

# Stabilization of Expansive Soil by Using Lime

Ebtihaj Abu-Elgasim<sup>1\*</sup>, Arafa Bakhiet<sup>1</sup>, Omer Abdelaziz<sup>2</sup>, Gwaram Abdullah Adamu<sup>3</sup>,  
Shamima Akter Shimky<sup>2</sup>

<sup>1</sup>School of Civil Engineering, College of Engineering, Sudan University of Science and Technology, Khartoum, Sudan

<sup>2</sup>College of Civil and Transportation Engineering, Hohai University, Nanjing, China

<sup>3</sup>School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an, China

Email: \*ebtihaj77@hotmail.com, omerbash92@gmail.com, Gwaramcee011@gmail.com, shamimaakter3493@gmail.com

**How to cite this paper:** Abu-Elgasim, E., Bakhiet, A., Abdelaziz, O., Adamu, G.A. and Shimky, S.A. (2025) Stabilization of Expansive Soil by Using Lime. *Open Journal of Civil Engineering*, 15, 621-632.  
<https://doi.org/10.4236/ojce.2025.154033>

**Received:** September 22, 2025

**Accepted:** October 21, 2025

**Published:** October 24, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

Expansive soils in Sudan pose significant challenges to infrastructure due to volumetric changes with moisture fluctuations. This study investigates the effect of adding quick lime (4%, 6%, and 8%) on stabilizing expansive soil from Shambat, Khartoum State. Laboratory tests showed that the addition of lime led to a substantial reduction in the plasticity index, from 35.97% to 14.63%, and a remarkable increase in the California Bearing Ratio (CBR) value, from 1.7% to 50.7%. This indicates significantly enhanced soil strength. These results suggest that adding lime at 6% - 8% is effective in improving the soil's engineering properties, offering a sustainable and cost-effective solution for stabilizing expansive soil in Sudan.

## Keywords

Expansive Soil, Quick Lime, Soil Stabilization, Shambat, Atterberg Limits, Compaction, CBR

## 1. Introduction

Expansive soils present one of the most significant geotechnical challenges in civil engineering worldwide [1]. Their inherent danger lies in their unique mineralogical composition, which contains a high percentage of swelling clay minerals like Montmorillonite [2] [3]. These minerals react directly to changes in moisture content, leading to drastic volumetric changes [4]. When expansive soils absorb water, they swell significantly, generating pressures that can exceed 200 kilopascals [5], often surpassing the bearing capacity of foundations. Conversely, when they

dry out, they shrink sharply, causing deep and wide cracks to form on the surface [6]. These cyclic volumetric changes lead to severe structural deformation, damage to buildings, roads, and infrastructure, resulting in costly maintenance that can, in some cases, equal the initial construction cost [7] [8].

In a regional context, expansive soil, locally known as “Black Cotton Soil” in Sudan, poses a major threat to infrastructure and construction projects. This soil, with its distinct characteristics, is widespread across vast areas of the country, particularly in the plains of Khartoum state. Preliminary studies indicate that this soil has very high plasticity indices, which highlights its significant potential for expansion and shrinkage [9] [10]. Given the increasing reliance on development and construction projects in highly populated areas like the Shambat region of Khartoum state, it has become essential to find effective and sustainable solutions to mitigate their negative impacts. The seasonal fluctuations in rainfall and drought in Sudan exacerbate the problem, as structures are subjected to repeated cycles of swelling and shrinking, which accelerate their deterioration [11].

While numerous engineering solutions have been proposed and applied to treat expansive soils, most of these studies have focused on soils from other regions without considering the specific properties of Sudanese soil [12] [13]. Consequently, a research gap exists in the lack of sufficient studies that focus on the specific characteristics of Shambat’s soil using a locally available stabilizing agent like quick lime (calcium oxide, CaO). Quick lime stands out as an effective and economical option for soil stabilization. It improves the engineering properties of soil through several chemical and physical mechanisms [5] [14]. First, cation exchange occurs, where calcium ions ( $\text{Ca}^{2+}$ ) from the lime replace the less-charged ions on the surface of the clay particles, reducing their swelling potential [15]. Second, a flocculation-agglomeration process takes place, causing the fine clay particles to clump together into larger, more stable masses [16]. Finally, over the long term, calcium ions react with silica and alumina present in the soil in the presence of water to form cementitious compounds, which significantly increases the soil’s strength and provides a durable stabilization effect [17].

This research aims to bridge the identified gap by studying the effect of adding varying percentages of quick lime (4%, 6%, and 8%) on the engineering properties of the expansive soil from the Shambat area. The study will analyze the impact of these additions on a range of properties, including Atterberg limits, CBR (California Bearing Ratio), and maximum dry density, with the goal of determining the optimal lime content to achieve the best results.

The significance of this research is that it not only contributes to addressing a major geotechnical problem but also provides practical, locally applicable solutions for sustainable construction in Sudan. By offering direct, data-driven insights into how to improve expansive soil properties, this work will enable engineers and designers to make more informed decisions in foundation design, helping to reduce economic and engineering risks and promoting the development of safe and stable infrastructure.

## 2. Related Work

### 2.1. Properties of Swelling Soils and Their Effect on Structures

Swelling soil, also known as expansive soil, is a type of soil that changes its volume significantly due to fluctuations in moisture content [18]. When this soil absorbs water, it expands and increases in volume, and when it dries, the soil shrinks considerably, leading to cracks on its surface [19]. This dynamic behavior makes it one of the most detrimental types of soil for engineering structures. Expansive soils often feature high clay content, which increases their ability to expand and shrink. Black cotton soil, for example, is a classic example of swelling soil, being rich in clay minerals that show visible cracks during dry periods and appear expanded during wet seasons [17]. This continuous change in volume leads to significant problems for foundations and structures built upon them, such as cracks in foundations and settling of walls [20].

Swelling soils are a major concern in many parts of the world, especially in countries with fluctuating climates that significantly affect soil moisture levels. During periods of high moisture, the soil expands, and during dry periods, it shrinks, placing immense stress on engineering structures such as roads, buildings, and foundations, causing rapid structural deterioration [21]. Therefore, scientifically and accurately managing these soils is crucial for ensuring the long-term stability of structures. This has been pointed out by several researchers, such as Ahmed Sharif in his study on the effects of expansive soils in Sudan, where he emphasized that these soils pose a significant threat to construction works [22].

### 2.2. Soil Stabilization Techniques

Soil stabilization is a process aimed at improving soil properties to increase its stability, either through mechanical or chemical modification. These techniques include a variety of methods designed to enhance the mechanical strength of the soil and reduce volume changes due to moisture variations [13].

#### 2.2.1. Mechanical Stabilization

Mechanical stabilization involves several methods such as compaction, replacing the soil with non-swelling materials, or reinforcing the soil with additional materials. Compaction is an effective method for increasing soil density and reducing air voids, thereby enhancing its load-bearing capacity [2]. Additionally, replacing expansive soil with non-swelling materials like sand or gravel is another solution. However, this may be impractical in some cases, especially in areas with large quantities of expansive soil [21].

#### 2.2.2. Chemical Stabilization

In contrast to mechanical stabilization, chemical stabilization focuses on improving the geotechnical properties of the soil using chemical agents, such as lime, cement, and fly ash, which chemically react with the soil's components. Chemical stabilization is often more effective in treating expansive soils, as the chemical agents alter the soil's internal structure and reduce its potential for expansion and

shrinkage [23]. One of the most well-known chemical techniques is the addition of lime to clayey soil, where lime helps to strengthen the soil and reduce its expansion. It also helps to decrease plasticity and improve the soil's compressive strength.

### **2.3. The Importance of Using Lime in Expansive Soil Stabilization**

Using lime is one of the most effective methods for stabilizing expansive soils. Lime significantly modifies the geotechnical properties of the soil, with both chemical and mechanical effects that contribute to reducing the soil's capacity for expansion and shrinkage. When lime is added to expansive soil, a cation exchange reaction occurs, where the positive ions from the lime replace the negative ions associated with the clay minerals. This reaction improves the molecular structure of the soil, reducing the plasticity index and consequently decreasing the soil's expansion when it absorbs water [24].

Lime also contributes to the formation of new chemical bonds between soil particles, enhancing its strength and stability. These chemical reactions allow lime to reduce the effects of moisture fluctuations, leading to more stable soil during both dry and wet periods, thus reducing the risks of cracking and shrinkage that can damage foundations and other structures [14]. A study by Zumerway (2016) confirmed that lime improves the resistance of soil to expansion and shrinkage, thereby enhancing the stability of foundations built upon it.

### **2.4. Improving Mechanical Soil Properties Using Lime**

Lime significantly increases the mechanical strength of expansive soils. Through the chemical stabilization process, the soil's ability to withstand heavy loads improves, which contributes to enhancing the stability of structures built on it. Lime also helps to improve the bearing capacity of the soil, making it more resistant to stress caused by loads or climatic changes. These improvements make the soil more resilient to pressure from loads or moisture fluctuations, contributing to the stability of the structures and reducing structural risks [25].

### **2.5. Environmental and Economic Impact of Using Lime**

Using lime for expansive soil stabilization is an excellent environmental and economic option. Lime is widely available and relatively inexpensive, making its use in soil treatment a cost-effective choice. Additionally, the use of lime reduces the need for soil replacement or costly modifications to foundations, promoting the sustainability of construction projects and reducing the environmental impact of excavation or replacement operations [25].

## **3. Methodology**

A series of physical and mechanical tests was conducted to assess the impact of lime addition on the properties of expansive soils. All tests were performed in accordance with the relevant American Society for Testing and Materials (ASTM)

standards to ensure the accuracy and reliability of the results.

### 3.1. Sample Preparation and Testing Program

Expansive soil samples were collected from the Shambat area in Khartoum State, Sudan. After drying and grinding, the samples were prepared for testing. The soil was mixed with different percentages of quick lime (CaO) (0%, 4%, 6%, and 8% by weight of dry soil). The lime used in this study was derived from heating limestone, a material commonly used in soil stabilization due to its ability to enhance the soil's strength and reduce its swelling and shrinkage properties.

The lime-treated samples were left to cure under controlled conditions for 7 days at a temperature of 25°C and a relative humidity of 55% to ensure the pozzolanic reactions between the lime and clay minerals in the soil.

The following geotechnical tests were conducted on both treated and untreated soil samples:

#### 1) Grain Size Analysis

To assess the effect of lime on the soil structure, grain size distribution was determined. The soil samples were washed, dried, and passed through a series of sieves. The percentage of fine particles passing through sieve No. 200 (0.075 mm) was calculated using the following Equation (1)

$$\% \text{ fine} = \frac{\text{Weight of particles passing through sieve}}{\text{Total weight of the sample}} \times 100 \quad (1)$$

#### 2) Specific Gravity Test

Specific gravity test was conducted under a control room temperature, pycnometer was filled with soil passing through sieve No 40 then, weighed. distilled water was added to fill about half to three-fourth of the pycnometer. Then the sample was soaked for 10 minutes and weighted. The pycnometer filled again with water and weighted and Gs was calculated using Equation (2)

$$G_s = \frac{W_2 - W_1}{(W_2 - W_1) - (W_3 - W_4)} \quad (2)$$

#### 3) Atterberg Limits Test

The liquid limit (LL) and plastic limit (PL) of the soil were determined to assess its plasticity. The Plasticity Index (PI) was calculated as the difference between the liquid limit and the plastic limit, using the following equation Equation (3)

$$PI = LL - PL \quad (3)$$

#### 4) Compaction Test (Proctor Test)

The Proctor compaction test as shown in **Figure 1** was conducted to determine the maximum dry density (MDD) and the optimum moisture content (OMC) for each lime-treated sample. This test is essential for determining the optimal compaction conditions for the soil. The Maximum Dry Density (MDD) was calculated using the formula Equation (4)

$$MDD \left( \text{g/cm}^3 \right) = \frac{\text{Dry weight of soil}}{\text{volume of soil sample}} \quad (4)$$



**Figure 1.** Compaction test.

### 5) Bearing Capacity Test

The soil sample was thoroughly mixed and then placed in five layers within a CBR (California Bearing Ratio) mold. Each layer was compacted using a hammer weighing 25.5 N. The prepared soil sample was then soaked for several days to simulate field conditions. After the soaking period, the CBR test as shown in **Figure 2** was conducted to evaluate the soil's load-bearing capacity. The California Bearing Ratio (CBR) was calculated using the formula Equation (5)

$$\text{CBR (\%)} = \frac{P_{\text{sample}}}{P_{\text{standard}}} \times 100 \quad (5)$$



**Figure 2.** CBR test.

### 3.2. Data Processing and Statistical Analysis

The experimental data collected from all tests were processed using statistical tools to ensure a precise evaluation of the results. Mean values and standard deviations for each tested property were calculated, providing a clear understanding of the data variability. A comparative analysis was performed between the results of untreated soil samples and those treated with varying lime percentages (0%, 4%, 6%, and 8%). Additionally, the lime-treated samples were compared with data from previous studies on alternative materials such as granite powder.

## 4. Results and Discussion

### 4.1. Natural Soil Characterization

The sieve analysis test conducted on the natural soil revealed a predominance of fine-grained particles, with 97.33% passing through sieve No. 200. The soil was classified as A-7-6 (high plasticity clay) according to the AASHTO classification system. The basic properties of the collected soil are presented in **Table 1**.

**Table 1.** Basic properties of collected soil and basic properties of lime.

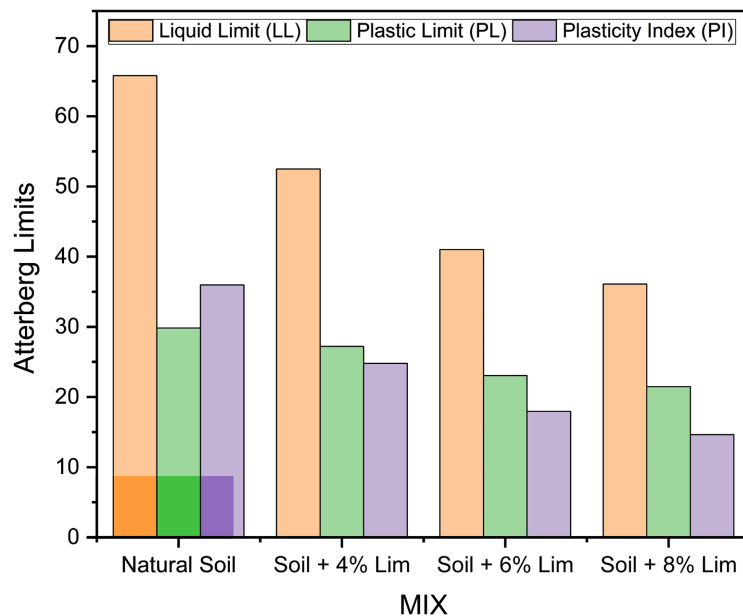
S. No.	Particulars	Test Results
1	Soil Classification (AASHTO)	A-7-6 (High plasticity clay)
2	Specific Gravity	2.62
3	Plasticity Index, (%)	35.97
4	Liquid Limit, (%)	65.8
5	Plastic Limit, (%)	29.83
6	Shrinkage Limit, (%)	16.5
7	California Bearing Ratio (CBR) (%)	1.7
8	Compaction Characteristics	Optimum Moisture Content (OMC) = 28%, Maximum Dry Density (MDD) = 1.44 gm/cm <sup>3</sup>
<b>Basic properties of lime</b>		
1	Physical appearance	Dry powder
2	Color	white
3	Specific gravity	2.44

### 4.2. Atterberg Limits Test

As shown in **Table 2**, the addition of lime significantly reduced both the liquid limit and plasticity index. With the increase in lime percentage from 0% to 8%, the liquid limit decreased from 65.8% to 46%, while the plasticity index decreased from 35.97% to 14.63%. This reduction is attributed to the chemical interactions between lime and clay particles, particularly the ion-exchange process, which reduces the soil's swelling potential and enhances its stability under varying moisture conditions as shown in **Figure 3**.

**Table 2.** Atterberg limits results for expansive soil mixed with different percentages of lime.

Characteristics	Liquid Limit (LL) %	Plastic Limit (PL) %	Plasticity Index (PI) %
Natural Soil	65.8	29.83	35.97
Soil + 4% Lime	52.5	27.21	24.79
Soil + 6% Lime	41	23.05	17.95
Soil + 8% Lime	36.1	21.47	14.63

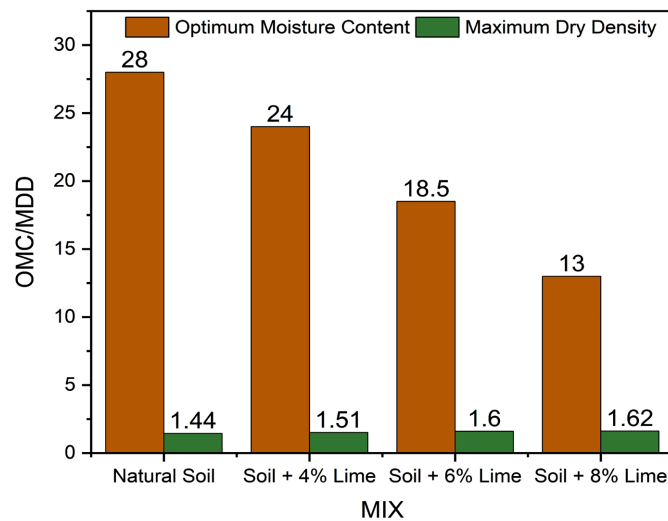
**Figure 3.** Atterberg limits results.

### 4.3. Compaction Test

As shown in **Table 3** the results from the compaction test showed that the addition of lime significantly improved the compaction characteristics of the soil. The dry density increased with higher lime percentages, with the maximum dry density (MDD) reaching  $1.62 \text{ g/cm}^3$  with the addition of 8% lime, and  $1.6 \text{ g/cm}^3$  with 6% lime. Additionally, the optimum moisture content (OMC) decreased gradually with the increasing lime content, indicating that lime effectively reduces the water required to achieve the maximum soil density as shown in **Figure 4**.

**Table 3.** Compaction results for expansive soil mixed with different percentages of lime.

Characteristics	Optimum Moisture Content (%)	Maximum Dry Density ( $\text{gm/cm}^3$ )
Natural Soil	28	1.44
Soil + 4% Lime	24	1.51
Soil + 6% Lime	18.5	1.6
Soil + 8% Lime	13	1.62



**Figure 4.** Compaction test results.

#### 4.4. Bearing Capacity Test

As shown in **Table 4**, the addition of lime had a significant positive effect on the soil's load-bearing capacity. The CBR values dramatically increased from 1.7% for untreated soil to 50.7% with the addition of 8% lime. This significant improvement is attributed to the pozzolanic reactions between lime and clay minerals, forming strong and durable bonds within the soil.

**Table 4.** CBR results for expansive soil mixed with different percentages of lime.

Characteristics	California Bearing Ratio (CBR) (%)
Natural Soil	1.7
Soil + 4% Lime	12.12
Soil + 6% Lime	33.3
Soil + 8% Lime	50.7

#### 4.5. Chemical Stabilization Mechanisms

Chemical reactions such as ion exchange between calcium ions from lime and less-charged ions on the surface of clay particles contribute to a reduction in plasticity and an increase in soil stability. Additionally, the process of flocculation-agglomeration helps fine particles cluster together to form larger, more stable masses, which improves the soil's mechanical properties and reduces its potential for expansion and shrinkage. Pozzolanic reactions occurring between lime, silica, and alumina in the soil lead to the formation of cementitious compounds, which enhance the soil strength and contribute to the significant increase in CBR values.

## 5. Conclusion and Recommendation

### 5.1. Conclusion

The study results demonstrated substantial improvements in the engineering

properties of expansive soil upon the addition of lime. This enhancement was reflected in a significant reduction in the Liquid Limit (LL) and Plasticity Index (PI), thereby mitigating the soil's potential for swelling and shrinkage.

Furthermore, compaction characteristics improved considerably; the Maximum Dry Density (MDD) increased to 1.62 g/cm<sup>3</sup> at 8% lime content, while the Optimum Moisture Content (OMC) decreased, indicating better soil stability. The California Bearing Ratio (CBR) test provided evidence of a massive increase in the soil's load-bearing capacity, with the CBR value soaring from 1.7% for untreated soil to 50.7% at 8% lime content, representing a substantial gain in strength.

Although continuous improvement in CBR and plasticity values was observed up to 8% lime content, prior research literature suggests that exceeding this concentration may lead to diminishing returns. Based on technical analysis and economic feasibility considerations—since higher additions increase project cost without commensurate performance improvement—the optimal lime content for stabilization was determined to be between 6% and 8%. This range provides the optimal balance between superior performance and cost-efficiency for stabilization applications.

## 5.2. Recommendation

1) Field Trials: It is recommended to conduct field trials on lime-treated soils in various regions of Sudan to evaluate the long-term effects of lime treatment on soil stability under natural conditions.

2) Exploration of Alternative Stabilizing Agents: While lime proved effective in stabilizing the soil, further research should explore other locally available stabilizing agents, such as fly ash or cement, to enhance the stabilization process.

3) Adopting Lime Stabilization in Construction: Lime stabilization techniques should be implemented in construction projects in areas with expansive soils, such as Shambat, to improve the stability of foundations and reduce the risks associated with expansive soils.

4) Economic Feasibility Studies: Conduct economic feasibility studies on the use of lime for soil stabilization in large-scale construction projects, particularly in urban areas, to ensure its cost-effectiveness and promote sustainable infrastructure development.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

- [1] Khazaei, J. and Moayed, H. (2019) Soft Expansive Soil Improvement by Eco-Friendly Waste and Quick Lime. *Arabian Journal for Science and Engineering*, **44**, 8337-8346. <https://doi.org/10.1007/s13369-017-2590-3>
- [2] Calik, U. and Sadoglu, E. (2014) Classification, Shear Strength, and Durability of Expansive Clayey Soil Stabilized with Lime and Perlite. *Natural Hazards*, **71**, 1289-1303. <https://doi.org/10.1007/s11069-013-0950-1>

- [3] Al-Gharbawi, A.S.A., Najemalden, A.M. and Fattah, M.Y. (2022) Expansive Soil Stabilization with Lime, Cement, and Silica Fume. *Applied Sciences*, **13**, Article 436. <https://doi.org/10.3390/app13010436>
- [4] Barker, J.E., Rogers, C.D. and Boardman, D.I. (2006) Physio-Chemical Changes in Clay Caused by Ion Migration from Lime Piles. *Journal of Materials in Civil Engineering*, **18**, 182-189. [https://doi.org/10.1061/\(asce\)0899-1561\(2006\)18:2\(182\)](https://doi.org/10.1061/(asce)0899-1561(2006)18:2(182))
- [5] Leite, R., Cardoso, R., Cardoso, C., Cavalcante, E. and de Freitas, O. (2016) Lime Stabilization of Expansive Soil from Sergipe-Brazil. *E3S Web of Conferences*, **9**, Article 14005. <https://doi.org/10.1051/e3sconf/20160914005>
- [6] Siva Gowri Prasad, S. (2022) Problems Due to Expansive Soils and Their Remedies. *NeuroQuantology*, **20**, 2707-2712. [https://www.neuroquantology.com/open-access/PROBLEMS-DUE-TO-EXPANSIVE-SOILS-AND-THEIR-REMEDIES-10522/?download=true&utm\\_source=chatgpt.com](https://www.neuroquantology.com/open-access/PROBLEMS-DUE-TO-EXPANSIVE-SOILS-AND-THEIR-REMEDIES-10522/?download=true&utm_source=chatgpt.com)
- [7] Jayashree, J. and Roja, S.Y. (2019) Stabilization of Expansive Soil Using Rice Husk Ash and Lime. *International Journal of Recent Technology and Engineering*, **8**, 2661-2665. <https://doi.org/10.35940/ijrte.c4942.098319>
- [8] Liu, Y., Su, Y., Namdar, A., Zhou, G., She, Y. and Yang, Q. (2019) Utilization of Cementitious Material from Residual Rice Husk Ash and Lime in Stabilization of Expansive Soil. *Advances in Civil Engineering*, **2019**, Article 5205276. <https://doi.org/10.1155/2019/5205276>
- [9] Nayem, N.H. (2023) Stabilization of Expansive Soil by Improving the Engineering Properties Using Lime and Fly Ash. *International Journal of Engineering Management*, **7**, 27-34. <https://www.sciencepublishinggroup.com/article/10.11648/j.ijem.20230702.12>
- [10] Dash, S.K. and Hussain, M. (2012) Lime Stabilization of Soils: Reappraisal. *Journal of Materials in Civil Engineering*, **24**, 707-714. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0000431](https://doi.org/10.1061/(asce)mt.1943-5533.0000431)
- [11] Kumar, K.S.R. and Thyagaraj, T. (2021) Comparison of Lime Treatment Techniques for Deep Stabilization of Expansive Soils. *International Journal of Geotechnical Engineering*, **15**, 1021-1039. <https://doi.org/10.1080/19386362.2020.1775359>
- [12] Sorsa, A. and Agon, E. (2022) Lime Stabilization of Expansive Clay Soil of Jimma Town Ethiopia. *Civil Engineering Infrastructures Journal*, **55**, 211-222. [https://cej.ut.ac.ir/article\\_88076\\_99c03f89f838e2ed642a50ac01f0e8fb.pdf](https://cej.ut.ac.ir/article_88076_99c03f89f838e2ed642a50ac01f0e8fb.pdf)
- [13] Sundaram, R., Shahu, J.T. and Havanagi, V. (2019) Geotechnics for Transportation Infrastructure: Recent Developments, Upcoming Technologies and New Concepts. In: *Lecture Notes in Civil Engineering*, Springer, 57-69. <https://link.springer.com/book/10.1007/978-981-13-6713-7>
- [14] Ghobadi, M.H., Abdilor, Y. and Babazadeh, R. (2014) Stabilization of Clay Soils Using Lime and Effect of Ph Variations on Shear Strength Parameters. *Bulletin of Engineering Geology and the Environment*, **73**, 611-619. <https://doi.org/10.1007/s10064-013-0563-7>
- [15] Zhao, H., Liu, J., Guo, J., Zhao, C. and Gong, B. (2015) Reexamination of Lime Stabilization Mechanisms of Expansive Clay. *Journal of Materials in Civil Engineering*, **27**, Article 04014108. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0001040](https://doi.org/10.1061/(asce)mt.1943-5533.0001040)
- [16] Al-Mukhtar, M., Lasledj, A. and Alcover, J. (2010) Behaviour and Mineralogy Changes in Lime-Treated Expansive Soil at 20°C. *Applied Clay Science*, **50**, 191-198. <https://doi.org/10.1016/j.clay.2010.07.023>

- [17] Thyagaraj, T. and Zodinsanga, S. (2015) Laboratory Investigations of in Situ Stabilization of an Expansive Soil by Lime Precipitation Technique. *Journal of Materials in Civil Engineering*, **27**, Article 06014028.  
[https://doi.org/10.1061/\(asce\)mt.1943-5533.0001184](https://doi.org/10.1061/(asce)mt.1943-5533.0001184)
- [18] Athira, T., Johnson, A. and Krishnankutty, S.V. (2017) Expansive Soil Stabilization Using Coconut Shell Powder and Lime. *International Journal of Engineering Research and Technology*, **6**, IJERTV6IS030512.
- [19] Buhler, R.L. and Cerato, A.B. (2007) Stabilization of Oklahoma Expansive Soils Using Lime and Class C Fly Ash. 2007 *Problematic Soils and Rocks and in Situ Characterization*, Denver, 18-21 February 2007, 1-10. [https://doi.org/10.1061/40906\(225\)1](https://doi.org/10.1061/40906(225)1)
- [20] Seco, A., Ramírez, F., Miqueleiz, L. and García, B. (2011) Stabilization of Expansive Soils for Use in Construction. *Applied Clay Science*, **51**, 348-352.  
<https://doi.org/10.1016/j.clay.2010.12.027>
- [21] Dang, L.C., Fatahi, B. and Khabbaz, H. (2016) Behaviour of Expansive Soils Stabilized with Hydrated Lime and Bagasse Fibres. *Procedia Engineering*, **143**, 658-665.  
<https://doi.org/10.1016/j.proeng.2016.06.093>
- [22] Mahedi, M., Cetin, B. and White, D.J. (2020) Cement, Lime, and Fly Ashes in Stabilizing Expansive Soils: Performance Evaluation and Comparison. *Journal of Materials in Civil Engineering*, **32**, Article 04020177.  
[https://doi.org/10.1061/\(asce\)mt.1943-5533.0003260](https://doi.org/10.1061/(asce)mt.1943-5533.0003260)
- [23] Thyagaraj, T., Rao, S.M., Sai Suresh, P. and Salini, U. (2012) Laboratory Studies on Stabilization of an Expansive Soil by Lime Precipitation Technique. *Journal of Materials in Civil Engineering*, **24**, 1067-1075.  
[https://doi.org/10.1061/\(asce\)mt.1943-5533.0000483](https://doi.org/10.1061/(asce)mt.1943-5533.0000483)
- [24] Seid, F. and Ali, A. (2025) Experimental Investigation on Stabilization of Expansive Subgrade Soil Using Industrial Waste (bagasse Ash) and Lime: A Case of Kosherabe Road Project, Central Ethiopia. *Discover Applied Sciences*, **7**, Article 1010.  
<https://doi.org/10.1007/s42452-025-07215-7>
- [25] Zhou, A., Du, J., Lin, X., Bu, Y. and Kodikara, J. (2023) Nanoscale Mechanism on Lime Stabilization of Expansive Soil. *Acta Geotechnica*, **18**, 2681-2701.  
<https://doi.org/10.1007/s11440-022-01751-x>