Analysis of the Effects of Temperature and Treatment Duration on the Resistance of Expansive Soil Improved with Lime in Baghdad, Iraq

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ABSTRACT

Multiple studies have revealed the challenge of constructing infrastructure on expansive soils, including pipelines, roads, or buildings. This predicament stems from the uneven moisture distribution inherent to the specific soil type. Numerous methods, involving the addition of chemicals, have been employed to enhance the properties of clayey soils. This study introduces lime as a cation exchange material and demonstrates its capacity to improve the load-bearing characteristics, rendering it a more favorable option for engineering construction purposes. Lime's reaction with clay minerals and water produces calcium hydroxide, which subsequently reacts with the silica and alumina in the clay to form new compounds that promote stability. Additionally, lime helps reduce the soil's water-holding ability, thereby decreasing its swelling potential. This research will focus on evaluating the influence of temperature and treatment duration on the osmotic pressure behavior of chemically treated expansive clayey soils using lime. The swell meter test was utilized to develop lime-clay samples containing 7% lime by dry weight. These samples were then subjected to compression at temperatures ranging from 20 °C to 40 °C over a period of up to 28 days. The findings indicate that the pozzolanic reaction results in higher compressive strengths when tested at the upper limits of the temperature range in laboratory experiments. Therefore, the combined effects of temperature and curing duration play a positive role in improving the compressive strength of expansive soils.

Keywords-soil improvement; lime; Anbar soil; geotechnical properties; temperature; time

I. INTRODUCTION

Climate change significantly impacts clay soil due to its high moisture content, leading to volumetric variations that adversely affect buildings constructed on it [1]. Consequently, researchers have proposed improving the characteristics of this soil through various methods, including chemical additives [2]. Lime is considered an essential and effective additive for enhancing the swelling properties of soil [3-13]. Studies have shown that using lime as an additive in clay can cause several changes in volume, Plasticity Index (PI), and strength [14]. The period of soil treatment is defined as the duration from the end of pressure application to the commencement of testing. The improved geotechnical features of lime-treated expansive soils have been observed in numerous studies, which cite four key reactions: cation exchange, accumulation and flocculation, lime carbonation, and pozzolanic reaction [15-19]. If sufficient water is present, cation exchange occurs rapidly, resulting in the decomposition of hydrated lime into Ca++ and OH- ions. This process leads to the replacement of Ca++ ions by other cations at the clay surface particles, consequently modifying the water films encapsulating them. This interchange affects particle flocculation and agglomeration, significantly altering soil texture. Consequently, it changes Atterberg limits and compaction properties because the hydration of calcium oxide results in an exothermic reaction, which enhances the compressive strength of expansive soils [20].

The widespread prevalence of expansive clay soil in the US has resulted in substantial losses and disruptions, exceeding the damages caused by natural disasters such as hurricanes and floods, with an estimated cost of approximately one billion dollars [21]. Identifying expansive soils during the pre-construction phase is essential due to their potentially damaging effects. When the soil fails to offer adequate stability and serviceability, designers explore remedial options, such as site avoidance, foundation modification, replacement of problematic soil with murram, or employment of ground improvement techniques. Although these methods have been applied to address expansive soil issues, some approaches are more commonly adopted by engineers. The ground improvement technique, also known as soil stabilization, involves unifying soil particles and modifying their fabric and texture to achieve enhanced strength and durability, which has gained significant attention from engineers over the years. However, replacing the troublesome soil with better borrow material can significantly increase construction expenses, making soil stabilization a more appealing and cost-effective alternative [22].

Researchers have discovered that when turbid soil samples are mixed, the ketone reaction ceases, and pozzolanic reactions begin due to the increased pH from the moisture in the clay soil [23]. Another study suggests that the localized pozzolanic reactions occur instantly as a result of lime adsorption and reaction on the clay surface. The discrepancies among studies may be attributed to the complexity of clay properties, which allow for various mechanisms to operate across different minerals and time frames. A thorough review of the technical literature indicates that most prior research on strength has focused on soils with a Liquid Limit (LL) below 90%. However, soils with a LL exceeding 90% are unsuitable for engineering works unless treated. This emphasizes the importance of managing highly malleable clays to provide long-term engineering solutions for these locations. Therefore, further investigation is required to determine the impact of lime on soils with higher LL and PI values. The current study assesses the strength of specimens treated with 7% lime at various temperatures and curing durations [24].

Chemical stabilization using lime has been found to be particularly effective for expansive soils, leading to its widespread application for stabilizing such soils globally [25]. The use of lime in soil stabilization dates back to the early 20th century, with the first recorded application occurring in 1924 on a highway in the USA [26, 27]. When lime reacts with atmospheric carbon dioxide, carbonation takes place, resulting in the formation of relatively weak cementing materials, such as calcite or carbonate of soda. This reaction diminishes the amount of lime available for pozzolanic reactions. Although these weak cementing agents contribute to a minor increase in strength, the pozzolanic reaction involving silica, alumina, and lime is hindered by the solidification of lime, which reduces lime availability and impedes future strength growth. Studies have revealed that the success of soil-lime stabilization lies in various factors, including the characteristics and mineralogy of the soil, the amount of lime present, the soil matrix pH, the curing period, temperature, freeze-thaw cycles, and the presence of sulfate in the soil [28].

II. METHODOLOGY

A. *Testing Methods*

This study utilized commercial Na-montmorillonite, renowned for its substantial swelling capacity, as the expansive material depicted in Figure 1. The chemical composition of the employed bentonite is documented in Table I, and its physical characteristics are detailed in Table II.

The investigation centered on utilizing highly reactive clay soil as a fundamental material, with lime and distilled water playing pivotal roles in the experimental procedures. Specifically, 7% lime hydrate (95% $Ca(OH)_2$) was incorporated into the dry weight of the clay to catalyze pozzolanic reactions, addressing the swelling characteristics of bentonite which formed a thick sludge, complicating pH assessments and initial lime consumption quantification. Distilled water was employed to ensure the soil-lime reactions and tests were free from contaminants, maintaining the precision and reliability of the results.

(a) (b)

Fig. 1. The (a) expansive clayey soil and (b) hydrated lime used in study.

TABLE I. ORGANIC MATTER CONTENT REPRESENTED BY THE LOSS UPON IGNITION

Composition	Percentage (%)
SiO_2	57
Al_2O_3	17.80
LOI_1	7.8
Fe_2O_3	4.63
MgO	3.67
Na_2O	3.28
K_2O	0.9
CaO	3.96
Mn_2O_3	0.06
TiO_2	0.77

TABLE II. GEOTECHNICAL PROPERTIES FOR USED CLAY

Property	Value
Moisture water content (%)	10.66
LL (%)	65
Plastic Limit (%)	30
PI (%)	35
Maximum dry density (kN/m³)	12.1
Optimum moisture content (%)	40

B. *Consistency Limit Tests*

The testing for consistency limitations was conducted in accordance with the procedures outlined in BS1377-2 [29].

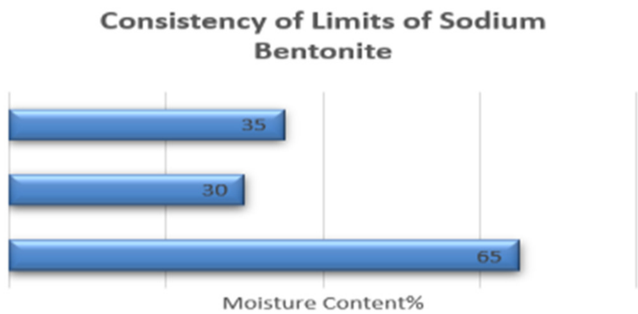

Fig. 2. Consistency of limits of sodium bentonite.

Specifically, the Plastic Limit (PL) represents the moisture content at which the soil breaks when kneaded between the fingers on a smooth glass surface to form a 3 mm diameter thread. The LL denotes the point at which the soil transitions from a plastic to a liquid state. The cone penetrometer method was utilized. The results reveal that sodium bentonite is a highly reactive clay, exhibiting an exceptionally high PL of 65% and LL of 35%, as depicted in Figure 2.

C. Compaction Test

The samples underwent a compaction procedure involving the application of 15 blows from a 12.50 kg sledgehammer dropped from a height of 15 cm onto each of six compressed layers. This process aimed to achieve dry unit weight (γ_d) values comparable to those obtained through the Standard Proctor test [30] illustrated in Figure 3. The study examined the behavior of two different material mixtures: untreated clay and lime-treated clay. The compaction test findings were crucial in preparing the specimens for subsequent strength evaluations. Compaction tests on the untreated clay were used to estimate the maximum γ_d (MDUW=12.2 kN/m³) and Optimum Moisture Content (OMC) equal to 40% for each specimen. This approach ensures that the mixture possesses the ideal moisture content for forming maximum bonds and achieving a specified configuration [31].

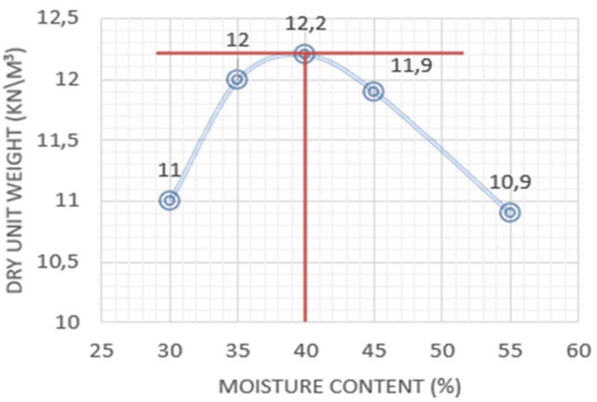

Fig. 3. The bentonite's untreated compaction curve.

D. The Unconfined Compressive Strength (UCS) Tests

Tests for UCS were conducted to evaluate the strength of lime-stabilized reactive clays due to their straightforward and cost-effective nature [32]. These tests adhered to British standards and utilized the British GDS bidirectional automated dynamic triaxial testing system [33]. Samples were prepared by mechanically mixing specified amounts of dry bentonite with lime based on dry weight. The mixing process continued until the additive was evenly distributed, as indicated by the uniform color of the mixture. The mixtures were subsequently blended further, with water being added gradually to prepare the samples. Each one was compacted in five distinct layers using a stationary load to achieve the target γ_d, employing a custom-made mold with adjustable upper and lower plungers. Each layer consisted of an identical amount of the mixed materials—clay, lime, and water. The applied force compressed the materials to ensure each layer reached a specific volume, with any excess force being transferred to the mold shaft through the plunger head [34]. Two identical samples were prepared for each testing condition to ensure accurate and reliable data. After removing the samples from the mold, the diameter, weight, and height measurements were taken. The samples were then immediately wrapped in cling film and placed in double-sealed bags. They were subsequently stored in an environmentally controlled cabinet set at a regulated temperature of 40 °C or 20 °C with a humidity level of 90%, for the designated curing periods. This comparison confirmed that the sample size and moisture content remained constant throughout the curing phase and no confining pressure was applied to them. The testing utilized a strain rate of one millimeter of axial movement per minute, and the maximum load for each sample was recorded. This test procedure adheres to British Standards, which stipulate that strain rates for such experiments should fall between 0.5% and 2.0% per minute.

III. RESULTS

A. Consistency Limits Test

Sodium bentonite, given its high LL of 65%, is recognized for its expansion capacity and 35 owing to its 35% PI it demonstrates a wide range of moisture content at which it retains its plastic properties. These characteristics indicate that sodium bentonite can be highly beneficial in applications necessitating water retention, such as caulking ponds and lining landfills. However, in structural contexts involving heave or settlement, it may give rise to significant challenges.

B. Compaction Test

The maximum compaction of the untreated clay is observed at an OMC of 40% and a density of 12.2 kN/m³. These values serve as a benchmark to compare the untreated and lime-treated clay samples. The findings from the compaction tests are utilized to determine the optimal moisture level required to achieve maximum density, which is crucial for establishing robust connections and ensuring the appropriate structural integrity of the clay composites.

C. UCS Characteristics

The findings of this study on untreated and lime-treated clay specimens, cured for a maximum of 28 days at 20 °C and 40 °C, are presented in Figure 4. The findings indicate that the strength of the treated clay was significantly influenced by the amount of hydrated lime and the length of curing. For the untreated bentonite, the UCS value was 551.9 kPa. Regardless of the curing duration, the addition of lime to the bentonite enhanced its strength performance compared to the untreated samples [35, 36]. Specimens treated with 7% lime and tested shortly after compaction exhibited an UCS of 1305.2 kPa. This immediate strength gain suggests rapid changes in the clay's properties, attributed to the quick reaction between the lime and clay in the presence of water. These alterations occur due to the substitution of hydroxyl ions from the lime with metal ions in the clay lattice [37]. The cation exchange process involves bivalent calcium ions from the lime replacing monovalent cations in the clay, facilitating the bonding of soil particles with negative charges. This reduces the thickness of the diffuse water layer and diminishes repulsive forces [38].

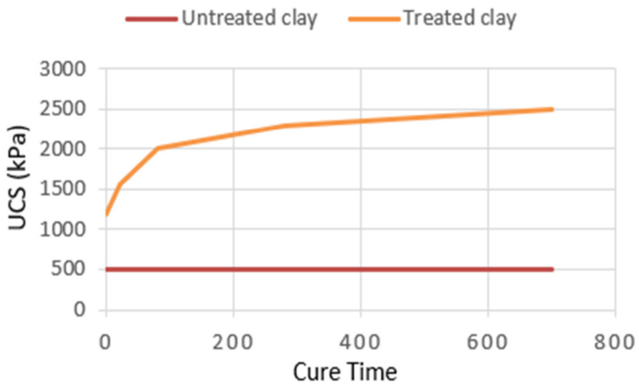

Fig. 4. Assessment of the strength with curing time on both untreated and bentonite modified with lime at 20 °C for curing.

Over extended curing durations of seven days, a notable strength increase was observed. The specimen treated with 7% lime and cured for two weeks exhibited significantly greater strength than those cured for just seven days, demonstrating continuous strength improvement throughout the curing process. Within seven days, the strength increased by 286%, and after 28 days, it rose to 346% compared to the untreated clay. This ongoing enhancement indicates continued pozzolanic reactions in the 7% lime-treated clay due to the presence of available hydrated lime [39-41]. The strength gain over time is attributed to the lime's pozzolanic activity, which fills voids and forms robust inter-grain bonds through cementation. The gradual increase in UCS during the lime stabilization of clay is driven by reactions between lime and clay, leading to the formation of calcium silicate hydrate (CSH) minerals from silica, soil, and lime compounds ($CaCO_3$, CaO, $Ca(OH)_2$), with these reactions becoming more pronounced with longer curing periods [42].

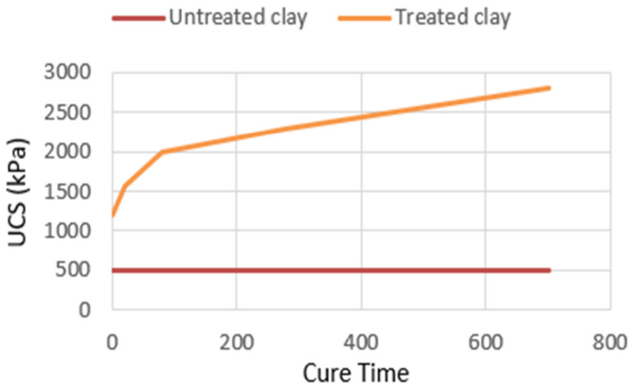

Fig. 5. An analysis of the strength and cure time of both untreated and lime-treated bentonite at 40 °C.

Figure 5 illustrates how lime affects the UCS of clay subjected to different curing temperatures. Increasing the curing temperature from 20 °C to 40 °C significantly enhances the clay's strength. Specifically, at 40 °C, the UCS of lime-treated clay rose from 550.9 kPa to 2400 kPa after 7 days of curing, marking a 350% increase. After 28 days of curing at 40 °C, the UCS of lime-treated samples increased from 2500 kPa to 2900 kPa, an 18.5% rise compared to curing at 20 °C. This improvement is attributed to the higher temperature promoting the chemical reactions between lime and clay particles, thereby enhancing the diffusion rate, which is influenced by the levels of water saturation [43].

Notably, the UCS values of samples cured with lime for 7 days at 40 °C were comparable to those cured for 28 days at 20 °C. The elevated temperature reduces the required curing duration by accelerating the formation of cementing phases [44]. Heightened temperatures expedite the lime-pozzolanic reactions, diminishing the time necessary for strength development. This swift strength acquisition is advantageous for applications such as road infrastructure, where lime-stabilized soil can withstand construction loads within 72 to 168 hours of curing [45-47].

IV. CONCLUSIONS

Expansive clay soils experience volumetric fluctuations, prompting researchers to propose their stabilization with various chemical additives, such as lime, which is considered the most crucial stabilizer. Numerous studies have revealed that the enhanced geotechnical characteristics of expansive soils treated with lime are attributed to four key processes: pozzolanic reaction, lime carbonation, flocculation and accumulation, and cation exchange.

This research presents a novel approach not previously explored, involving the use of varying temperatures under constant conditions to enhance the strength and expedite the soil-lime treatment process. Additionally, this challenging soil type was investigated and both short-term and long-term improvements were analyzed, which were not observed together in prior studies that were limited to one or the other. The study investigated the influence of temperature and curing duration on the Unconfined Compressive Strength (UCS) of expanding clays treated with lime, employing a comprehensive suite of laboratory experiments.

The laboratory tests revealed a notable positive effect on clayey soils treated with lime. Applying a 2 second compaction of steel dust and sand, followed by immediate assessment, resulted in a substantial increase in unconfined compressive strength from 551.9 kPa to 1305.2 kPa, an increase of 136.5% compared with untreated clay. Additionally, it was found that the strength of lime-treated clay increases with time and temperature. The results indicated that retaining the samples facilitated strengthening due to extended curing durations. Remarkably, the lime-treated clay mix aged seven days already exhibited a 286% higher strength compared to the untreated material. Furthermore, the strength improvements were even more pronounced with longer curing periods, as evidenced by a 346% increase in strength for specimens cured for 28 days relative to the untreated clay. Elevating the curing temperature from 20 °C to 40 °C significantly enhanced the strength of the clay. After 28 days of curing, the UCS of the lime-treated samples increased from 2519.1 kPa at 20 °C to 2986 kPa at 40 °C. The findings indicate that elevated temperatures accelerate the chemical reactions between lime and clay, resulting in more rapid and pronounced strength improvements.

The results of this study emphasize the effectiveness of hydrated lime in enhancing the mechanical characteristics of expansive clays, where both the duration of curing and the temperature are pivotal factors in attaining considerable strength improvements. Extended curing periods and elevated temperatures can significantly augment the UCS of expansive clays. Therefore, these parameters should be carefully considered in practical applications to ensure the maximum benefits from lime stabilization techniques.

In summary, the experimental program has clearly demonstrated that lime treatment, coupled with appropriate curing conditions, can greatly enhance the strength of expansive clays. This improvement is crucial for various engineering applications where the stability and durability of clay soils are of paramount importance. The information and experiences obtained in this study can help achieve soil stabilization in the future.

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