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Mechanism of improvement and best-fit models for the prediction of geotechnical properties of lime stabilized expansive soil used in pavement subgrade

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ABSTRACT

The performance of a pavement mainly depends on the quality of the subgrade layer. Expansive soils (ES) are extensively found worldwide including Pakistan. The inadequate strength and swelling behavior of these soils are the main problems in any road construction project. Several researchers in the last decades have attempted to improve expansive soil utilizing various materials such as lime, brick kiln dust and fly ash. The purpose of this research was to evaluate the effect of lime on the engineering properties of the ES of a highway subgrade in the Sialkot region of Pakistan. The influence of different lime dosages (0%, 2%, 4% and 6%) at curing ages (1, 7, 14 and 28 days) has been examined by pH tests, plasticity tests, compaction tests, unconfined compressive strength (UCS), free swell index, and California Bearing Ratios (CBR). A field CBR and plate load test (PLT) on the natural soil and optimum lime-treated soil with various curing periods have been carried out for applicability as subgrade material. The test findings demonstrated that higher lime dosages increased the strength and ultimate bearing capacity (q_{ult}) of improved ES and at the same time decreased the free swelling index (FSI), optimum moisture content (OMC), maximum dry density (MDD) and permanent deformation of the subgrade soil. The UCS values of soil treated with 2%, 4% and 6% lime increased almost by 324%, 523%, and 249% for unsoaked samples and 285%, 351% and 231% for soaked samples respectively as compared to the plain soil at 28 days curing period. The laboratory CBR values significantly increased 2.35-8.50 times and field CBR improved 5.6 times as compared to the plain soil. The q_{ult} of lime-treated soil increased by 162% as compared to the plain soil and permanent deformation reduced from 33 mm to 2 mm after 28 days. Furthermore, equations were developed to estimate the best fit for the prediction of various geotechnical parameters and coefficient of determination (R^2) values for all equations were found higher than 0.90. From the results, it has been concluded that adding the optimum lime content of 4% by weight satisfies the requirement for the subgrade construction of highways and the developed expressions can provide a scientific basis for estimating the geotechnical parameters.

1. Introduction

Expansive soils are usually found in most regions all over the world [1, 2]. These soils possess complex behavior of volume changes such as shrinking and swelling at low depths due to variations in soil moisture content [3, 4]. The volume change behavior is caused by the expansive clay minerals such as smectite which has the capability to absorb water [1, 5]. ESs are believed as weak materials due to their inexpedient characteristics. These soils are hard in dry conditions and lose stiffness with progressive water saturation. Due to this response, the construction of civil engineering infrastructures on these soils is considered a major issue. The construction of pavement on such a weak subgrade layer can extremely affect the performance of a roadway [6]. Consequently, the stabilization of the subgrade ES is necessary before initiating a roadway construction. Higher swelling potential and low strength of ES are critical for any geotechnical issues specifically for construction of roadway on the ESs [7].

Soil stabilization methods are mostly adopted for enhancing the geotechnical properties of soil for the construction of highways [8-11]. One of the commonly practiced techniques is chemical stabilization such as using lime or cement, which is used to enhance the performance in the long run and decrease the life costs of road pavement. Due to environmental challenges associated with its production and higher costs, the usage of cement for soil stabilization is rarely recommended [12, 13]. However, lime stabilization significantly decreases the environmental effect and cost constraints [14].

Lime has been frequently used to stabilize the subgrade for pavement construction [15, 16]. As a consequence of lime improvement, the clayey particles adhere to each other and make bigger particles. Lime stabilization beneficially changes the engineering properties of expansive clays such as reducing the plasticity, free selling index, and OMC and increasing the MDD, UCS, ultimate bearing capacity, CBR and as well as overcoming the swelling issues [13, 17-19]. Besides the enhancement in geotechnical characteristics, a considerable increase in the UCS values has been observed. Fig. 1 presents the results of UCS tests of natural clay and clay stabilized with 5% lime for 7 days (d) and 365d of curing periods obtained by Kavak and Akyarlı [20]. The UCS values increased by 282% and 370% for the lime-stabilized soil at 7d and 1 year respectively as compared to untreated clay. The stabilized soil specimens displayed brittle behavior.

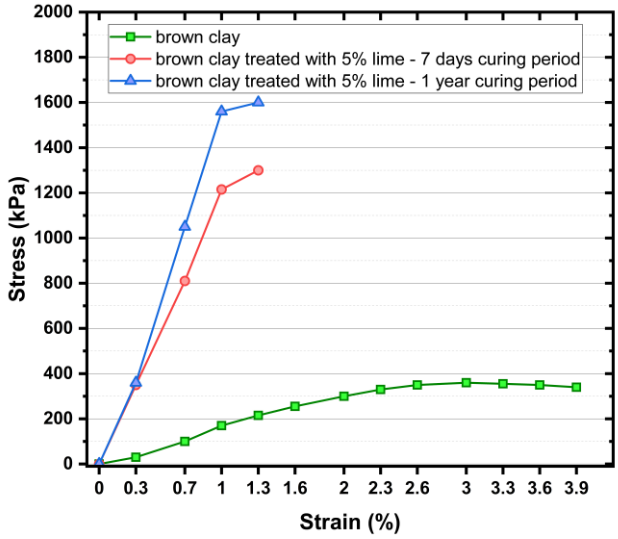

Fig. 1. UCS Test Results Of Untreated And Lime-Treated Clay, Modified After Kavak And Akyarlı [20]

Several researchers have attempted to stabilize ESs utilizing various dosages of limes from 2% to 10% [12, 13, 21-23]. The strength development of lime-stabilized soil depends on the amount of cementitious gel created and subsequently on the consumption of lime quantity. Indeed, the lime quantity must be aligned with the amount of soil clay mineral. Ingles [24] defined a general rule based on practice to permit 1% of the lime by weight for every 10% of clay composition in the soil. The precise amount can be determined following tests and partly to both sides of this value. Therefore, it is unusual for the clay percentage in the soil to surpass 80%, it is generally not essential to use lime beyond 8%. Goufi, et al. [25] reported the lime fixation point at 3% lime by weight, which resulted in the optimum improvement of soil plasticity. Bell [21] conducted a study on the effect of different lime dosages ranging between 0% and 10%. The optimal strength gain was reported to be with lime content between 4-6%. The strength development is affected by the volume of mixing water, the duration of the curing age and the curing temperature. The main reactions responsible for the enhancement in soil properties due to lime addition are ion exchange, flocculation, carbonation and pozzolanic reactions. The ion exchange occurs between the calcium ions from the lime and other ions attached to the clay particles. The impact of ion exchange and attractive forces tends to bring the clay particles closer and make flocs, which is known as flocculation. The improvement in the properties of ESs is mainly because of flocculation and their cementation subsequently due to pozzolanic reactions [26, 27].

Although, numerous studies are available on lime-treated soil, but their use for pavement construction in the ES of the Sialkot region in Pakistan is the primary objective of this study. In this region, the ESs cannot be directly used for the subgrade due to their undesirable physico-mechanical properties not satisfying the specifications of existing regulations. The current study was conducted to examine the effect of lime on the engineering properties of soil collected from the project area. The influence of different lime dosages at various curing ages was examined by pH tests, plasticity tests, compaction tests, free swell index, and CBR tests. A field CBR and plate load test on the natural soil and optimum lime-stabilized soil at various curing ages was conducted to assess their suitability for pavement construction. In addition, equations were developed to estimate the best fit for the prediction of various geotechnical parameters. The study of soil stabilization for pavement construction in such regions is vital, considering that the usage of lime would be cost-effective and environmentally friendly as well as a benchmark for future planning of other highway construction in these regions.

2. Material and Testing Methods

2.1 Materials

ES was gathered from the subgrade of a highway project in Sialkot, Pakistan. The representative soil sample was taken from a 1m depth and passed from a No. 10 mesh sieve [28]. The commercially available quicklime after passing through sieve No 200 was used for the improvement of ES, which is intended to be used for the purpose of vehicular movement during wet conditions. The characteristics of ES and quicklime achieved from the experiments are demonstrated in Table 1. The ES is highly plastic and ranked as A-7-5 as per AASHTO M145 [29] and CH as per ASTM D2487-06 standard for the classification of soils [30].

Table 1

Characteristics of ES and Quicklime

Parameter	Values	
	ES	Lime
Classification (ASTM D2487-06)	CH	CH
AASHTO M145	A-7-5	A-7-6
Coarse grain %	8.3	0.54
Fine grain %	91.7	99.46
Silt size particles (%)	69.36	61.71
Clay size particles (%)	22.34	37.75
Specific gravity	2.63	3.26
Liquid limit, LL (%)	55.1	69.7
Plastic limit, PL (%)	26.58	22.44
Plasticity index, PI (%)	28.52	47.3
Maximum dry density (lb/ft^3)	122.8	-
Optimum moisture content (%)	11.4	-

2.2 Testing Methods

A mixture of ES and quick lime was prepared by adding 2%, 4% and 6% of lime to the ES by weight. The tests performed on untreated/treated ES were classified into three phases. In the first phase, the index properties and compaction tests were carried out on the treated and untreated ES. In the second stage, the UCS test, CBR test and swell potential tests were carried out for 1 day (d), 7d, 14d and 28d of the curing period. In the third phase, field CBR and plate load tests were performed on untreated and optimum lime-treated field specimens at 1d, 7d, 14d and 28d of curing age. Based on the results obtained, equations were developed to estimate the best fit for the prediction of various geotechnical parameters.

The plasticity limits for the ES fraction of less than 425 µm were achieved by following the ASTM-D4318 [31]. The modified proctor compaction tests were conducted on the untreated/treated soil samples as per ASTM-D698 [32]. Soil-lime pH test was performed by adding lime with different dosages of 2%, 3%, 4%, 5%, 6%, 8% and 10 % to the soil following the standard methodology ASTM D-6276 [33]. The UCS and CBR tests were performed for the comparison of the pre and post-treatment behavior of the soil. The UCS tests for the soaked and unsoaked samples were carried out by the ASTM D2166 [34]. Cylindrical samples with height of a 100 mm and a diameter of 50 mm were prepared based on the MDD and OMC achieved. CBR tests for the soaked and unsoaked soil specimens were conducted following the ASTM D1883 [35]. The UCS and CBR tests were conducted on the samples cured at 1, 7,14 and 28 days. Plate load tests on natural and optimal lime-stabilized subgrade soil in the field were performed as per the ASTM D1195 [36]. The PLT setup in the field is presented in the Fig. 2.

Fig. 2. Plate Load Test Setup In The Field

3. Presentation and Discussion of Results

3.1 Optimal Percentage of Lime From Lime-Soil pH

This test gives information for evaluating the lowest soil-lime percentage, which resulted in a maximum pH of 11.98 indicating the specification of lime for soil improvement. Chitragar, et al. [37] reported a pH value of 12.4 for the 7% lime and soil solution used for soil stabilization. The test was performed on a 25-gm soil sample with different percentages of lime such as 0, 2, 3, 4, 5, 6, 8 and 10% mixed in 100 ml distilled water. Fig. 3. demonstrates the pH variation for various dosages of lime. Increasing the dosage of lime tends to decrease the pH value. From the findings, it can be noted that a lime dosage of 6% resulted in a pH of 11.98, which was used as a maximum limit in this study. ASTM D6276-19 [38] suggests a pH value of 12.4 for the soil-lime and water solution.

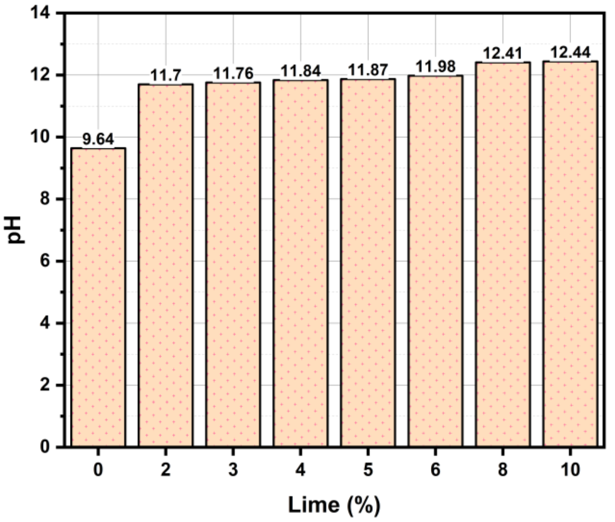

Fig. 3. Changes In Ph For Various Percentages Of Lime

3.2 Particle Size Distribution

Sieve analysis and hydrometer analysis were carried out on the ES samples containing lime 0% (Sample L0), 2% (L2), 4% (L4) and 6% (L6). Fig. 4 shows the gradation curve of ES with different percentages of lime. The ES with zero lime dosage consists of 91.7% fine fraction and 22.3% clay content. The incorporation of lime makes the ES-lime mixture coarser. The ES with 6% lime consists of 12.5% clay content and 87.5% fine fraction, which indicates that increasing the lime dosage increases the coarser particles.

3.3 Consistency Limits

The consistency limits of the plain/lime-stabilized soil are demonstrated in Fig. 4. Particle Size Distribution Of The Study Soil

Fig. 5. The LL of the soil decreases with an increase in the percentage of lime. The LL of the L0, L2, L4 and L6 samples were achieved as 55%, 45%, 37% and 32% respectively. The PL for the treated samples showed a decreasing trend. The variation in PL is insignificant beyond the 4% lime. Thus, it could be designated as the lime fixation point, it correlates to the optimum workability of the soil attained after the lime treatment. Goufi, et al. [25] reported the lime fixation point at 3% lime for the same CH class soil. The PI for the treated samples follows a decreasing trend. The PI of the treated samples L2, L4 and L6 decreased by 52%, 114% and 156%, respectively as compared to the plain soil.

Overall, the LL and PI of the ES reduced significantly with an increase in the percentage of lime. Similar findings were obtained by Sujit and Monowar [39], Amadi and Okeiyi [40] and Utami [41]. As a consequence, the soil mixture's workability is enhanced due to the exchange of cations which happens when calcium ions are freed by the lime and replaced with metal ions on or within the clay network. The cation replacement and decrease of diffuse double-layer thickness may decrease the plasticity index [22, 42, 43]. The plasticity index further reduces with time due to the pozzolanic reaction occurring. This diminution in plasticity behavior makes the soil and lime mixtures brittle fabric, making the ES more equipped to movement and tackle with onsite machinery.

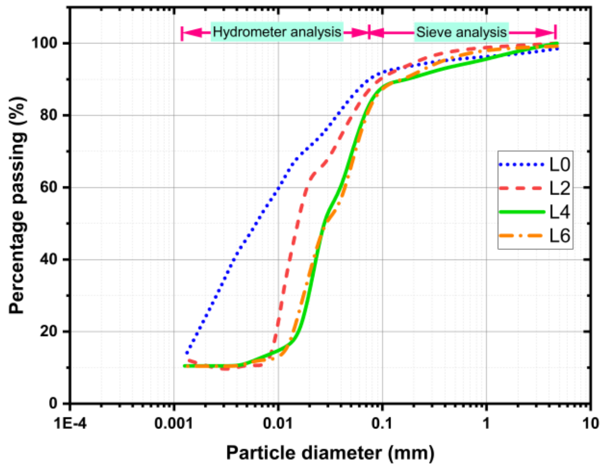

Fig. 4. Particle Size Distribution Of The Study Soil

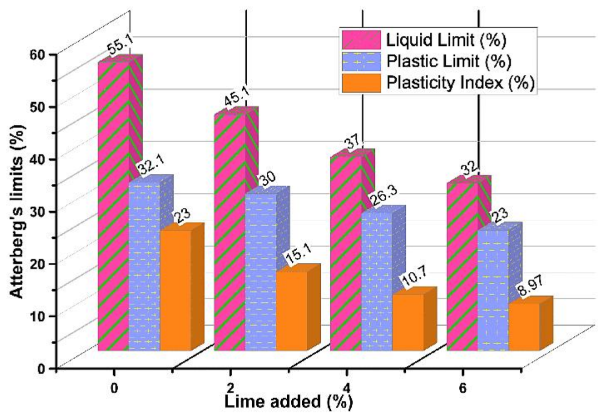

Fig. 5. Consistency Limits Values For The Plain And Lime-Stabilized Soil

3.4 Compaction Parameters

It is worth noting that the compaction of soil is a crucial component of the construction operation, especially for highway projects. To ensure proper compaction of soil for supporting the load from the building foundations and highways, evaluation of the MDD and OMC of the particular soil is required. Fig. 6 presents the changes in the compaction parameters for the soil improved with various dosages of lime. Increasing the lime percentage decreases the values of MDD and increases the OMC. Similar trends were achieved by other researchers for lime-improved soils [4, 6, 40]. The reduction in MDD can be attributed to the low density of lime relative to clay and the instant reaction between soil and lime, which is depicted by aggregation and flocculation. Moreover, elevated pH conditions in the stabilized ES alter the surface charge arrangement in the ES grains, which tends to enlarge the repulsion of particle layers. This, together with modification in the grain size distribution, resulted in a reduction in MDD [17, 44]. According to the literature, the elevation in OMC with the incorporation of lime may be due to the rise in the water holding capacity and possible change in effective particle fractions of the soils and hydration of lime, which need extra water for the pozzolanic reactions [45-47].

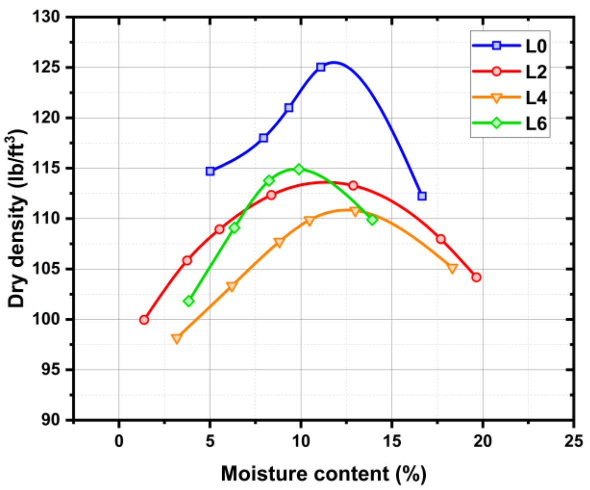

Fig. 6. Relationship Between Dry Density And Moisture Content For The Plain And Lime-Stabilized Soil

3.5 Unconfined Compressive Strength

The UCS of ES is one of the key designing variables employed for the design of roadway subgrade, particularly for highway embankment construction. Actually, it may be employed to endorse the efficacy of the soil improvement, to decide the maximum stabilizer dosage and to examine the significance of decisive factors on the strength of stabilized soil [48].

The UCS tests were performed at the curing age of 1, 7, 14 and 28d, in order to evaluate the strength development characteristics of the specimens over time. Fig. 7 and Fig. 8 represent the stress-strain relationship of plain and lime-stabilized soil for unsoaked and soaked conditions respectively. It can be seen that UCS test results consist of two types of curves for untreated and lime-treated soils. The untreated soil indicated plastic behavior, a linear increase in UCS values was noted initially and then the UCS value became almost constant. The soil improved with different lime dosages showing brittle behavior, and the UCS values increased linearly until the sample failed abruptly. The UCS values of soil improved with lime enhanced by increasing the lime percentage and curing period. Meanwhile, the shape of the stress-strain peak remains sharper. Similar stress-strain behavior for the soil stabilized with lime was observed by Driss, et al. [4] and Majumder and Venkatraman [6].

The overall tendency of an increase in UCS values with higher lime dosage has been reported. Beyond the optimal lime content, no remarkable increase in UCS values was observed. In this study, higher UCS was achieved for soil treated with 4% lime, which agrees well with the findings obtained by Bell [21]. In fact, the strength does not improve linearly with the incorporation of lime and adding extra lime such as for L6 decreases the strength. It can be explained by the fact that lime has insignificant cohesion and friction, an amount exceeding acts as a lubricant to the soil and thus reduces the UCS [21]. Kumar, et al. [49] featured the deduction to the platy shapes of non-reactive particles of the lime. Furthermore, the increment in UCS values is more pronounced at early curing age. The early improvement in UCS is because of the short-term reaction (flocculation and cations exchange), which makes the soil more friable and granular [43]. A considerable improvement in UCS was reported for prolonged curing age, this improvement is attributed to the pozzolanic activity between clay minerals such as Al_2O_3 and SiO_2 and calcium from lime-producing cementing materials which combine the soil particles simultaneously [50].

According to the North Carolina Department of Transportation [51], the strength of the soil stabilized with lime for the low-level traffic roads should be 420 kPa. Furthermore, the IRC 37-2018 [52] suggested a strength of 560 kPa for high-level traffic roads. The strength achieved for the soil treated with lime percentages of 2%, 4% and 6% are 660, 757 and 507 kPa respectively for the unsoaked condition and 422, 507 and 288 kPa for the soaked condition at 7d curing period. In roadway construction nominal curing age of 7d is considered instead of 14d or 28d because of impedes in construction activities and also put into traffic in the shortest possible time [37]. Based on the UCS findings obtained, the soil treated with 4% lime is suggested for the study soil.

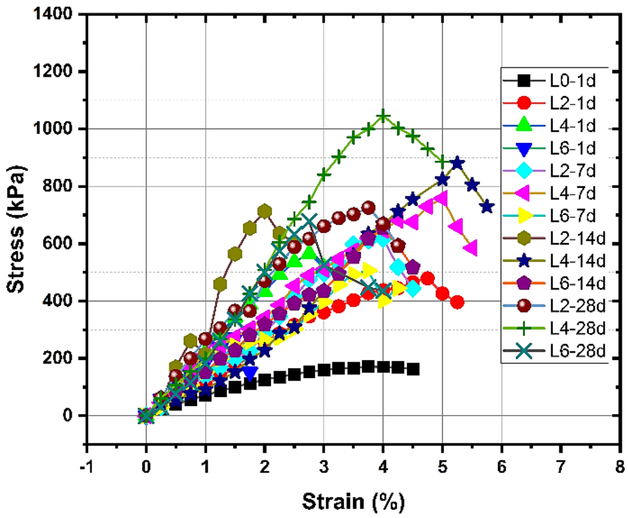

Fig. 7. Stress-Strain Relationship of The Unsoaked Lime-Stabilized Samples At Various Curing Ages

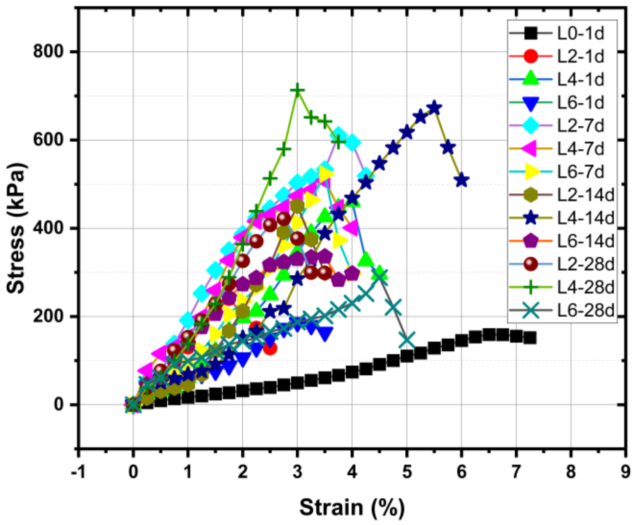

Fig. 8. Stress-Strain Relationship Of The Soaked Lime Stabilized Samples At Various Curing Ages

3.6 Laboratory CBR

CBR tests for the soil improved with different lime contents were carried out in the laboratory for the unsoaked and soaked conditions. The soaked samples represent the behavior of subgrade soil exposed to intense rainfall. Fig. 9 and Fig. 10 demonstrate the variation of CBR at various curing ages for the unsoaked and soaked lime-stabilized soil respectively. The CBR value enhanced for the higher lime percentage and curing period for both conditions. These findings are in good agreement with the outcomes obtained by Du, et al. [53]. It can be observed that CBR values for both conditions significantly increased. The CBR values of soil treated with 2%, 4% and 6% lime increased almost by 343%, 462%, and 487% for unsoaked samples and 500%, 622% and 850% for soaked samples respectively as compared to the plain soil at 28d of curing period. The improvement in CBR values may be attributed to the cementation and pozzolanic reaction. Majumder and Venkatraman [6] noticed an increase of 400-800% in soaked and unsoaked CBR for the ES treated with various lime dosages. In addition, the CBR values should not be less than 5% for low-level traffic roads and must be greater than 10% for the highways [37]. For the soil improved with various percentages of lime, both soaked and unsoaked samples for all curing ages resulted in higher CBR. However, soil treated with 4% lime can be used in roadways by considering the other test results such as UCS and PL outcomes.

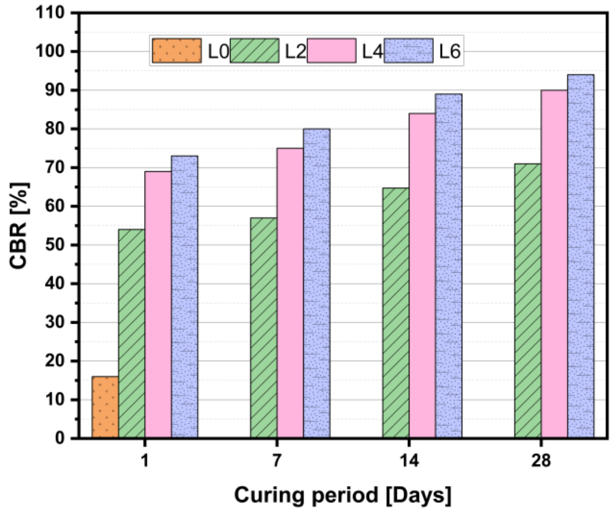

Fig. 9. Modifications In Unsoaked CBR Values Of Lime Improved Soil At Various Curing Age

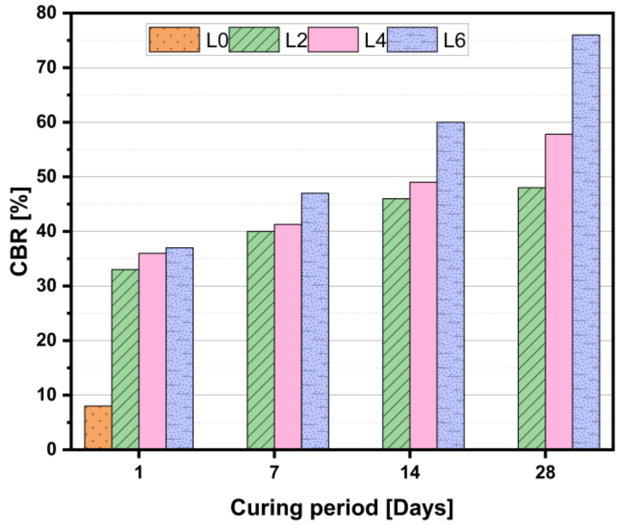

Fig. 10. Modifications In Soaked CBR Values Of Lime Improved Soil At Various Curing Age

3.7 Swelling Characteristic by CBR and FSI Test

CBR moulds with a surcharge load of 4.5 kg were placed inside a water tank and a swell gauge was arranged to measure swell potential. The variation of CBR swell test results against different curing periods is provided in Fig. 11. It can be seen that the incorporation of lime effectively decreases the swelling potential. The highest swell value of 5.69% was observed for the plain soil and the lowest value of 2.42 was measured for soil treated with 6% for the curing period of 28d.

Furthermore, the FSI was measured by taking 1000 ml water and 100 gm soil after passing through sieve size No 200. The swelling characteristic of lime-treated soil against various curing ages is presented in Fig. 12. The maximum FSI of 100% was obtained for the untreated soil and the values tend to decrease below 18% for the lime dosages at various curing periods. Chitragar, et al. [37] recommended that the swelling index for the subgrade soil should be less than 50%. The addition of lime provides a free swelling index lower than 20%, which meets the requirement specified above for the subgrade soil.

The incorporation of lime into the soil causes the agglomeration of soil particles and cation exchange. Due to these two changes, the tiny soil particles make floc and cause the accumulation of larger soil particles. The overall consequence is a significant decline in the swelling behavior of the ES. Furthermore, pozzolanic activity between soil and lime develops a cementitious network, creating resistance to the soil volume change up to a considerable extent [40, 43].

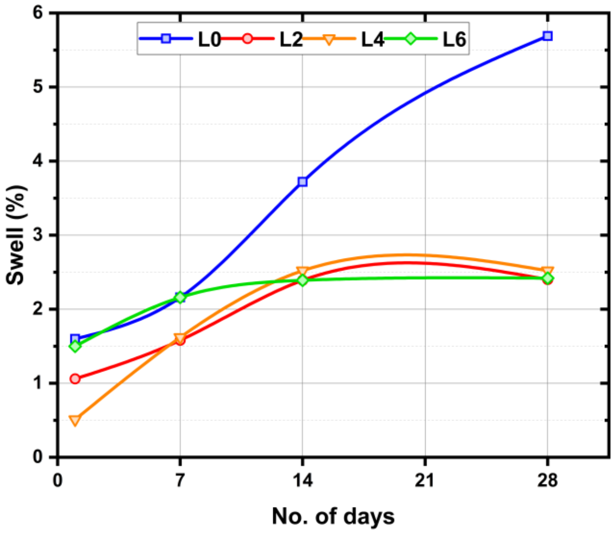

Fig. 11. Variation In Swell Potential With Curing Age

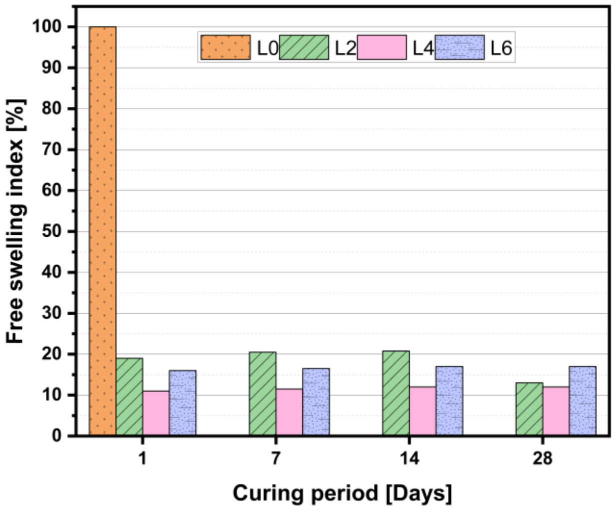

Fig. 12. Variation In FSI With Different Curing Age

3.8 Field CBR

Field CBR test is usually used during the construction of a highway to evaluate the load-carrying capacity of subgrade materials. In order to design the pavement of a new roadway, the bearing capacity and strength of the subgrade must be assessed so that it can resist cyclic traffic loading. In transportation geotechnology, the field CBR is believed as the most reliable test to examine the characteristics of base and subgrade materials [54].

A field CBR test has been conducted on the field specimens at 0% and 4% lime-treated soil as per ASTM-D-4429 [55]. Field-soaked CBR tests were performed on sample sizes of 3ft × 2ft at various curing ages of 1d, 7d, 14d and 28-days. Fig. 13 shows the variation in field-soaked CBR for the plain and lime-treated soil at various curing ages. A remarkable increase in CBR results can be seen with the addition of lime against various curing periods. Kavak and Akyarlı [20] observed that field CBR values increased with lime content as compared to plain soil. The increase in CBR values may be because of the cation exchange process between the metallic ions on the soil surface and the calcium ions of lime, which makes the soil grains flocculate and create aggregates [54].

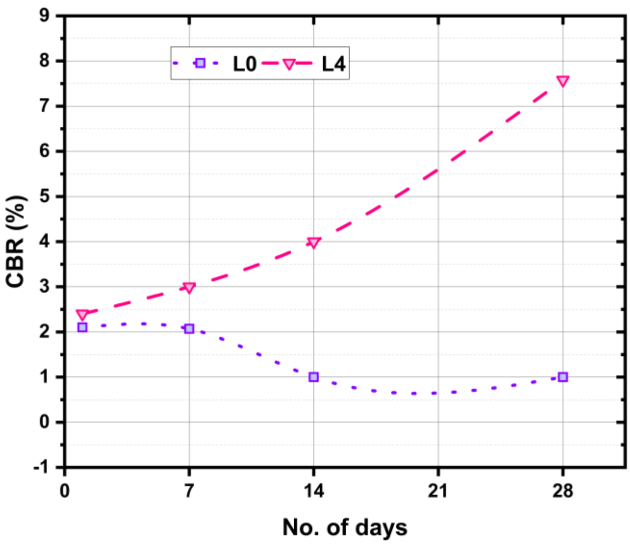

Fig. 13. Modifications In Field CBR Values Of Lime Stabilized Soil At Various Curing Age

3.9 Plate Load Test

The effect of lime stabilization on the field specimen was assessed using a plate load test (PLT). The tests were carried out with a 300 mm circular plate. A vertical load of 5kN was applied to the plate for 5 minutes. The test was terminated when the soil deformation became unchanged. The ultimate bearing capacity (q_{ult}) was achieved from the stress-settlement relationship using the double tangent method [56]. The selected soil collapsing/failure criteria in the soaked condition of the specimen were to determine the vehicular load that the soil can bear during a wet period or inclement weather conditions. The experiments were performed on the plain soil and optimum lime-treated specimen (4%) in soaked condition at curing ages of 1d, 7d, 14d and 28d.

Fig. 14 shows the variation of q_{ult} with various curing ages. It can be seen that the q_{ult} increased with the addition of lime. The ultimate bearing capacity value increased from 0.5 T/ft^2 to 1.31 T/ft^2 with the incorporation of lime for the 28d curing period. The lime-treated samples indicated an improvement of 162% as compared to the plain soil. The permanent deformation value achieved from the PLT has decreased from a value of 33 mm to 2 mm after 28d. Similar declining trends in deformation were observed by Kavak and Akyarlı [20]. The utilization of lime in the field as a stabilizing agent has successfully increased the q_{ult} of the subgrade.

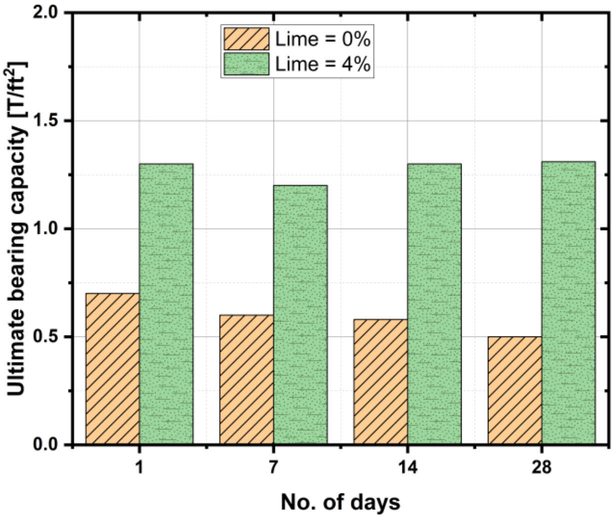

Fig. 14. Changes In Field q_{ult} Values Of Lime Treated Soil At Various Curing Age

3.10 Development of Mathematical Expressions

Several mathematical expressions were developed based on the results obtained from the experiments. **Error! Reference source not found.** presents the Eqs. (1)-(6) to estimate the best fit for the prediction of LL, PI, MDD, OMC, UCS soaked/unsoaked, CBR soaked and unsoaked and FSI for understanding the behavior and performance of lime-stabilized soils. These equations provide a scientific basis for estimating the geotechnical parameters of lime-stabilized soils and are useful for designing lime stabilization projects. Two major mathematical parameters were computed for measuring the precision of all mathematical models such as the determination coefficient (R^2) and root-mean-square error (RMSE) (as described in Table 2), where the values of RMSE were evaluated using Eq. (7).

$$RMSE = \sqrt{\left(\frac{\left(V_{\exp} - V_{pre}\right)^2}{N}\right)} \tag{7}$$

Where V_{exp} is experimental value and V_{pre} is the predicted values from the mathematical models. Low total RMSE values were obtained for the experimental and predicted values. The coefficient of determination is a useful tool to determine the accuracy of the equations, wherever the accuracy of the expressions is related to the higher value of the R^2, close to unity [57]. Each mathematical expression was tested by comparing the experimental values and predicted data. The regression values of the LL, PI, MDD, OMC, UCS soaked/unsoaked, CBR soaked and unsoaked and FSI models are 0.99, 0.99, 0.99, 1.00, 0.91/0.95, 0.95/0.98, and 0.99 respectively. Sari Ahmed, et al. [48] proposed mathematical models for LL, PI, UCS, FSI, MDD and OMC with determination coefficients of 0.92, 0.83, 0.84, 0.97, 0.87 and 0.86, respectively for the high plasticity clayey soils stabilized with fly ash. Thus, the models developed in this study give more accurate values. As displayed in Fig. 15 - Fig. 23, it is quite clear to notice that the comparative evaluation shown that all the established mathematical expressions are in good agreement with the test results and can be applied as a reliable method for estimating the properties of lime treated ES.

The application of these equations is important for estimating the geotechnical parameters of lime-stabilized soils used in various civil engineering projects, especially for the subgrade in pavement constructions. By using these equations, the designer can select the appropriate lime content and soil mixture to achieve the desired geotechnical properties for the specific application.

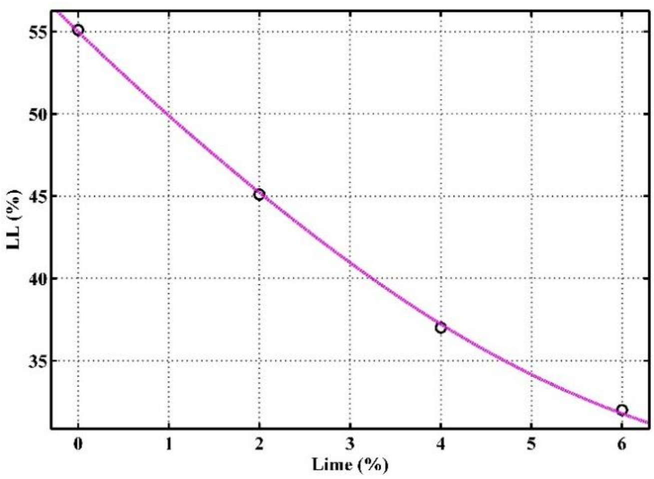

Fig. 15. Experimental And Predicted Values Of Liquid Limit

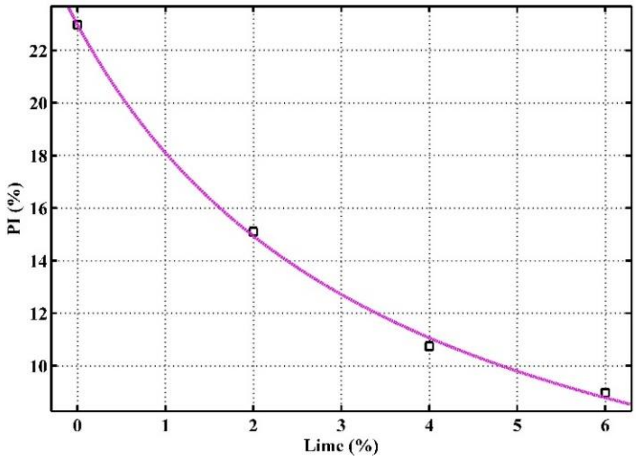

Fig. 16. Experimental And Predicted Values Of The PI

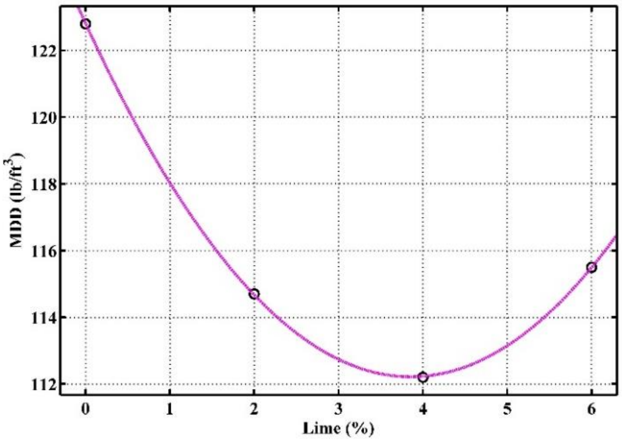

Fig. 17. Experimental And Estimated Values Of MDD

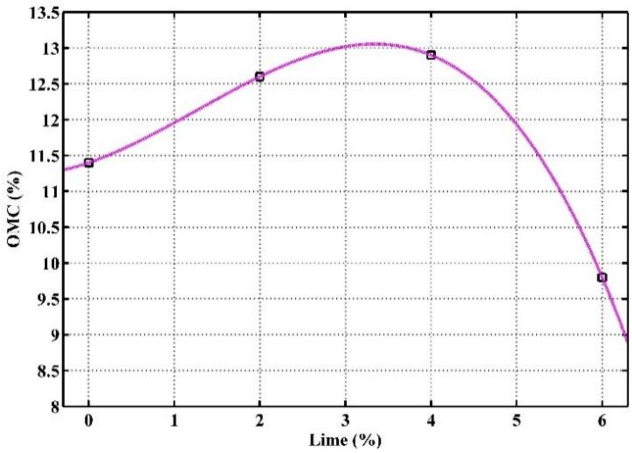

Fig. 18. Experimental And Predicted Values Of OMC

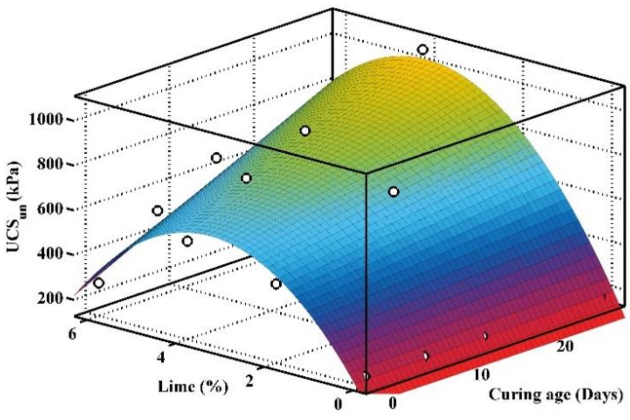

Fig. 19. Experimental And Estimated Values Of UCS For The Unsoaked Condition

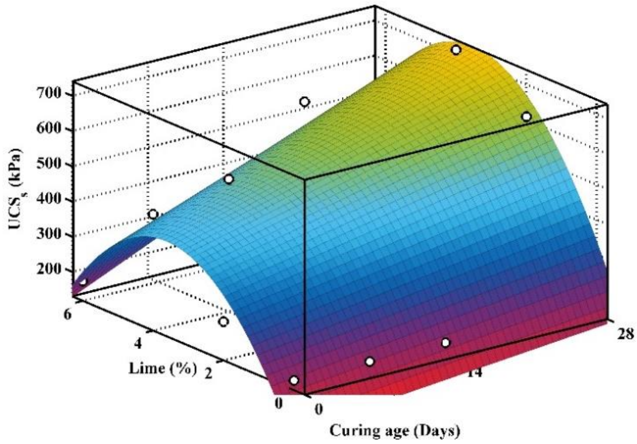

Fig. 20. Experimental and estimated values of UCS for the soaked condition

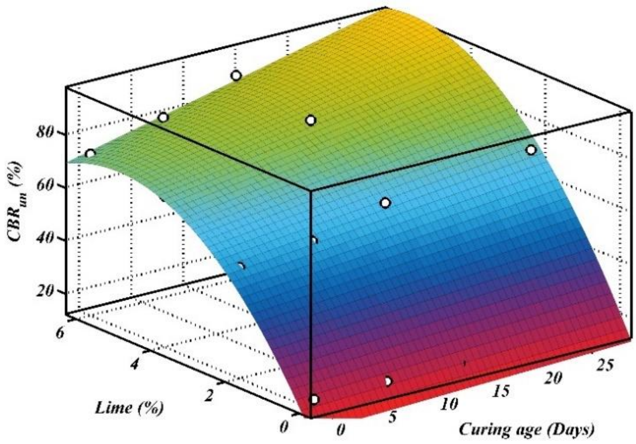

Fig. 21. Experimental And Estimated Values Of CBR For The Unsoaked Condition

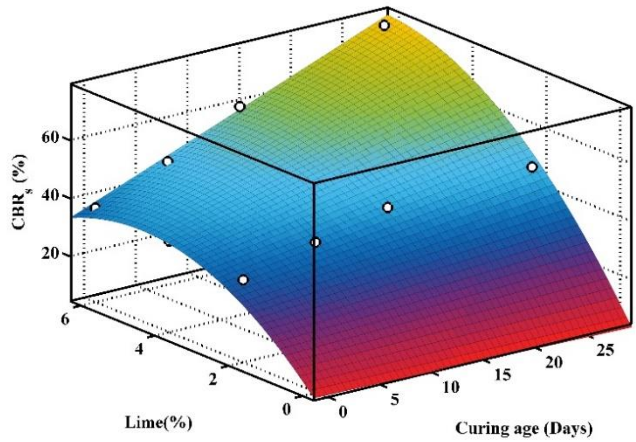

Fig. 22. Experimental And Estimated Values Of CBR For The Soaked Condition

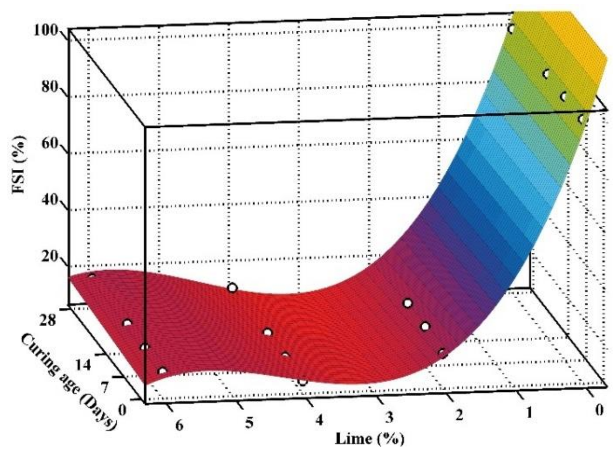

Fig. 23. Experimental And Predicted Values Of FSI

Table 2

Summary of the best-fit models

Geotechnical parameter	Equation	Model parameter	R^2	RMSE	Eq No.
Consistency limit	$LL = a_1\left[\sin\left(L-\pi\right)\right] + a_2\left(L-10\right)^2 + \left(a_3 \times LL_0\right)$	a_1 = -0.1638 a_2= 0.2756 a_3= 0.4977	0.99	0.340	(1)
	$PI = \dfrac{PI_0}{\left(1+a_1 L\right)}$	a_1 = 0.269	0.99	0.235	(2)
Compaction parameters	$MDD = a_1 L^2 + a_2 L + MDD_0$	a_1 = 0.7118 a_2 = -5.489	0.99	0.324	(3)
	$OMC = a_1 L^3 + a_2 L^2 + a_3 L + OMC_0$	a_1 = -0.05208 a_2 = 0.2 a_3 = 0.4083	1.00	0.00	(4)
Strength parameters	UCS_{un}	a_1 = 170.7 a_2 = -0.3326 a_3 = 269.2 a_4 = 4.498 a_5 = -41.35	0.95	66.49	
	UCS_s	a_1 = 100.5 a_2 = 3.466 a_3 = 211.9 a_4 = 1.632 a_5 = -32.95	0.91	66.6	
	$= a_1 + a_2 C + a_3 L + a_4 CL + a_5 L^2$				(5)
	CBR_{un}	a_1 = 14.54 a_2 = 0.1783 a_3 = 25.07 a_4 = 0.119 a_5 = -2.573	0.98	3.423	
	CBR_s	a_1 = 9.642 a_2 = 0.00543 a_3 = 13.81 a_4 = 0.2241 a_5 = -1.548	0.95	5.008	
Swelling	$FSI = a_1 + a_2 C + a_3 L + a_4 CL + a_5 L^2 + a_6 CL^2 + a_7 L^3$	a_1 = 100 a_2 = -0.01639 a_3 = -68.96 a_4 = -0.08032 a_5 = 17.04 a_6 = 0.0159 a_7 = -1.314	0.99	1.73	(6)

LL liquid limit
LL_0 LL for the plain soil
PI plasticity index
PI_0 PI for the plain soil
MDD_0 MDD for the plain soil
OMC_0 OMC for the plain soil
L lime percentage
C curing period
$_{un}$ unsoaked
$_{s}$ soaked

4. Conclusion

In this paper, the influence of various lime dosages on the geotechnical properties of ES was studied. Based on the findings obtained in this study, the following statements are concluded.

- The Atterberg's limits and free swelling index of soil decrease with increasing the lime contents. The reduction in soil-lime plasticity and swelling behavior is mainly due to the exchange of cations and a decrease in the thickness of the diffused double layer. The FSI of lime-treated soil was lower than 20%, which meets the requirement for the subgrade soil.

- The increase in lime content in the treated soil developed a more flocculated soil matrix and elevated the pH, the flocculation of soil particles and pH increase resulted in the reduction of MDD. The increase in OMC may be due to a change in effective particle sizes and an increase in water-holding capacity.
- The UCS values of ES treated with 2%, 4% and 6% lime increased almost by 324%, 523%, and 249% for unsoaked samples and 285%, 351% and 231% for soaked samples respectively as compared to the plain soil at 28d of curing period. This improvement is caused by the pozzolanic reaction between clay minerals and calcium from the lime. The UCS and PL results have the same lime fixation point which leads to an optimum enhancement and was equal to 4% lime.
- The CBR values of ES treated with 2%, 4% and 6% lime increased almost by 343%, 462%, and 487% for unsoaked samples and 500%, 622% and 850% for soaked samples respectively as compared to the plain soil at 28d of curing period. The improvement in CBR values may be attributed to the cementation and pozzolanic reaction.
- The field CBR values improved with an increase in the curing period. The increase may be due to the cation exchange process between the metallic ions on the soil surface and the calcium ions of lime. The Field CBR values for the lime-treated soil improved 5.6 times as compared to the natural soil at 28d.
- The q_{ult} of subgrade soil achieved from the PLT demonstrated substantial improvement with the incorporation of lime. The q_{ult} of lime-treated soil increased by 162% as compared to the plain soil. The permanent deformation decreased from a value of 33 mm to 2 mm after 28d.
- Mathematical expressions were developed to estimate the best fit for the prediction of LL, PI, MDD, OMC, UCS soaked/unsoaked, CBR soaked and unsoaked and FSI for understanding the behavior and performance of lime-stabilized soils. The R^2 values for all the equations were found higher than 0.90.

As per the current study, it has been reported that the lime fixation point of 4% lime by weight satisfies the requirement for the subgrade construction of highways and roads. The results obtained will provide a better understanding of the performance of lime-treated soil and its application as a subgrade.

5. References

[1] S. Amena, "Experimental study on the effect of plastic waste strips and waste brick powder on strength parameters of expansive soils," Heliyon, vol. 7, no. 11, p. e08278, 2021.

[2] A. Seco, F. Ramírez, L. Miqueleiz, and B. García, "Stabilization of expansive soils for use in construction," Applied Clay Science, vol. 51, no. 3, pp. 348-352, 2011.

[3] L. D. Jones and I. Jefferson, "Expansive soils," 2012.

[4] A. A.-E. Driss, K. Harichane, M. Ghrici, and H. Gadouri, "Assessing the effect of moulding water content on the behaviour of lime-stabilised an expansive soil," Geomechanics and Geoengineering, vol. 17, no. 3, pp. 896-908, 2022.

[5] M. T. Miah, E. Oh, G. Chai, and P. Bell, "Effect of swelling soil on pavement condition index of airport runway pavement," Transportation Research Record, p. 03611981221090517, 2022.

[6] M. Majumder and S. Venkatraman, "Utilization of the lime as subgrade stabilizer in the pavement construction," Arabian Journal for Science and Engineering, vol. 47, no. 4, pp. 4929-4942, 2022.

[7] H. A. Chenarboni, S. H. Lajevardi, H. MolaAbasi, and E. Zeighami, "The effect of zeolite and cement stabilization on the mechanical behavior of expansive soils," Construction and Building Materials, vol. 272, p. 121630, 2021.

[8] U. Arshad, A. Kassim, S. Ahmad, R. Ullah, M. Junaid, and M. D. Zia, "Experimental analysis of embankment on soft soil improved with bottom ash columns," Transportation Geotechnics, p. 100881, 2022.

[9] C. C. Okoro, J. Vogtman, A. Yousif, M. Agnaou, and N. Khoury, "Consolidation characteristics of soils stabilized with lime, coal combustion product, and plastic waste," in Geo-Frontiers 2011: Advances in Geotechnical Engineering, 2011, pp. 1202-1209.

[10] J. Pooni, D. Robert, F. Giustozzi, C. Gunasekara, and S. Setunge, "A review on soil stabilisation of unsealed road pavements from an Australian perspective," Road Materials and Pavement Design, pp. 1-45, 2022.

[11] M. J. Roshan, M. Abedi, A. G. Correia, and R. Fangueiro, "Application of self-sensing

cement-stabilized sand for damage detection," Construction and Building Materials, vol. 403, p. 133080, 2023.

[12] J. A. Baldovino, E. B. Moreira, W. Teixeira, R. L. S. Izzo, and J. L. Rose, "Effects of lime addition on geotechnical properties of sedimentary soil in Curitiba, Brazil," Journal of rock mechanics and geotechnical engineering, vol. 10, no. 1, pp. 188-194, 2018.

[13] A. Al-Swaidani, I. Hammoud, and A. Meziab, "Effect of adding natural pozzolana on geotechnical properties of lime-stabilized clayey soil," Journal of Rock Mechanics and Geotechnical Engineering, vol. 8, no. 5, pp. 714-725, 2016.

[14] S. K. Dash and M. Hussain, "Lime stabilization of soils: reappraisal," Journal of materials in civil engineering, vol. 24, no. 6, pp. 707-714, 2012.

[15] A. R. Ghanizadeh, M. Salehi, and F. Jalali, "Investigating the effect of lime stabilization of subgrade on the fatigue & rutting lives of flexible pavements using the nonlinear mechanistic-empirical analysis," Geotechnical and Geological Engineering, pp. 1-21, 2022.

[16] A. H. Ahmed, A. M. Hassan, and H. A. Lotfi, "Stabilization of expansive sub-grade soil using hydrated lime and dolomitic-limestone by-product (DLP)," Geotechnical and Geological Engineering, vol. 38, pp. 1605-1617, 2020.

[17] E. Garzón, M. Cano, B. C. Okelly, and P. J. Sánchez-Soto, "Effect of lime on stabilization of phyllite clays," Applied Clay Science, vol. 123, pp. 329-334, 2016.

[18] M. A. Sakr, M. A. Shahin, and Y. M. Metwally, "Utilization of lime for stabilizing soft clay soil of high organic content," Geotechnical and Geological Engineering, vol. 27, pp. 105-113, 2009.

[19] A. A. M. S. Mohamed, M. Al-Ajamee, A. Kobbail, H. Dahab, M. M. Abdo, and H.-E. Alhassan, "A study on soil stabilization for some tropical soils," Materials Today: Proceedings, vol. 60, pp. 87-92, 2022.

[20] A. Kavak and A. Akyarlı, "A field application for lime stabilization," Environmental geology, vol. 51, no. 6, pp. 987-997, 2007.

[21] F. G. Bell, "Lime stabilization of clay minerals and soils," Engineering geology, vol. 42, no. 4, pp. 223-237, 1996.

[22] T. Thyagaraj and S. Zodinsanga, "Laboratory investigations of in situ stabilization of an expansive soil by lime precipitation technique," Journal of Materials in Civil Engineering, vol. 27, no. 7, p. 06014028, 2015.

[23] S. M. Rao and P. Shivananda, "Compressibility behaviour of lime-stabilized clay," Geotechnical & Geological Engineering, vol. 23, pp. 309-319, 2005.

[24] O. H. Ingles, "Soil stabilisation. Chapter 38," Ground Engineer's Reference Book; Bell, FG, Ed.; Butterworths: London, UK, p. 38, 1987.

[25] A. E. Goufi, K. Harichane, Z. Harichane, M. Ghrici, and A. A. E. Driss, "Improvement of the geotechnical properties of a clay–sand mixture treated with lime," Innovative Infrastructure Solutions, vol. 7, no. 1, p. 114, 2022.

[26] K. E. Clare and A. E. Cruchley, "Laboratory experiments in the stabilization of clays with hydrated lime," Geotechnique, vol. 7, no. 2, pp. 97-111, 1957.

[27] M. H. Ghobadi, Y. Abdilor, and R. Babazadeh, "Stabilization of clay soils using lime and effect of pH variations on shear strength parameters," Bulletin of Engineering Geology and the Environment, vol. 73, pp. 611-619, 2014.

[28] R. Ullah et al., "Effectiveness of laser diffraction method for particle size evaluation of residual soil," Indian Geotechnical Journal, pp. 1-11, 2022.

[29] AASHTO M145, "Classification of soils and soil-aggregate mixtures for highway construction purposes," American Association of State Highway and Transportation Officials (AASHTO): Washington, DC, USA, 1995.

[30] ASTM D2487-06, "Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)," ASTM International, West Conshohocken, PA, 2006.

[31] ASTM-D4318, Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM international, 2010.

[32] ASTM-D18, Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 Ft-lbf/ft3 (2,700 KN-m/m3)) 1. ASTM International, 2009.

[33] ASTM-D6276. Standard test method for using pH to estimate the soil-lime proportion requirement for soil stabilization," ed: ASTM

International: West Conshohocken, PA, USA, 2006.

[34] ASTM-D2166, "Standard test method for unconfined compressive strength of cohesive soil," ed: ASTM International West Conshohocken, PA, USA, 2000.

[35] ASTM-D883-07, "Standard test method for CBR (California Bearing Ratio) of laboratory-compacted soils," ed: ASTM International West Conshohocken, PA, 2007.

[36] ASTM-D1195, "Standard test method for repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements," ed: ASTM International West Conshohocken, PA, 2015.

[37] S. F. Chitragar, C. B. Shivayogimath, and R. H. Mulangi, "Study on strength and volume change behavior of stabilized black cotton soil with different pH of soil-lime mixes for pavement subgrade," International Journal of Pavement Research and Technology, vol. 14, no. 5, pp. 543-548, 2021.

[38] ASTM-D6276, "Standard test method for using pH to estimate the soil-lime proportion requirement for soil stabilization," ed: West Conshohocken PA: ASTM International, 2019.

[39] K. D. Sujit and H. Monowar, "Lime stabilization of soils," Journal of Materials in Civil Engineering, vol. 24, no. 6, pp. 707-714, 2012.

[40] A. A. Amadi and A. Okeiyi, "Use of quick and hydrated lime in stabilization of lateritic soil: comparative analysis of laboratory data," International Journal of Geo-Engineering, vol. 8, no. 1, pp. 1-13, 2017.

[41] G. S. Utami, "Clay soil stabilization with lime effect the value CBR and swelling," ARPN journal of engineering and applied sciences, vol. 9, no. 10, pp. 1744-1748, 2014.

[42] M. R. Asgari, A. Baghebanzadeh Dezfuli, and M. Bayat, "Experimental study on stabilization of a low plasticity clayey soil with cement/lime," Arabian Journal of Geosciences, vol. 8, no. 3, pp. 1439-1452, 2015.

[43] A. K. Jha and P. V. Sivapullaiah, "Mechanism of improvement in the strength and volume change behavior of lime stabilized soil," Engineering Geology, vol. 198, pp. 53-64, 2015.

[44] W. Zoubir, K. Harichane, and M. Ghrici, "Effect of lime and natural pozzolana on dredged sludge engineering properties," Electronic Journal of Geotechnical Engineering, vol. 18, no. c, pp. 589-600, 2013.

[45] K. Harichane, M. Ghrici, S. Kenai, and K. Grine, "Use of natural pozzolana and lime for stabilization of cohesive soils," Geotechnical and geological engineering, vol. 29, no. 5, pp. 759-769, 2011.

[46] F. S. Ackah, W. Hailiang, F. Huaiping, L. Cheng, and L. Z. Feng, "Use of Taguchi method to evaluate the unconfined compressive strength of quicklime stabilized silty clayey subgrade," Case Studies in Construction Materials, vol. 17, p. e01417, 2022.

[47] N. H. A. Rizal et al., "Effects of lime on the compaction characteristics of lateritic soil in UTM, Johor," 2022, vol. 971: IOP Publishing, 1 ed., p. 012031.

[48] B. Sari Ahmed, H. Gadouri, M. Ghrici, and K. Harichane, "Best-fit models for predicting the geotechnical properties of FA–stabilised problematic soils used as materials for earth structures," International Journal of Pavement Engineering, vol. 21, no. 7, pp. 939-953, 2020.

[49] A. Kumar, B. S. Walia, and A. Bajaj, "Influence of fly ash, lime, and polyester fibers on compaction and strength properties of expansive soil," Journal of materials in civil engineering, vol. 19, no. 3, pp. 242-248, 2007.

[50] H. Gadouri, K. Harichane, and M. Ghrici, "Effects of Na2SO4 on the geotechnical properties of clayey soils stabilised with mineral additives," International journal of geotechnical engineering, vol. 11, no. 5, pp. 500-512, 2017.

[51] North Carolina Department of Transportation, Cement and lime stabilization of subgrade soils, Project Special Provisions, NCDOT, 2007.

[52] I. R. Congress, "Guidelines for the design of flexible pavements," Indian code of practice, IRC, vol. 37, 2018.

[53] Y. J. Du, Y. Y. Zhang, and S. Y. Liu, "Investigation of strength and California bearing ratio properties of natural soils treated

by calcium carbide residue," Proceedings of Geo-Frontiers, pp. 1237-1244, 2011.

[54] S. Dhar and M. Hussain, "The strength and microstructural behavior of lime stabilized subgrade soil in road construction," International Journal of Geotechnical Engineering, 2019.

[55] ASTM-D4429, "Standard Test Method for CBR (California Bearing Ratio) of Soils in Place," ed: ASTM International West Conshohocken, PA, 2009.

[56] M. Y. Fattah, K. T. Shlash, and M. J. M. Al-Waily, "Stress concentration ratio of model stone columns in soft clays," Geotechnical Testing Journal, vol. 34, no. 1, pp. 50-60, 2011.

[57] H. M. Jafer, K. S. Hashim, W. Atherton, and A. Al-attabi, "A statistical model for the geotechnical parameters of cement-stabilised hightown's soft soil: A case study of Liverpool, UK," International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, vol. 10, no. 7, pp. 885-890, 2016.