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RESEARCH ARTICLE

Stabilization of Algerian Clayey Soils with Natural Pozzolana and Lime

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Abstract

Cohesive soils with a high plasticity index present difficulties in construction operations because they usually contain expansive clay minerals. However, the engineering properties of soils can be improved by different techniques. The aim of this paper is to study the effect of using lime, natural pozzolana or a combination of both lime and natural pozzolana on plasticity, compaction and shear strength of two clayey soils classified as CH and CL according to the unified soil classification system (USCS). The obtained results indicated that for CH class clay soil, the plasticity index decreased significantly for samples stabilized with lime. On the other hand, for the soil classified as CL class clay, a high decrease in the plasticity index value was observed for samples stabilized with natural pozzolana compared to those stabilized with lime. Also, both the cohesion and internal friction angle in lime added samples were demonstrated to increase with time. The combination of lime and natural pozzolana exhibits a significant effect on the enhancement of both the cohesion and internal friction angle at later stages. The lime-natural pozzolana combination appears to produce higher shear strength parameters than lime or natural pozzolana used alone.

Keywords

lime, natural pozzolana, soil stabilization, Atterberg's limits, shear strength

1 Introduction

There are many types of problematic soils that hinder urban development in large cities. These could be swelling/shrinking clays, collapsible soils, quick sands, frozen soils and peat. The consequences that may be attributable to the behavior of such problematic soils can result in considerable financial loss. For instance, in the last decade, swelling and shrinkage in clayey soils have caused losses of up to £3 billion in Britain [1].

Problematic soils have been avoided for long time for construction sites in favour of more quality soils with reduced technical difficulties and hence lower construction costs. Nowadays, it has become difficult to find suitable sites for construction and suitable materials for earth structures such as highways, dams or runways at an economic distance. For example, in Algeria and due to the lack of land for urban development, buildings are constructed on deposits of fine grained soft and compressible soils (clays, muds...) or loose sands resulting from recent alluvial deposits which are frequent in the valleys, around the rivers and in coastal regions [2]. Typical approach was the use of deep foundations and stone columns technique resulting in higher cost. In Ankara (Turkey), it has been reported that approximately two thirds of the city of Ankara is founded on medium to highly plastic expansive clayey soils. Hence, some damages on light one storey buildings, roads and water pipes [3]. Subgrade soils are also reported to be common problems in Wisconsin in the USA [4].

Unsuitable soils are also frequently encountered elsewhere. Hence, there is a need to improve the physical and mechanical characteristics of these soils to make them more suitable for construction. This can be done by using different mechanical and chemical methods. This process is known as soil stabilization. Lime and cement are the most used chemical stabilizers.

Lime as an additive is most commonly used to stabilize fine soils due to its effectiveness and economic usage. Moreover, lime improves significantly the engineering properties of soft soils. Lime stabilisation is achieved through cations exchange, flocculation/agglomeration, lime carbonation and pozzolanic reactions. Cations exchange and flocculation/agglomeration reactions take place rapidly bringing immediate changes in soil

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properties, whereas pozzolanic reactions are time dependent. These pozzolanic reactions involve interactions between soil silica and /or alumina and lime to form various types of cementation products responsible for the gain of stregth.

References to the use of lime for improving soil go back several hundred years BC, when the Romans were constructing the pyramids of Shenshi. The early Chinese used clayey gravels stabilized with lime for massive bridge footings. Other early uses were in India where lime-stabilized soil was used for making rough roads, and in the construction of masonry dams. The use of lime stabilization in the United States has been widespread. The effect of lime on the strength and swelling of expansive clays was studied in the 60's [5]. Deep mixing using lime was first used in practice in Sweden, in the mid 1970's [6]. In the United Kingdom many kilometres of the M40 motorway north of Banbury were stabilizing using lime [7]. More recently, extensive studies have been carried out on the stabilization of soft soils using additives such as lime and cement [8].

Industrial by-products such as quarry limestone [9], fly ash [10–13], rice husk ash [14–17], silica fume [18] and cement kiln dust [19] have been widely used for soil stabilization.

Combining cementitious materials with lime, increases greatly the efficiency of lime stabilisation, as cementing additives react with the lime more effectively than alone. Some investigators [11, 15, 18] found that workability and strength behavior of soft soils were greatly improved after a combined treatment.

However, limited research had been conducted in order to investigatethe suitability of using natural pozzolana (NP) in soil stabilization in combination with lime. Hossain et al. [20] used volcanic ash from natural resources of Papua New Guinea for stabilization of soils. Several tests of compaction, unconfined compressive strength and durability were conducted, but this research work did not analyse the plasticity and shear strength behaviors.

Natural pozzolana is found abundantly in extensive areas of Beni-Saf quarry in the West of Algeria [21]. The use of natural pozzolana and its combination with lime in conjunction with soft clayey soils needs to be investigated. As clayey soil contains alumina, the effects of lime treatment can improve to a great extent if the apparent shortage of silica can be adequately supplemented by the addition of natural pozzolana, which has a high reactive silica content. Moreover, factors that should be considered in choosing stabilizing agents are abundance, cost and easiness to obtain. Natural pozzolana is very cheaper and abundant in the western part of Algeria.

The present research work is a part of a research project focused on the evaluation of effects of lime, natural pozzolana and their combination on the improvement of the performance of some local clayey soils. This paper presents only the results of the effect of the use of lime, natural pozzolana and their combination on plasticity and shear strength of two local clayey soils classified as CH and CL according to the unified soil classification system (USCS).

2 Experimental Program

2.1 Site selection and materials used

The first soil used in this study was obtained from an embankment project site (Fig. 1) and the second soil (Fig. 2) was obtained from a highway project site both near Chlef town in the West of Algeria. Previous soil investigations carried out at the site indicated the presence of soft clays. These soft clays were encountered at a depth of about 4 to 5 m. The disturbed soil was excavated, placed in plastic bags, and transported to the laboratory for preparation and testing. Laboratory tests were carried out to classify each type of soil.

Fig. 1 Grey soil

Fig. 2 Red soil

The engineering properties of clayey soils are presented in Table 1. Also the Chemical and mineralogical properties of both soils are presented in Table 2.

Table 1 Physical characteristics of soils

Basic characteristics	Soil 1	Soil 2
Color	Grey	Red
Depth (m)	4m	5m
Natural water content (%)	32.87	13.77
Specific gravity	2.71	2.84
Passing 80 μm sieve (%)	85	97.5
Liquid limit (%)	84.8	47.79
Plastic limit (%)	32.78	23.23
Plasticity index (%)	52.02	24.56
Classification (USCS)	CH	CL
Optimum water content (%)	28.31	15.27
Maximum dry density (kN/m^3)	13.8	16.9
Cohesion (kPa)	17.3	56.6
Internal friction angle (°)	4.6	26.1

All physical tests were performed in accordance with the ASTM standard. The natural pozzolana (NP) used in this investigation was collected from Beni-Saf in the West of Algeria. The NP was ground in a laboratory mill to a specific surface area of 420 m^2/kg.

Table 2 Chemical and mineralogical properties of both soils

Chemical name	Chemical formula	Soil 1 (%)	Soil 2 (%)
Calcium oxide	CaO	14.43	2.23
Magnesium oxide	MgO	1.99	2.14
Iron oxide	Fe_2O_3	5.56	7.22
Alumina	Al_2O_3	14.15	19.01
Silica	SiO_2	43.67	57.02
Sulfite	SO_3	0.04	0.19
Calcite	$CaCO_3$	26.00	4.00
Albite	$NaAlSi_3O_8$	-	8.00
Illite	$2K_2O.Al_2O_3.24SiO_2.2H_2O$	16.00	24.00
Kaolinite	$Al_2Si_2O_5(OH)_4$	12.00	16.00
Montmorillonite	$Al_2((Si_4Al)O_{10})(OH)_2.H_2O$	20.00	-
Chlorite	$Mg_2Al_4O_{18}Si_3$	-	9.00
Ferruginous minerals and others	-	6.00	7.00
Organic matter	-	0.33	-

Pozzolans are generally siliceous materials which, having no cementitious value themselves, will in finely divided form and in the presence of moisture, chemically react with calcium hydroxide (lime) at ordinary temperatures to form compounds possessing cementitious property. The natural pozzolana used in this investigation has been proved to have a pozzolanic activity [21].

The lime used was a commercially available lime typically used for construction purposes. The chemical and physical properties of lime (L) and natural pozzolana (NP) are presented in Table 3.

Table 3 Chemical and physical properties of lime and natural pozzolana

Physical or chemical name	Lime (%)	Natural Pozzolana (%)
Physical form	Dry white powder	Dry brown powder
Specific Gravity	2.00	-
Over 90 µm (%)	< 10.00	-
Over 630 µm (%)	0	-
Insoluble material (%)	< 1.00	-
Bulk density (g /L)	600 – 900	-
Loss on ignition	-	5.34
CaO	> 83.30	9.90
MgO	< 0.50	2.42
Fe_2O_3	< 2.00	9.69
Al_2O_3	< 1.50	17.50
SiO_2	< 2.50	46.40
SO_3	< 0.50	0.83
Na_2O	0.40 - 0.50	3.30
K_2O	-	1.51
CO_2	< 5.00	-
TiO_2	-	2.10
P_2O_3	-	0.80
$CaCO_3$	< 10.00	-

2.2 Stabilized soil mixtures and combination schemes for stabilizer

A series of laboratory tests consisting of Atterberg's limits were conducted on both selected clayey soils. Many combinations of natural pozzolana and lime were used for stabilization of both clayey soils. The percentages of NP were 0, 5, 10, 15 and 20%, while the percentages of lime were 0, 2, 4, 6, 8 and 10%. A total of 40 combinations was studied based on soil 1 and soil 2 with single and mixed modes of stabilizers (Table 4).

A series of laboratory tests consisting of proctor standard compaction and direct shear tests were conducted on both selected clayey soils. Many combinations of natural pozzolana and lime were used for stabilizing of both clayey soils. The percentages of NP were 0, 10, and 20%, while the percentages of the lime were 0, 4, and 8%. A total of 18 combinations was studied based on soil 1 and soil 2 with single and mixed modes of stabilizers (Table 5).

2.3 Specimen's preparation and testing procedures

Liquid and plastic limits tests were carried out according to ASTM D4318 [22]. The air dried soils (passing the N° 40 sieve) were initially mixed with the predetermined quantity of NP, L or a combination of NP and L in a dry state. Distilled water was added to the soil mixture. To let the water permeate through the soil mixture, the paste was allowed to stand in an airtight container for about 24h prior to testing. The mixture was remixed with each stabilizer thoroughly for at least 15 minutes before performing tests.

Table 4 Combinations of the untreated and treated samples

Designation	Sample mixture (%)		
	Soil	NP	L
P0L0	100	0	0
P0L2	98	0	2
P0L4	96	0	4
P0L6	94	0	6
P0L8	92	0	8
P0L10	90	0	10
P5L0	95	5	0
P10L0	90	10	0
P15L0	85	15	0
P20L0	80	20	0
P5L4	91	5	4
P10L4	86	10	4
P15L4	81	15	4
P20L4	76	20	4
P5L8	87	5	8
P10L8	82	10	8
P15L8	77	15	8
P20L8	72	20	8
P10L10	80	10	10
P20L10	70	20	10

Both liquid and plastic limits tests were conducted in a room at a temperature of 20 ± 2°C.

Proctor standard compaction test according to ASTM D698 [23] was applied to determine the maximum dry density (MDD) and the optimum moisture content (OMC) of both clayey soils. The soil mixtures, with and without additives, were thoroughly mixed for 1 hour prior to compaction. The first series of compaction tests were aimed to determine the compaction properties of the untreated soils. Secondly, tests were carried out to determine the proctor compaction properties of both clayey soils upon stabilization with varying amounts of natural pozzolana and lime.

Table 5 Stabilizer combination scheme for stabilized soils

Designation	Sample mixture (%)		
	Soil	NP	L
P0L0	100	0	0
P0L4	96	0	4
P0L8	92	0	8
P10L0	90	10	0
P20L0	80	20	0
P10L4	86	10	4
P20L4	76	20	4
P10L8	82	10	8
P20L8	72	20	8

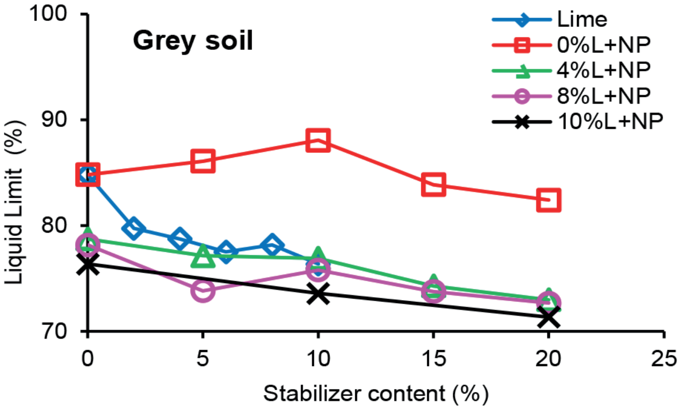
The direct shear tests were carried out according to ASTM D6528 [24]. Tests were conducted on both treated and untreated samples compacted at maximum dry density and optimum moisture content. Since the specimens were not saturated, no excess pore water pressure would be expected in them. The direct shear test was unconsolidated undrained and and the load was applied at a rate of 1 mm/min. The normal stress was chosen 50, 100 and 200 kPa for all the specimens. Six specimens from each mixture were prepared for each curing period. In order to avoid excessive moisture loss, the specimens were wrapped up with a polyene film after removing from moulds. The specimens were kept in the laboratory at a temperature and relative humidity of (20 ± 2) °C and 100%, respectively until the test time (1, 7, 28 and 90 days).

3 Results and discussions

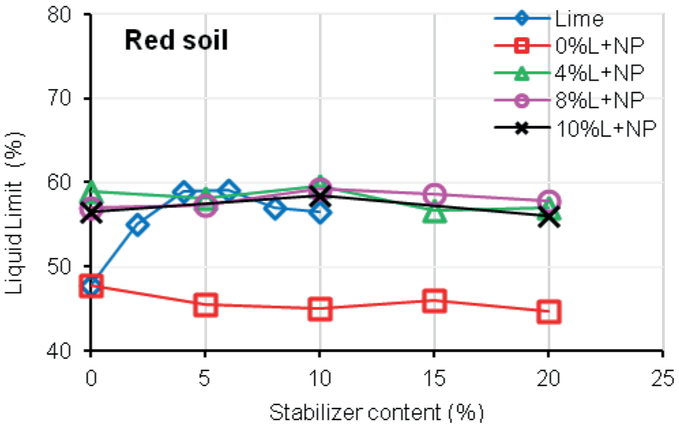
3.1 Atterberg limits

3.1.1 Variation of liquid limit

Fig. 3 shows the variation of the liquid limit (LL) with stabilizers content. For grey soil classified as CH class clay, the liquid limit decreased from 84.8% to 76.4% with the addition of 10% lime. For a similar class soil, Manasseh and Olufemi [25] observed comparable results. A decrease of the liquid limit from 72% to 62% for the addition of 10% lime was observed. Muntohar [26] found a decrease of the liquid limit from 89.7% to 81% for the addition of 9% lime. For the red soil classified as CL class clay, the liquid limit increased from 47.8% to 59% for the addition of 6% lime. For a similar class soil, Yong and Ouhadi [27] observed that the liquid limit increases from 45.8% to 55% for the addition of 6% lime, whereas Bell [28] reported an increase from 30% to 37% for the addition of 8% lime.



(a)



(b)

Fig. 3 Effect of stabilizers on the Liquid limit: (a) grey soil; (b) red soil

The increases and decreases in Atterberg's limits depend on the type of soil. The increase in liquid limit occurs more frequently for kaolinitic soils whereas the decrease in liquid limit occurs for montmorillonitic soils [29]. The reduction in liquid limit value was attributed to cations exchange due to the action of divalent calcium ions [11]. Moreover, clays with lower valence cations such as sodium experience significant cation exchange resulting in a significant reduction in liquid limit with increasing lime content [19]. The liquid limit of kaolinitic soils is generally more affected by particle arrangement (clay fabric), and the presence of divalent cations which promote flocculation which leads to the increase of liquid limit [11]. On other hand, calcium saturated clays tend to exhibit an increase in liquid limit when treated with lime [19].

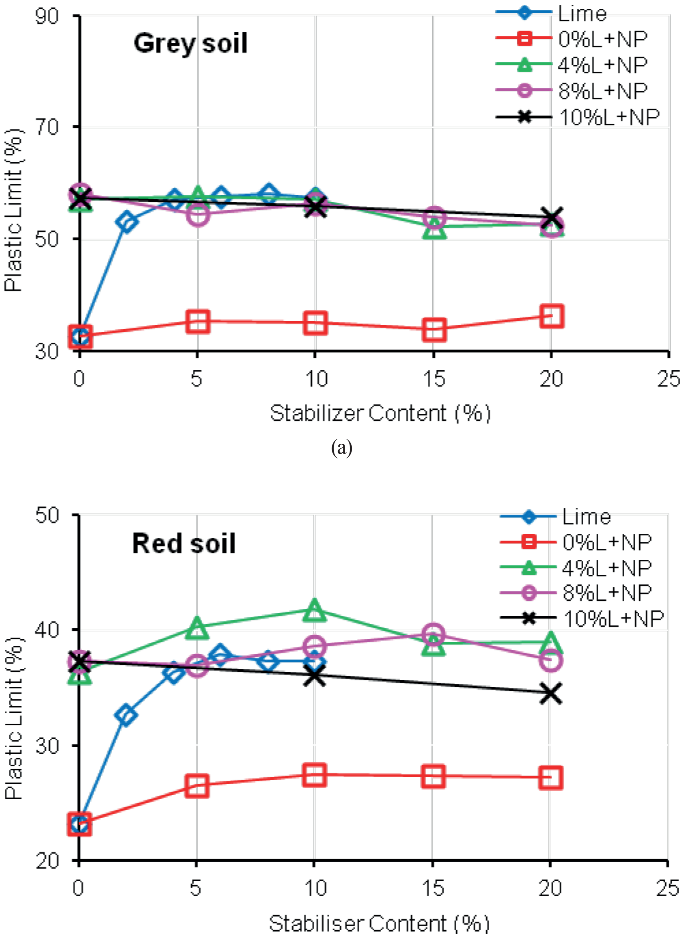
Consequently, the difference in liquid limit behavior exhibited by grey (CH) and red (CL) soils is likely to be due to different complexes cations exchange in each of these soils. It can be seen for the grey soil (CH) that the addition of natural pozzolana affects marginally the liquid limit probably because of the low free lime content in the natural pozzolana. Similar trends in liquid limit have been reported by several researchers using pozzolanic materials from waste. Muntohar and Hantoro [15] and Muntohar [26] used rice husk ash (RHA), Turker and Cokca [30] used class F and class C fly ashes. Degirmenci et al. [31] used class C fly ash (SCA) and Reyes and Pando [32] used circulating fluidized bed combustion (CFBC), and all of them found that the addition of 10% to 25% of different stabilizers reduce the liquid limit by 7% to 20%. For the red soil (CL), the liquid limit decreased from 47.8% to 44.6% with the addition of 20% natural pozzolana. As the NP used had a liquid limit much lower than the liquid limit of the soil, its addition had a diluting effect that reduced the liquid limit of the mix [11]. As NP does not possess any diffuse double layer, the liquid limit decreased with percentage of NP. Moreover, as the amount of free lime in the mixes was very low, its effect in terms of increasing the liquid limit was insignificant. The observed decrease in the liquid limit of the mixes confirmed that the diluents factor of NP was dominant.

It should be noted that the combination of lime and natural pozzolana stabilization shows a slight decrease of the liquid limit compared to the use of lime alone. However, for the same class soil and with the use of 20% rice husk ash, Basha et al. [16] and Rahman [17] observed that the liquid limit increases from 49.8% to 54.3% and from 36.8% to 47% respectively. The combination of lime and natural pozzolana stabilization showed no significant changes compared to the use of lime alone. For the same class soil, Ansary et al. [33] observed that the liquid limit decreases from 42.8% to 41% for the combination 3% lime + 12% fly ash.

3.1.2 Variation of plastic limit

Fig. 4 shows the variation of the plastic limit (PL) with stabilizers content. For the grey soil (CH), the plastic limit increases from 32.8% to 57.3% for 10% lime addition. For a similar class soil, Nalbantoglu [34] observed that the plastic limit increases from 22.2% to 37.5% for the addition of 7% lime, and Rahman [17] indicated an increase from 24.9% to 47.7 for the addition of 10% lime. The increase of the plastic limit for the red soil (CL) was from 23.2% to 37.4% for the addition of 10% lime. For the same class soil, Okagbue and Yakubu [9] reported that the plastic limit increases from 21.6% to 33.6% for the addition of 10% limestone. Similar behaviors have also been reported by several researchers [28,29].

The immediate increase in plastic limit was due to the flocculation of clay particles. In general, the increase in plastic limit of clays upon the addition of lime is considered significant in the sense that the plastic limit is the best indicator of the lime content necessary to achieve the required modification. This is because the variation pattern of plastic limit changes in consistent for any clay [11].



(a)

(b)

Fig. 4 Effect of stabilizers on the Plastic limit: (a) grey soil; (b) red soil

The addition of 20% natural pozzolana to the grey soil (CH) increased the plastic limit from 32.8% to 36.4%. For the same class soil, Muntohar and Hantoro [15] indicated that the addition of 10 % RHA increases the plastic limit from 32.3% to only 34.3%. The plastic limit for red soil (CL) increases from 23.2% to 27.2% with the addition of different percentages of natural pozzolana. For the same class soil, Basha et al. [16] indicated that the addition of 10% RHA increases the plastic limit from 23% at 26%. A similar behavior for similar soils was found by several researchers [17,26,30]. The addition of a low-calcium fly ash to expansive soils was also found to increase the plastic limit and this effect was due mainly to the replacement of finer soil particles by coarser fly ash particles [11]. Also the net effect was the replacement of the soil with non-plastic particles of NP.

The combination of natural pozzolana and lime decreased the plastic limit of grey soil (CH). A combination of 4% L+NP showed a decrease from 57.3% to 52.8% for the addition of 10% natural pozzolana. For the combinations 8%L+NP and 10%L+NP, the plastic limit presented a better decrease as compared to the use of 8% or 10% lime alone. The combinations of 4% lime and different contents of natural pozzolana gave the highest values of plastic limit. An increase of about 16% and 4% for both combinations 4%L+NP and 8%L+NP respectively compared to 4%L and 8%L has been obtained. However, for the combination 10%L+NP the plastic limit shows a decrease of about 9% compared to 10%L. For the same class soil, Ansary et al. [33] observed that the plastic limit was increased from 29.7% to 31.2% and from 29.7% to 32.3% respectively with the addition of 6% and 12% fly ash in combination with 3%L.

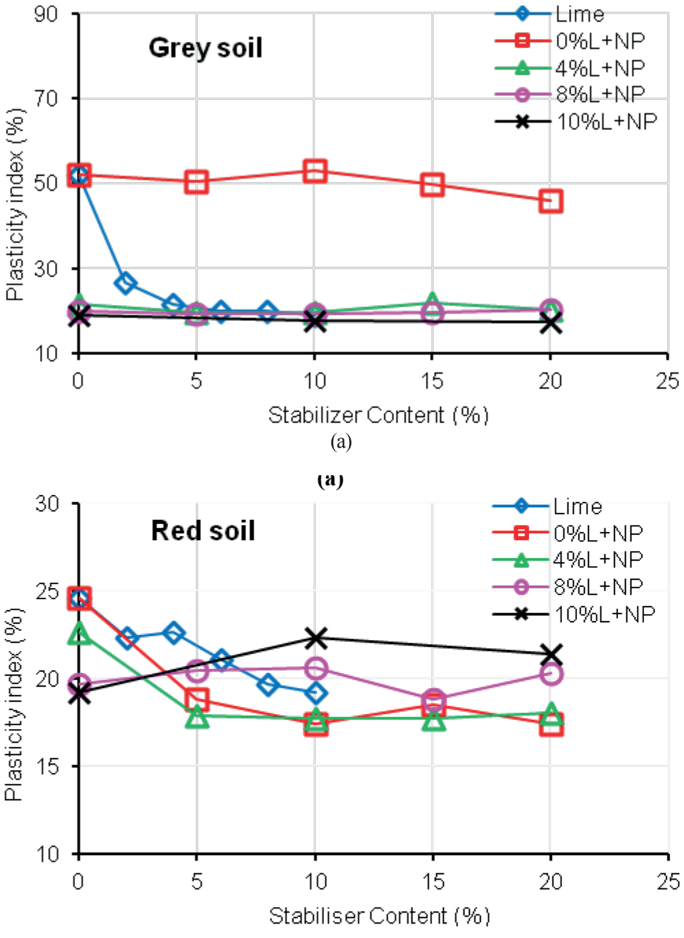
3.1.3 Variation of plasticity index

The plasticity index (PI) variation for the soils and mixes are presented in Fig. 5. The decrease in plasticity index indicated an improvement of the soil characteristics. The grey soil (CH) shows an immediate decrease in plasticity index upon the addition of lime. It is apparent that the addition of 6% lime was sufficient to enhance the workability of the soil (CH) by reducing the plasticity index from 52% to 19.9%. Increasing the lime content beyond 6% had a marginal effect on reducing the plasticity index. For the same class soil, Nalbantoglu [34] observed that the plasticity index decreased from 45.6% to 13.5% for the addition of 7% lime. For the red soil (CL), the plasticity index was decreased from 24.6% to 19.7% for the addition of 8% lime. Beyond this value, a marginal effect in reducing plasticity index was observed.

For the same class soil, Okagbue and Yukubu [9] observed that the plasticity index decreased from 19.9% to 14.4% for the addition of 10% limestone. A similar behavior was found by several researchers [18,29,33].

The addition of natural pozzolana alone to the grey soil (CH) enhanced its workability to some extent by reducing the plasticity index. A reduction of the plasticity index from 52% to 46% was observed for 20% natural pozzolana addition. The addition of different levels of natural pozzolana alone to the red soil (CL) enhances significantly its workability by reducing the plasticity index from 24.6% to 18%. A similar trend was observed by Parsons and Kneebone [13] and Rahman [17] where they used fly ash and RHA, respectively. ash and RHA respectively. This trend may be attributed to the replacement of the finer soil particles by the NP with consequent reduction in the clay content and plasticity index.

The combination of natural pozzolana and lime exhibited a marginal effect on reducing the plasticity index of grey soil (CH) compared to lime addition alone. The combination of 4%L+NP shows a similar decrease in plasticity index for red soil (CL) as with natural pozzolana alone. However, with higher lime contents, the plasticity index increases compared to natural pozzolana alone.



(a)

(a)

(b)

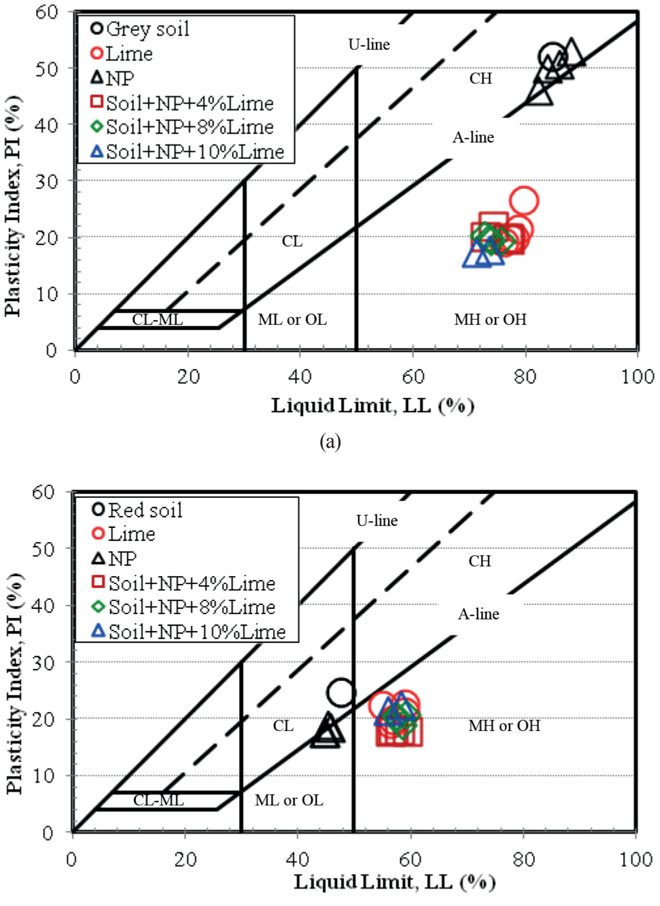
Fig. 5 Effect of stabilizers on the Plasticity index: (a) grey soil; (b) red soil

3.1.4 Effect of stabilizers on the clay classification

The consistency limit test results were marked on the Casagrande plasticity chart in order to determine the new soil classification according to the unified soil classification system (USCS) (Fig. 6). It is clearly seen on Fig. 6 that for the grey soil classified as CH class clay, the point representing soil class was above the A-line and then dropped under this A-line when stabilizers contents were increased. However, when the natural pozzolana was used, no change in class clay was observed.

The CH class clay was transformed to MH class soil (high plasticity silt) for stabilization with lime alone or a combination of L+NP. A similar trend was observed for the red soil classified as CL class clay which was transformed to MH class soil for stabilization with either lime alone or a combination of L+NP.

The addition of natural pozzolana alone moves the CL class clay to a region between ML class (low plasticity silt) and CL class.



(a)

(b)

Fig. 6 Change in class clay after the tests: (a) grey soil; (b) red soil

The changes in soil classes could be attributed to the flocculation of clays stabilized with lime and natural pozzolana stabilizers. In other words, the modification of the plasticity characteristics of both grey and red soils caused by the addition of natural pozzolana and lime is likely to render these soils more satisfactory for most construction projects even under severe environmental conditions such as rain.

4 Compaction characteristics

The maximum dry density (MDD) and the optimum moisture content (OMC) of both clayey soils mixed with lime, natural pozzolana or their combinations are reported in Figs. 7 and 8.

The results show that the OMC increases but the MDD decreases with the increase of lime addition. A similar behavior was observed before in lime stabilized clayey soils by several researchers [7,17,20,25,28,35,36]. The following reasons could explain this behavior; 1) the lime added causes the aggregation of the particles to occupy larger spaces and hence alters the effective grading of the soils, 2) the specific gravity of lime is generally lower than that of the soils tested, and 3) the pozzolanic reactions between clay particles (alumina and silica) and calcium (from lime addition) are responsible for the increase in OMC.

Figures 7 and 8 show the effect of natural pozzolana (NP) added with different contents on both OMC and MDD. The OMC decreases and the MDD increases as the NP content increases from 0 to 20%. The increase in MDD is an indicator of the improvement of soil properties. Hossain et al. [20] observed an increase in OMC and a decrease in MDD when the content of volcanic ash added increases from 0 to 20%. This is different from our study in NP.

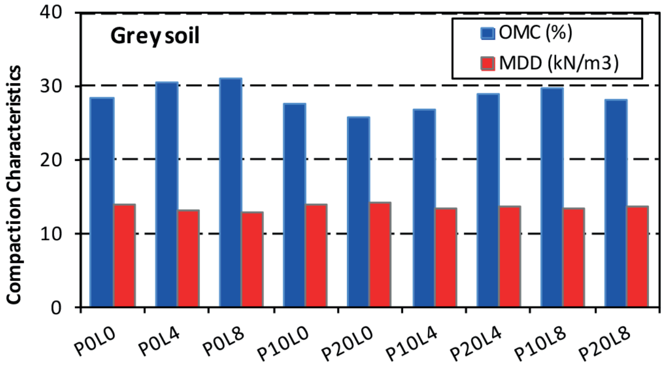
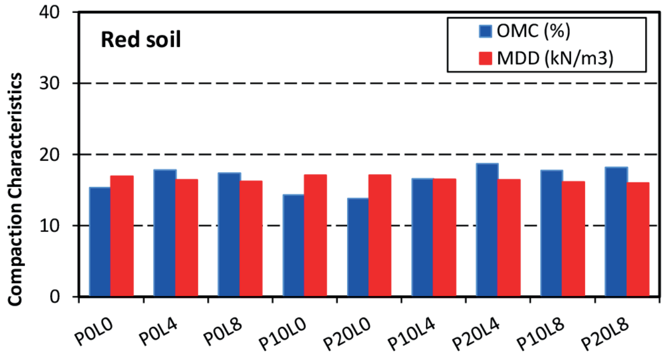


Fig. 7 Compaction characteristics of the grey soil under the different combi-



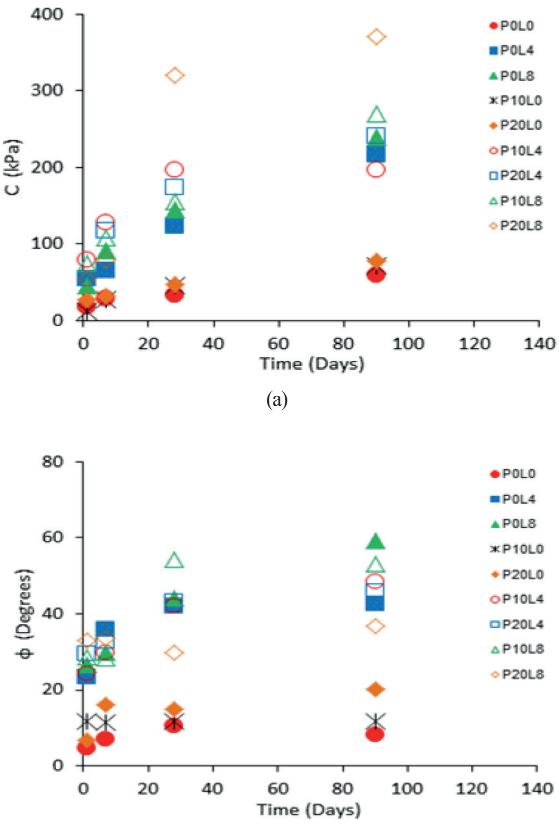
nations of additives

Fig. 8 Compaction characteristics of the red soil under the different combinations of additives

The decrease in OMC observed in our study could apparently have resulted from the lower affinity of NP for water. In addition, the increase in MDD is probably attributed to the relatively higher specific gravity of NP. The addition of a combination of lime with natural pozzolana to the grey soil decreases the OMC but increases the MDD. In the case of the red soil, the combination of lime with natural pozzolana increases the OMC but reduces the MDD, particularly at 20%NP content. Several researchers found that the change in MDD occurs due to the differences in both the particles size and specific gravity between the soil and stabilizers [17,35,37].

5 Shear strength

In slope stability analysis, the maximum shear strength is generally of primary importance. For this reason only the shear strength parameters using the maximum shear stresses were calculated here. The effect of lime, NP and their combinations on the variation of the shear parameters, cohesion and internal friction angle of both grey and red soils was shown in Figs. 9 and 10, respectively.



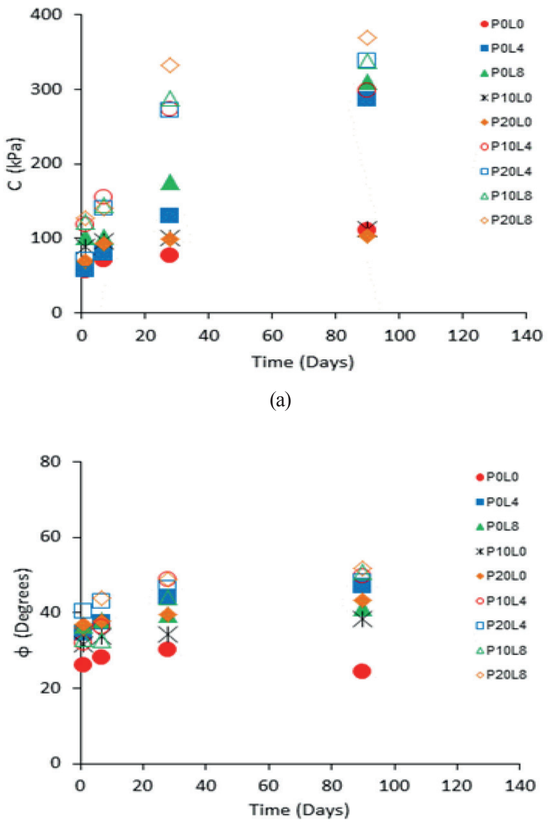
(a)

(b)

Fig. 9 Effect of curing time on the variation of shear strength parameters in the grey soil (a) cohesion and (b) friction angle

The variation of the cohesion of both grey and red soils was shown in Figs. 9(a) and 10(a). The addition of lime has a significant effect on the temporal variation of the cohesion. A considerable increase in cohesion was noticed at later stages and in the samples containing 8% lime. A similar behavior was found by Gay and Schad [36]. This behavior is probably due to the self-hardening effect related to the lime. Ola [38] considered the increase in cohesion with the lime content, to be due to the bonding of particles to form larger aggregates so that the soil behaves as a coarse-grained, strongly bonded particulate material. Others researchers explained this behavior by the cementation and pozzolanic reactions which occur over time [39,40].

The use of natural pozzolana alone as an additive has a marginal effect on the cohesion with curing time. This effect may be slightly pronounced in the grey soil at 90 days. In comparison, however, a considerable increase in cohesion was found at later stages in samples stabilized with the combination of lime and natural pozzolana. In both soils, the combination of 20% NP with 8%L exhibits a high increase in the cohesion beyond 28 days. This trend is particularly noticeable in the grey soil.



(a)

(b)

Fig. 10 Effect of curing time on the variation of shear strength parameters in the red soil (a) cohesion and (b) friction angle

It can be seen from Figs. 9(b) and 10(b) that in both stabilized soils, the internal friction angle increases with time as the lime content increases. However, in the grey soil there is a considerable increase in the internal friction angle beyond 28 days. A similar trend was found by Sezer et al. [41] where they used a very high lime-fly ash content and concluded that this behavior is probably due to the fact that the internal friction angle of the fly ash is more greater than that of the soil.

On the other hand, the addition of natural pozzolana alone has a marginal effect on the internal friction angle with the curing time. In contrast, for the samples stabilized with the combination of lime and natural pozzolana, there is a significant increase in the internal friction angle at later stages. However, for the grey soil, the combination of 20%NP with 8%L has a negligible effect on the internal friction angle independent of the curing period.

The improvement in both cohesion and internal friction angle values may be due to the pozzolanic activity and self-cementitious characteristics of the mixed lime-natural pozzolana. This behavior is more pronounced beyond 28 days.

6 Conclusions

A laboratory investigation was undertaken to study the plasticity (Atterberg's limits), compaction and the shear strength of two clayey soils mixed with different percentages of natural pozzolana, lime and a combination of both. Based on the results obtained from this study, the following conclusions can be drawn:

The plasticity of the soil can be modified by the addition of lime alone. For the grey soil classified as CH class clay, a reduction in liquid limit and an increase in plastic limit have been observed. On the other hand, for red soil classified as CL class clay an increase in both liquid and plastic limits were observed. However, for both investigated clayey soils, the plasticity index (PI) decreased with increasing lime addition.

The addition of natural pozzolana alone to the soil changes to some extent the liquid and plastic limits. A marginal effect on liquid limit and an increase in plastic limit has been observed for the grey soil (CH). For the red soil (CL), a reduction in liquid limit and an increase in plastic limit are noticed. However, for both clayey soils, the plasticity index (PI) decreases with increasing natural pozzolana content.

When both natural pozzolana and lime were added to the soil, an appreciable change of the plasticity behavior has been observed. For the grey soil (CH), this resulted in a marginal decrease in liquid limit and an increase in plastic limit. Their combined effect marginally reduced the plasticity index. For the red soil (CL), no significant change was observed in liquid limit. However, an increase in plastic limit has been observed, whereas the plasticity index reduces considerably, especially for the combination 4%L+NP.

Changes in both CH and CL clayey soils classification according to the unified soil classification system (USCS) are observed. The use of lime alone or in combination with NP transforms both CH and CL classes clays into MH class soils. However, the use of natural pozzolana alone did not affect soil classification for CH class clay but transformed CL class clay to a region between ML and CL class soils.

The maximum dry density of lime-stabilized soils decreases with increasing lime content, in contrast with the natural pozzolana-stabilized soils. The combined treatment of lime and NP affects the maximum dry density which increased in the gray soil but decreased in the red soil. The optimum moisture content of lime-stabilized soils increases with increasing lime content, in contrast with pozzolana-stabilized soils. The combined treatment of lime and NP affects the optimum moisture content which decreased in the grey soil but increased in the red soil.

There is a considerable increase in both cohesion and internal friction angle of samples containing lime especially with curing period. The addition of natural pozzolana results in a marginal effect on both cohesion and internal friction angle with increasing curing period. The combination of lime with natural pozzolana exhibits a significant effect on both cohesion enhancement and internal friction angle at later stages. In both soils and particularly in the grey soil, the combination of 20%NP and 8%L exhibits a high increase in the cohesion beyond 28 days but has a negligible effect on the internal friction angle independent of the curing period. The results showed that the combination of lime with natural pozzolana produces higher shear strength parameters than lime or natural pozzolana used alone.

The results of tests show that the combination lime-natural pozzolana can effectively improve the workability of clayey soils from poor to excellent. There is a lack of information about soil stabilisation with natural pozzolana. Hence, there is a need for further studies on soil treatment with natural pozzolana on different problematic soils in order to identify criteria for lime-natural pozzolana combination selection.

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