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SHEAR STRENGTH BEHAVIOUR OF REMOULDED FINE-GRAINED SOILS TREATED WITH HYDRATED LIME

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ABSTRACT: This paper presents an experimental study to assess the effect of lime treatment on the shear strength of low plastic clay and silt soils. The triaxial and direct shear tests determined the total and effective shear strengths for soil samples of the CL and ML soil groups prepared in their natural state and after treatment with 2% and 4% hydrated lime. The test specimens were initially compacted at their standard Proctor OMC and MDD conditions and allowed to cure before being tested. The study showed that the addition of lime significantly affected the basic properties of the soil types by modifying their gradation, rendering them non-plastic, and changing their OMC and MDD values. The lime treatment produced positive results by improving the total and effective soil strengths; however, the two study soils responded differently. Significant shear strength improvements were achieved in the lime-treated CL soil, but generally, the effect was relatively small for the ML soil. The gain in soil strength due to lime addition may be attributed to the clay particles flocculation and aggregation, increasing the adequate grain size, thus improving the soil matrix strength. In general, the addition of hydrated lime produced increases in the soil cohesion and reductions in the angle of internal friction; however, the effects are more pronounced in the CL than in the ML soil. Different effective strength parameters were revealed from the CU and DS test methods. The former tended to give higher cohesion and lower friction angles compared to the latter.

Keywords: Remoulded Fine-grained soils, Shear strength, Lime treatment, Triaxial CU test, Direct shear test

1. INTRODUCTION

Fine grained soils are generally considered as low-grade construction materials in civil engineering works but find use in water retaining structures. In general, such soils naturally have low strength and are they might experience large settlements if subjected to excessive loads. The geotechnical properties of fine-grained soils must be improved if they are to be used as a foundation soil to adequately support engineering structures or to qualify them to be used as a suitable construction material for earth dams and road embankment projects. In its broadest sense soil improvement is the alteration of any soil property to enhance its engineering performance. Several techniques such as compaction, reinforcement, grouting and stabilization have been developed for improving the properties of fine-grained soils.

It has been reported [1-3] that chemical stabilization of soils improves their shear strength, decreases compressibility, reduces plasticity and improves compaction and workability when used as fill materials [4]. The effectiveness of chemical additives depends on the soil type and the amount of admixture used. When lime (hydrated (Ca $(OH)_2$) or quick (CaO)) is added to soil, reactions such as exchange of cations, flocculation and aggregation and cementation take place [5]. It was reported that these reactions occur to some extent with all fine grained soils but they tend to be more effective in highly plastic clay soils.

Several previous studies have been undertaken to investigate the degree of success of lime stabilization in increasing the shear strength of natural and remoulded fine grained soils [6-8].The findings drawn indicated that lime stabilization could produce a significant increase in shear strength of fine grained or clayey soils explained by gaining high soil cohesion with curing time due the cementation process [9].

This paper presents the results and main findings of an experimental study undertaken to investigate the role of lime treatment in improving the shear strength and other basic properties of compacted low plastic clay and silt soils from Sudan.

2. EXPERIMENTAL PROGRAM

2.1 Study Soils

Low plastic clay (CL) and silt (ML) soils collected from sites located near Merowe Hydropower dam project in Northern Sudan were considered in this study. The main intention was to evaluate the suitability of such soils for use as dam core materials. Representative samples of the two soils were subjected to laboratory testing to determine their basic index and compaction properties in their natural state. Representative samples of the two soils were subjected to laboratory testing to determine their basic index and compaction properties in their natural state. The soils were then stabilized by adding 2 and 4% hydrated lime and the samples were then thoroughly mixed and allowed to cure for one week before testing.

Basic laboratory tests which included soil classification and standard Proctor compaction tests were performed on representative samples and the results are summarized in Table 1 for untreated and treated CL and ML soils.

Table 1: Classification and compaction test results

Soil type	Low plastic clay (CL)			Low plastic silt (ML)		
Sample	Added lime (%)			Added lime (%)		
State	0	2	4	0	2	4
FC (%)	57	63	48	75	62	62
CC (%)	11	7	1	12	7	6
LL (%)	44	39	42	37	36	37
PI (%)	17	NP	NP	12	NP	NP
Activity	1.5	-	-	1.0	-	-
OMC (%)	21	26	30	21	25	28
MDD kN/m^3	16	14	14	16	15	15

2.2 Shear Strength Tests

The shear strength of natural and lime treated soil samples was determined by the consolidated undrained (CU) triaxial compression and drained direct shear (DS) test methods. The treated soils were stabilized by adding 2 and 4% hydrated lime and the samples were then thoroughly mixed and allowed to cure for a minimum duration of one week before testing. The shear strength tests were carried out on samples compacted to the standard Proctor maximum dry density (MDD) and optimum moisture content (OMC) placement conditions.

The soil specimens tested in the triaxial apparatus were 76mm in height and 38mm in diameter. The specimens were first saturated and subsequently consolidated to give a difference equals to the required effective pressure. The soil specimens were first saturated by adjustment of the pore water pressure and back pressure such that the pore air is absorbed into the pore water and the specimens were considered to be saturated when the pore water pressure coefficient (B value) was equal or greater than 0.95. The specimens were subsequently consolidated by increasing the cell pressure to a difference equals to the required consolidation pressure and the consolidation was continued until at least 95% of the excess pore water pressure was dissipated. The specimens were finally sheared in compression under initial cell pressures of 100, 200, 300 and 400kPa and the deformations were recorded until failure of the specimen has occurred as defined according to one of three criteria; namely maximum deviator stress, maximum effective principal stress or constant shear stress with constant pore water pressure.

The direct shear tests were performed on soil samples manually compacted at standard Proctor optimum and maximum dry density in a 60mm by 60mm size shear box apparatus. The test specimens were saturated with de-aired water through the top and bottom porous disks by filling the shear box carriage to a level just above the top of the specimen. Each soil specimen was allowed to consolidate by applying normal force to the specimen to give the desired vertical (normal) stress. The saturation water level in the shear box carriage was maintained after the application of the normal force throughout the test. The shearing was done in a drained condition under normal pressures equal to 100, 200, 300 and 400kPa at specimen shearing strain rate of 0.1mm/min.

3. SHEAR STRENGTH TEST RESULS

The triaxial CU test results were presented in the forms of stress-strain and pore-water pressure relationships for untreated and treated soil samples as shown in Figs. 1, 2 and 3 for CL soil and Figs. 4, 5 and 6 for ML soil.

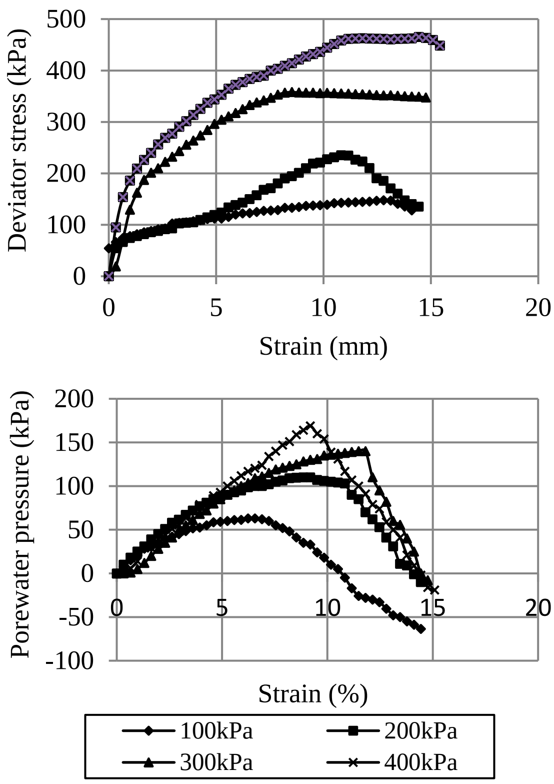

Fig. 1 Stress strain and pore-water pressure strain relationships for untreated CL soil.

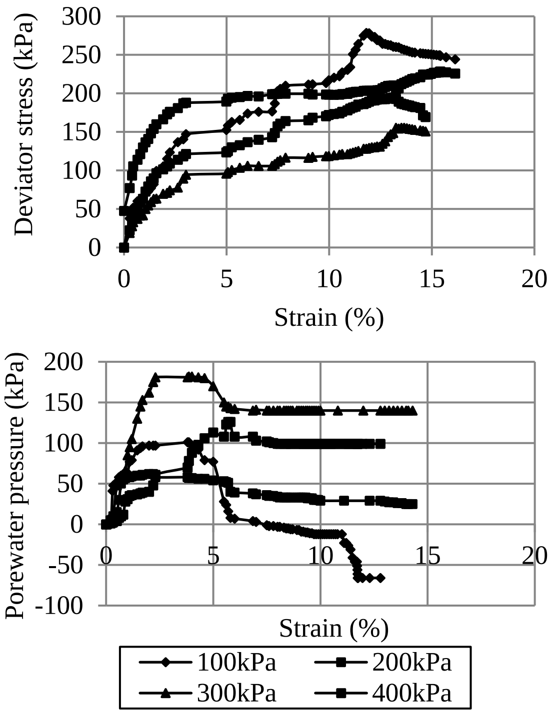

Fig. 2 Stress strain and pore-water pressure- strain relationships for CL soil treated with 2% lime

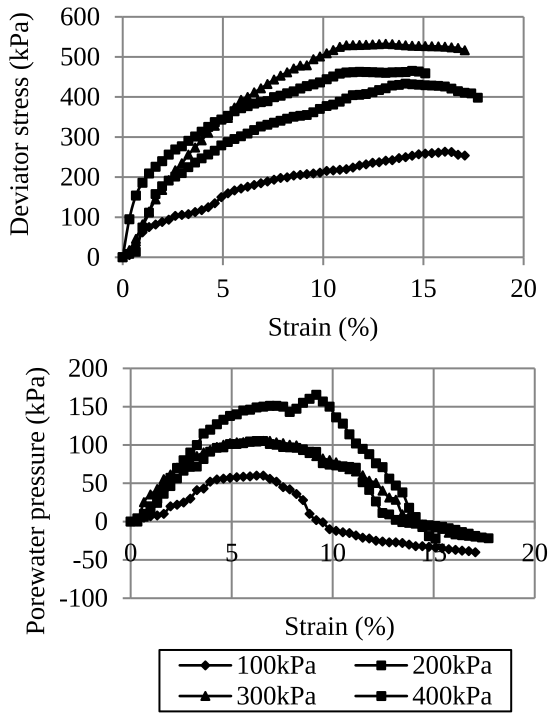

Fig. 4 Stress strain and pore-water pressure-strain relationships for untreated ML soil

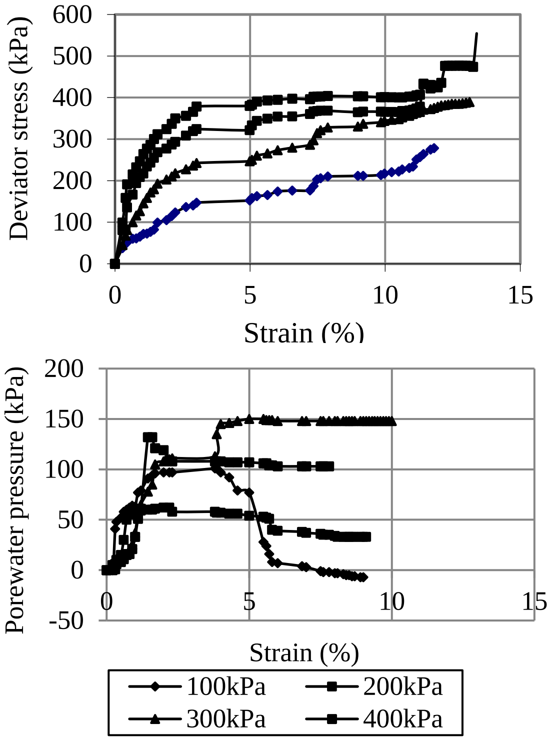

Fig. 3 Stress strain and pore-water pressure- strain relationships for CL soil treated with 4% lime

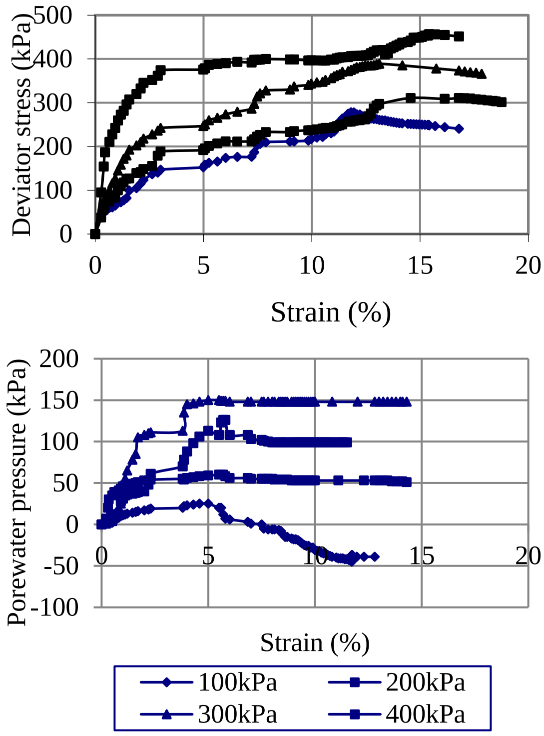

Fig. 5 Stress strain Pore-water pressure strain relationship for ML soil treated with 2% lime.

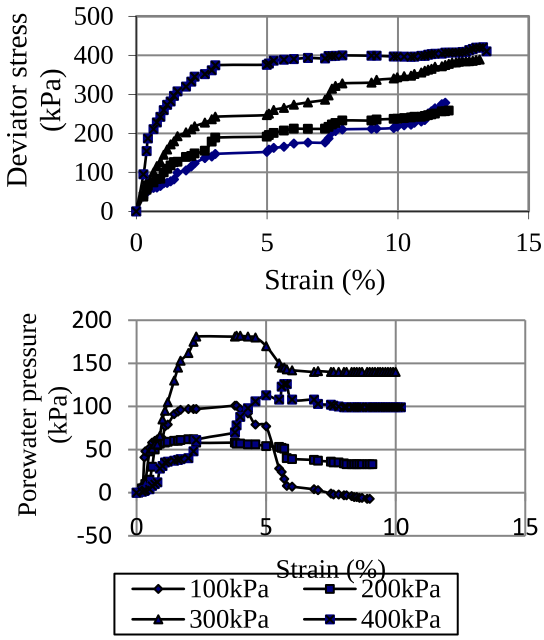

Fig. 6 Stress-strain and pore-water pressure strain relationship for ML soil treated with 4% lime

Stress path curves were also prepared by plotting the differences versus summations of the effective major and minor principal stress σ'_1 and σ'_3 obtained from the CU test data for all untreated and treated CL and ML samples. Typical stress path plots are presented in Figs. 7 for two selected CL and ML samples treated with 2% lime content

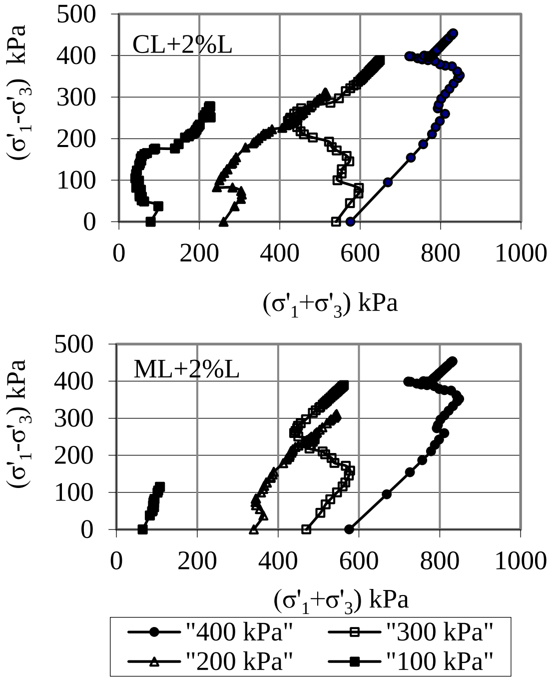

Fig. 7 Typical stress path plots for CL and ML samples treated with 2% lime

The stress-strain relationships derived from the direct shear test results are shown in Fig. 8 for untreated CL and ML samples, Fig. 9 CL treated with 2% lime and Fig. 10 for ML treated with 4% lime.

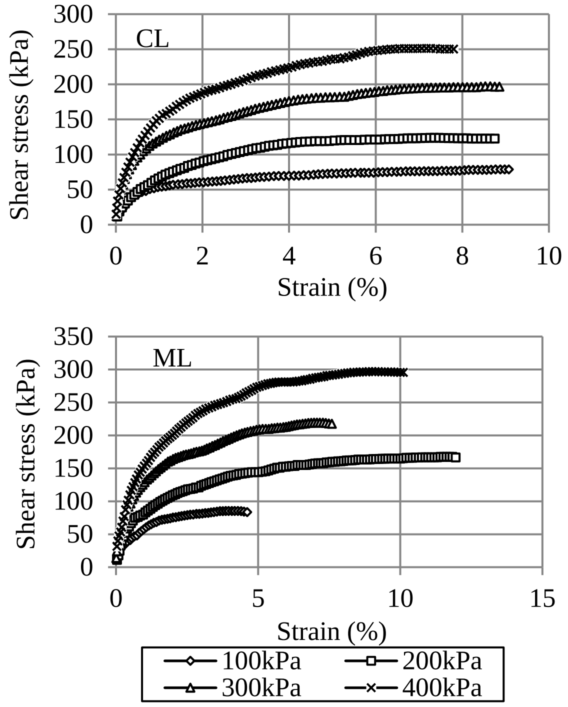

Fig. 8 Stress strain relationship for untreated CL and ML tested by direct shear method

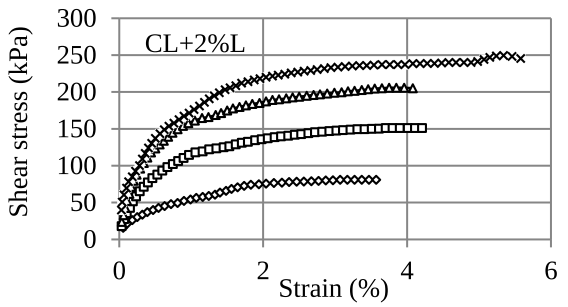

Fig. 9 Stress strain relationships for CL and ML soils treated with 2% lime

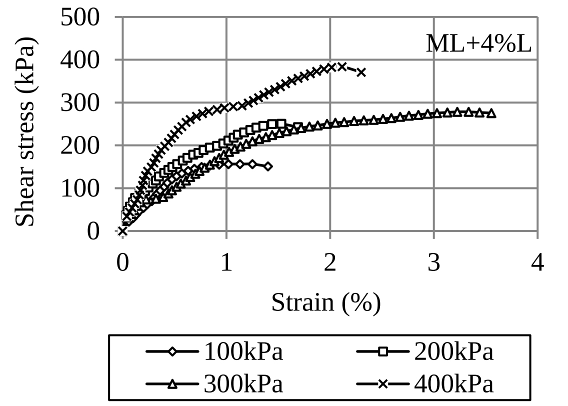

Fig. 10 Stress strain relationships for CL and ML soils treated with 4% lime

4. ANALYSIS AND DISCUSSION

4.1. Effects of Lime on Basic Soil Properties

As may be noted from the data in Table 1, the natural CL soil has much lower fines content than the ML soil but the two soils have comparable clay fraction contents. However the two soils exhibited variations in the plasticity and activity indices suggesting that they may have some differences in the type and amount of their clay mineralogy.

For the ML soil mixed with lime appreciable reduction in fines content was indicated associated with a substantial reduction in the clay content. Thus, the treatment with lime seems to have caused aggregation of particles in both soils but such features that can only be seen at the soil microfabric observation level. The liquid limit of both soils did not change much before and after lime treatment but mixing with lime rendered the two soils non-plastic.

4.2. Effect of Lime on Soil Shear Strength

4.2.1 Effect of Lime on Soil Strength Parameters

The total and effective soil cohesion and angle of internal friction strength parameters were determined from the Mohr-Coulomb failure envelopes derived from the results of the CU and DS tests performed under applied confining/normal stresses of 100, 200, 300 and 400kPa. Fig. 11 depicts the lime treatment effects on the total and effective cohesion and angle of internal friction derived from CU test results for the CL and ML soils.

It can be noted that the total cohesion increased drastically with increase in lime content in the CL soil from a very low value in untreated sample to 65kPa and 85kPa upon mixing with 2% and 4% lime respectively. In the ML soil the total cohesion changed from 75kPa for untreated sample to 100kPa and 145kPa in the samples mixed with 2% and 4% lime respectively.

The total friction angle of untreated CL soil dropped significantly and steadily after being mixed with lime. On the other hand, the total friction angle of ML increased slightly upon mixing with 2% lime then dropped substantially after mixing with 4% lime.

The effects of lime treatment on the effective cohesion (c´) and angle of internal friction (φ´) of the two soils determined from CU test results are also illustrated in Fig. 11.

The CL soil exhibited drastic increases in effective cohesion (c´) upon treatment with lime and for the limited data a very strong linear relationship was found between c´ and lime content. The effective cohesion of ML soil did not change upon addition of 2% lime but a 26.6% increase in its value was revealed when the sample was mixed with 4% lime. A significant reduction in effective friction angle (φ´) of CL soil was noted upon treatment with lime. The φ´ of ML soil increased by 20% after mixing with 2% lime but decreased by 12% when 4% lime content was added to the same soil.

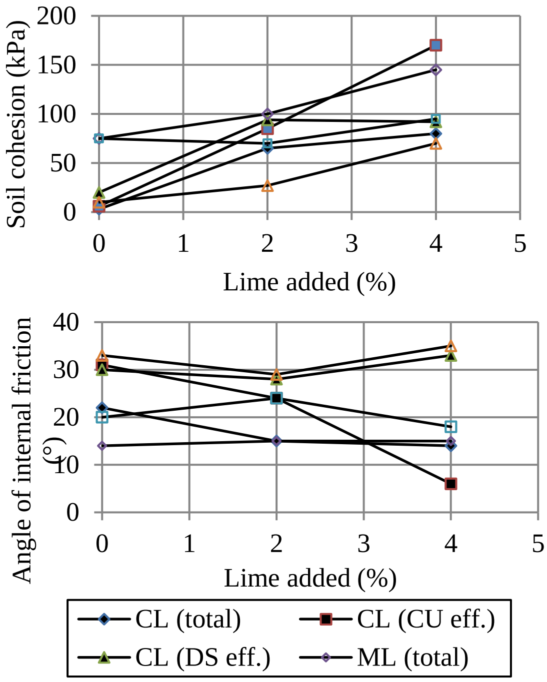

Fig. 11 Effect of lime on total and effective shear strength parameters based on CU and DS tests

Fig. 11 also illustrates the effects of lime treatment on the effective strength parameters determined from the results of direct shear tests for the CL and ML soils. The addition of 2% lime produced an increase in effective cohesion c´ of both soil types but the effect is more pronounced in the ML samples. However, upon mixing with 4% lime the c´ increased significantly in the CL soil and virtually remained unchanged in ML soil compared to their respective values in the samples mixed with 2% lime. The addition of 2% lime to CL and ML soils caused reductions in the φ´ while its values increased in both soils upon mixing with 4% lime.

4.2.2 Variability of Soil Strength with Lime

The total and effective soil strengths were computed for the untreated and lime treated samples subjected to the assumed normal pressures of 100 to 400kPa and the variations using the appropriate strength parameters. The relationships showing the variations of total and effective strength derived from CU and direct shear tests with normal stress and lime content indicated were plotted in Figs. 12 and 13 for the CL and ML soils respectively.

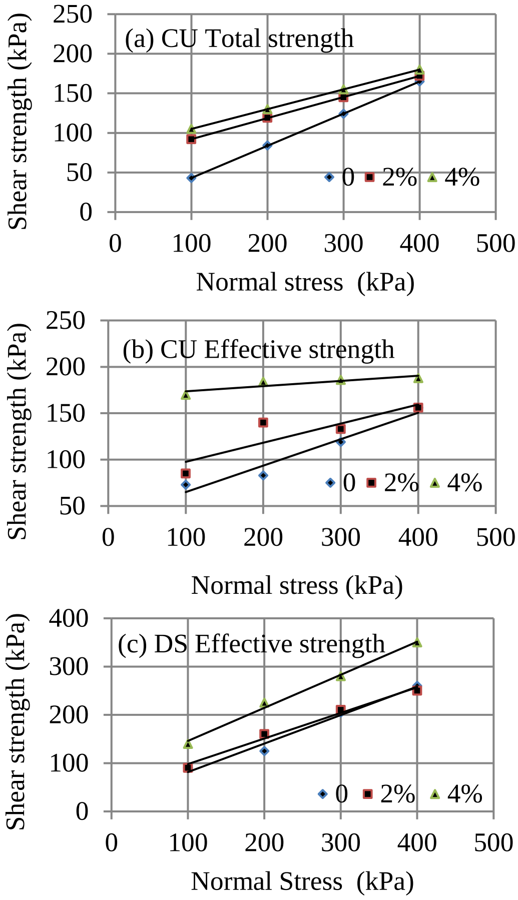

Fig. 12 Variations of total and effective strength of CL soil with normal stress and lime content.

Fig. 12 indicates that the total and effective shear strength of the CL soil increase with lime content at all normal stress levels but the effect of lime treatment is more pronounced in the effective strength case. The total strength increased drastically upon mixing with 2% lime while a little more improvement was indicated in the samples mixed with 4% lime. The gain in total strength is more pronounced at lower than at higher normal stresses suggesting that the relationship between shear strength and added lime amount is also dependent on applied pressure level. A slight to moderate increase in effective strength deduced from both test methods was noted in the CL samples mixed with 2% lime. In the CL samples treated with 4% lime a drastic improvement in effective strength was achieved and the effect was more significant in the samples subjected to CU testing (81.2%) than those tested by the DS method (51.7%).

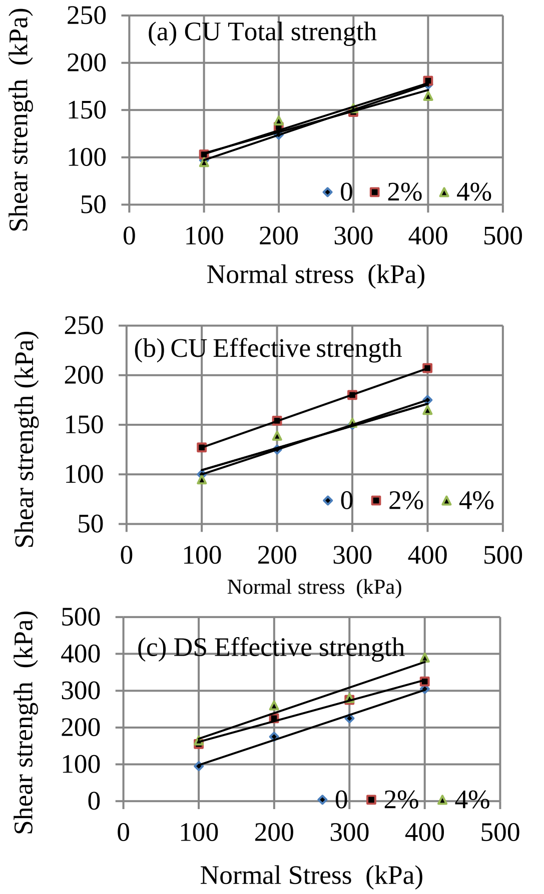

Fig. 13 Variations of total and effective strength of ML soil with normal stress and lime content

Fig. 13 shows that the addition of up to 4% lime to the ML soil did not cause any significant change in the total strength at all levels of normal stress. Fig. 13(b) shows that the addition of 2% lime produced reasonable increase in the effective strength based on CU test data (22.5%) but the effects were negligible in the samples mixed with 4% lime. This implies that some improvement could be achieved in effective strength of ML with small lime content while adding more lime may not be useful in enhancing its strength. However, the relationship trends revealed for the ML soil from the DS test data show that the addition of 2 and 4% lime produced significant improvements in effective strength. The lime treatment of ML soil was noted to be more effective at lower than at higher normal stresses.

4.2.3 Efficacy of Lime Treatment in Improving Soil Shear Strength

Based on the behaviour and trends exhibited by the CL and ML soils a discussion on the usefulness of hydrated lime as a strength improvement agent is presented hereunder.

Generally, it may be stated that the addition of 2 to 4% lime produced improvements in the shear strength evaluated from CU and CD test data; however the two soils behaved differently with respect to the observed responses. In the CL soil, both the total and effective strength increased with lime content at all applied normal stresses but the effect was more pronounced in the effective strength case.

For the ML soil, the lime addition did not cause any significant change in total strength. The lime treatment produced an increase in the effective strength of the ML samples tested by the DS method while the effect was insignificant in those tested by CU method. These results and observations demonstrate that the role of hydrated lime in enhancing shear strength is material type dependent such that it is quite effective in the CL soil and much less effective in the ML soil. Though both soils have about the same amount in percentage of the total mass of clay fraction, however, their plasticity indices differ implying that the CL clay contains more active clay minerals compared to the ML soil. The above observations are in agreement with the experience of previous authors [8, 11] who reported that the gain in strength due to lime treatment occurs to some extent with almost all fine-grained soils, but the most substantial improvement occurs in clays of moderate to high plasticity.

To understand the mechanisms involved in enhancing the strength of lime treated soils some researchers [5, 8] explained that the improvement in strength is caused partly by rapid physico-chemical reactions and partly by the long-term pozzolanic soil-lime reaction.

The gain in soil strength takes two modes; modification and stabilization [8]. Modification occurs primarily due to physico-chemical reactions involving cations exchange and the flocculation and aggregation of soil. The sodium, magnesium, and other cations adsorbed on the clay mineral surface are replaced by the calcium cations from the available calcium hydroxide. Due to the high charging of calcium cations, the clay particles flocculate and form aggregations resulting in a significant reduction in soil plasticity. More plastic soils tend to aggregate more than silty and sandy soils. The flocculation and aggregations of soil particles increase the effective grain size thus improving the soil matrix strength which is normally reflected on the macro-level soil behavior. The stabilization mode differs in that the soil-lime pozzolanic reaction produces a cemented material that develops significant soil strength gain with time. Since the soils considered in this study were allowed to cure after mixing with lime for a relatively short time (7days) the gain evolved in their shear strength is believed to be basically due to the modification form. This may be inferred from the observed changes in grain size and the significant reductions in soil plasticity of lime treated samples caused by the flocculation and aggregations of the clay particles. However, the contribution of the stabilization mode should not be totally excluded as there is some evidence from previous research work [8] that the pozzolanic reaction can begin within short time after with lime addition and are responsible for some soil modifications.

An interesting behavior was observed for the ML samples subjected to CU testing wherein a significant increase in effective strength was exhibited when it was treated with 2% lime while the effect on strength was negligible upon mixing with 4% lime. Such a behavior is not unusual as a similar observation was previously reported [10]. A hypothetical reasoning for such phenomenon was given in terms of the changes occurring in soil microfabric features during lime treatment. The microfabric is an important component of soil microstructure and is defined as the spatial arrangement of soil particles, particle groups and the associated pore spaces [11]. Initially, i.e. before treatment the soil microfabic is mainly comprised of elementary particles and inter-particle pores and when the soil is mixed in small lime quantity, it partially fills the pores leading to a reduction in soil porosity. When the porosity decreases, the soil density increases because the soil and lime act as skeleton which forms a force chain structure and enhances soil strength. When more lime is added it enters the inter-particles pores, acts as a lubricating material and the particles are separated resulting in damage in soil microstructure. In view to the low friction of lime surfaces soil cohesion and internal friction are decreased leading to reduction in soil strength. However, such a soil phenomenon needs to be further investigated and verified through microscopic observations using the scanning electron microscope (SEM) or any other suitable technique of the changes that take place in the microfabric features in the soils treated with lime.

The test results and trends demonstrated and explained in the preceeding paragraphs show that:

- The improvement in strength of the two lime treated soils could be attributed to the development of cohesive forces rather than to the increase in frictional resistance.
- The effective cohesion is well developed in the stabilized CL clay compared to the stabilized ML soil for the 2% and 4% lime contents.

The dissimilarity of the effective strength and strength parameters of soils with similar conditions determined from to the CU and DS test methods may be attributed firstly to the variations in test method and procedure followed with respect to specimen drainage applied during shearing (i.e. undrained versus drained conditions) and secondly to the differences in the state of stress developed during the testing of soil specimens (i.e. saturated versus unsaturated conditions).

5. CONCLUSIONS

The following conclusions are drawn from studying the shear strength and some basic properties of remoulded clay (CL) and silt (ML) soils treated with hydrated lime:

i. The addition of lime by 2 and 4% to the two soils significantly affected their grain size distribution by reducing the fines and clay content fractions as a result flocculation and aggregation of clay particles. Addition of lime rendered the two soils non-plastic and produced significant changes in compaction properties by increasing OMC and decreasing MDD.
ii. The study show that the lime treatment by hydrated lime can improve total and effective shear strength of CL and ML soils but there is remarkable difference in their responses which indicates that the strength enhancement effect is soil type dependent. Although both soils have the same clay content and the ML soil has higher fines content, lime treatment is more effective in the more active CL soil.
iii. The improvement in the shear strength of the lime treated soils may be attributed to clay particles flocculation and aggregation caused by physico-chemical reactions which are responsible for increasing effective grain size thus improving the strength of soil matrix.
iv. The lime addition produced important modifications in the total and effective shear strength parameters of the CL and ML soils. The total cohesion increased significantly in both soils after being treated with lime. The total friction angle decreased significantly in the CL but did not change much in the ML soil. The CL soil exhibited drastic increases upon lime treatment in effective cohesion however for the ML the c′ increased only upon mixing with 4% lime.
v. The study test results indicate that, the improvement gained in strength of the lime treated soils could be attributed to the development of cohesive forces rather than the increase in their friction resistance**.**

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