Regasa et al. International Journal of Geo-Engineering (2023) 14:17
https://doi.org/10.1186/s40703-023-00197-8

International Journal of Geo-Engineering

ORIGINAL RESEARCH Open Access

Subgrade soil stabilization using the Quicklime: a case study from Modjo- Hawassa highway, Central Ethiopia

Hailu Regasa[1], Muralitharan Jothimani[1*] and Yonas Oyda[1]

*Correspondence:
Muralitharan Jothimani
muralitharangeo@gmail.com
[1]Department of Geology, College of Natural and Computational Sciences, Arba Minch University, Po Box- 21, Arba Minch, Ethiopia

Abstract
This study examined the index properties, strength, and swelling pressure by mixing the Quicklime with five soil samples taken from the Meki-Abossa road section part of the Modjo- Hawassa highway. The main goal of this study was to provide more insight into the effects of Quicklime stabilization on the Atterberg limit like (LL, LP, and PI), OMC, MDD, CBR, and CBR swell percent of subgrade soil along the selected route alignment. Five disturbed samples were collected from the Meki-Abossa Road section to achieve the objectives. The samples were collected using the open pit sampling method with an average 1-1.5 m depth. Laboratory works were carried out for natural sub-grade soil and soil mixed with Quicklime. The natural sub-grade soil was classed as A-7-5 (38) by AASHTO and MH & CH by USCS, with a maximum LL of 75, PI of 41.6, MDD of 1.59, and OMC of 28, with CBR values less than five and CBR swell > 2%. The recommended lime (4%, 6%, and 8%) was mixed with the subgrade material. The result shows that the soil treated with Quicklime 4%, 6%, and 8% improved or lowered the untreated expansive soil plasticity index by 18.5%, 28.9%, and 23.8%, respectively, and increased OMC by 15.2% and reduced MDD by 18.23%. On the other hand, CBR values of the treated soil were increased by an average of 56.9%, with lower swelling potential decreases by 93.3%, higher workability, and stabilized soils were feasible to be used as subgrade material.

Keywords Expansive soil stabilization, California bearing ratio, Maximum dry density, Quicklime

Introduction

Pavement is a hard crust constructed over the soil to give a stable and even surface for the vehicles; likewise, buildings meant for habitation [1]. But if the material supporting the buildings and pavements is weak, it will lead to failure. So, the supporting soil requirements must be improved [2]. Therefore, stable and economical pavement structures require subgrade materials with good engineering properties. It is also serious that the subgrade soil maintains good engineering behavior for its design life and withstands seasonal high moisture conditions and repeated dynamic loading. As stated in [3], subgrade material may withstand the strains created by traffic loads. It is important to note that soft soils have poor shear strength when used as a road subgrade, which leads to unnecessary consolidation settlement and bearing capacity failure.

It is necessary to improve inappropriate subgrade soils for the superstructure of roads to stabilize them. Soil development results in an increase in bearing capacity and an improvement in surface performance [4]. Hardening and stiffening soft and weak subgrade materials with modest quantities of chemicals may be more appropriate rather than excavating and discarding them. In the present situation, it is becoming increasingly necessary to search for new, low-cost materials that can improve building methods and facilitate road network expansion. More emphasis has been placed on developing novel, less expensive soil stabilizers, and techniques that utilize locally available construction materials [5]. Following [6], soil enhancement by chemical stabilization depends on the micro-stage interaction between soil moisture and fine content material. In consequence, the effect of the soil's mineral composition and plasticity index is determined by the soil's mechanical behavior. Besides, soil stabilization is an economical and environmentally friendly process for altering soils' mechanical and chemical traits through pozzolanic reactions to enhance their engineering qualities [7].

According to [7–9], lime can cope with soils to numerous degrees, counting on a particular project's stabilization. Most treatments became used to dry, modify soil's properties, and enhance the soil strength resistance for supporting roads [7]. Lime stabilization improves soil engineering resistance by improving strength, susceptibility to cracks, fatigue, permanent deformation, robust behavior, minimized swelling, and resistance to moisture's detrimental effects. The property of problematic soil is effectively improved by using different percentages of lime. In the present study, experimental studies looked into the qualities of expansive soils when lime had been used as a subgrade in road construction. Pavement layers suffer considerable deterioration due to various conditions, including expansive soil swelling and shrinkage [10–12].

Moisture fluctuations caused by seasonal changes weaken the subgrade by causing cracks in the overlying pavement layers. In contrast, volumetric changes weaken the subgrade by causing cracks in the overlying pavement layers. This destroyed several engineering structures. The soil swelling caused fissures to develop in foundations, pavements, and basement walls [13]. In Ethiopia, expansive soils cover an estimated 24.7 million acres, causing widespread problems [14]. The following road sectors in Ethiopia are highly affected by expansive soils: Addis-Ambo, Addis-Wolliso, Addis-Debrebirhan, Addis-Gohatsion, and Addis-Modjo [14]. This study aims to understand the effects of quicklime stabilization on Atterberg limitations such as (LL, LP, PI), OMC, MDD, CBR, and CBE swell % of subgrade soil, as well as the selected route alignment. The present study aims to achieve the following specific objectives:

- To look at the index and strength properties of natural sub-grade soil without using.
- treatments and with treatments.
- To classify soil primarily based totally on AASHTO and USCS methods.
- To look at the impact of Quicklime on the plasticity index.
- To examine the impact of Quicklime contents on the CBR values and CBR swell.
- To decide the impact of curing duration at the subgrade soil combined with Quicklime.

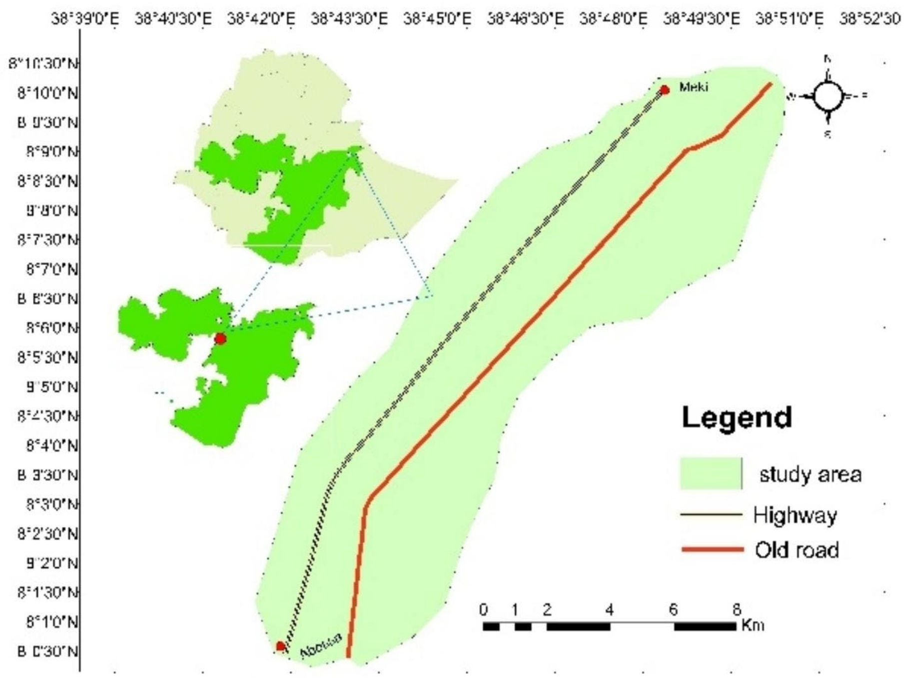

Fig. 1 Location map of the study area

Materials and methods

Study area

The Meki-Abossa road corridor's current study area is part of the Modjo Hawassa section. Meki- The Abossa road is 21 ers long (Fig. 1). It is located approximately

Fig. 2 Shows sample collection activities from the road route alignment

Table 1 Standards and Specification for this Study

S.No	Laboratory Test	Standards	
		AASHTO	**ASTM**
1	Grain size analysis	AASHTO T88	D422-63
2	Moisture content	T99	-----
3	Atterberg limit test	T89	ASTM D 1843
4	Soil classification	-----	D2487-98
5	Standard proctor Compaction test	-----	D698-98
6	CBR	T193-93	-----

128kilometers east of Addis Ababa. The study area's geographical location is defined by 8°10' 30" N latitude and 38°39' 0" E longitude, as well as 8°0' 30"N latitude and 38°51' 0" E longitude. Distributed samples were adequate to examine the suitability of the soil. Total five disturbed samples at the interval of one kilometer along the alignment of the road if the same type of soil is found throughout. If soil type changes earlier, at least one sample is taken from each new stretch of ground. The soil samples were taken along the main highway in the Abomsa district.

Samples preparation

A variety of clay sample specimens were examined in this investigation. Quicklime was given to each specimen at room temperature to examine how lime affects the characteristics of these soils. First, a #40 sieve was used to dry all components thoroughly. The Quicklime was then well blended until homogeneity was achieved. All tests were conducted using distilled water. The percentage of Quicklime in the soil admixture ranged from 4 to 8%. This established mixture aims to examine how lime affects sample pH. Total five disturbed samples at the interval of one kilometer along the alignment of the road if the same type of soil is found throughout. If soil type changes earlier, at least one sample is taken from each new stretch of ground. The soil samples were taken along the main highway in the Abomsa district (Fig. 2). Tests were conducted on virgin soil and lime-treated soil samples, including sieve analysis, the Atterberg limit, the standard proctor compaction test, and the California bearing ratio test. The soil sample utilized in this investigation was expansive soil collected at an average depth of 1. 5 m beneath the soil floor to avoid organic components.

The samples were taken from the natural ground or the side of the road (Fig. 2). According to Ethiopian Road Authority requirements, samples for the CBR test were taken at 1.5 km and 0.5 km intervals for every soil category. This study used pit sampling to collect an adequate sample for a laboratory experiment. This sampling method was presented to determine the expansive clay soil's index characteristics and strength along the route alignment. As shown in Table 1, AASHTO and ASTM standards and specifications were adapted for this study.

Sample preparation

The samples were categorized according to AASHTTO T87-86 before being treated and tested.

This method includes:

- Air and oven-dried the samples.

- Preparing uniform samples for Atterberg limits, compaction, and Californian bearing ratio tests, mixing soil and Quicklime manually to get the uniform mix for each test.

Quicklime description

Numerous subgrade improvement options include grouting, removal and replacement, and chemical stabilization. However, various academic studies imply that lime is most suited for stabilizing soil with fine particle sizes (A-4, A-5, A-6, A-7), high PI values, low CBR, high CBR swell, etc. At the same time, cement is best suited for stabilizing soil with coarse grain sizes [22]. As a stabilizing agent, dry powder hydrated lime [$Ca(OH)_2$] from suppliers that is commercially accessible has been used. It was produced locally and purchased from DERBA MIDROC CEMENT FACTORY PLC. To assess the effectiveness of chemical additions on the sub-grade soils at various amounts and with various curing times, fast lime-soil combinations were subjected to laboratory testing (Fig. 3). It is anticipated that adding lime to the soil base will boost durability, reduce the risk for swelling, and increase soil strength.

Calculation of the initial chemical consumption

Its purpose is to determine the chemical (Lime) required to satisfy rapid lime-soil reactions and maintain an excessive residual pH and long-term pozzolanic reactions [15]. A soil with a PI of 10 or higher and a minimum of 25% passing 0.075 mm should be stabilized by lime, according to [15, 23]. In order to dissolve silicates and aluminates from clay matrix and fine silt soil, a pH of 12.4 is required, particularly for Quicklime. Therefore, the preliminary lime intake is determined following [15] across the current experiment. Based on the $_pH$ test results, the first lime input was anticipated to be 4%. To verify the dosages determined by the $_pH$ test, various tests such as Atterberg limits, moisture density relation, CBR, and percentage swelling of CBR were conducted using quick lime proportions of 4%, 6%, and 8%. (Fig. 4)

The "Eades and Grim" test was used to determine the first lime consumption. The minimum lime content for stabilizing the soil is the lowest proportion of lime in soil that results in a laboratory pH of 12.4, or the flat region of the pH versus lime % curve produced by the test [24]. PH readings remain constant at 12 because the minimum

Fig. 3 Shows the prepared soil spacemen (**a**) and Quicklime powder (**b**) to be mixed

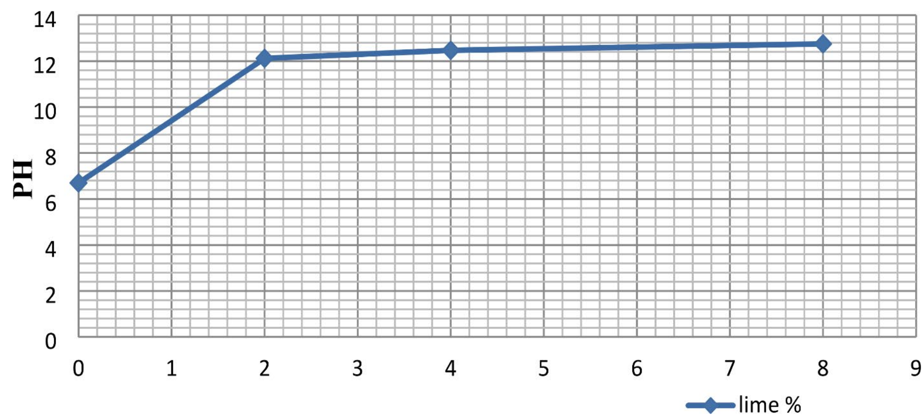

Fig. 4 Determining initial consumption of Quicklime

Qquicklime required to stabilize the soil is 2% or higher. The pH graph after 12 is unchanged since 2% Quicklime is the bare minimum needed to stabilize the soil. The experiments were conducted with 4%, 6%, and 8% quicklime concentrations and curing times of 7, 14, and 28 days. To evaluate the overall performance of the locally synthesized Quicklime on an inappropriate subgrade soil, the Atterberg limits (liquid, plastic, and plasticity index), the moisture-density relationship between the subgrade material and the CBR, and % swell of the CBR were used. Based on the categorization results, the subgrade soil throughout the roadway segment is uniform and designated as A-7 by AASHTO and MH, CH by USCS.

Procedures for blending

The blending technique used for this investigation was based on the test procedure of [16]. After mixing the subgrade material with the lime (4%, 6%, and 8%), the mixture was allowed to settle for two days. The treatment of subgrade materials was scattered throughout the integration and aging process to maintain an optimal wetness and moisture content level. Continue mixing the mixture until it has reached a uniform, brittle consistency. Following the mellowing period, the soil was tested as per the untreated soil examination and cured for 7, 14, and 28 days.

Results and discussion

An experimental protocol developed by [16] guided the mixing technique for this experiment. Subgrade material was well mixed with lime at 3% (4%, 6%, and 8%) and left to settle for two days. The subgrade material was treated throughout the integration and softening process to achieve the optimal wetness and moisture content. Continue mixing the mixture until it has reached a uniform, friable consistency. After the mellowing period, the soil was tested using the same methodology as the untreated soil and was cured for 7, 14, and 28 days. The performance of locally produced Quicklime on the inappropriate sub-grade soil under investigation has been examined based on test findings of Atterberg limits (liquid limit, plastic limit, and plasticity index), moisture-density relations of the sub-grade material and CBR, and CBR % swell. This study examined how different lime ratios affected index characteristics, moisture-density correlations, California bearing ratios, and CBR swell treatment in a poor soil layer.

Table 2 Percent pass in 75 µm, Plasticity index and classification of natural sub-grade soil samples

Sample	Depth in m	% Pass no. 200 (75 µm) sieve	Atterberg Limits			Classification	
			LL	PL	PI	(AASHTO T88, 2020)	USCS
S1	1-1.50	65	63	35	28	A-7-5(25)	MH
S2	1.2–1.80	74	65	33	32	A-7-5(23)	CH
S3	1-1.4	85.9	71	32.7	38	A-7-5(38)	CH
S4	1.00	74	72	41.6	30.4	A-7-5(31)	CH
S5	1-1.5	80	75	39	36	A-7-5(34)	MH

Fig. 5 Shows atterbeg limit test preparation (**a**) and roled sample foe plastic limit test (**b**)

After crushing the materials, they were carefully air-dried. According to [16], the Atterberg limit test was performed on soil samples that failed to pass through forty sieves, whereas other tests were conducted on soil samples that failed to pass through four sieves.

Soil classification

Following the study's findings, the sub-grade soil is homogeneous along the trial road section and at depth. It is classified as A-7-5 (25), A-7-5(23) on the [17], and MH and CH on the USCS soil classification systems, respectively. The influence of locally manufactured Quicklime on such unsuitable subgrade soils has been evaluated by collecting five representative soil samples. Table 2 below shows the plasticity index; percent pass 0.075 m sieve, and classification of five representative samples of the sub-grade soil under investigation. The fine particles of expansive soil decrease, and the coarse particles rise after quicklime mixing, according to tests on the particle size distribution of expansive soil stabilized by quicklime [25].

Effect of Quicklime on Atterberg limits test (AASHTO T 90)

The study's main goal was to see how Quicklime affected liquid limits, plastic limits, and plasticity index in unsuitable soil samples. Liquid-limit and plastic-limit tests and a consistency test were performed on quicklime soil mixtures in line with [17, 18]. On the LL, PL, and PI, untreated soil showed maximum and minimum values of 75, 41.6, 38, 63, 33, and 28, respectively. Figure 5 shows Atterbeg limit test preparation (a) and rolled sample for plastic limit test (b).

The soil samples were air-dried, crushed, and sieved with no 40 sieves [17]. Soil sample that passed the no 40 sieves was mixed with various chemical additives at the appropriate moisture level and stored in plastic bags for curing. Quicklime was used in the following proportions: 4%, 6%, and 8%. (Fig. 6). After 7, 14, and 28 days of curing, Quicklime, and soil combination experiments were conducted to assess the effects of time on Atterberg limit values. Measurements of the liquid and plastic limits were taken on soil samples at various percentages ranging from 4 to 8% to study the impact of Quicklime on the consistency limits. The liquid limit and plasticity index for the five treated samples were reduced due to adding varying percentages of Quick lime to soil samples [26]. The likely cause of this behavior is the cation exchange when lime is added to the soil. This exchange tends to replace other cations on the clay particle's surface and reduce the thickness of the double layer. Soon after adding the lime, cation exchange, and flocculation occur, causing the soil's plasticity to decrease. Additionally, the short-term reactions that caused the lime-treated soil texture to become more granular can be attributed to the reduction of plasticity (cation exchange and flocculation-agglomeration). A laboratory study determined that the maximum plasticity index was 38% when untreated. When Quicklime was applied at 4%, 6%, and 8%, the expansive soil plasticity index was reduced by 18.5%, 28.9%, and 23.8%, respectively. These outcomes concur with those reported by [22, 27].

Effect of Quicklime on Moisture Density Relation (AASHTO T89)

The moisture-density relationship of soil blended with varying amounts of chemical additives was determined using air-dried and pulverized soil that passed through sieves of number four. Quicklime was used in three different quantities in the soil: 4%, 6%, and 8%. A regular proctor test was also conducted [19]. The maximum dry density of untreated soil was 1.590, while the optimal moisture content was 28. After the treatments, the soil performances on MDD and OMC were changed to 1.3 and 33, respectively. This resulted in agreement with several scholars. So that many scholars were also stated that the maximum dry density (MDD) decreases while optimum moisture content (OMC) increases with increasing lime content [23, 28, 29]. The findings demonstrate that lime significantly influences the maximum dry density and ideal moisture content (OMC). The maximum dry density (MDD) is reduced by 18.23%. The optimum moisture content (OMC) is enhanced by 15.2% with a 6% quicklime solution and a 14-day curing

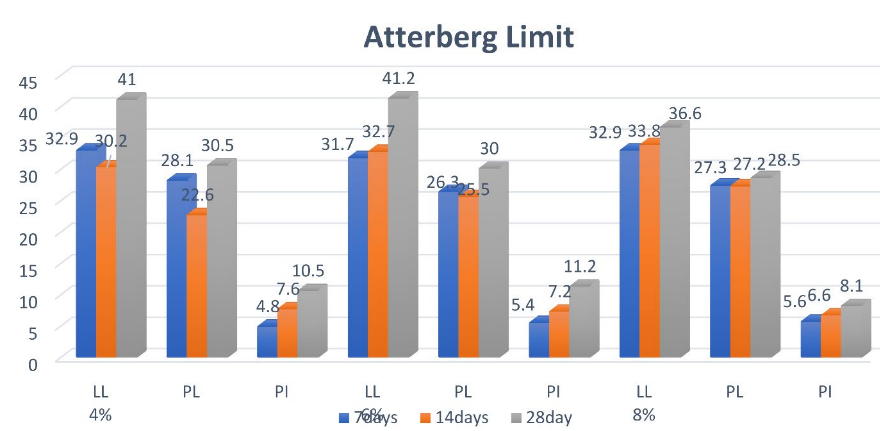

Fig. 6 Effects of Quicklime on the Liquid limit(LL), Plastic limit (PL), and Plasticity index (PI) properties of the soil

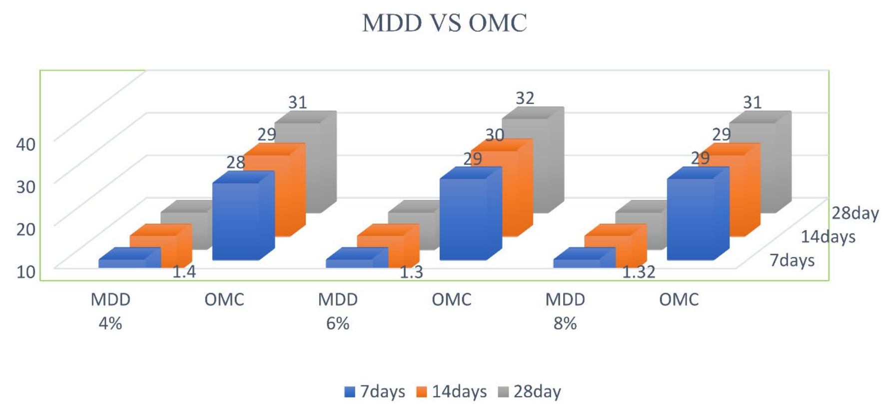

Fig. 7 the effects of different Quicklime percentages on the maximum dry density(MDD) and optimum moisture content (OMC)

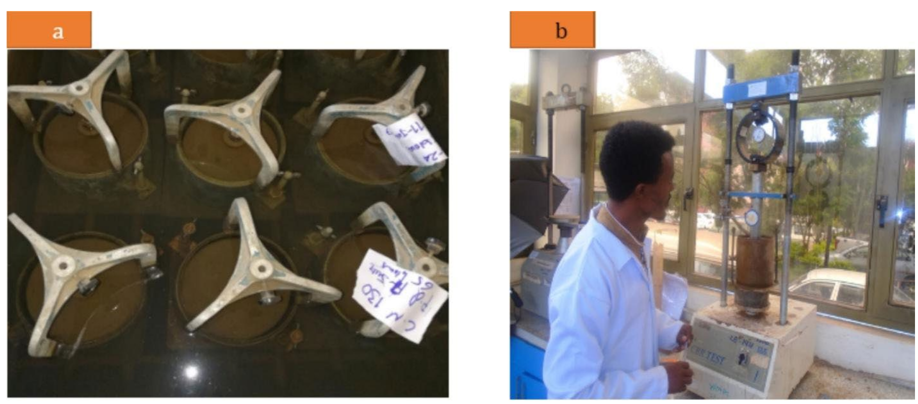

Fig. 8 Shows soaked CBR test soil for 96 h (**a**) and soil casted in CBR molds and reading (**b**)

time (Fig. 7). The density of lime-treated soil is greater than that of natural soil, according to a study on lime-stabilized subgrade soil [13].

Effect of Quicklime on California bearing ratio test and CBR swell

According to [20], a natural subgrade soil test was conducted before the addition of Quicklime. Untreated sub-grade soil has maximum and minimum CBR values of 4.5 and 3, respectively. Figure 8 Shows soaked CBR test soil for 96 h(a) and soil cast in CBR molds and reading (b). According to [21], subgrade soil with a CBR value of less than 5 is unsuitable for pavement design. The same soil samples that passed through number 40 sieves were blended with chemical additives at the optimal moisture level and compacted in CBR molds to achieve maximum dry density. Quicklime and soil mixtures were cured for 7, 14, and 28 days to determine whether time affected the CBR value. Following the curing period, which included soaking for 96 h or four days, CBR tests were conducted (Fig. 8). Adding 4%, 6%, and 8% quicklime to unsuitable soil, followed by seven days of curing, increased the CBR from 6 to 12.5%, 17.5%, and 25%, respectively [30, 31]. Additionally, the CBR increased to 52.4%, 55%, and 63.3 by adding 4%, 6%, and 8% quick lime and extending the curing period to 14 days and 28 days, respectively (Fig. 9).

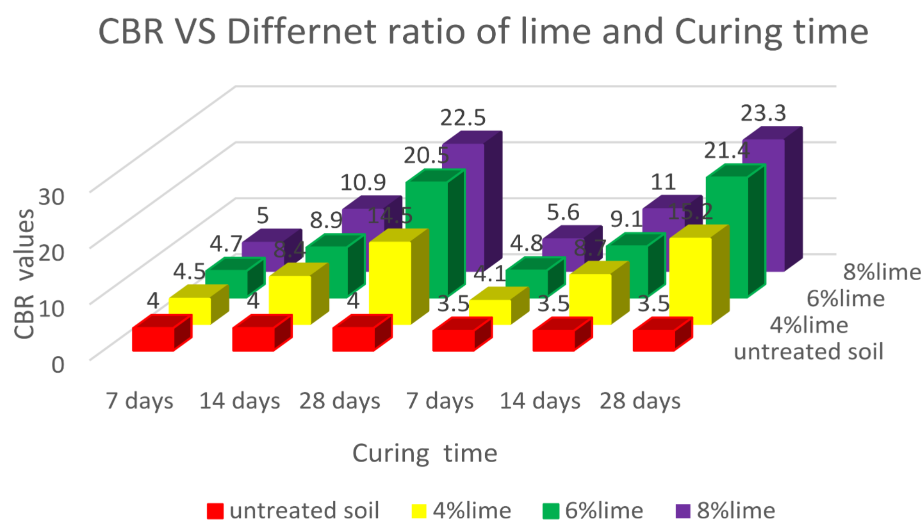

Fig. 9 The effects of different Quicklime percentages on the maximum dry density(MDD) and optimum moisture content (OMC).

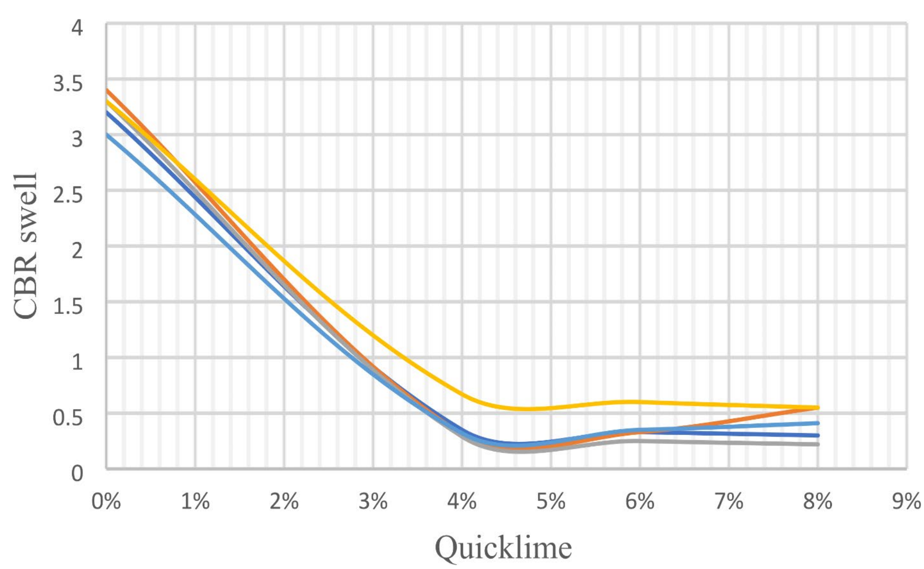

Fig. 10 Effect of different Quicklime percentages on the CBR swell

CBR tests indicate that the strength of subgrade soil is improved by increasing the % of Quicklime and allowing it to cure for longer. A mixture of soil and Quicklime was compacted in CBR molds at an optimum moisture content. These findings are following those published by [25, 32]. In order to calculate the percentage swell, the maximum dry density and swelling parameters were evaluated before and after soaking (Fig. 8). As a result, the CBR swell has been reduced by 93.3%, from 3.3% to 0.22% [33]. Adding Quicklime to the subgrade soil raises CBR while CBR swell is reduced (Fig. 10).

Conclusion

These conclusions were reached as a result of the experimental investigation's findings. The chosen subgrade soil was categorized as having inadequate engineering properties due to the test findings and the examination of the natural subgrade soil. It failed to adhere to the ERA standard specifications' requirements. Therefore, it must be altered and treated to be utilized as a sub-grade material. Utilizing Quicklime considerably improves subgrade soils' strength, compaction, and index characteristics. In the current research area, sub-grade soils with CBR values lower than five and CBR swell rates above 2% are not recommended for use as road sub-grade materials. So, to determine the first Quicklime consumption, ASTM D 6276 (Eades and Grim test) was utilized. As a result, three distinct percentages of Quicklime were identified and used, with curing times of 7, 14, and 28 days. The calculated Quicklime consumption was used in the Aatterberg limit test, the moisture density relation test, the California bearing ratio test, and the CBR swell test. 4%, 6%, and 8% of Quicklime by weight dry soil were treated after 7, 14, and 28 days of curing to see how the treatment influenced the engineering performance of natural subgrade soil. Using Quicklime dramatically changed the geotechnical characteristics of the native subgrade soil at the current research location. Q. The percentage of Quicklime applied and the curing period directly affects the geotechnical characteristics change in expansive subgrade soils. However, the Quicklime content matters more than the cure period.

Declarations

Competing interests
The authors declare that they have no competing interests.

Consent for publication
The authors agreed to publish this research article in "International Journal of Geo-Engineering".

Received: 22 September 2022 / Accepted: 3 October 2023
Published online: 13 October 2023

References
1. Sobhan K (2017) Challenges due to problematic soils: a case study at the crossroads of geotechnology and sustainable pavement solutions. Innov Infrastruct Solut 2(1):1–18
2. Jalal FE, Yongfu X, Babak J, Shazim AM (2020) On the Recent Trends in Expansive Soil Stabilization Using Calcium-Based Stabilizer Materials (CSMs): A Comprehensive Review,'Advances in Materials Science and Engineering, 2020. https://doi.org/10.1155/2020/1510969
3. Pancar EB, Akpinar MV (2016) Comparison of Effects of Using Geosynthetics and Lime Stabilization to Increase Bearing Capacity of Unpaved Road Subgrade,' Advances in Materials Science and Engineering, 2016. https://doi.org/10.1155/2016/7129356
4. Aswathy CM, Raj AS, Sayida MK (2021) Effect of bio-enzyme-chemical stabilizer mixture on improving the subgrade properties. Problematic soils and geo environmental concerns. Springer, Singapore, pp 779–787
5. Alrubaye AJ, Hasan M, Fattah MY (2016) Engineering properties of clayey soil stabilized with lime. ARPN J Eng Appl Sci 11(4):2434–2441
6. Cabezas R, Cataldo C (2019) Influence of chemical stabilization method and its effective additive concentration (EAC) in non-pavement roads. A study in andesite-based soils. Cogent Eng 6(1). https://doi.org/10.1080/23311916.2019.1592658
7. Jafer H, Jawad I, Majeed Z, Shubbar A (2021) The development of an ecofriendly binder containing high volume of cement replacement by incorporating two byproduct materials for the use in soil stabilization. Sci Rev Eng Environ 30(1):62–74. https://doi.org/10.22630/pniks.2021.30.1.6
8. Basma AA, Tuncer ER (1991) Effect of lime on volume change and compressibility of expansive clays. Transp Res Rec 1296:54–61
9. Calik U, Sadoglu E (2014) Classification, shear strength and durability of expansive clayey soil stabilized with lime and perlite. Nat Hazards 71:1289–1303
10. Ismaiel HAH, BadryMM (2013) Lime chemical stabilization of expansive deposits exposed at El-Kawther quarter, Sohag Region. Egypt Geosci J 3(3):89–98. https://doi.org/10.5923/j.geo.20130303.02
11. Sharma A, Sharma RK (2021) Sub-grade characteristics of soil stabilized with agricultural waste, constructional waste, and lime. Bull Eng Geol Environ 80:2473–2484. https://doi.org/10.1007/s10064-020-02047-8
12. Negi AS, Faizan M, Siddharth PD, Singh R (2013) Soil stabilization using lime. Int J Innov Res Sci Eng Technol 2(2):448–453
13. Srikanth SR, Prasad ACSV, Vamsi Krishna N (2018) Lime-Stabilized Black Cotton Soil and Brick Powder mixture as Subbase Material. Adv Civil Eng. https://doi.org/10.1155/2018/5834685
14. Mekonnen E, Amdie Y, Etefa H (2022) Stabilization of expansive black cotton soil using bioenzymes produced by ureolytic bacteria. Geo-Engineering 13:10. https://doi.org/10.1186/s40703-022-00175-6
15. ASTM (1999) Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization
16. AASHTO T87 (1996) Dry Preparation of Disturbed Soil and soil aggregate sample for test

17. ASTM D4318 (2019) ASTM D4318: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils'. American Association of State Highway and Transportation Officials, pp 1–21
18. AASHTO (2008) Standard Method of Test for Determining the Liquid Limit and Plasticity Index of Soils, 00, pp. 0–4
19. AASHTO (2014) Moisture density relation of soil using standard compaction test method,' American Association of State Highway and Transportation Officials, 180(October), pp. 1–14
20. AASHTO (2002) The California bearing ratio. Spill Sci Technol Bull 8(1):698–703. https://doi.org/10.1155/2013/704806
21. ERA (2013) Pavement Design, Deterioration and Maintenance of Pavements. I, pp. 233–243. https://doi.org/10.1680/dmp.41141.233
22. Ahmed AH, Hassan AM, Lotfi HA (2019) Stabilization of expansive sub-grade soil using hydrated lime and dolomitic-limestone by-product (DLP). Geotech Geol Eng 38(2):1605–1617. https://doi.org/10.1007/s10706-019-01115-5
23. Chitragar SF, Shivayogimath CB, Mulangi RH (2020) Study on strength and volume change behavior of stabilized black cotton soil with different ph of soil-lime mixes for pavement subgrade. Int J Pavement Res Technol 14(5):543–548. https://doi.org/10.1007/s42947-020-0117-x
24. Zukri A (2013) Pekan soft clay treated with hydrated lime as a method of soil stabilizer. Procedia Eng 53:37–41. https://doi.org/10.1016/j.proeng.2013.02.006
25. Liu Y, Su Y, Namdar A, Zhou G, She Y, Yang Q (2019) Utilization of cementitious material from residual rice husk ash and lime in stabilization of expansive soil. Adv Civ Eng 1–17. https://doi.org/10.1155/2019/5205276
26. Thyagaraj T, Rao S, Sai Suresh P, Salini U (2012) Laboratory studies on stabilization of an expansive soil by lime precipitation technique. J Mater Civ Eng. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000483
27. Kavak A, Akyarlı A (2006) A field application for Lime Stabilization. Environ Geol 51(6):987–997. https://doi.org/10.1007/s00254-006-0368-0
28. Barman D, Dash SK (2022) Stabilization of expansive soils using chemical additives: a review. J Rock Mech Geotech Eng 14(4):1319–1342. https://doi.org/10.1016/j.jrmge.2022.02.011
29. De Paiva SC, Lima MAD, Ferreira M, Ferreira SRD (2016) Geotechnical properties of a lime-treated expansive soil. Materia-Rio De Janeiro 21(2):437–449
30. Osinubi KJ, Ijimdiya TS, Nmadu I (2009) Lime stabilization of black cotton soil using bagasse ash as admixture. Adv Mater Res 62–64:3–10. https://doi.org/10.4028/www.scientific.net/AMR.62-64.3
31. Attah IC, Okafor FO, Ugwu OO (2021) Optimization of California bearing ratio of tropical black clay soil treated with cement kiln dust and metakaolin blend. Int J Pavement Res Technol 14:655–667. https://doi.org/10.1007/s42947-020-0003-6
32. Mishra EN (2012) Strength characteristics of clayey sub-grade soil stabilized with fly ash and lime for road works. Indian Geotech J 42(3):206–211. https://doi.org/10.1007/s40098-012-0015-5
33. Amadi AA, Okeiyi A (2017) Use of quick and hydrated lime in stabilization of lateritic soil: comparative analysis of laboratory data. Geo-Engineering 8(1). https://doi.org/10.1186/s40703-017-0041-3

Publisher's Note