INVESTIGATION ON THE EFFECTS OF COMBINING LIME AND SODIUM SILICATE FOR EXPANSIVE SUBGRADE STABILIZATION

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ABSTRACT

Expansive clay is unsuitable subgrade material covering about 40% of the area of Ethiopia. Engineering properties of such problematic soils can be improved by chemical stabilization. This study investigated the effects of combining slightly alkaline liquid sodium silicate with hydrated lime for stabilization of expansive clay. The experimental study involved Particle-Size Analysis, Atterberg Limits, Standard Compaction and California Bearing Ratio tests. Expansive clay was combined with 2, 4and 6% of lime; 1, 2.5and 6% of liquid sodium silicate and the respective combinations of the two additives by dry weight of the soil. Test samples were typically soaked for 30minutesto account for strength loss due to compaction delay. Samples were cured for 3 and 7 days before testing for Atterberg Limits and California Bearing Ratio values. Additional 28 days of curing were considered for Atterberg Limits test samples. Test results manifested that sodium silicate reduced plasticity indexes by least12% compared to untreated soil. Expansive soil treated with sodium silicate or combination of lime and sodium silicate resulted in unusual compaction curves from which maximum dry densities and optimum moisture contents could not be determined. Sodium silicate and its combination with lime decreased shear strength and increased swelling properties of expansive clay compared to the respective lime series. Curing enhanced strength development and reduced swelling properties of treated soils. The study revealed that sodium silicate or its combination with lime is not a suitable means of expansive clay stabilization.

Keywords: California Bearing Ratio, Dry Density, Expansive Clay, Lime, Plasticity Index, Sodium Silicate, Soil Stabilization

INTRODUCTION

The necessity of improving the engineering properties of soils has been considered as old as construction has existed. Many of the ancient Chinese, Romans and Incas buildings and road ways utilized different techniques of soil stabilization [1]. For example, the use of lime as a building material dates back 5,000 years when lime and clay were mixed and compacted to form bricks for the construction of pyramids of Shensi in Tibet. The Romans also used lime to improve the quality of their roads 2,000 years ago [2].

The modern era of soil stabilization began in the United States during 1960’s and 1970’s [1]. Tests with lime stabilization have been carried out since the 1930's but success was achieved only ten years thereafter [2]. Conversely, non-traditional stabilization products have been in development since the 1960’s. However, the acceptance of these stabilization products is yet to be realized [3].

Expansive soil is one of the most abundant problematic soils in Ethiopia. Over the past 13 years,40% of the total road sector development expenditure in Ethiopia was allocated to rehabilitation and upgrading of trunk roads with additional 11% utilized to maintenance works alone [15]. This problem urges the need for wider application of cost effective and environmentally friendly technologies of improving soil properties, such as chemical stabilization, to be customized and adopted to the current road construction trend in the country.

The subject of stabilization is relatively well researched; studies made by post graduate students of Addis Ababa University include: Tesfaye A. (2001), Tadesse S. (2003), Nebro D. (2002), Tadege A.(2007), Agru Y. (2008), Ashuro T. (2010)[4-9]. Most of these studies focused on evaluating the suitability of additives introduced in the country for expansive sub grade stabilization. Sodium silicate is one of the safest industrial chemicals with diverse application, including soil stabilization [10]. Studies that evaluated sodium silicate as a soil stabilizer include Rauch A. et al (2003) and Abdel N. et al (2010) [11, 12].However, no research result had been reported on the suitability of sodium silicate for soil stabilization in Ethiopia.

Polymers like sodium silicate primarily stabilize soils by physical bonding. As such stabilization by polymers is less effective in fine grained soils, such as montmorillonitic (expansive) clay, due to reduced mixing efficiency resulting from high surface area of the soil [13]. Lime significantly improves engineering properties of a wide range of soils; typically medium, moderately fine and fine grained soils [14]. Studies also show applying cementitious additives with sodium silicate improved engineering properties of soils [13]. Hence, it is worth evaluating if stabilizing properties of sodium silicate on engineering properties of fine grained soils can be improved by blending sodium silicate with lime.

This study investigated the effects of applying liquid sodium silicate and hydrated lime on the engineering properties of expansive clay by using locally manufactured products. The study had specific objectives of investigating the effects of blending lime and sodium silicate on plasticity index, strength development and swelling properties of expansive clay at various curing durations. The study also examined how the duration between mixing and compaction and the mode of mixing is related to the dry densities of expansive clay treated with sodium silicate.

SOIL CHARACTERIZATION

Soil sample that represents expansive sub grade was collected from Bole Senior Secondary and Preparatory School located at Bole area $8^0 59'53''$N, $38^0 47'20''$E, Addis Ababa [16]. Grain size analysis of native soil was made according to ASTM D422-63as shown on Fig. 1. Index properties were determined according to ASTM D4318-98. Organic content of the soil was checked using liquid limit values of oven dried sample according to ASTM D 2488. Table 1 shows classification of the soil sample according to ASTM D 2487-98.

Table 1: Soil Sample Classification

Index and swelling properties					Soil classification
Clay (%)	LL (%)	PL (%)	PI (%)	Free Swell (%)	ASTM D 2487 (Unified Soil Classification System)
80.05	130*	38	92	115	Inorganic Fat clay

*LL obtained for oven dried sample is 117%

COMPOSITION OF ADDITIVES

Liquid sodium silicate used for this study was manufactured by Alied Chemicals P.L.C, Ethiopia. Total alkalinity of the chemical was determined using hydrochloric acid titration based on the OxyChem manual methods of analysis [17]. Specific gravity and pH of the chemical were measured at room temperature at the Chemical Engineering Laboratory of Addis Ababa Institute of Technology. Weight ratio and viscosity of the chemical were reported by the manufacturer and results are summarized in Table2 below.

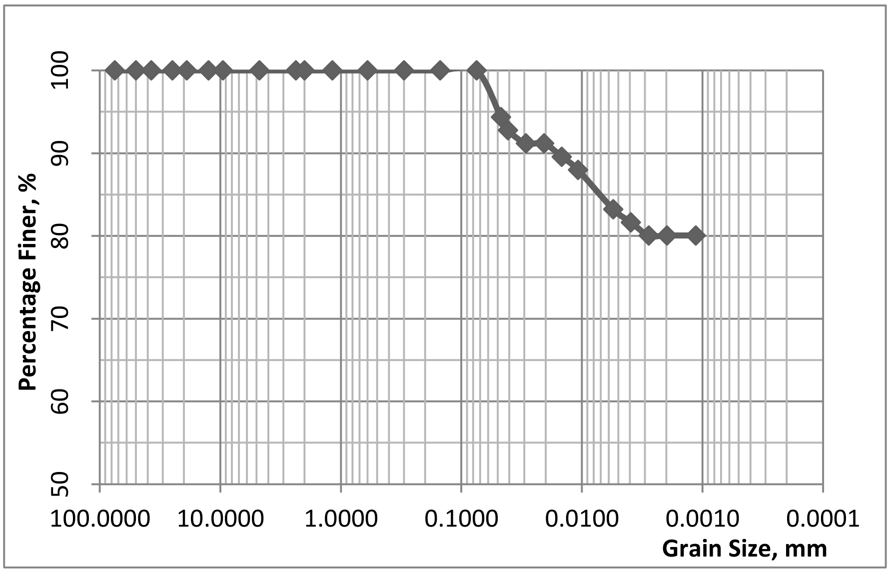

Figure 1 Grain size distribution

Table 2: Properties of liquid sodium silicate used for the study

Properties	Results
Color	Light olive green
Specific gravity	1.44
pH	12.2
Total alkalinity as sodium oxide	10.4
Viscosity	42 boome
Weight ratio	2.2

Hydrated lime used for the study was obtained from Senkele lime factory, Ethiopia. Chemical composition of Senkele hydrated lime studied by Solomon H. (2011) using X-Ray Fluorescence analysis is presented in Table3 below [18].

Table 3: Composition of hydrated lime used for the study

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

*Loss on ignition is 17.04%

SELECTION OF MIXING RATIOS

As implied on the soil classification in Table 1, the soil type used for this study is highly expansive gray clay commonly known as “black cotton” soil. Such montmorillonitic soils are best stabilized using lime [14]. For this study, series of control and test samples were prepared by treating the soil with no additive, with lime, with sodium silicate and combination of lime and sodium silicate at various curing durations.

Sodium silicate was added to the soil at mixing ratios of 1, 2.5and 6% by dry weight of the soil according to 1 to 4% mixing ratio recommendation of the PQ manual [19].Maximum mixing ratio was taken as 6% by dry weight of the soil. The minimum mixing ratio was limited to 1%by dry weight of the soil based on the findings of Rauch A. et al (2003) that such smaller ratios do not result in improvements in the engineering properties of the soil [11].

The optimum amount of lime (the lowest percentage of lime that results in a soil-lime pH of 12.4) added to expansive clay was estimated using pH test according to ASTM D 6276. As illustrated in Fig. 2, the optimum amount of lime was 6% by dry weight of the soil. The proportion of lime combined with the soil was taken as6, 4 and 2% by dry weight of the soil. Series of mix ratios considered and their sample designations are presented in Table 4 below.

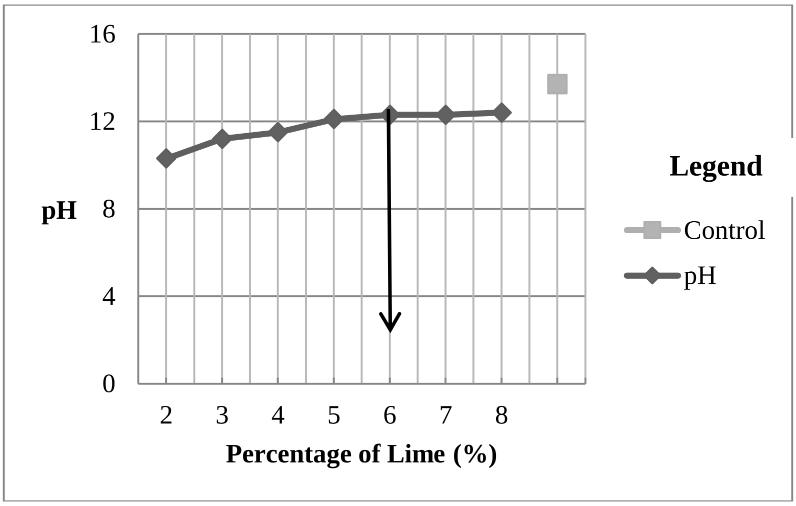

Figure 2 pH test results

Table 4: Mixing ratios and sample designations

Mix no.	Hydrated Lime (%)	Sodium Silicate (%)	Designation of Samples
1	-	-	0%
2	2	-	L2
3	4	-	L4
4	6	-	L6
5	-	1	SS1
6	-	2.5	SS2.5
7	-	6	SS6
8	2	1	L2SS1
9	2	2.5	L2SS2.5
10	2	6	L2SS6
11	4	1	L4SS1
12	4	2.5	L4SS2.5
13	4	6	L4SS6
14	6	1	L6SS1
15	6	2.5	L6SS2.5
16	6	6	L6SS6

MIXING PROCEDURE

Additives were mixed with the soil in such a way that the additive was first added to the pulverized, sieved and air dried soil sample and dry mixed thoroughly. When lime and sodium silicate were applied in combination, the soil sample was dry mixed with lime first and sodium silicate was added thereafter. Finally, wet mixing was done by sprinkling measured amount of water followed by a through mixing until a uniform soil-additive matrix was obtained.

LABORATORY TESTS AND CONSIDERATIONS

I. ATTERBERG LIMIT TEST

Atterberg limits were determined according to ASTM D 4318 on particles passing No. 40 sieve after samples were cured for 0, 3, 7 and 28 days. It was observed that it became increasingly difficult to run the tests at reduced curing durations, especially for lime treated samples. This can be attributed to relatively increased reduction in Plasticity Index (PI) as a result of lower risk of PI revere due to possible carbonation reaction.

II. STANDARD COMPACTION TEST

Moisture-density relationships were determined using standard compaction test according to ASTM D 629. Loss of strength due to compaction delay for this research was accounted for by soaking treated samples typically for 30minutes before compaction according to the recommendations of Geiman, C. et al (2005) [20].

To study how mellowing time (time between mixing and compaction) is related to dry density of expansive clay treated with sodium silicate, compaction tests were made after 30 minutes, 6hours and 24 hours of soaking. Keeping the rest of the parameters constant, mixing ratios of 1, 2.5 and 6% of sodium silicate by dry weight of the soil and moisture content obtained at the third trial of the respective standard compaction test results were considered for the test.

Attempt has also been made to study the effect of mixing mode on dry density of expansive clay treated with sodium silicate. Keeping the rest of the parameters constant, the first set of samples were compacted after dry mixing the soil with the chemical first and adding compaction water afterwards. The second set of samples were compacted by diluting the same amount of chemical with the same amount of water first and applying it to the soil. Mixing ratio of 2.5% and moisture content obtained at the third trial of the standard compaction test results were randomly chosen for the trial.

III. CALIFORNIA BEARING RATIO TEST

Addis Ababa City Roads Authority pavement design manual (2004) specifies subgrade materials with CBR values less than 3% and swelling potential greater than2% need to be treated with stabilizing agents or replaced. The manual also recommends subgrade material which has been stabilized should not be assigned a CBR value of more than 15% for design purposes. [21]

Gautrans manual (2004) states CBR is not suitable for testing cementitious stabilization due to possible under or over estimation of strength values as a result of water infiltration caused by the soaking process [2]. For this study the use of CBR for testing strength parameters was justified for the following reasons;

- Strength assessment of this study involved evaluating sodium silicate as sub grade soil stabilizer in addition to lime. But unlike lime, there is no formal standard specification (e.g. ASTM or AASHTO) for non-traditional stabilizers such as sodium silicate [3]. Therefore, CBR test is used as a consistent comparison mechanism.

- CBR measures shear strength at worst field conditions, simulated through 96 hours of soaking. Sodium silicate which does not precipitate or involve in cementitious reactions has a tendency to dissolve in water. CBR test, therefore, is used as assessment of durability to certain extent in this study answering how strength of sodium silicate treated expansive clay is affected by the presence of extra moisture.

However, compaction curves of expansive clay treated with sodium silicate or its combination with lime resulted in curves from which a definite optimum moisture content or maximum dry density could not be determined from. Such unusual compaction curves according to Lee and Suedkamp (1972) are also known as odd curves [22]. CBR samples for this study were prepared using moisture content obtained at the third trial of the compaction test results on soil passing No. 4 sieve. Curing duration of 0, 3 and 7 days were considered before testing.

No surcharge loads have been applied to compacted CBR samples over curing durations assuming minimal traffic flow during construction. After the allocated curing period is completed, the samples were soaked in a water tab for 96 hours. CBR penetrations were made with a surcharge load of approximately 4.5 kg according to ASTM recommendations.

IV. SAMPLE CURING

Applying impervious plastic to soak and/or cover the samples (covering with impermeable sheeting) was the curing technique used for the study. Atterberg limit test samples were cured for 3, 7 and 28 days while CBR samples were cured for 0, 3 and 7 days.

LABORATORY TEST RESULTS AND DISCUSSION

I. PROPERTIES OF SODIUM SILICATE

As discussed in composition of additives earlier, the liquid sodium silicate used for this study has apH of 12.2 and weight ratio of 2.2 which complies with the theoretical range. From these values of pH and weight ratio, it is also possible to infer that the sodium silicate used for the study is slightly alkaline [19].

II. ATTERBERG LIMITS

Plasticity indexes (PI) of expansive clay treated with lime, sodium silicate and combination of lime and sodium silicate over various curing durations are presented in Figs. 3, 4, 5 and 6 below.

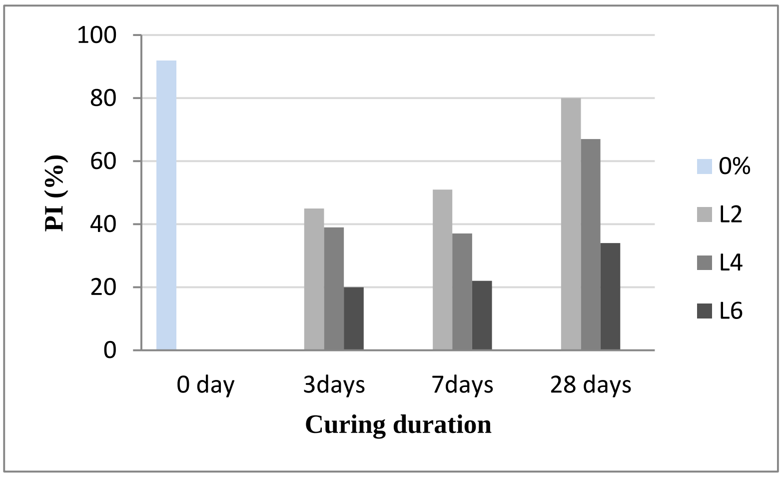

Figure 3 PI values of expansive clay treated with lime

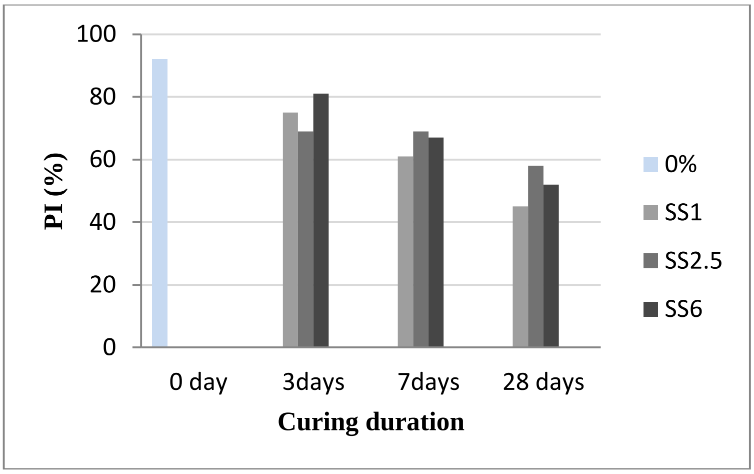

Figure 4 PI values of expansive clay treated with sodium silicate

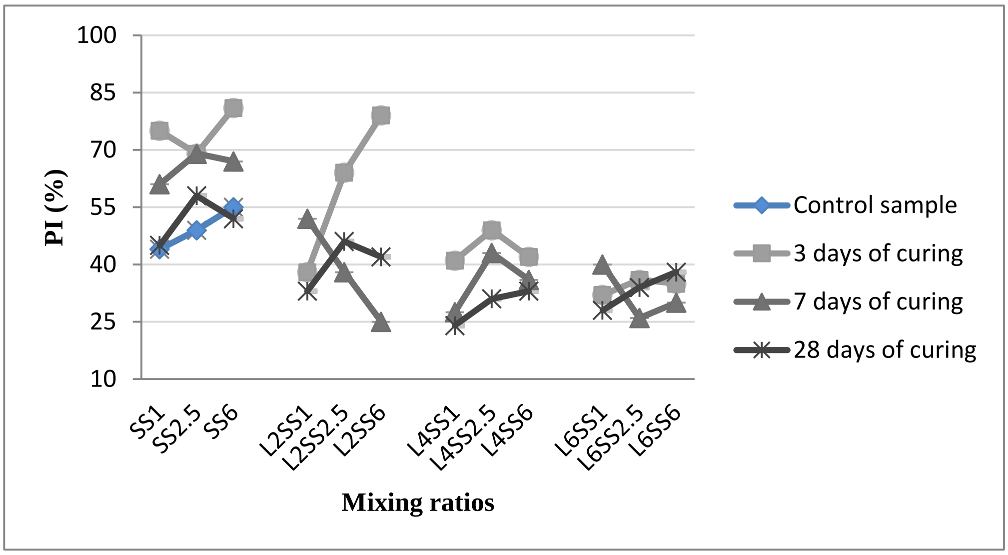

Figure 5 PI values of expansive clay treated with lime and sodium silicate

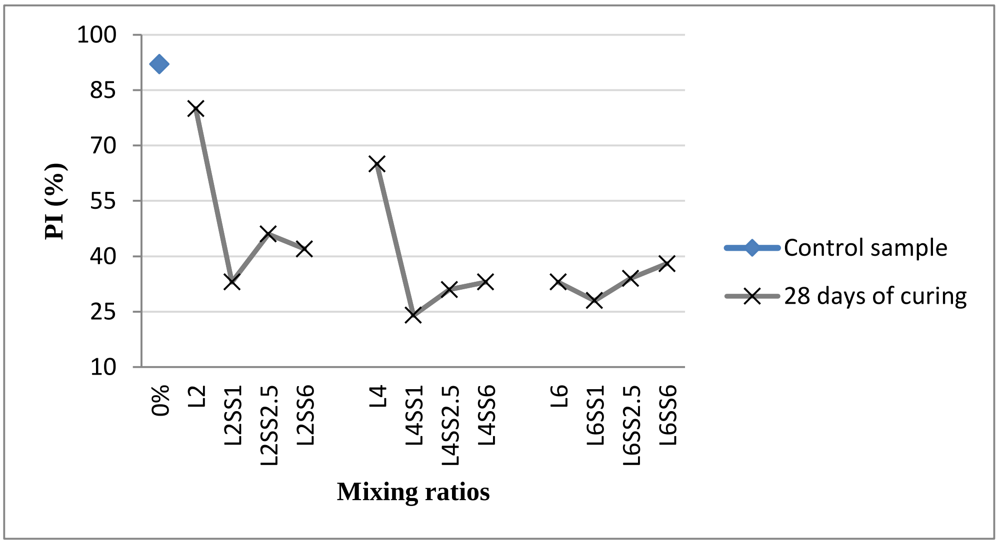

Figure 6 Significant reduction of PI values at 1% Sodium Silicate and Lime

A) Expansive Clay treated with Lime

The highest reduction in PI was observed for 6% lime treatment cured for 3 days with 78.26% reduction in PI compared to native soil. Increased reduction in PI associated with increased amount of lime is expected as more calcium is available for action exchange to take place. However, this reduction of PI decreased with increasing curing durations.

Gautrans stabilization manual (2004) states plasticity of stabilized materials should not increase after it has been effectively treated with lime. The manual further states if improvement of plasticity in cementitious stabilizers is reversed, it can be attributed to one or more of the following factors;

- Insufficient stabilizer added to the material
- Poor mixing of the stabilizer with the material
- Destruction of the stabilizer, such as premature wetting/drying, before it reacted with all the clay particles in the material
- Stabilizer or soil types that form clods, the stabilizer reacted only with the outer surface of clay lumps [2].

Accordingly, the reverse of improvements in PI, shown in Fig. 3 above, can possibly be attributed to carbonation reaction aggravated by premature wetting of samples during soaking. The reverse of PI was also magnified for smaller quantities of lime verifying that stabilizing effects of lime decreases with its quantity.

B) Expansive Clay treated with Sodium Silicate

Sodium silicate reduced the PI of soils compared to native soil for all quantities considered, with a minimum of 11.96% reduction in PI for 6% sodium silicate cured for 3 days. Results also show that there is a general reduction of PI values associated with increased curing durations. This decrease in PI might be attributed to stronger film formation of sodium silicate due to further dehydration reactions. However, results are inconsistent in showing how the quantity of sodium silicate added to expansive clay relates to the reduction in PI.

C) Expansive Clay treated with Lime and Sodium Silicate

Combinations of lime and sodium silicate reduced PI by at least 11.95% for expansive clay treated with 2% lime and 6% sodium silicate, cured for 3 days. Maximum reduction of 52.17% compared to untreated soil was obtained for soil treated with 4% lime and 1% sodium silicate cured for 28 days. These values are comparable to improvements gained by applying sodium silicate alone. Reduction in PI when lime and sodium silicate are applied together can be resulted from metal ion reactions between deploymerized silicate and lime in addition to lime-clay ion-exchange reactions. The result, however, is inconsistent in showing how curing durations or quantities of sodium silicate and its combination with lime relate to the reduction in plasticity. This inconsistency of results can be attributed to the differences in stabilizing mechanisms of the two additives. That is lime causes flocculation while sodium silicate just does the opposite by making montmorillonite particles repel one another.

Results depicted in Fig. 6 also show adding 1% sodium silicate in combination with lime yielded encouraging results in reducing the reverse of PI possibly due to carbonation reaction. However, further investigations are necessary to explain this finding and implement results.

III. MOISTURE-DENSITY RELATIONSHIPS

Native soil and expansive soil treated with lime yielded the typical bell shaped compaction curves with the highest density being 1.27g/cm^3 for 0% additive. However, expansive clay treated with sodium silicate or its series of combinations with lime yielded compaction curves in Figure 7.

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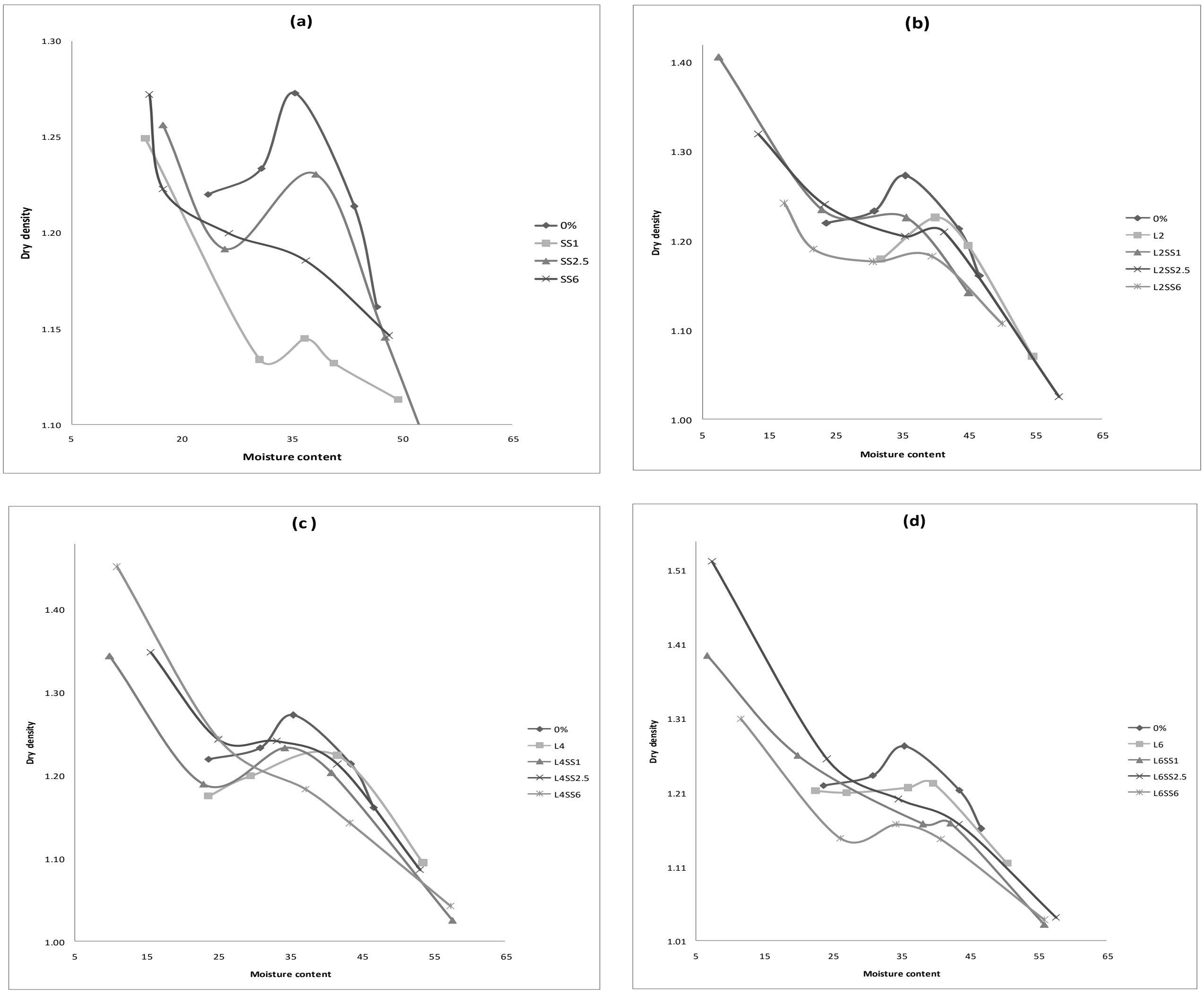

Figure 7 Compaction Curves

(a) Sodium silicate series (b) 2% lime and sodium silicate series

(c) 4% lime and sodium silicate series (d) 6% lime and sodium silicate series

The highest dry density is obtained at the direst side of the compaction curves for expansive clay treated with sodium silicate due to surface charge modification effect of liquid sodium silicate. That is clay particles dispersed as a result of extra negative charge made available by the depolymerization of silicate. Dispersed particles are compressed easily resulting in increased dry density [23]. However, chemical alteration of clay layers is not expected according to the studies of Alen F. et al (2003) [11].

On the other hand the decrease in dry density associated with increasing moisture content shows the surface charge modification effect of the sodium silicate which decreases with the addition of water. Therefore, for montmorillonitic clay, it can be expected that stabilization mechanism of sodium silicate by agglomerating soil particles proposed by Alen F. et al (2003) and (Jeb S., 2007) is put to its best use at the driest side of compaction [11, 13]. That is, with addition of more water, silicate dissolves losing its sticking power in addition to decreased surface modification effects explained above. The "pick" points that are sometimes obtained in the odd curves can be attributed to the normal bell shaped compaction curves of clay overlapping with the deflocculation phenomenon.

A) Effect of Time Variation

For standard compaction tests conducted to study the effect of time variation on dry density of expansive clay soil treated with sodium silicate, results show there can be a relationship between soaking time and dry density. As shown in Fig. 8, for all quantities of sodium silicate considered, the highest dry density was obtained for compaction tests made after 6hours of soaking.

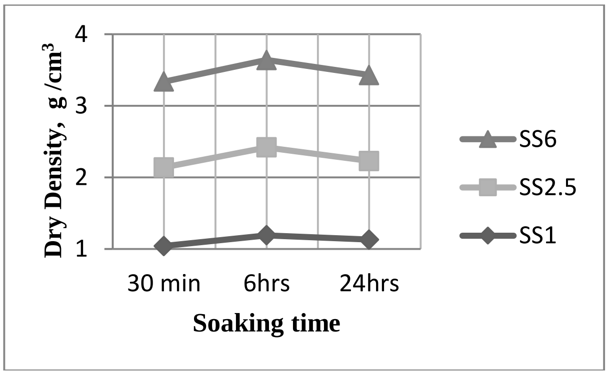

Figure 8 Effects of time variation

B) Effect of Mixing Mode

For tests done by varying the mode of mixing, results summarized in Table 5 show mode of mixing did not bring change on the maximum dry density of the expansive clay treated with sodium silicate. This finding is also in harmony with the conceptual background [18]. However, it should be noted these results apply for thorough and uniform mixing.

Table 5: Effect of mixing mode on maximum dry density

Mode of mixing		Dry density, g/cm^3		
		Trial 1	Trial 2	Trial 3
1	Wet mixing*	1.20	1.16	1.17
2	Dry mixing**	1.21	1.15	1.19

* Wet mixing refers to applying diluted chemical with measured amount of water for compaction.

** Dry mixing refers to blending sodium silicate with soil first and applying water of compaction afterwards.

IV. CBR TEST

A) CBR Values

Expansive clay treated with sodium silicate using the third moisture content of the compaction test result did not show any improvement in strength compared to untreated soil sample. CBR values decreased as the quantity of sodium silicate was increased. Results summarized in Figure 9 show that curing enhances strength development. For example, comparing 7 days of curing versus 3 days of curing for 1, 2.5 and 6% sodium silicate; there are 14.63, 33.33 and 22.86% increase in strength. However, the data is inconsistent in showing how the quantity of lime and sodium silicate relates to strength development.

Soil treated with 2% lime and cured for 7 days fulfilled the strength requirements of a sub grade, but since the quantity of lime is low, this result may not necessarily imply long term stabilizing effects. CBR values of 22.85%, obtained for expansive clay treated with 4% lime, can effectively be used as a sub grade material. Expansive clay treated with 6% lime yielded CBR of 42.19% which is 180% greater than the minimum CBR value requirement for sub grade design.

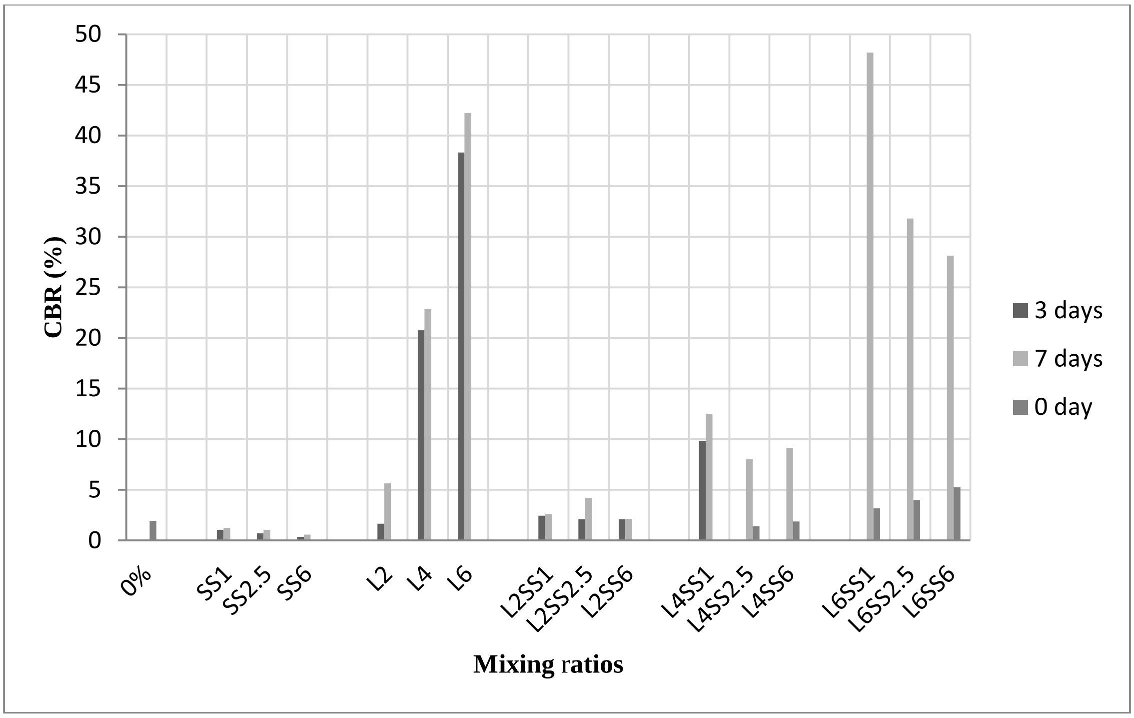

Figure 9 CBR values of expansive clay

B) CBR Swell Values

Sodium silicate increased CBR swell values compred to untreated or lime treated soil. The largest CBR swell value was obtained for 6% sodium silicate and its value is 59.67% larger than untreated sample. As shown in Figure 10, curing reduced swelling potential of sodium silicate treated soil. CBR swell of 1% sodium silicate showed the largest improvement in swelling potential with 7 day cured sample having 31.44% less CBR swell value compared to samples cured for 3 days. Curing samples treated with 2.5% and 6% of sodium silicate and cured for 7 days showed 22.66% and 11.77% reduction in CBR swell compared to samples cured for 3 days.

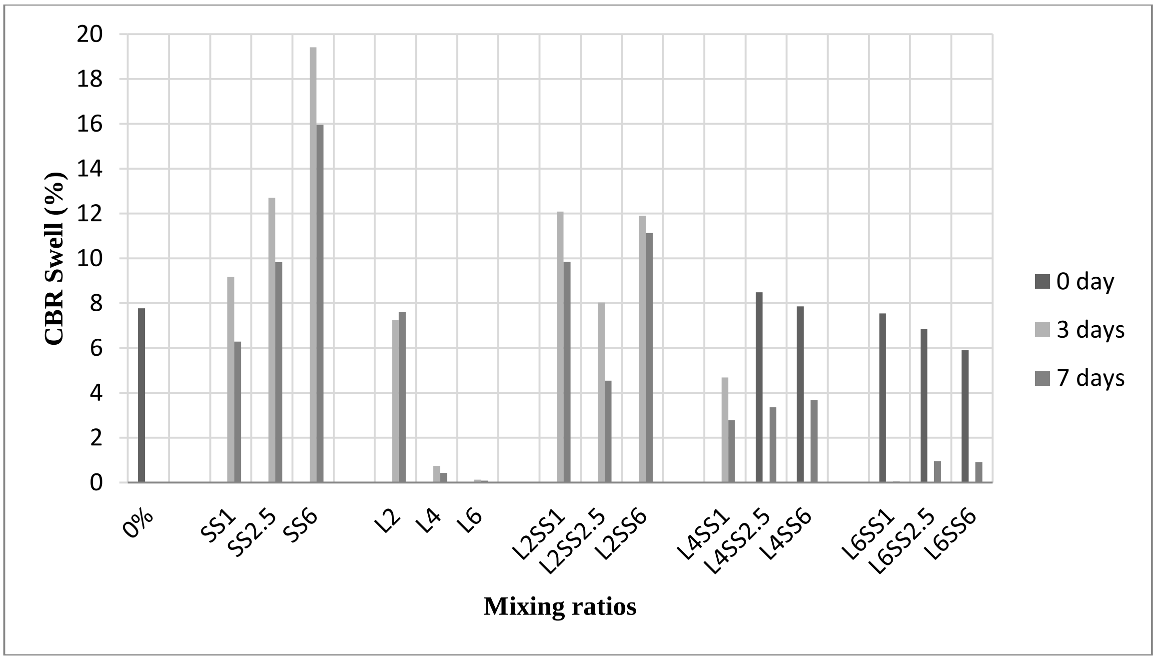

Figure 10 CBR swell values

The CBR values of expansive clay treated with sodium silicate showed significant increase in swell values opposed to the improvements in swelling properties reported by Abdel N. et al (2010) on silty clay sample [12]. This can be attributed to the difference in the type of clay used for this experiment and the later. Findings of this study revealed that sodium silicate is not a suitable additive to stabilize expansive (montmorillonitic) clays.

Expansive clay treated with sodium silicate showed more swelling compared to untreated sample. This swelling value also increased with increasing the quantity of sodium silicate. Expansive clay treated with combination with lime and sodium silicate also showed more swelling than expansive clay treated with lime alone.

Expansive clay is venerable to swelling due to dispersion of its mineral sheets of weak bonds being set apart by water. Surface charge modification property of liquid sodium silicate aggravates this dispersion, therefore, the swelling property of expansive clays. This is demonstrated by the increased swell values that are observed with the increase in the amount of sodium silicate added to the soil.

EFFECTS OF CURING

In general, curing yielded increased strength and reduced swelling values for all the additives considered including sodium silicate. Strength values increased as the curing durations were lengthened. However, specific techniques of curing used might have implications on the results.

CONCLUSIONS

The following are the main conclusions drawn from this study;

1) Sodium silicate resulted in at least 12% reduction in PI of native soil, which led to the belief that sodium silicate decreases plasticity of expansive clay. However, sodium silicate decreased shear strength and increased swelling properties of expansive clay.

2) Compaction curves of expansive clay treated with sodium silicate or combination of lime and sodium silicate resulted in unusual compaction curves from which an optimum moisture content or maximum dry density could not be determined.

3) Combination of lime and sodium silicate resulted in decreased shear strength and aggravated swelling properties of expansive clay compared to the respective lime treatments. Treating expansive clay with lime improves (reduces) PI of expansive clay; however, this improvement can be reversed possibly due to carbonation reaction.

4) Curing enhances strength and reduces swelling properties of expansive soil treated with lime, sodium silicate or combination of the two. Proper curing is mandatory for strength development of lime stabilization.

5) Varying the mode of mixing, that is applying diluted chemical or adding the chemical first and compaction water afterwards, does not bring a change in dry density of expansive clay treated with sodium silicate.

6) Neither sodium silicate nor applying sodium silicate in combination with lime is a suitable means of expansive (montmorillonitic) clay stabilization.

The following topics are recommended for further study:

- Effects of sodium silicate in reducing carbonation reaction in lime treated soils
- Evaluation of sodium silicate for stabilization of lateritic soils in Ethiopia

ACKNOWLEDGEMENTS

Many thanks to Highway, Geotechnical and Chemical Engineering Laboratories of Addis Ababa Institute of Technology. Special thanks to Janice Hamilton from PQ Corporation for sharing useful references on sodium silicate. Special thanks to Allied Chemicals Plc. for sponsoring sodium silicate and Bole Secondary and Preparatory School for offering the soil sample used for the study.

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