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Effectiveness of Two-Stage Stabilization for Improvement of Geotechnical Properties of Expansive Soils

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Abstract: *The effectiveness of two-Stage mixing operation of stabilization of expansive soils by firstly treating the soil with lime, leaving it to mellow and then treating it with cement is investigated in this study through laboratory experiments. The initial lime consumption (ICL) or lime fixation point (Lm) of the soil that refers to the amount of lime required for early cation exchange and flocculation reactions, and still providing sufficient amount of free calcium and high residual pH necessary to initiate long-term pozzolanic reaction, was determined to be 3.5%. Therefore, 4%, 6%, 8% and 10% of lime (by weight) was added to the soil and cured for 7, 14 and 28 days after which laboratory experiments were conducted. Cement contents of 2%, 4% and 6% were used on lime-modified soil samples. The tests included mineralogical and chemical analyses, classification tests, determination of ICL, swelling potential, swell pressure, unconfined compressive strength, compaction, California Bearing Ratio, CU triaxial compression and consolidation tests. Lime modification improved the texture and workability of the initially highly plastic expansive soil to a non-expansive material that is suitable for geotechnical works. At 4% lime content, the swell potential of the soil reduced significantly from 19.2% to 0.23% and swell pressure from 560 kPa to 0 kPa after 7 days. In 28 days curing period CBR increased from 17% to 71% and UCS from 109 kPa to 462 kPa and 2.65 MPa for 4% and 10% lime contents, respectively. Treatment with 6% lime increased the internal angle of friction from 14° to 32° and cohesion from 17 kPa to 300 kPa. Addition of 4%-6% cement to lime-modified soil increased the UCS to values between 2 MPa and 3 MPa in 7 to 28 days curing period. The study has therefore indicated that lime and lime-cement stabilization can greatly improve engineering properties of expansive soils, where two-stage stabilization produces much better effects than lime stabilization alone.*

Keywords: *Two-stage stabilization, expansive soil, smectite, montmorrilonite, mellowing, swell potential, swell pressure, lime modification, workability*

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I. INTRODUCTION

Improper treatment of the expansive soils present in the Kibaha-Chalinze belt, Coast Region, has caused widespread structural defects, mainly in form of cracks in the buildings and pavements constructed in this area ([17]). This is mainly attributed to the localized internal stresses and non-uniform movements caused by swelling and/or shrinking of the expansive soils when they absorb water or dry up, respectively. Soil stabilization using lime, cement or a combination of lime and cement is the common type of treatment used to improve the geotechnical properties of such soils, ([1], [2], [6], [13], [14], [20] and [21]). While lime-stabilization normally modifies the soil without generating sufficient compressive strength in a reasonably practicable period of time, cement stabilization needs pre-treatment with lime to reduce the plasticity of the soil and improve its workability before cement is added; i.e. 'two-stage' stabilisation ([18]). The two-stage stabilization technique had previously not been studied and well documented for the expansive soils in the Kibaha-Chalinze belt. A laboratory study has, therefore, been carried out to investigate the potential and effectiveness of soil stabilization for improvement of the geotechnical properties of the expansive soils of Kibaha.

Geotechnical properties that can be improved by soil stabilization include reduction of soil plasticity, increase of workability, increase of volume stability, improvement of soil compactability, increase of strength and stiffness and increase of imperviousness ([3], [5], [7] and [23]). Effectiveness of soil stabilization depends on many factors, including the type, composition and texture of soil, composition and reaction of the pore water, type, texture and quantity of stabilizing agent, and mixing and curing conditions and duration ([4], [7], [16], [19] and [22]). Correct characterization of both candidate soil and stabilizing agent is therefore important for design and implementation of a stabilization scheme ([10] and [12].

Lime is commonly used for improving the shrink/swell characteristics of expansive soils because they contain clay minerals which possess pozzolanic properties, i.e. silica and alumina compounds which react with lime to produce cementitious materials, namely calcium-silicate-hydrates (C-S-H) and calcium-aluminate-hydrates (C-A-H), similar to the products of the hydration of Portland cement. However, since these pozzolanic reactions are highly time- and temperature-dependent, the strength development is normally slow and continuous for a long period of time. Therefore, cement is normally added to a lime-modified soil to increase the rate of strength development; the process which is known as two-stage stabilization.

II. CHARACTERIZATION OF EXPANSIVE CLAY FROM KIBAHA

A *Study Area*

The area chosen for study was the clayey belt within the coastal belt where plastic clay soil is predominant. In the study area, cracks in concrete block and brick work buildings as well as asphalt concrete pavement on the Dar es Salaam – Morogoro highway are very common and give an impression of presence of expansive soils. Some distinct structures have developed horizontal movement and step cracks in Concrete Block/Brick Foundation as shown in Fig. 1. Such cracks are mainly caused by internal forces developed in the supporting soils during cyclic swelling and shrinkage.

Figure 1: Cracks in buildings caused by expansive soil at Tumbi, Kibaha

B *Source and Classificasion of the Sample*

Soil samples were collected from Tumbi Catholic Church area at Kibaha, Coast Region. Both undisturbed samples (using a 100 mm diameter core cutter) and disturbed bulk samples were recovered from a depth of 1.3 m to 1.5 m below the ground level in a 3.5 m deep test pit. The stratum of the sampled expansive soil extends from a depth of about 1 m to 2 m below the ground level, over- and underlain by less expansive clayey soils of intermediate plasticity.

The results of the granulometric analysis indicate that the sampled soil is constitued of 29% clay fraction (< 2 μm), 11% silt fraction (2-63 μm), 55% sand fraction (0.063-2.0 mm) and 5% gravel fraction (2.0-63 mm). The soil had a natural moisture content of 11.1%, liquid limit (LL) of 60.2% and plastic limit (PL) of 23.5%, resulting in the plasticity index (PI) of 36.7%, liquidity index (I_L) of -0.34, consistency index (I_C) of 1.34 and clay activity (A) of 1.27. The soil was therefore classified as a very stiff active clayey SAND of high plasticity (SCH). The activity of the clay fraction suggests a presense of potassium montmorillonite, subordinated with sodium montmorillonite (A = 7) and calcium montmorillonite (A = 1.5). The high plasticity index (PI>35%) indicates presense of clay of very high swelling potential ([11])

C *Chemical and Mineralogical Analysis*

Chemical and mineralogical analyses were carried out at the African Minerals and Geosciences Centre (AMGC) laboratories. Analysis of the major elements was done by the XRF method, whereas the XRD method was used for mineralogical analysis ([8] and [15]). The results show that the Kibaha expansive soil is mainly composed of quartz subordinated with magnetite and feldspar (albite) [Fig. 2], whereas the clay fraction of the sample is mainly composed of smectite (montmorillonite), subordinated with kaolinite minerals [Fig. 3]. The major elements analysis gives a composition of about 55% silica (SiO_2), 18% aluminate (Al_2O_3), 7% ferric oxide (Fe_2O_3), 3% lime (CaO), 2% magnesium oxide (MgO), 1% each of potassium, sodium and titanium oxides, 0.4% sulphate (SO_3), 0.2% chloride (Cl) and 11.3% loss on ignition (LOI)

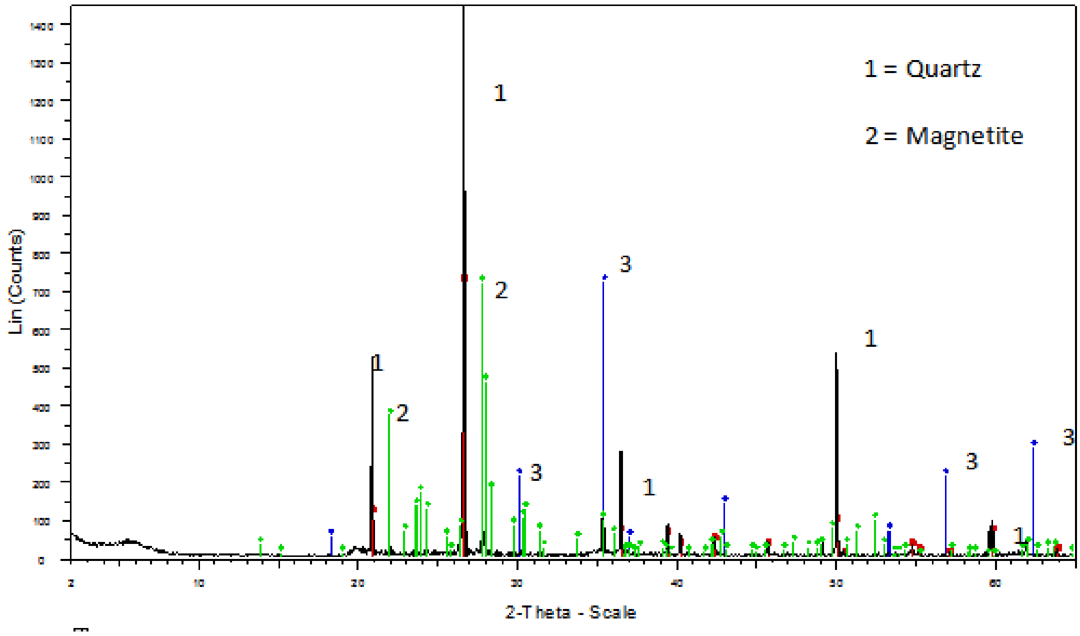

Fig. 2: Mineralogical analysis of Kibaha expansive soil (by XRD)

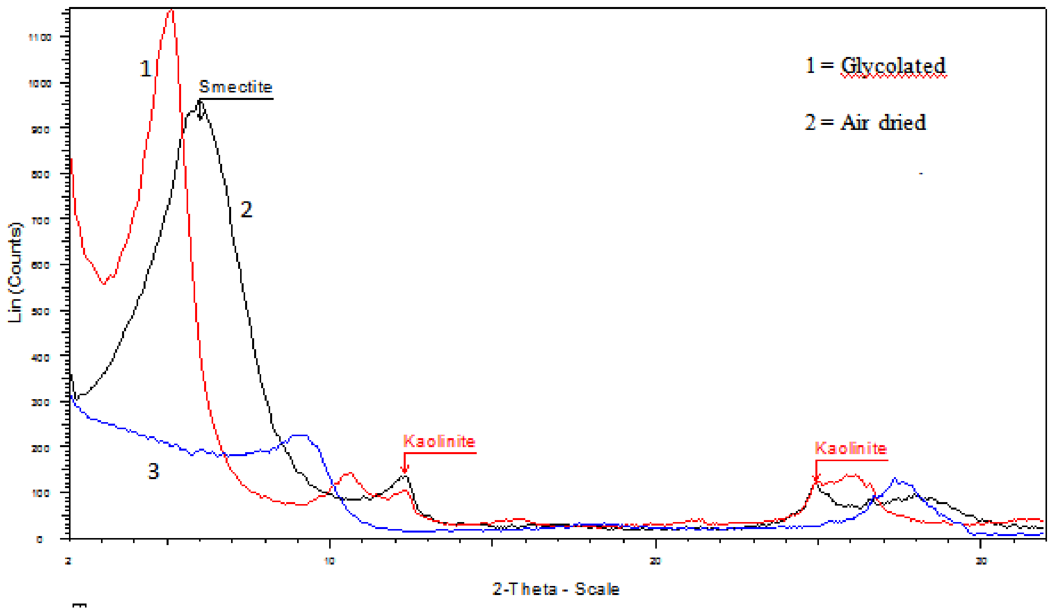

Fig. 3: Mineralogical analysis of the clay fraction (by XRD)

D Geomechanical Parameters

The determined geo-mechanical parameters of the research soil are summarized in Table 1. As an example, the swell pressure of 560 kPa indicates that the tested clayey soil has a very high swell-ability in its natural state.

Table 1: Geomechanical parameters of Kibaha expansive soil

Bulk density	Dry density	Density of solids	Swell potential	Swell pressure	Compaction (Heavy Proctor)		CBR		UCS	Triaxial test (CU)		Consolidation (Oedometer)		
ρ	ρ_d	ρ_s	S	P_s	MDD	OMC	Soaked	Unsoaked	q_f	Φ	c	E_s	E_{sr}	C_c
	kg/m^3		%	kPa	kg/m^3	%	%	%	kN/m^2	°	kN/m^2		MN/m^2	
2120	1910	2650	19.2	560	1944	11.7	18	17	106	14	17	10.3	11.7	0.04

III. LABORATORY TEST RESULTS ON STABILIZED SAMPLES

A Samples and Test Types

Hydrated lime and Ordinary Portland Cement were used to stabilize samples of the expansive soil from Kibaha. The initial consumption of lime (ICL) of the soil was determined to be 3.5% and mellowing period to be 4 hours. Thus, 4%, 6%, 8% and 10% of lime by weight of dry soil was added to the soil and cured for 7, 14 and 28 days after which laboratory experiments were conducted. For the 4% lime- and 6% lime- treated samples curing was extended to include tests after 56 and 90 days. Also, to lime-modified soil samples cement was added for cement contents of 2%, 4% and 6%, cured and subjected to the same laboratory tests as for lime-stabilized samples. The tests included PSD and plasticity tests, swell potential, swelling pressure, unconfined compressive strength, compaction, California Bearing Ratio (CBR) and CU triaxial compression tests. The results of these tests are discussed in the following sub-sections.

B Characterization of Lime-treated Samples

Modification of the expansive soil (by treatment with 4% lime) reduced the plasticity index from 36.7% to 5.9% and clay fraction from 29% to 4% (activity from 1.27 to 1.48) within the mellowing period of 4 hours. For the lime contents of 6%, 8% and 10% the plasticity index was also reduced to 7.9%, 9.5% and 8.5%, respectively, and clay fraction to 4% for all lime mix proportions. Lime-treatment, therefore, changed the soil from an active, highly plastic clayey SAND (SCH) to a silty SAND of intermediate plasticity (SMI) and normal activity within a period of 4 hours only. From 7 days onwards, the treated soil was found to be non-plastic gravelly SAND (Fig. 4 and 5). This suggests that lime modification can improve the workability and particle size distribution of an expansive plastic soil to a material that is more suitable for geotechnical works. With 4% lime content, the swell potential of the soil reduced significantly from 19.2% to 0.23% and swell pressure from 560 kPa to 0 kPa in a curing period of 7 days.

C Compaction Characteristics and CBR Values

Compaction characteristics, using the BS Heavy test procedures ([9]), and CBR strength values of lime-modified soil (4% lime) were determined for unsoaked fresh sample (after 4 hours mellowing period) as well as for soaked sample (96 hours soaking). The results, including those of the native soil for comparison purposes, are summarised in Table 2.

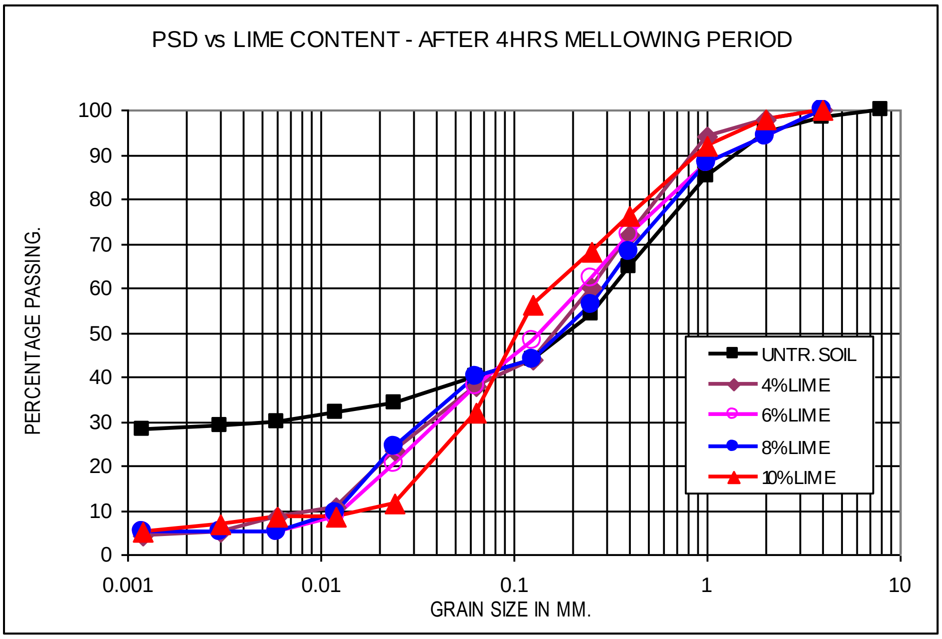

Fig. 4: Effect of lime content on PSD of lime-modified clayey SAND

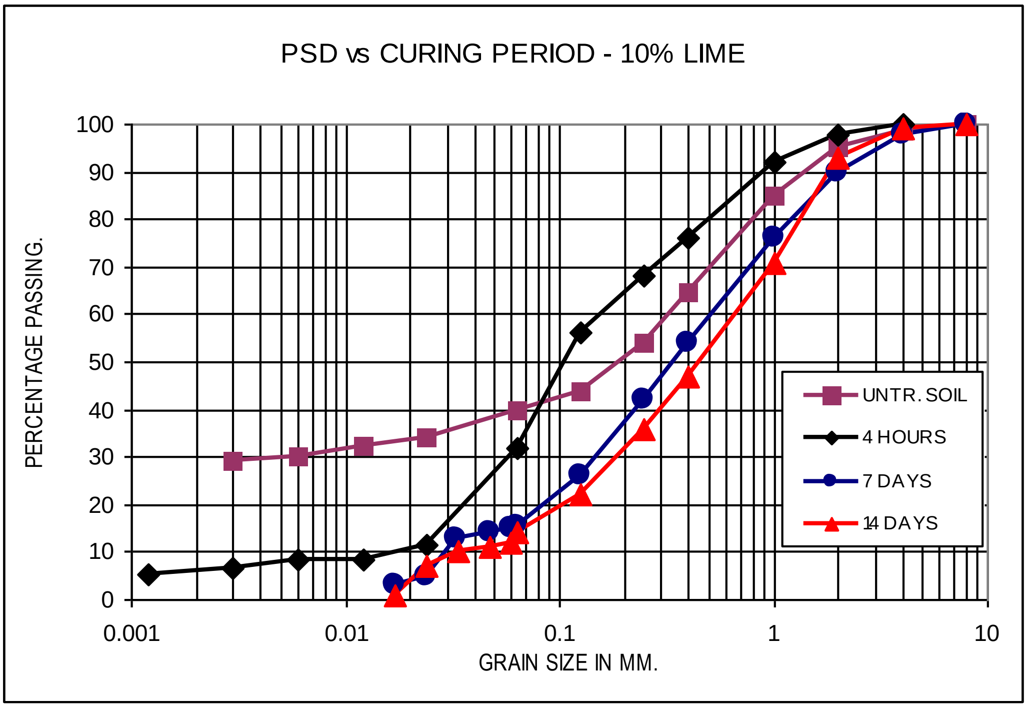

Fig. 5: Effect of curing time on PSD of lime-treated clayey SAND for 10% lime content

Table 2: Compaction and CBR parameters

Test	Proctor (BS Heavy)		CBR/SWELL			
	MDD	OMC	Fresh sample		Soaked (96 hrs)	
Sample	[kg/m^3]	[%]	CBR (%)	Swell (%)	CBR (%)	Swell (%)
Soil (untreated)	1944	11.7	17	19.2	18	19.2
4%-modified soil	1825	11.5	39	8.6	71	0.23

The results in Table 2 reveal a 129% (from 17% to 39%) increase of the CBR value of the soil when mixed with 4% lime and allowed to mellow for 4 hours. After 4 days (96 hours) the soaked CBR increases by 294% (from 38% to 71%) and the swell potential decreases from 19.2% to 0.23%. Lime-treatment, therefore, substantially improves the strength and volume stability of the expansive soil.

D Unconfined Compressive Strength

The unconfined compressive test was carried out on samples of various lime-, cement- and lime and cement mix proportions. The results are summarised in Table 3 and Fig. 6 and 7. The Unconfined Compressive Strength (UCS) increased considerably with increase in lime content and curing period. In 28 days curing period, USC increased from 106 kPa of untreated soil to 462 kPa and 2.65 MPa for 4% and 10% lime contents respectively (Fig. 6 a & b). Two-stage stabilized soil with 4% lime and 2% cement increased the UCS to 1.05 MPa, 1.32 MPa and 1.55 MPa in 7, 14 and 28 days curing periods, respectively (Table 3 and Fig. 7a), whereas 4% lime-and-6% cement resulted in the UCS of 2.25 MPa, 2.43 MPa and 2.51 MPa in the same curing periods (Table 3). Higher percentages of lime and cement produced higher UCS values, up to 3.0 MPa in 28 curing days. Therefore lime-cement stabilization produces CM, C1 and C2 materials in 28 days of curing. Fig. 7(b) reveals that the two-stage stabilized samples develope higher UCS than both lime-stabilized and cement-stabilized samples for all tested curing periods. This may be explained by the fact that addition of cement to a lime-modified sample increases the rate and extent of strength development, whereas cement treatment of unmodified soil generates lower strength due to poor workability of the plastic soil that results into a non-uniform material and formation of chunks.

Table 3: Unconfined compressive strength for different mixtures and curing periods

Curing period	UCS (kN/m^2)																
Mix type	Soil	4%L	6%L	8%L	10%L	2%C	4%C	6%C	4%L+ 2%C	4%L+ 4%C	4%L+ 6%C	6%L + 2%C	6%L + 4%C	6%L+ 6%C	8%L + 2%C	8%L + 4%C	8%L + 6%C
4 Hrs Mellow	106	244	319	234	237	-	-	-	-	-	-	-	-	-	-	-	-
7 Days	106	237	351	1560	790	405	868	786	1048	1540	2252	1640	1280	1842	1048	1739	2117
14 Days	106	253	387	1800	2034	485	990	1090	1320	1900	2426	1713	1840	1854	1530	2190	2320
28 Days	106	462	515	2136	2650	570*	1150*	1360*	1550	2210	2514	1858	2400	2292	1880	2216	2983
56 Days	106	454	531	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90 Days	106	652	585	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* Cement-treated samples were crushed after curing for 35 days instead of 28 days

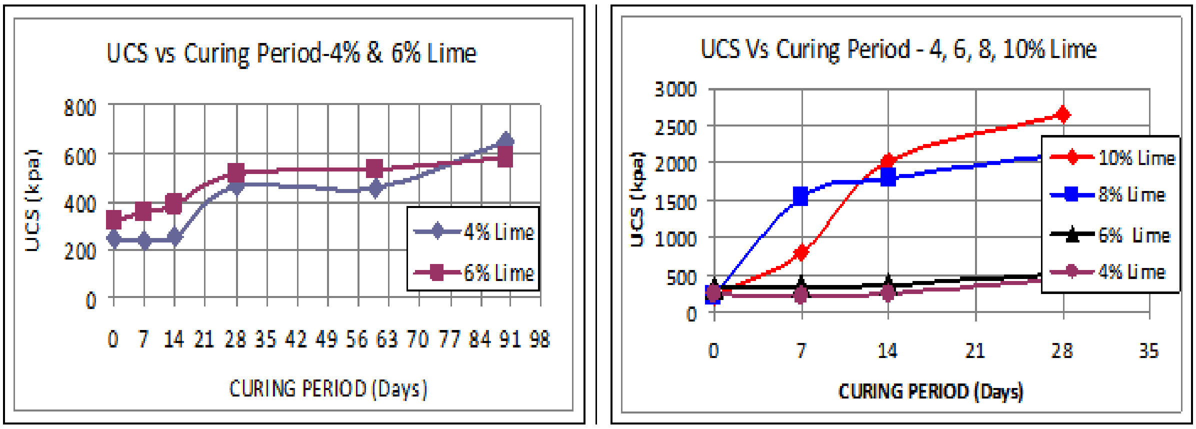

Fig. 6: Effect of lime content and curing period on unconfined strength of lime-treated clayey SAND

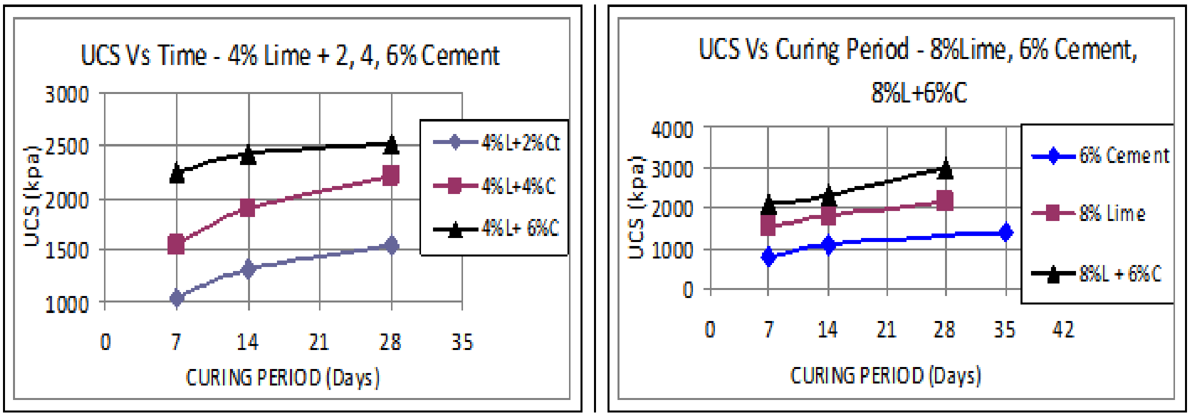

Fig. 7: UCS development with time and lime-and-cement content in two-stage stabilization of clayey SAND

E *Triaxial Compression*

Untreated soil and Lime-treated samples were subjected to CU triaxial compression tests four hours after preparation (mellowing time). The results are presented in Table 4 and Fig. 8 and 9.

Table 4: Triaxial strength parameters

	Untr. Soil	4% Lime	6% Lime	8% Lime
Φ´ [°]	14	31	32	33
c [kN/m^2]	17	152	300	187

Fig. 6: Triaxial compression (CU) samples after test

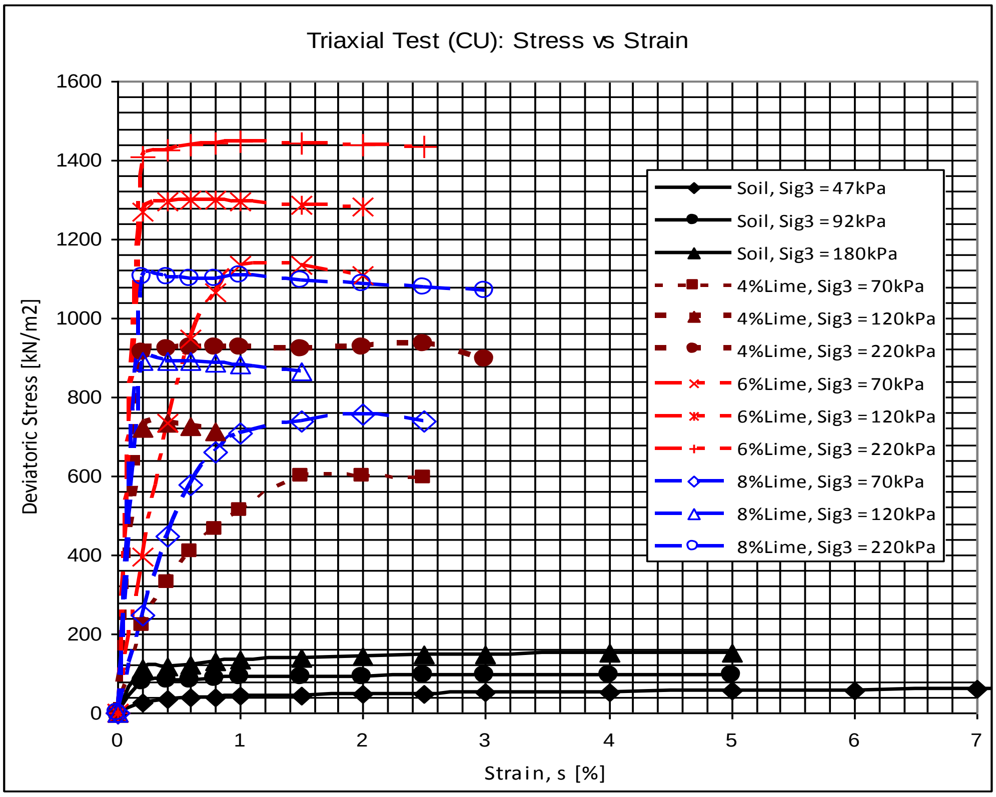

Fig. 7: Results of CU triaxial compression on natural and lime-treated soil samples

The results of the triaxial compression test indicate that lime-treatment greatly improves the strength of the soil, both in terms of the internal angle of friction (from 14° to 33°) and cohesion (from 17 kPa to 300 kPa) in four hours mellowing period (Table 4). Further, the samples treated with 6% lime show better strength properties than the other tested mix proportions (Table 4 and Fig. 9). It is likely that higher lime content (e.g. 8% lime) creates excess lime in the mixture that makes the sample less cohesive and weaker than the lower (6%) lime-treated samples. The semi-barrelling form of failure for the 8% lime-stabilized sample supports this argument, when compared with the 6% lime-treated sample which shows a clear shear form of failure (closely similar to that of granular soils).

IV. CONCLUSION

The results of this study have indicated that lime and lime-cement stabilization can greatly improve engineering properties of expansive soils, and thereby change them into non-swelling and suitable ground or materials for construction purposes. Two-stage stabilization of plastic soils produces relatively higher strength than both lime- and cement-stabilization when treated separately. Cement stabilization alone becomes difficult in such expansive soils due to the high plasticity and poor workability of the soil. Therefore prior application of lime rapidly and significantly improves soil workability by reducing soil plasticity, making the soil more friable and easily workable with cement. This is particularly important when early strength is required, such as in structures that will carry large loads at an early age. Therefore, two-stage stabilization is strongly recommended whenever expansive soil similar to that in the Kibaha-Chalinze that has too much clay for cement stabilization.

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