33 and a coefficient of uniformity (Cu) of 1.66. Notably, 98.5% of the bentonite passes through sieve No. 200 (0.075 mm) and 80% is finer than 0.002 mm.

4.2.2 Atterberg Limits

Atterberg limits for the materials are presented in Table (4-1), and the specific gravity (Gs) results for bentonite and sand are detailed in Tables (4-2) and (4-3).

Table 4-1: Atterberg Limits

soil	Liquid Limit (LL%)	Plastic Limit (PL%)	Plasticity Index (PI%)
Bentonite	118°/o	42%	76%

Table 4-2: Specific Gravity of Bentonite and Sand

Material	Specific Gravity (Gs)
Sand	2.67
Bentonite	2.81

Table 4-3: Specific Gravity of Bentonite/Sand Soil Mixtures

Percentage of Bentonite in Mix	Specific Gravity (Gs)
20%	2.68
30%	2.75
40%	2.78

4.2.3 Soils Classification

According to the Unified Soil Classification System (USCS), the fine sand is classified as SP (poorly graded sand) and the bentonite is classified as CH (high plasticity clay).

4.3 Compaction characteristics

The influence of dry density on expansive soil was analyzed with specimen compositions by dry density values of 15 kN/m³ and 17 kN/m³.

4.4 Swelling Test

4.4.1 Swelling Pressure

4.4.1.1 Swell Pressure – Time Relationship

The swelling percentage is plotted against time from Figures (4-1) to (4-8), illustrating that expansive soils take a prolonged period to reach full expansion. An increase in swelling is dependent on the percentage of bentonite and the value of the swelling pressure.

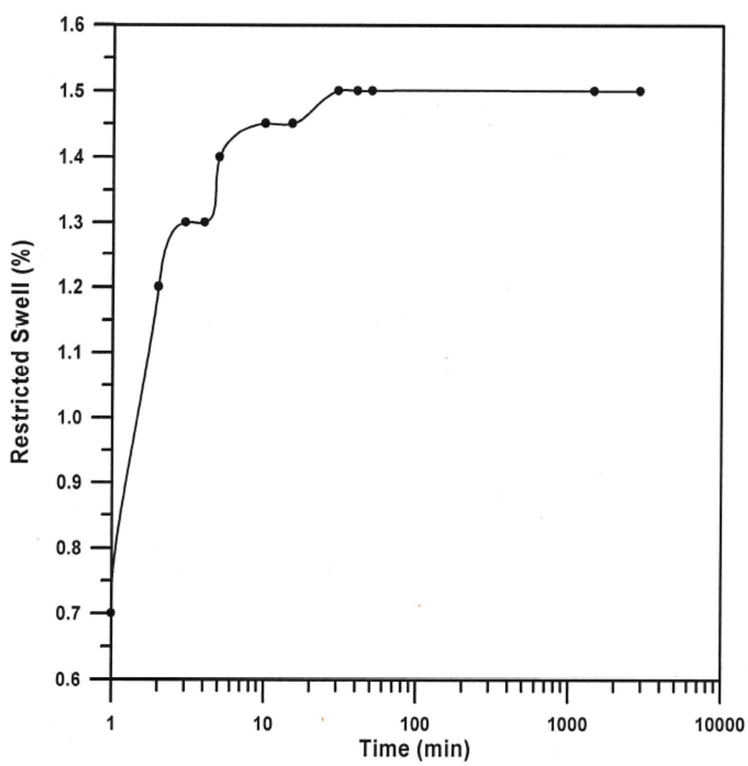

Figure 4-1: γ_{dmax} = 15 KN/m^3, Percentage of Bentonite = 30%, Setting pressure= 12.5 KN/m^2

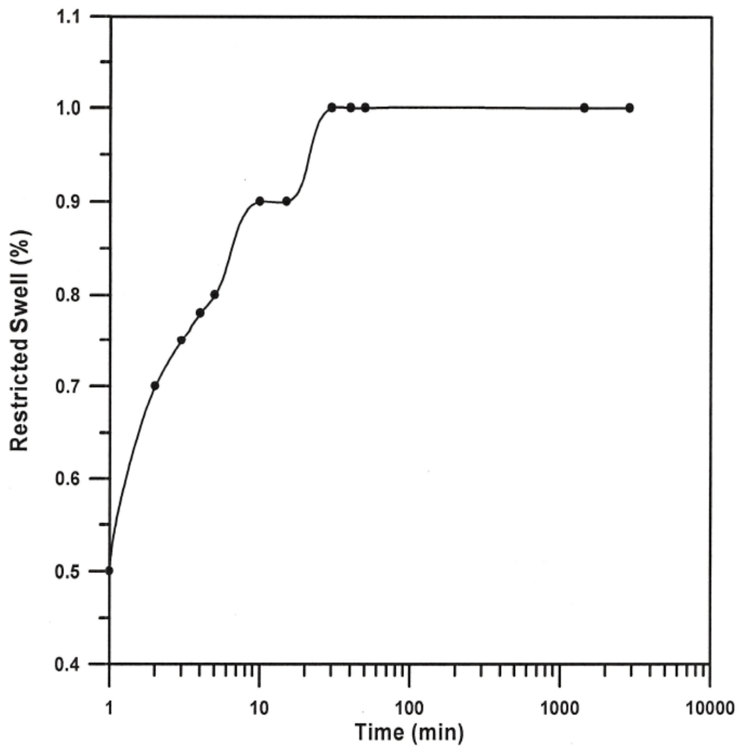

Figure 4-2: γ_{dmax}= 15 KN/m^3, Percentage of Bentonite = 30%, Setting pressure= 25 KN/m^2

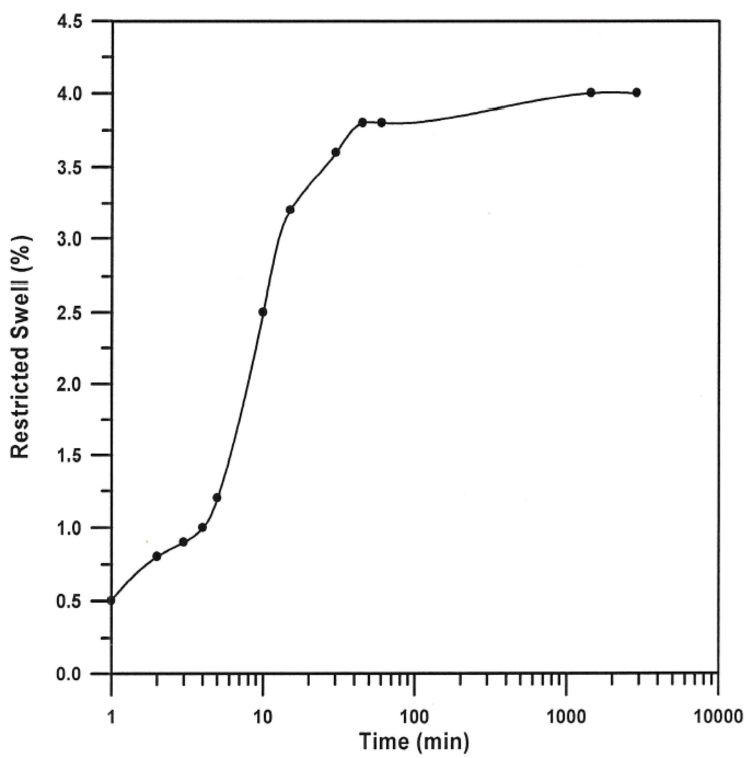

Figure 4-3: γ_{dmax}= 15 KN/m^3, Percentage of Bentonite = 40%, Setting pressure= 12.5 KN/m^2

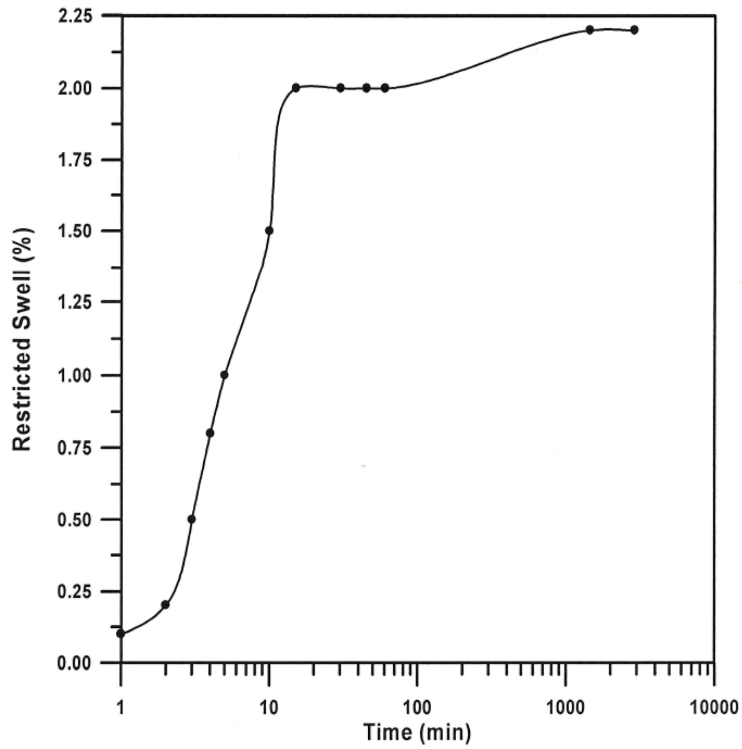

Figure 4-4: γ_{dmax}= 15 KN/m^3, Percentage of Bentonite = 40%, Setting pressure= 25 KN/m^2

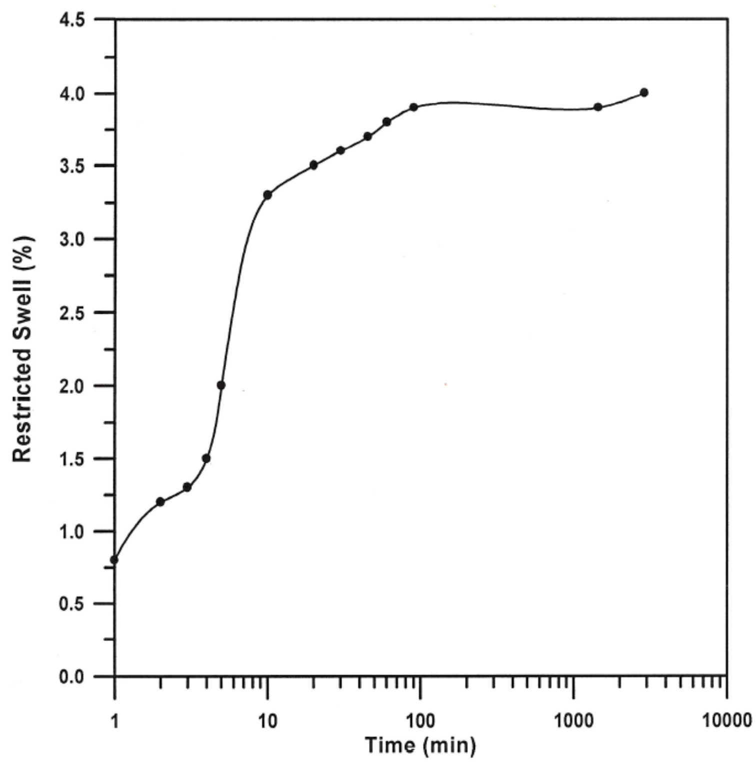

Figure 4-5: γ_{dmax}= 17 KN/m^3, Percentage of Bentonite = 30%, Setting pressure= 12.5 KN/m^2

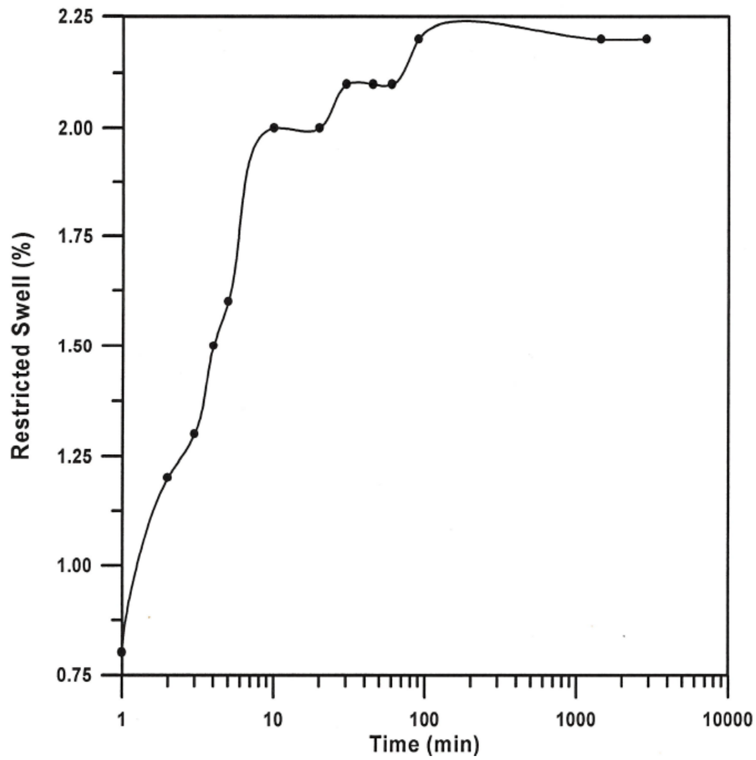

Figure 4-6: γ_{dmax}= 17 KN/m^3, Percentage of Bentonite = 30%, Setting pressure = 25 KN/m^2

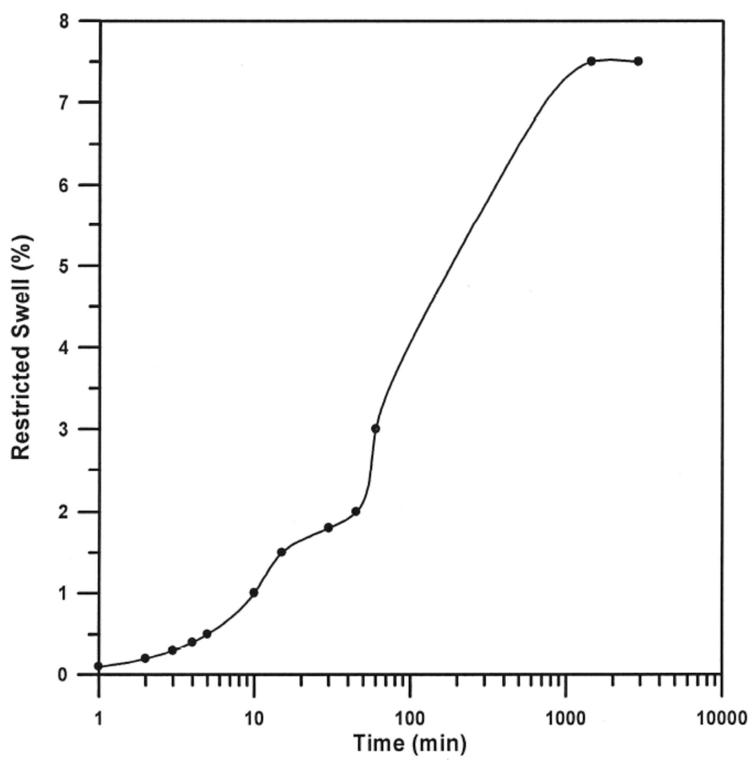

Figure 4-7: γ_{dmax}= 17 KN/m^3, Percentage of Bentonite = 40%, Setting pressure= 12.5 KN/m^2

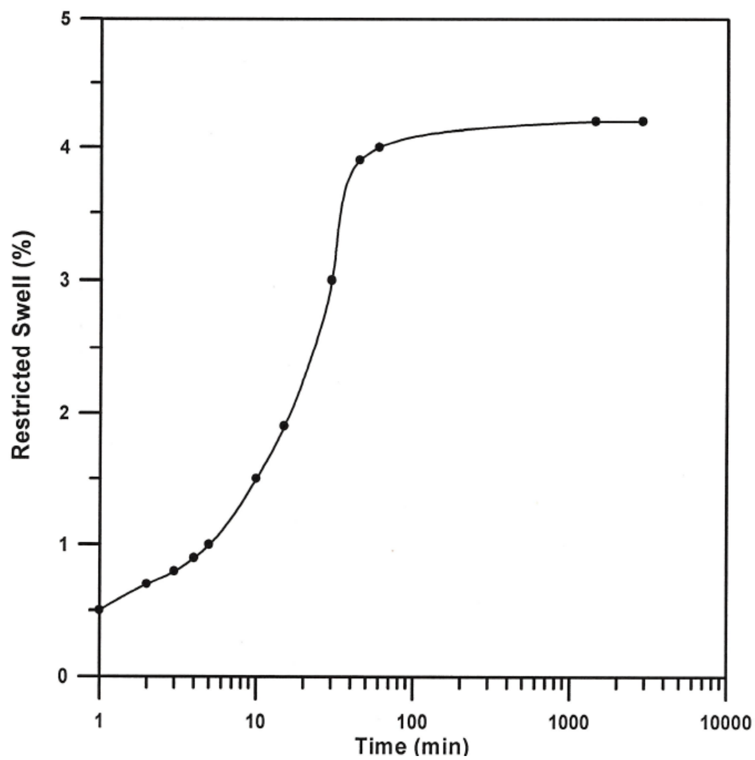

Figure 4-8: γ_{dmax}= 17 KN/m^3, Percentage of Bentonite = 40%, Setting pressure = 25 KN/m^2

4-4-1-2Influence of percentage of Bentonite on expansive soil

Swelling percentages at different bentonite contents are illustrated in Figures (4-9) and (4-10). The results indicate a significant reduction in free swell after limited initial loading, as well as a convergence of swelling values under the studied loading conditions. Notably, in samples with a density of 15 kN/m^3 and a bentonite ratio of 30%, there is no noticeable difference in the restrained swelling under pressures of 12.5 kN/m^2 and 25 kN/m^2 due to the unchanged swelling in the sample containing 30% bentonite.

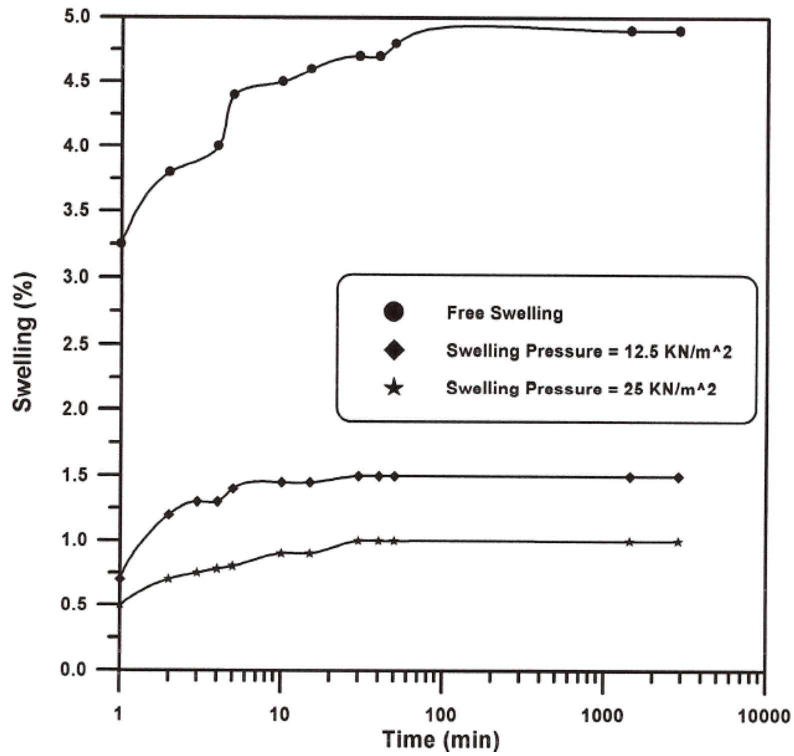

Figure 4-9: γ_{dmax}= 15 KN/m3, Percentage of Bentonite = 30%

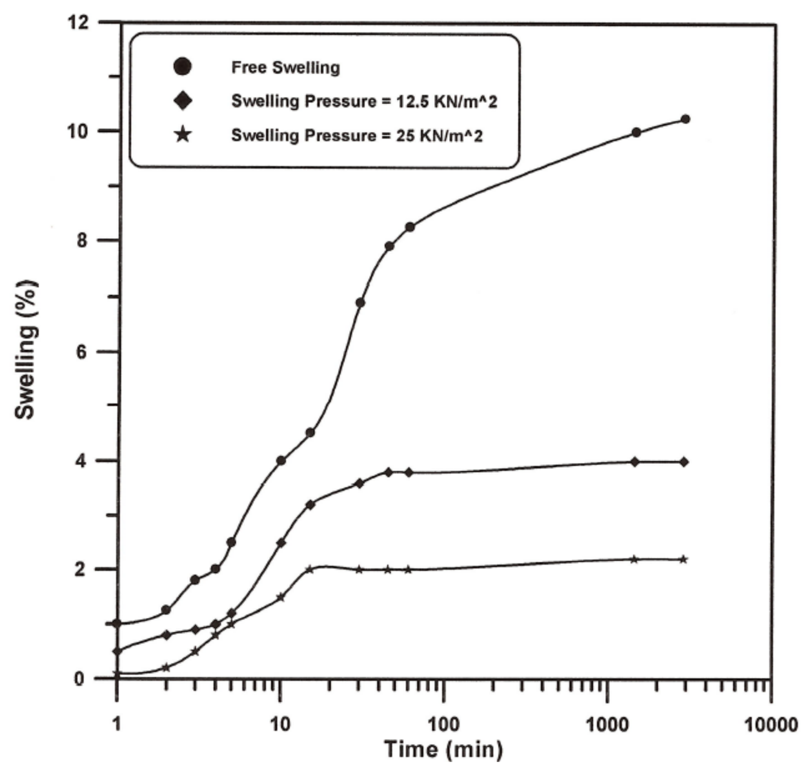

Figure 4-10: γ_{dmax}= 15 KN/m3, Percentage of Bentonite = 40%

From Figures (4-9) and (4-10), it is evident that the swelling pressure increases significantly with an increase in the percentage of bentonite, highlighting the critical role of bentonite content in the expansive behavior of the soil.

5. Conclusions and Recommendations

5.1 Conclusions

I. In samples with a similar bentonite content, both free swelling and relative swelling increase with the density. This implies that determining the field density that leads to unacceptable swelling is crucial, or alternatively, applying an initial load to control the swelling is necessary.

II. For a given dry density of the sample, both swelling and relative swelling increase with the bentonite ratio. This underscores the importance of thoroughly analyzing the soil to specify the bentonite ratio and quality and taking appropriate measures when this ratio exceeds levels that cause significant swelling.

III. For a specified dry density and bentonite content, swelling decreases with an increase in primary pressure. Previous tests confirm the effectiveness of this primary loading, even at low values, in preventing excessive swelling. Practical benefits should be derived from these findings.

5.2 Recommendations

I. The findings of this study should be applied in field studies on expansive soil layers. Techniques such as plowing and mixing with a recommended sand ratio followed by compaction to maximum density can be utilized.

II. Consider using a small percentage of Portland cement mixed with the Bentonite/Sand soil mixture to enhance soil stability and reduce swelling.

III. Further tests should be conducted using different percentages of bentonite to refine the mixture's properties and optimize performance.

IV. Investigate the influence of soil density on the expansive behavior of soils to better understand and mitigate the impact of swelling on structural integrity.

These conclusions and recommendations aim to improve the management and mitigation strategies for dealing with expansive soils in construction and engineering projects.

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