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RESEARCH PAPER

Lime Stabilization of Expansive Clay Soil of Jimma Town, Ethiopia

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ABSTRACT: The engineering properties of stabilized soils are varied for many factors such as soil heterogeneity, soil composition, soil structures, geological conditions, and the difference of interaction between the soil and stabilizers. These variations required the consideration of stabilization at a specific site option. These natural materials, therefore, critically influence the success of a construction project. The reason for this study was to quantify the improvements achieved in the engineering properties of expansive soils due to lime stabilization. This study considered quantitative experimental to determine lime-stabilized expansive clay soil's engineering properties using a laboratory program. Laboratory tests were to determine Atterberg Limits, compaction test, free swell test, California Bearing Ratio (CBR), and pH values of the mixtures. The collected soil samples were stabilized using 2, 4, 5, 6, and 8% of hydrated lime by weight. The optimum lime for the stabilization of expansive soils was 5% using hydrated lime. As percentages of hydrated lime increased, there were improvements in stabilized subgrade soil properties. The more significant upgrade in engineering properties was observed on California Bearing Ratio (CBR), and lower improvements were on maximum dry density. The result indicated that the stabilizer is very effective in improving strength parameters than index parameters. The hydrated lime stabilized soils under the optimum ratio fulfill the standard requirements as subgrade soils.

Keywords: Engineering Properties, Expansive Soil, Laboratory Tests, Lime Stabilization, Optimum Lime Content.

1. Introduction

Soils are naturally occurring materials used for road construction and other civil engineering works, such as the structure of all pavement layers except the surface made of concrete or asphalt. Therefore, these natural materials critically influence the success of a construction project (USDA, USAF, USN, 2004). There are different methods of minimizing structural damages due to the high swelling potential of expansive soils. The most common forms are reducing expansive soil swelling, using a solid structure that cannot be damaged for soil swelling, not constructing structures on swelling soil (Kalantari, 2012). Expansive soils are predominant soil in various parts of the world. Lime has been widely used to reduce the expansiveness of the soil by

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forming pozzolanic products such as calcite and calcium-silicate-hydrate (Akula and Little, 2020). The expansiveness of soils is because of the presence of clay minerals. Clay particles have sizes of 0.002 mm or less. However, according to Chen (1984), the grain size alone does not determine clay minerals, and he highlighted that the essential property of fine-grained soils is their mineralogical composition. The most common clay minerals in engineering studies are Kaolinite, Illite, and Montmorillonite. Expansive soils can be recognized using mineralogical identification, indirect index property tests, or direct expansion potential tests. The expansiveness of soil is governed by the type and proportion of clay minerals it contains. Knowing the type and ratio of the clay mineral in the soil indicates the swelling potential (Chen, 1984). However, Lytton (1999) observed that the small size of clay grains makes the minerals challenging to distinguish in either hand specimens or petrographic microscopy. He also indicated the absence of a single or straightforward procedure for identifying clay minerals or their quantification and recommended the application of several methods for even approximate identification and rough quantification. Rao et al. (2007) pointed out the nature and characteristics of the expansive soils. The nature of expansive soil is water-absorbing, swelling, shrinking, and weak strength. These soils are stiff when dry, easily compressible when it gets water, and highly expansive when the Free Swell Index (FSI) is higher than 50 percent.

Soil stabilization is a method of soil modification by physical and chemical means in density increment, reinforcement, cementation, and volume control of the soil for construction purposes (Fang, 2019; Negi et al., 2013). Soil stabilization is a process by mechanical or chemical soil improvement to increase the strength and stability of the soil. The improvements mainly attained are increased soil gradation, reduction of swelling and shrinkage potential, increased shear strength, and stability (Islam et al., 2019; USDA, USAF, USN, 2004). The purposes of lime used in construction engineering are to dry, modify, stabilize medium to fine-grained soils (ARBA, 2004; NASEM, 2009; Negi et al., 2013). A long-term pozzolanic reaction among flocculates and agglomerates of soil particles increases the strength based on the amounts of pozzolanic products and the reactivity of the soil minerals with lime used for stabilization (NASEM, 2009). Several procedures like the Illinois procedure, Thompson procedure, Eades and Grim procedure, and the Texas procedure, as summarized by the NRC and TRB (1987), involve comparing strength testing results using various lime contents till a lime content provides the maximum strength is obtained. For the Thompson and Eades and Grim procedures, the optimum lime ratio is estimated by evaluating the pH of several soil lime mixtures with changing lime contents. The lowest lime content that provides a pH of 12.4 is then used as the starting point for determining the optimum lime content. The Texas procedure, as summarized by the NRC and TRB (1987), first estimates the optimum lime content using the plasticity index of the soil and the percentage of soil passing the No. 40 sieves. After evaluating the optimum lime content, strength testing is then used to verify the actual optimum lime content. While the procedures outlined above help identify the lime content that will provide the greatest strength, many factors influence the strength of soil-lime mixtures. The variability of these factors makes it practically impossible to pinpoint the strength achieved for the lime stabilization of a particular soil. Therefore, the strengths of soil-lime mixtures through strength tests such as CBR, unconfined compressive strength, or resilient modulus must be verified. Lime contents between 2 to 10 percent can produce significant strength gains (Ikeagwuani et al., 2019). Jawad et al. (2016) reviewed previous studies on lime-treated soil and suggested that lime is the oldest and traditional soil stabilization system.

Soil treated using lime makes the soil particles agglomerate and flocculation that results in a pozzolanic reaction. Lime stabilization of soil efficiently increases soil strength, workability, and durability. The properties of lime-treated soil depend on many factors, such as soil type, lime type, lime percentage, curing time, and temperature conditions (Ali and Mohamed, 2019; Balaji et al., 2018; Di Sante et al., 2014). However, according to Kassim and Chern (2004), soil stabilization depends on the lime quality, clay fraction, soil mineralogy, and alkalinity. The influence of lime on the physical-mechanical properties of black cotton soils was studied using laboratory tests including Atterberg limits, California Bearing Ratio (CBR), swell percent, Unconfined Compressive Strength (UCS), X-Ray Diffraction (XRD), and pH test. The result revealed that lime significantly improved the physical-mechanical properties of the soil (Cheng et al., 2018; Dang et al., 2016). Alkali-activated materials are more sustainable and environmentally friendly construction materials in improving durability, strength, corrosion resistance, and a high degree of reaction when appropriate amounts are used (Wang et al., 2020).

The engineering properties of stabilized soils vary for many factors such as soil heterogeneity, soil composition, soil structures, geological conditions, and the interaction difference between the soil and stabilizers. These variations required the stabilization of a specific site option (NASEM, 2009). The envisioned transportation system in the future will be characterized as a “five-zero" system, such as zero casualties, zero delays, zero emissions, zero maintenance, and zero failure. The realization of the system needs the coordination and interaction between each element in the transportation system (i.e., peoples, vehicles, the road, and the environment) to be considered for systematic optimization (Sun et al., 2018).

In Ethiopia, as a general practice, the conventional method of removing expansive soil and replacing it with quality fill material has been common practice for a problem of expansive subgrade soils. This method is also practical around Jimma Town due to the lack of knowledge on stabilizing and reusing weak soils. Ikeagwuani and Nwonu (2019) stated that soil replacement might not be considered adequate when the soil condition is very critical; for the case of expansive soils, it involves prolonged physical activity to execute in situ when quality control is essential and thus could be time-consuming. According to Sarkar et al. (2016), using 5% of lime for expansive soil stabilization saved a cost of 32.5% than using quality material replacement. Stabilizing clays with lime can improve subgrade soils at a lower cost than removing and replacing materials (Prusinski and Land, 1999). Therefore, this study quantifies the improvements achieved on the engineering properties of expansive soils due to lime stabilization and determines the optimum lime content required for the stabilization of Jimma expansive clay. The stabilization of expansive soil is essential to ensure the stability of soil that can successfully sustain the load of the superstructure without failure. This research determines the proper ratio of stabilizer to be used in future construction on Jimma Town expansive clay soil. In designing a better sub-grade of road pavements, the laboratory results and the statistical analysis from this study can be helpful.

2. Materials and Methods

2.1. Description of the Study Area

This study considered the expansive clay soil of Jimma city of Ethiopia. Jimma town is one of the old and largest towns of the country, located in the southwestern part of the country at 354 km distance from Addis Ababa, the capital city of the country. The town is in the Jimma Zone of Oromia state; its geographical coordinates are approximately 7°41'N latitudes and 36°50'E longitudes. The city has an average temperature range from 20–30 °C, annual rainfall of average ranges from 800-2500 mm, and an elevation of 1718-2000 m above mean sea level. From Ethiopia's Central Statistical Agency (CSA) 2007 census report, the city's total population is 130,254. Its climate is in the climatic zone, which is very suitable for agriculture and the life of a human (Sun et al., 2018).

2.2. Materials

2.2.1. Soils

The type of soil considered for the stabilization using lime is expansive clay soil characterized by Sorsa et al. (2020) and summarized in Table 1.

2.2.2. Lime

Hydrated lime used for this study was obtained from Sankale Lime Factory. The chemical composition of Sankale hydrated lime was tested by (Solomon, 2011). The composition result is presented in Table 2.

2.3. Experimental Design

To characterize and understand the engineering properties of lime stabilized expansive clay soil laboratory experimental methods of (AASHTO T193-93, 1993; ASTM D3282-93, 1993; ASTM D422-98, 1998; ASTM D4318-00, 2000; ASTM D4643-00, 2000; ASTM D6276-99a, 1999; ASTM D698-00a, 2000; ASTM D854-02, 2002) procedures were considered. The soil specimens were from the Jimma city around Kidane-Mihret Church as shown in Figure 1 and Rift Valley University Jimma Campus (Sample 2).

2.3.1. Lime and Expansive Soil Mixing Ratios

As proposed in most of the previous studies conducted on soil stabilization using lime, the ratio of lime should be from 2%-10% by weight. The stabilization was done using 2, 4, 5, 6, and 8% of hydrated lime by weight for this study. The optimum amount of lime added to expansive clay was estimated using the pH test method (ASTM D6276-99a, 1999). This test method gives a means for evaluating the soil-lime proportion requirement for the stabilization of soil.

Table 1. Engineering properties of Jimma town soft, expansive clay soil (Sorsa et al., 2020)

Parameters/Samples name	S1	S2
Moisture content (%)	40.77	54.50
Specific gravity	2.7	2.77
Percentage Finer # 200 (%)	78	78
Liquid limit (%)	81	67
Plastic limit (%)	41	31
Plasticity index (%)	40	36
Classification	A-7-5	A-7-5
MDD (gm/cm^3)	1.41	1.48
OMC (%)	33.5	32
CBR (%)	1.8	2.4

Table 2. Sankale hydrated lime chemical composition

Constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	SO_3
Percentage (%)	6.21	2.18	3.57	59.47	3.91	0.61	0.79	0.3286	0.208	0.2785	0.58

Fig. 1. Photo of expansive soil observed at Kidane-Mihret (Jimma) Church Site (S1)

2.3.1. Laboratory Testing Procedures for Lime Stabilization

The collected soil samples should be first air-dried and sieved through a 425 μm sieve. Next, prepare hydrated lime of 2, 3, 4, 5, 6, and 8% of the soil samples. Finally, conduct laboratory tests by mixing hydrated lime with soil based on ASTM C977-02 (2002) that is dry mixing of hydrated lime with soil, then adds distilled water and thoroughly distributed throughout the soil.

3. Results and Discussions

3.1. Laboratory Results of Lime Stabilized Expansive Clay Soil

For this study, two subgrade soil samples were collected along the road section to evaluate the effects of hydrated lime for expansive subgrade soil. The most critical parameters used to assess the impact of chemical additives for this study were the Atterberg limit and CBR tests.

3.1.1. Atterberg Limits

The Atterberg limit tests were conducted at different ratios of lime. Based on the soil type and added chemicals, there were changes in index properties of stabilized soil. The variation of Atterberg limit values for the present study was reported in Figure 2.

As observed from Figure 2, changing stabilization ratio changes liquid limit, plastic limit, and plasticity index values of the soil. The highest reduction in plastic index occurred when stabilized with maximum percentages, and the minimum reduction occurred at minimum ratios. For example, the liquid limit, plastic limit, and plasticity index of natural soils of sample 1 were 67%, 31%, and 36%, respectively, whereas 5% hydrated lime stabilized soil 53%, 45%, and 8%, respectively. This study agrees with previous findings (Islam et al., 2019; Phanikumar and Raju, 2020; Solomon, 2011). According to Islam et al. (2019), adding 12% of lime to expansive soil reduced the liquid limit from 54.6% to 52.2% and increased the plasticity index from 24.3% to 34.6%. According to Phanikumar and Raju (2020), there were decreases in LL and PI, from 84% to 72% and 58% to 40.5%, respectively, when the lime content was increased from 0% to 12%. In general, from Figure 2 for lime stabilization, the following observation has been made. The liquid limit and plasticity index reduce with increasing lime ratios, but the plastic limit increases with increasing lime ratios. The purpose of reducing the liquid limit with increasing lime content is calcium silicate in a hydrated lime with absorbing water.

On the other hand, the plastic limit shows the opposite trend. The plastic limit increases with an increasing percentage of lime, as shown in Figure 2. The plasticity index drops as lime content increases due to the rapid occurrence of flocculation and pozzolanic reaction. Lime has been widely used to reduce the expansiveness of the soil by forming pozzolanic products such as calcite and calcium-silicate-hydrate (Akula and Little, 2020).

Table 3. Laboratory testing procedures used for this study

Laboratory test	ASTM standards	AASHTO standards
Natural moisture content	D 4643-00	
Specific gravity	D 854-83	
Grain size analysis	D 422-63	
Atterberg limits	D 4318-98	
pH	D 6276-99a	
Standard compaction	D 698-98	
CBR		T 193-93

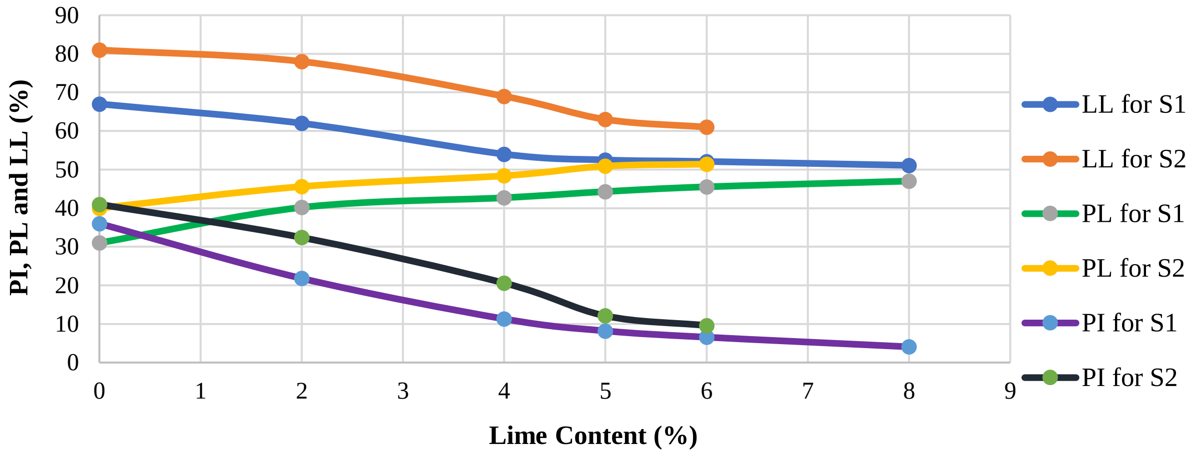

Fig. 2. Atterberg limit test result of hydrated lime stabilized expansive clay soils

3.1.2. Free Swell Test Result of Lime Stabilized Expansive Clay Soil

Free swell tests result indicated the potential expansiveness of soil samples without being loaded was very high. The Free Swell (FS) of the stabilized soil sample is presented in Figure 3.

The swelling potential of expansive soils was greater than 50% (Figure 3). This result indicated that the two soils were highly expansive soil. It was supported by Rao et al. (2007) soils are highly expansive when the free swell index exceeds 50%. Such soils undergo volumetric changes, leading to pavement distortion, cracking, and general unevenness due to seasonal wetting and drying. The soil samples' expansiveness for this study was identified based on parameters obtained from the test results of free swell and CBR swell percentage results. As indicated in Figure 3, increasing the proportion of stabilizers reduces the swelling of soils. For instance, the stabilization of expansive clay soil with 5% hydrated lime decreased the swelling potential of the soil from 85% to 29%, which is a very significant improvement. Thus, the result showed a stabilizer is effective in reducing the swelling potential of expansive soils.

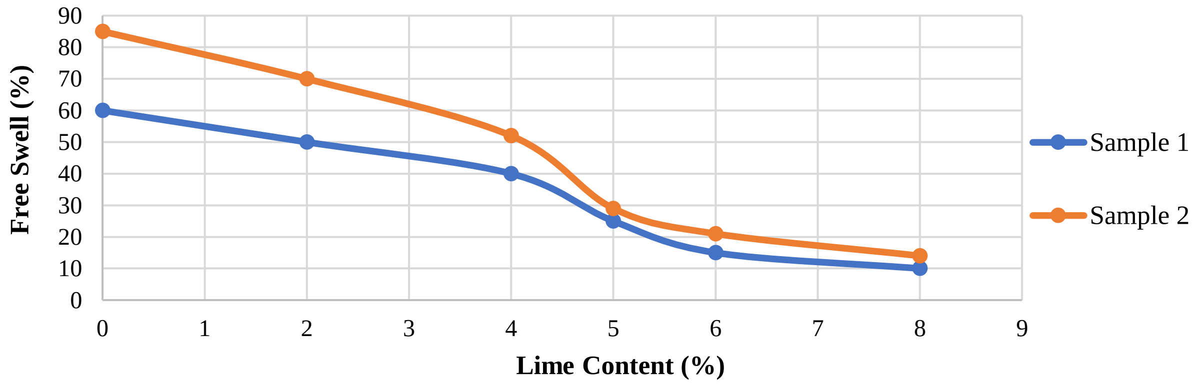

Fig. 3. Free swell result of stabilized soils

3.1.3. Moisture–Density Relationship

Moisture-density relationships were determined using the standard proctor compaction test according to ASTM D698-98. The OMC and maximum dry density of stabilized soils are presented in Table 4.

OMC and MDD showed that the stabilization proportion increased, optimum moisture content decreased, and maximum dry density increased. The results show that OMC decreases with increasing lime content due to fine and light particles in the mixtures. The pozzolanic reaction between clay and lime also reduces the OMC and increases MDD (Phanikumar and Raju, 2020). The use of 5% lime decreased OMC from 33.5% to 31% and increased MDD from 1.41 g/cm^3 to 1.48 g/cm^3. This concept is the same as Darsi et al. (2021) and Solomon (2011) concept, was concluded that the addition of chemical stabilizers to subgrade soils has decreased the OMC and has increased MDD of stabilized subgrade expansive clay soils. According to Solomon (2011), OMC decreases from 31% to 26%, and MDD increases from 1.44 g/cm^3 to 1.48 g/cm^3, when the lime content was increased from 0% to 6%. The decreasing moisture content had a significant influence on the stiffness of improved ground and the soil bearing capacity (Toufigh et al., 2017).

3.1.4. California Bearing Ratio (CBR) Result

California bearing ratio (CBR) is an essential parameter in pavement design (Nasrizar and Muttharam, 2019). This CBR test was conducted using the AASHTO procedure T193-93. The CBR value is a value at 2.54 mm penetration and 95% of MDD. The soils stabilized by hydrated lime showed an improvement in strength. Therefore, CBR is one of the parameters used to measure strength.

According to Nasrizar and Muttharam (2019), the CBR values can be affected by the lime content, curing period, and curing temperature. For example, stabilizing expansive soil by 5% lime improves CBR values from 1.8% to 18.1% for Sample 1. From Table 5, the following observations have been made:

- CBR increased with increased hydrated lime proportions.
- CBR values of natural subgrade soils of the two samples did not fulfill the requirement of subgrade soils as per the ERA standard (CBR > 5%).
- The improvement done at 5% hydrated lime fulfills the ERA standard (CBR > 5%) for sub-grade.

The increasing and decreasing of different parameters with an increasing percentage of lime were agreed with (Karatai et al., 2017; Phanikumar and Raju, 2020). Based on the finding of Gunjagi et al. (2016), adding 10% lime improved the CBR of expansive soil from 0.36% to 27.65%. The improvement in the CBR values of lime stabilized expansive soil is due to a cation exchange, flocculation, and agglomeration produced by lime (Nasrizar and Muttharam, 2019). The reason for soil strength increase after stabilization was there is a higher energy at the initial stage of reaction and a faster hydration process, resulting in the completion of their pozzolanic reactions in a short period (Bargi et al., 2021). According to the Ethiopian Road Authority (ERA) (2013), it is not allowed to use CBR values less than 5% because, from both a technical and economic perspective, it would generally be inappropriate to lay a pavement on soils of such bearing capacity.

Table 4. OMC and MDD of stabilized soil for typical ratios stabilizer

Sample	Lime percentage (%)	0	4	5
S1	OMC (%)	33.5	32	31
	MDD (g/cm^3)	1.41	1.45	1.48
S2	OMC	32	30.6	28.7
	MDD (g/cm^3)	1.48	1.50	1.54

Table 5. CBR values of stabilized and natural sub-grade soil

Sample name	lime percentage	CBR (%)	CBR requirements (%)
S1	0%	1.8	> 5
	5%	18.1	
S2	0%	2.4	
	4%	3.4	
	5%	8.4	

3.1.5. CBR Swell Result

The hydrated lime-soil mixtures compacted in CBR molds at optimum moisture content with maximum dry density gauged for swelling characteristics before and after soaking for four days to evaluate the swell percent. The test results at different ratios are presented in Table 6.

The CBR and CBR swell percentage test results, as shown in Tables 5 and 6, conclude that the subgrade soils have a low load-bearing capacity and high swelling potential, making the soils unsuitable for subgrade without improvement. The comparison above confirms that both soil samples did not fulfill the ERA standard requirements as subgrade soils, which are CBR should be greater than 5%, and CBR swell should be less than 2%. Therefore, treating expansive soils using appropriate improving methods before using the soil for subgrade materials is better. For this study, hydrated lime stabilization was considered. Chemicals such as lime and cement improve the low load-bearing capacity of poor subgrade soil and lower the plasticity index and percent swell of highly expansive subgrade soils (NASEM, 2009). The use of 5% lime reduced the swelling potential of an expansive soil from 4.30% to 1.08%, which is a very significant improvement. According to Cheng et al. (2018), adding 6% lime to expansive clay soil reduced the free swell percent of soil from 15.8% to 1.3%.

3.1.6. Estimation of the Optimum Lime for Expansive Soil Stabilization

One of the aims of this study was to determine the optimum lime ratio to stabilize the expansive soil of Jimma Town. The optimum lime was estimated for Jimma Town expansive clay based on laboratory test analysis and literature review. The optimum ratio of hydrated lime was calculated based on the pH meter method according to ASTM D6276. The optimum proportion is determined at a pH of 12.4.

Table 6. CBR swell test result of stabilized and natural subgrade soils

Sample name	CBR swell (%)	CBR Swell (%) minimum requirements
Natural S1	2.26	< 2%
5% stabilized S1	1.40	
Natural S2	4.30	
5% stabilized S2	1.08	

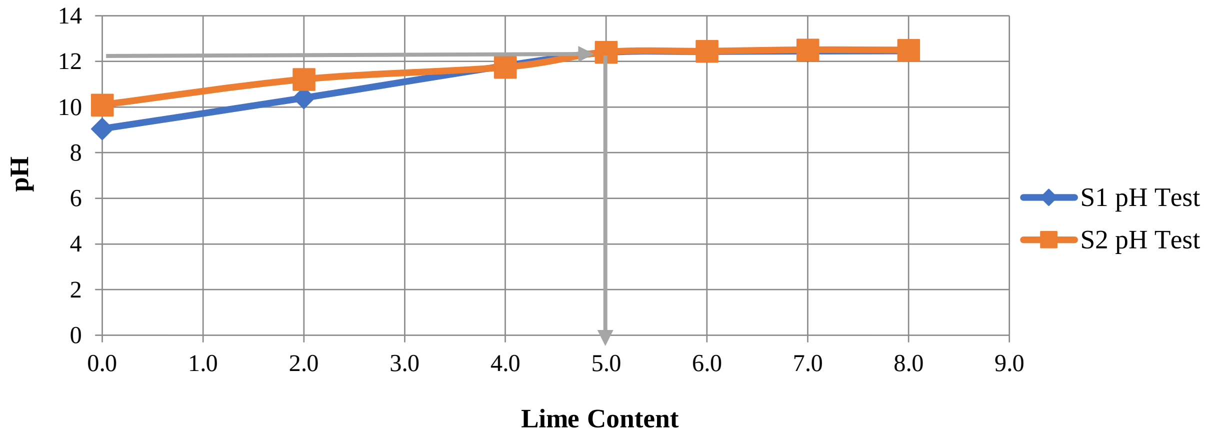

Fig. 4. Estimation of optimum lime ratio using pH method

As shown in Figure 4, the optimum ratio at 12.4 pH value is 5% of hydrated lime for both soils considered for this study. This result has similar trends observed in the study of (Mahedi et al., 2020). Different researchers found various optimum lime content for the stabilization of expansive soil. Based on the finding of Islam et al. (2019), 7% lime, Sarkar et al. (2016), 5% lime, Gunjagi et al. (2016), 10% lime, Nikookar et al. (2016), 9–12% lime is the optimum lime content for lime stabilization in short-term and long-term curing. The difference was because of soil property variation from place to place. The spatial variability of the soil had significant effects on the bearing capacity of the shallow foundations (Chenari, 2014). The mixture of expansive soil with lime increased the pH and salinity, creating a suitable environment for pozzolanic reactions (Kumar and Thyagaraj, 2020). Elsharief et al. (2013) suggested that soils having different mineralogical constituents had different optimum lime content. As the study conducted on three different Sudan tropical soil showed, the optimum lime was 4%, 6.5%, and 7%, which were different.

This study evaluated the effects and performance of hydrated lime on expansive soils based on the laboratory test results of Atterberg limits, free swell, CBR, and CBR swell percentage.

The test result in Table 7 shows that the more significant improvements were observed on CBR, and lower improvements were on maximum dry density. The degree of improvements for CBR and MDD are 905.5% and 4.1%, respectively. Thus, the result indicated that the hydrated lime improved strength parameters more effectively than index parameters. The reason is all index parameter tests considered immediate effects of lime. However, CBR depends on curing time effects. CBR was soaked for seven days for this study, so a more significant change was observed in CBR values. Therefore, the analysis shows lime is more effective when it takes time to react with soils. Nasrizar and Muttharam (2019) stated that soil engineering properties' improvement depends on the percentage of lime, curing period, and curing temperature.

4. Conclusions

This study was to quantify the improvements achieved in the engineering properties of expansive soils due to lime stabilization. Stabilizing soils with lime is now a cost-effective method of converting poor-quality soil into a strong, impermeable medium. The laboratory tests conducted for this study were Atterberg limits, compaction test, free swell test, California Bearing Ratio, and CBR swell tests. The test methods were based on AASHTO and ASTM laboratory test standards. The stabilization was done using 2, 4, 5, 6, and 8% of hydrated lime by weight. From the study, the following findings are concluded:

Table 7. Summary of the improvements on engineering properties at the optimum ratio

Sample name	Parameters	Natural soil	Improved soil using 5% lime	Degree of Improvements (%)
S1	LL (%)	67	52.5	21.6
	PL (%)	31	45.46	46.6
	PI (%)	36	7.04	80.4
	Free Swell (%)	60	25	58.3
	CBR (%)	1.8	18.1	905.5
	CBR Swell (%)	2.26	1.4	38.1
	OMC (%)	33.5	31	8.1
	MDD (g/cm^3)	1.41	1.48	4.96
S2	LL (%)	81	63	22.2
	PL (%)	41	50.9	24.1
	PI (%)	40	12.1	69.8
	Free Swell (%)	85	24	71.8
	CBR (%)	2.4	8.4	250
	CBR Swell (%)	4.3	1.08	74.9
	OMC (%)	32	28.7	10.3
	MDD (g/cm^3)	1.48	1.54	4.1

- The engineering properties of natural subgrade soils studied, the two soils were expansive clay of A-7-5 class soil.
- The subgrade soils considered for this study have a low load-bearing capacity and high swelling potential, making the soils unsuitable for subgrade without improvement. The CBR and CBR swell of natural soil was 1.8% and 2.26%, respectively.
- The optimum ratio for the expansive soils is at 5% hydrated lime using the pH meter method.
- The higher improvements in engineering properties were observed on CBR, and lower improvements were on maximum dry density. The result indicated that the hydrated lime was very effective in improving strength parameters than index parameters. Stabilizing expansive soil by 5% lime improves CBR values from 1.8% to 18.1% for Sample 1. The use of 5% lime increased MDD from 1.41 g/cm^3 to 1.48 g/cm^3.
- The two soil samples stabilized using hydrated lime at optimum ratio fulfilled the standard requirements as subgrade soils.
- The finding of this study is a potential solution to improve expansive clay soil by adding the optimum lime before constructing any structure. However, further investigation is recommended on different stabilization methods to select the suitable stabilizer.

5. Declaration of Interests

The authors declare no conflict of interest or financial conflicts to disclose.

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