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Lime Stabilization of Tropical Soils from Sudan for Road Construction

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ABSTRACT: The objective of this paper is to study the effects of hydrated lime on the engineering properties of interest for road design and construction for three tropical clays, two highly plastic potentially expansive soils from Republic of Sudan and one red tropical "lateritic" soil from Republic of South Sudan. The studied properties include Atterberg limits, compaction parameters, permeability, CBR, M_R and unconfined strength. The effects of compaction energy on the end result compaction material property parameters were studied. Also, the effect of salinity/sodicity on the plasticity and strength of lime stabilized swelling soils was studied. The study showed that lime efficiently reduces the plasticity of the three soils considered and that for the same increment of lime content the reduction in plasticity is higher for montmorillonitic clays compared to kaolinitic clays. The addition of lime to the three soils increased their maximum dry density and reduced their optimum moisture content. Substantial improvement in the strength and compaction characteristics of lime stabilized tropical clays could be expected on increasing the compaction effort. Permeability substantially increased on adding the optimum lime content to the three soils. Lime increased the strength and stiffness of the treated soils and the amount of lime needed to improve lateritic clay soils is less than that needed to improve swelling soils. The M_R test results indicate increased stiffness of the lime stabilized kaolinitic clay soils compared to montmorillonitic clays. The increase in salinity/sodicity resulted in decrease of plasticity and increase in strength for the natural untreated and lime treated sodic soil tested.

Keywords: Lime Stabilization, Tropical Soils, Salinity, Compaction Energy, CBR, M_R

1. INTRODUCTION

Stabilization of soils with chemical additives has been practiced for decades to improve the performance of pavement and subgrade materials [1, 2]. Soil stabilization has been a topic of interest and discussion for all these years due to potential reduction in the construction and maintenance costs, particularly if the pavement infrastructure is built on problem grounds. Moreover, this treatment enhances riding comforts to travelers. Extensive research was documented with regards to the engineering properties, reliability and durability of various types of stabilized materials [3, 4].

Tropical soils are principally the product of chemical weathering. Many factors add to the complex process of weathering in tropical environments amongst which are climate, composition and texture of the parent rock, topographical features, type and amount of vegetation cover and time [5]. The main tropical soil groups are: red tropical soils; volcanic soils and black clay soils. The red tropical soils which are often termed lateritic soils are known to be relatively stable and good as subgrade and or embankment and pavement materials whereas the volcanic soils are known for their strange and misleading behavior [5]. Swelling soils are known for their deleterious properties. They are highly plastic and therefore suffer from poor workability, low strength when wetted, heaving on absorbing water and shrinking on drying. The swelling problem is more pronounced in an arid climate where the soils are desiccated and dry most of the year and inundated by rain water during the rainy season. Traffic-ability becomes very poor during the rainy season in areas dominated by these soils.

Sudan is a developing country. Extensive fertile clay plains (vertisols) cover most of the country. These plains witness most of the development projects. Lateritic soils are found in the southern parts of the country where rainfall is high and vegetation cover is rich. Large residential areas in the clay plains of Sudan become isolated for several weeks during the rainy season. Major challenges are facing engineers when constructing roads on the swelling clay plains, e.g. the very poor workability of the subgrade when wetted; it's very low strength when saturated and the scarcity in alternative natural construction road materials (embankment, base and subbase materials). Wetting of expansive subgrades leads to volume increase (heaving) and subsequently decrease in shear strength [6]. Uneven wetting results in uneven surface profile and pavement surface roughness. The California Bearing Ratio CBR measures very small values under soaked conditions (CBR is less than 2%). Replacement or improvement of the natural subgrade is therefore a requirement when its strength is very low [7]. As for the pavements on lateritic plains, conditions look better. The subgrade strength is relatively high (above 6%). Subbase quality material is available in selected areas but there is still a shortage in natural base course materials. The improvement of the native soil could result in stabilized base course quality material or stabilized subbase material.

Saline-sodic soils occur in large areas within the clay plains of central and northern Sudan [8, 9]. Salinity seems to increase with aridity. Highly saline soils occur in areas with rainfall less than 200 mm, i.e. most of the central, eastern and northern Sudan [8]. Cation dominance was studied in selected areas in central Sudan and it was found that sodium was the dominant cation in the upper 1.0 m depth [9]. Chloride and sulphate were the dominant anions. Salinity and sodicity are measured by the electrical conductivity ECe expressed in decisiemens per meter (dS m^{-1}) of the extract of the saturated soil paste. Typical values for Sudanese soils are less than 20 dS m^{-1} [9].

Soil stabilization by hydrated lime has been widely used worldwide to improve the engineering properties of tropical soils for use as road building materials. Research and practice worldwide has shown that hydrated lime can improve workability of swelling soils, and increase strength and stiffness [6, 7, 10]. Practically, hydrated lime may be considered as the most effective stabilizer for montmorillonitic clay soils. Similarly, lime has been used to stabilize lateritic soils as well. Plasticity was reduced and strength, stiffness and permeability increased on addition of lime. Most of the research on these soils was carried out on soils obtained from sites with relatively heavy rainfall.

This paper attempts to study the effects of hydrated lime on the engineering properties of interest for pavement design and construction for three tropical soil samples obtained from the vast clay plains of Sudan. The soils were selected to represent the different types of clays encountered in these clay plains. Two of the samples are vertisols or expansive clays whereas the third is a red tropical "lateritic" clay soil. The study attempts to compare the response of the three soils to the addition of hydrated lime given the difference in their formation and mineralogical constituents. Since some of the vertisols in Sudan are relatively saline, the effect of salinity and/or sodicity on the hydrated lime-soil interaction was also studied. The effects of different compaction levels on the strength of the stabilized material were also studied.

2. MATERIALS

Three tropical soils samples were selected for this study. These soils cover the main types of tropical clay soils encountered in the country. Soil 1 is highly plastic potentially expansive soil obtained from Alfao town, the headquarter of Rahad Irrigation Scheme, in eastern Sudan (about 400 kilometers south east of Khartoum); Soil 2 is also a highly plastic expansive soil from Khartoum and Soil 3 is red tropical clay from Wau-Tumbura road in the Republic of South Sudan. Semi-qualitative evaluation of the mineral constituents of the three soils has shown that the clay fraction of Soil 1 is basically montmorillonite (90%) with 10% chlorite. As for Soil 2 montmorillonite is still the dominant mineral (about 70%), followed by kaolinite (about 20 %) and then illite (10%). The lateritic sample from Tumbura is basically kaolinitic (90%) mixed with about 10% of illite.

The hydrated lime used in this study was produced by heating high quality limestone obtained from Butana in eastern Sudan at 900 C° in the laboratory to produce quick lime. Water was added to the quick lime to produce hydrated lime (Ca $(OH)_2$) of high quality (ASTM C977) [11]. The term lime will be used for hydrated lime in the remaining sections of this paper.

3. TEST METHODS AND RESULTS

The test program intends to study the effect of adding lime to the three tropical soils on their engineering properties of interest for pavement design and construction on them. The test program constitutes performing the following:

- Atterberg limits for untreated and treated soil samples. This test attempts to study the effect of lime on plasticity and workability and to find the optimum lime content.
- Compaction tests on treated and untreated samples. In this respect a test program was executed to investigate the effect of compaction effort or energy (over-compaction and under-compaction in the field) on the strength of the lime treated samples.
- Strength and Stiffness tests: California Bearing Ratio (CBR) and Resilient Modulus tests were performed on the untreated and treated soil samples.
- Permeability tests on untreated and treated soil samples. This is important for swelling soils since water infiltration through the stabilized layers could lead to swelling of the underlying soils.
- A special test program was carried out to study the effects of salinity/sodicity on the plasticity and strength of the studied soils. This program was designed because the top clay soils in the arid northern clay plains of Sudan are known for their salinity.

Atterberge Limit Tests

The soil samples were sieved through No. 40 Sieve. Lime was added in increments of 0.5% by weight to the tested soil up to 10.5% for Soil 1, 5.5% for Soil 2 and 9.5% for Soil 3 then mixed carefully with distilled water and left for two hours to cure and obtain homogeneous paste. The liquid and plastic limit tests were carried out for each increment using the falling cone method and B.S. 1377-1990 test procedures. The test results are given in Figures 1, 2 and 3 for Soil 1, Soil 2 and Soil 3, respectively.

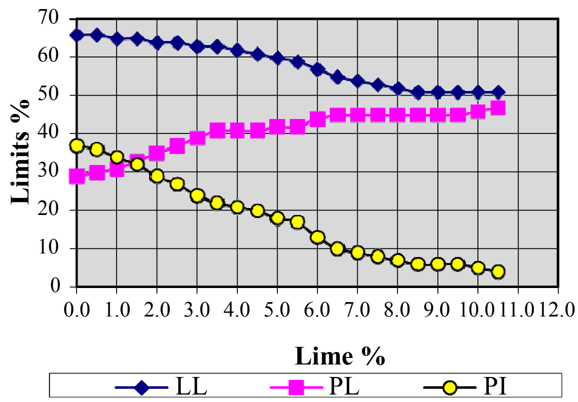

Fig.1 Atterberg limits vs. Hydrated lime content for Soil 1

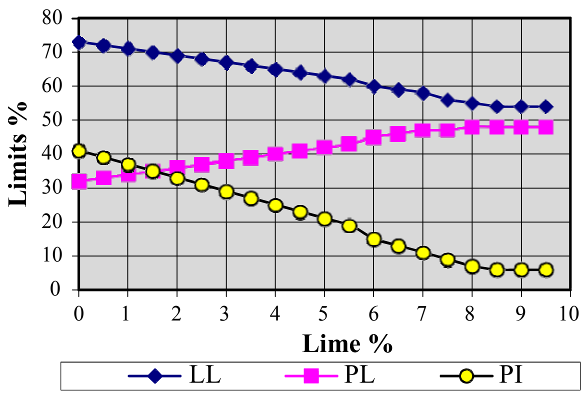

Fig.2 Atterberg limits vs. Hydrated lime content for Soil 2

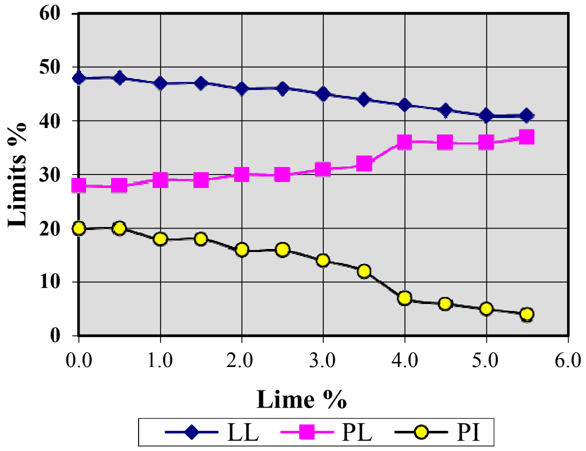

Fig.3 Atterberg limits vs. Hydrated lime content for Soil 3

Compaction Characteristics

Standard Proctor (compaction) test was carried out on treated and untreated samples to obtain their moisture-density relationship. The soil samples were sieved through Sieve No. 4. The compaction test for the treated samples was carried out at optimum lime content and about 50% of the optimum lime content. Mechanical dry mixing method was used in mixing lime and soil. Water was added and the samples were carefully mixed and left for two hours to obtain homogeneous mix. The tests were carried out according to British Standards BS 1924 -1990 test procedures [12]. The compaction parameters for each test are summarized in Table 1.

Table 1 Compaction test results for natural and stabilized soil samples

Samples	Lime %	Compaction	
		O.M.C (%)	MDD (g/cm^3)
Soil 1	0.0	24.3	1.43
	3.0	22.0	1.50
	6.5	19.2	1.56
Soil 2	0.0	25.7	1.53
	3.5	22.2	1.59
	7.0	18.9	1.62
Soil 3	0.0	21.0	1.64
	2.0	20.2	1.68
	4.0	19.2	1.71

To study the effects of compaction effort on the strength of the lime treated tropical soils, four compaction energies were applied to the three soil samples; the first is the Modified Proctor energy, i.e. 56 blows using the heavy rammer, the second is taken to be between the Modified and Standard Proctor energy (35 blows), the third is the Standard Proctor energy (13 blows), and the fourth is taken to be smaller than the Standard Proctor energy (9 blows). All tests were performed in the Modified compaction mould. The density moisture relationships are displayed in Figure 4 for Soil 1, Soil 2 and Soil 3, respectively. Unconfined compression test was performed on the samples stabilized with optimum lime and compacted at the optimum moisture content. The results of different compaction efforts are shown in Figure 5.

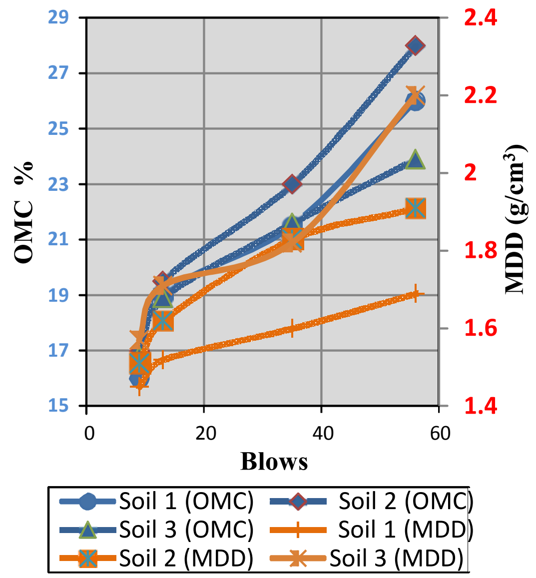

Fig.4 Blows vs. (MDD and OMC) for the three soils

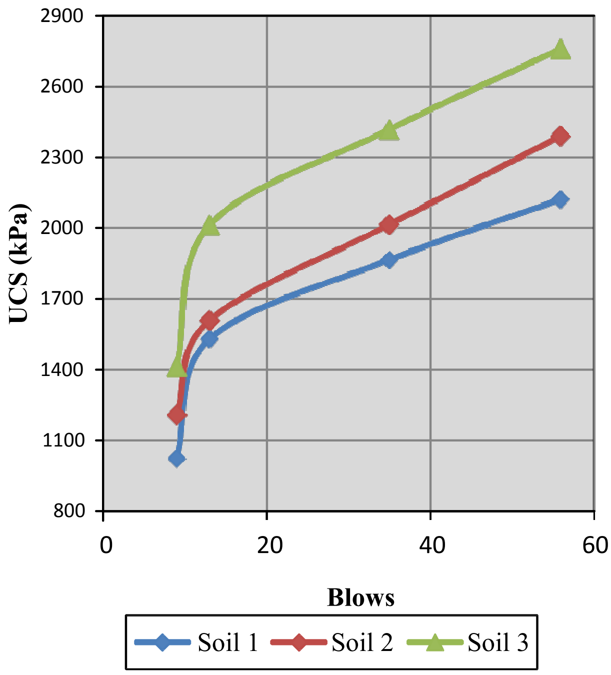

Fig.5 Blows vs. (UCS) for the three soils

Permeability Tests

A triaxial cell apparatus was used to examine the effect of hydrated lime on the hydraulic conductivity of untreated and treated soil samples applying flexible membrane permeability test method (BS 1377: 1990, Part 6) [13]. The tested soil was air dried and passed through No. 4 sieve. The test was carried out on untreated soil and soil treated with optimum lime content. The samples were compacted in the Standard Proctor mould at optimum water content using Standard Proctor energy. After preparation of the test specimen it was mounted in the triaxial cell. The sample was then saturated (to over 95% degree of saturation) using back pressure saturation. The test was conducted according to the mentioned standard. The results are given in Table 2.

Table 2 Permeability values for the natural and stabilized soil samples (m/sec)

Samples	Lime (%)	K (m/sec)
Soil 1	0.0	1.5E-10
Soil 1	6.5	9.0E-6
Soil 2	0.0	1.0E-10
Soil 2	7.0	6.0E-5
Soil 3	0.0	1.0E-8
Soil 3	4.0	7.5E-4

California Bearing Ratio and Resilient Modulus

The sample preparation techniques and lime percentages used for the CBR and M_R tests are the same as those detailed above for the Proctor compaction test. Soil samples passing through Sieve No.4 were dry mixed carefully with lime (dry weight) using laboratory mixer. The optimum lime percentage was used. Water was added to the mix (OMC %) and the samples were then compacted in the Modified Proctor mould using the Modified Proctor energy. The extracted specimens were left for 7, 14, 28 and 56 days to cure in sealed plastic bags. The soaked CBR test was carried out on each sample following British Standards BS 1377-1990 test procedure [13]. The results are summarized in Table 3.

Resilient modulus, M_R, is an important parameter which characterizes the subgrade ability to withstand repetitive stresses under traffic loadings. It is currently adopted by most of the Highway agencies around the world for evaluation of the stiffness and deformation characteristics for subgrade and pavement materials [14, 15]. The resilient modulus (M_R) test was performed in accordance with the AASHTO T307–99 [16] (Subgrade soils) test method. The test procedure consisted of applying 15 stress sequences using a cyclic haversine shaped load with duration of 0.1 second and rest period of 0.9 second. The resilient modulus was obtained for a maximum confining pressure of 41.4 kPa and maximum deviator stress of 68.9 kPa. The results are summarized in Table 3.

Table 3 CBR and M_R test results for natural and stabilized soil samples

Sample Name	Lime (%)	CBR (%)	M_R (kPa)		
			7 days	28 days	56 days
Soil 1	0.0	1	22.5		
	3.0	89.6	57.8	79.8	91.8
	6.5	104.7	91.9	116.3	142.4
Soil 2	0.0	1	39.8		
	3.5	64.9	75.6	118.6	148.6
	7.0	112.7	191.7	228.4	262.9
Soil 3	0.0	18	59.3		
	2.0	90.1	93.5	164.5	224.5
	4.0	125	390.2	436.8	486.9

Sodicity and Salinity Tests

To assess the effect of salinity and sodicity on the lime-soil reaction it was decided to add diluted (Na CL) salty water to the swelling soil from Alfao (Soil 1) to get four salinity-sodicity levels for the pore water (0.5, 2.5, 7.0 and 12 dS m^{-1}). The natural soil measured an ECe value of 0.5 dS m^{-1} whereas the other three samples were artificially salinated. Lime was added in two steps 3% and 6.5% and Atterberg limits and unconfined compression strength were determined. The soil samples were sieved through Sieve No.4 and mechanical dry mixing method was used in mixing lime and soil. The optimum water was added and the samples were carefully mixed and left two hours to obtain homogeneous mix. The mixed samples were compacted into the moulds and left to cure in sealed plastic bags for 7 days. The unconfined compression test was performed in accordance with the British Standards BS 1924 -1990 test procedures [12]. The results are given in Table 4.

Table 4 Atterberg limits and unconfined compression test results for different Salinity/Sodicity levels

Samples	Ec (dSm^{-1})	Lime %	Atterberg Limits			UCS (kPa)
			LL	PL	PI	
Soil 1	0.50	0	66	29	37	275
		3	63	39	24	405.8
		6.5	55	45	10	1565
Soil 1	2.5	0	66	29	37	281
		3	61	40	21	520.8
		6.5	55	45	10	1654
Soil 1	7.0	0	64	30	34	290
		3	60	40	20	580
		6.5	51	41	10	1680.8
Soil 1	12	0	61	32	29	297
		3	58	40	18	610.6
		6.5	50	42	8	1705.7

4. DISCUSSION OF THE RESULTS

Background

The three studied soils are tropical clays of different origin. Soil 1 and Soil 2 are black cotton highly plastic clays and are known to be highly expansive whereas Soil 3 is residual red lateritic clay. Based on their formation and origin, Soil 1 from Alfao and Soil 2 from Tumbura are residual soils whereas Soil 3 from Khartoum had been transported by the Blue and White Niles. Soil 1 is basically montmorillonitic, Soil 3 is basically kaolinitic whereas Soil 2 has mixed clay minerals dominated by montmorillonite. Soil 1 and Soil 3 have clay content 20 to 24 % whereas Soil 2 has high clay content, 54%. Soil 3 has 33% of sand and gravel whereas the other two black clay soils have sand content of about 10%. Soil 2 has the highest value of plasticity index (41) whereas Soil 3 has the lowest value (20).

Effect of lime on Atterberge limits

The results shown in Figures (1, 2 and 3) for the three soil samples show that the addition of lime to the natural samples decreased their liquid limit, increased their plastic limit and consequently reduced their plasticity index. The optimum lime content (OLC) is the lime content at which no change in plastic limit takes place on addition of lime to the soil or the lime content for which PI is equal to or less than 10 (British Lime Association, 1990) [17]. It is observed from the test results that OLC is 6.5% for Soil 1, 7.0% for Soil 2 and 4.0% for Soil 3. It is interesting to observe that the response of the three soils to changes in LL and Pl looks similar given the fact that the three soils differ considerably in their mineralogical constituents. The general observation is that lime is very efficient in reducing the plasticity of tropical clays and therefore improves their workability during construction. The reduction in plasticity for the same increment in lime content is higher for montmorillonitic clays compared to kaolintic clay (Figures 1 and 3). Previous research [10] has shown that the drop in plasticity index (δPI) divided by plasticity index (PI) or (δP/PI) is 40% to 50% for swelling soils from Sudan.

Effect of lime on the Compaction Characteristics

The results of the compaction tests are summarized in Table 1. The results show that addition of lime to the natural samples increases their maximum dry density and reduces their optimum moisture content for the same compaction effort. The drop in optimum moisture content is almost the same for the two incremental steps.

The Proctor compaction energy test results show increase in the maximum dry density and its corresponding optimum water content with increase in the compaction effort for the three soil samples treated at optimum lime content. This is better illustrated by Figure 4. Substantial improvement in the strength and deformation characteristics of lime stabilized tropical clays could be measured on increasing the compaction effort (Figure 5). Therefore, increasing the compaction effort could be an important element in improving the engineering behavior of lime stabilized clays. At the same time, being under compaction could result in lower densities and correspondingly lower strength of the three stabilized soils. Substantial drop in MDD could be observed when the Standard Proctor energy (13 blows) is reduced by 4 blows (the 9 blows in Figure 4).

Effect of lime on Permeability

The flexible membrane permeability test results are given in Table (2). The results show that the addition of hydrated lime resulted in very high increase in K-values (> 1000 times) for the treated soil samples compared to the untreated ones. The three soils responded similarly in terms of the increase in permeability when the optimum lime content was added. The increase in permeability is an indirect evidence of the increase in porosity of a soil system [18]. The reaction of hydrated lime with clay has led to the formation of aggregates of various sizes. Previous studies have provided very limited data regarding the hydraulic conductivity (K-value) of lime treated stabilized soils. Bell and de Brito et al [18, 19] reported that the K-value of the treated stabilized soils increased when lime is added to clay soils. The test results show high increase in K-value and therefore a relatively porous stabilized subgrade. The increase in permeability will enhance seepage of water to the untreated subgrade causing heaving in case of swelling subgrades. This issue needs further consideration and study especially for potentially expansive clays.

Effects of lime on Mechanical Properties (CBR and M_R)

The stiffness of the lime stabilized soil samples was assessed by the CBR and Resilient Modulus test results. The CBR and M_R test results are given in Table 3. The CBR for the untreated swelling soils was found to be 1% mainly because of the swelling of the top soil through which the penetration took place. However, the stable lateritic clay measured CBR equals 18%. The CBR substantially increased for the 3.0 to 3.5% addition of lime to the swelling soils (90% for Soil 1 and 65% for Soil 2). The optimum lime percentage resulted in CBR of 105% for Soil 1 and 113% for Soil 2. The lateritic soil showed lesser amount of increase in CBR compared to the swelling soils. The CBR increased to 95% for 2% lime and 125% for 4% lime. The CBR test results indicate increase in stiffness of the stabilized soils when compared with the same untreated soils. The swelling soils showed very high increase in stiffness.

Table 3 shows the M_R test results for the two lime increments after 7, 28 and 56 days of curing time. It should be noted that the M_R is measured for compacted unsaturated specimens; therefore the M_R values for the untreated swelling soils at optimum moisture are realistic. The highest M_R values were measured for the lateritic soil (Soil 3) for the intermediate and optimum lime contents whereas the lowest were measured for Soil1. The M_R test measures the dynamic modulus; therefore, it is a better indicator of the sample stiffness rather than of the the sample strength. The results therefore show that the bonds created by the reaction of lime with the lateritic soil “kaolinitic clay” are stronger than those formed by the reaction with the swelling soils. The mixed clay mineral soil (Soil 2) measured higher strength and was more rigid when stabilized with lime compared to the montmorillonitic clay (Soil 1). Small amounts of lime are needed to improve the stiffness and compressibility characteristics of lateritic soils and soils containing kaolinitic clays (notice that Soil 1 and Soil 3 contain the same amounts of clay fraction but differ in their mineralogy). The results show continuous increase of stiffness “M_R” with time up to 56 days, for the three soils.

Salinity-Sodicity Effects on lime-Soil Interaction

Salinity-sodicity effects have been assessed by imposing artificial sodicity to a typical vertisol sample from AlFao. The natural salinity of the soil was ECe 0.5 dS m^{-1}. The Atterberg limits and unconfined compression strength were obtained for the natural, sodic and lime-treated sodic samples (Table 4). The results showed almost no difference in LL and PI for the samples with low NaCL concentration (ECe 0.5 and 2.5 dS m^{-1}) and the same amount of added lime. The liquid limit and plasticity index decreased with increase in salinity for the untreated samples with ECe equals 7.0 and 12.0 dS m^{-1}.

The unconfined compression strength (UCS) of the untreated sodic samples decreased with increase in electrical conductivity, i.e. the increase in sodicity caused an increase in strength. The strength also increased with increase in ECe for the lime treated sodic soils (3.0% and 6.5% lime content). Therefore, the increase in sodicity caused an increase in strength for the untreated and lime-treated soils.

5. CONCLUSION

This paper presented the outcome of intensive laboratory tests aimed at studying the effects of hydrated lime on the engineering properties of three tropical clay samples obtained from Sudan. Two soils (Soil 1 and Soil 2) are swelling soils from the central and eastern clay plains whereas the third (Soil 3) is a lateritic clay soil from South Sudan. The soils differ in their mineralogical characteristics of the clay fraction. Soil 1 is predominantly montmorillonitic, Soil 2 is of mixed clay mineral but with montmorillonite as the dominant mineral (60%) and the third is predominantly kaolinitic. The following engineering properties were assessed for natural and lime-treated soils: Atterberg limits, compaction characteristics, permeability and mechanical behavior. The effects of compaction effort on the compaction characteristics and mechanical behavior were assessed. Since the swelling soils in the semi-arid and arid climate of the country are known for their high salinity, an experimental program was executed to study the effect of different salinity/sodicity values on the plasticity and strength of natural and lime-treated swelling soil (Soil 1). Diluted salt solution (Na Cl) was added to the soil to prepare soil samples with sodicity (ECe) values within practical limits (2.5, 7.0 and 12 dS m^{-1}). The study reached the following conclusions:

- Lime is very efficient in reducing plasticity of tropical clays and therefore improves their workability. The decrease in plasticity for the same increment of lime content is higher for montmorillonitic clays compared to kaolinitic clays.
- The addition of lime to the three soils increased their maximum dry density and reduced their optimum moisture content. The three soils behaved similarly in this respect. The compaction effort experiments have shown that substantial improvement in the strength and compaction characteristics of lime stabilized tropical clays could be expected on increasing the compaction effort.
- Permeability increased substantially (> 1000 times) on adding the optimum lime content to the three soils. The increase in permeability of the stabilized swelling soil subgrades could enhance penetration of water to the lower un-stabilized soils and therefore cause heaving of the pavement.
- Lime increased the strength and stiffness of the treated soils. The amount of lime needed to improve lateritic clay soils is less than that needed to improve swelling soils. The M_R test results indicate that the bonds created by the reaction of lime with kaolinitic clay soils are stronger that those formed by the reaction with swelling soils. The M_R showed increase with time up to 56 days for the three soils.
- The increase in sodicity for Soil 1 resulted in decrease of its plasticity. The increase of sodicity caused increase in strength for the natural untreated and lime treated sodic soil tested.

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