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Effect of adding natural pozzolana on geotechnical properties of lime-stabilized clayey soil

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A B S T R A C T

Clayey soils in Syria cover a total area of more than 20,000 km^2 of the country, most of which are located in the southwestern region. In many places of the country, the clayey soils caused severe damage to infrastructures. Extensive studies have been carried out on the stabilization of clayey soils using lime. Syria is rich in both lime and natural pozzolana. However, few works have been conducted to investigate the influence of adding natural pozzolana on the geotechnical properties of lime-treated clayey soils. The aim of this paper is to understand the effect of adding natural pozzolana on some geotechnical properties of lime-stabilized clayey soils. Natural pozzolana and lime are added to soil within the range of 0%–20% and 0%–8%, respectively. Consistency, compaction, California bearing ratio (CBR) and linear shrinkage properties are particularly investigated. The test results show that the investigated properties of lime-treated clayey soils can be considerably enhanced when the natural pozzolana is added as a stabilizing agent. Analysis results of scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) show significant changes in the microstructure of the treated clayey soil. A better flocculation of clayey particles and further formation of cementing materials in the natural pozzolana-lime-treated clayey soil are clearly observed.

1. Introduction

Clayey soils usually have the potential to demonstrate undesirable geotechnical properties, such as low bearing capacity, high compressibility, shrinkage and swell characteristics and high moisture susceptibility (Sakr et al., 2009). Several methods have been adopted to improve the geotechnical properties of such soils so that the stability and serviceability requirements can be met. Among these methods, stabilization of the clayey soils using different additives can basically be considered, because the replacement of the unsuitable soil with good quality soils becomes more and more uneconomical and non-ecological practice. In addition, cement stabilization is nowadays not preferable because of the increasing cost of cement and the environmental concerns related to its production.

Lime is the oldest traditional stabilizer used for soil stabilization (Mallela et al., 2004). Many significant geotechnical properties of clayey soils can be beneficially modified by lime treatment, as lime decreases the plasticity index (PI), increases the workability, shrinkage limit, strength and California bearing ratio (CBR) as well as eliminates almost all swelling problems (Rogers and Glendinning, 1996; Sakr et al., 2009). Lime stabilization refers to the stabilization of soil by the addition of burnt limestone products, either calcium oxide, CaO, or calcium hydroxide, $Ca(OH)_2$. Quick lime is the most frequently used lime product for lime stabilization in Europe (Bell, 1989).

Extensive studies have been carried out on the stabilization of clayey soils using lime (Bell, 1996; Kassim and Chern, 2004; Rao and Shivananda, 2005; Sakr et al., 2009; Ghobadi et al., 2014). Bell (1996) indicated that the optimum addition of lime needed for maximum modification of the soil is normally between 1% and 3% lime by weight, and further addition of lime does not bring changes in the plastic limit (PL), but increases the strength. However, other studies reported the use of lime between 2% and 8% in soil stabilization (Basma and Tuncer, 1991). When lime is added to clayey soils in the presence of water, a number of reactions will occur, leading to the improvement of soil properties. These reactions

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include cation exchange, flocculation, carbonation and pozzolanic reaction. The cation exchange takes place between the cations associated with the surfaces of the clay particles and calcium cations of the lime. The effect of cation exchange and attraction causes clay particles to become close to each other, forming flocs; this process is called flocculation. Flocculation is primarily responsible for the modification of the engineering properties of expansive clayey soils when treated with lime (Ghobadi et al., 2014).

In Syria, clayey soils cover more than 20,000 km^2 of the country, most of which are located in the southwestern region (Abed, 2008). The clayey soils in this region are generally brown to red in color. These clayey soils are the weathering products of the volcanic rocks particularly the basalts. In many places in Syria, these clayey soils caused severe damage to infrastructures. In view of this, the need to improve these soils is necessary. Syria is rich in both limestone and natural pozzolana with estimated reserves of about 12 billion cubic meters and one billion tonnes, respectively (GEGMR, 2007, 2011). Few studies have been carried out to investigate the influence of adding natural pozzolana on the geotechnical properties of lime-treated clayey soils (Hossain et al., 2007; Harichane et al., 2011). However, the recent encouraging results obtained by Al-Swaidani and Aliyan (2015) on adding natural pozzolana as cement replacement were the motivation for this study. According to their study, adding natural pozzolana as a partial substitute for cement can provide economic and ecological benefits. In addition, durability of natural pozzolana-based cement concrete has significantly been enhanced. Better acid, chloride ions penetration and reinforcement corrosion resistances have been proved. Furthermore, cements with higher dosages of natural pozzolana can be used instead of sulfate-resisting Portland cement (SRPC) in sulfate-bearing environments (Al-Swaidani and Aliyan, 2015).

The objective of this paper is to investigate the influence of adding natural pozzolana on some geotechnical properties of lime-stabilized clayey soils. Consistency, compaction, CBR, and linear shrinkage properties have particularly been investigated. Scanning electron microscope (SEM) fitted with energy-dispersive X-ray spectrometer (EDX) was employed to identify the microstructural modification and to analyze the chemical composition of the investigated lime-stabilized clayey soil after adding natural pozzolana. The study is of particular importance not only for Syria but also for other areas of similar geology, e.g. Harrat Al-Shaam, a volcanic field covering a total area of some 45,000 km^2, third of which is located in Syria (Fig. 1). The rest covers parts of Jordan and Saudi Arabia.

2. Materials and methods

2.1. Materials

2.1.1. Soil

The soil samples used in the study have been obtained from a site called Aalqeen situated at about 40 km southwest of Damascus.

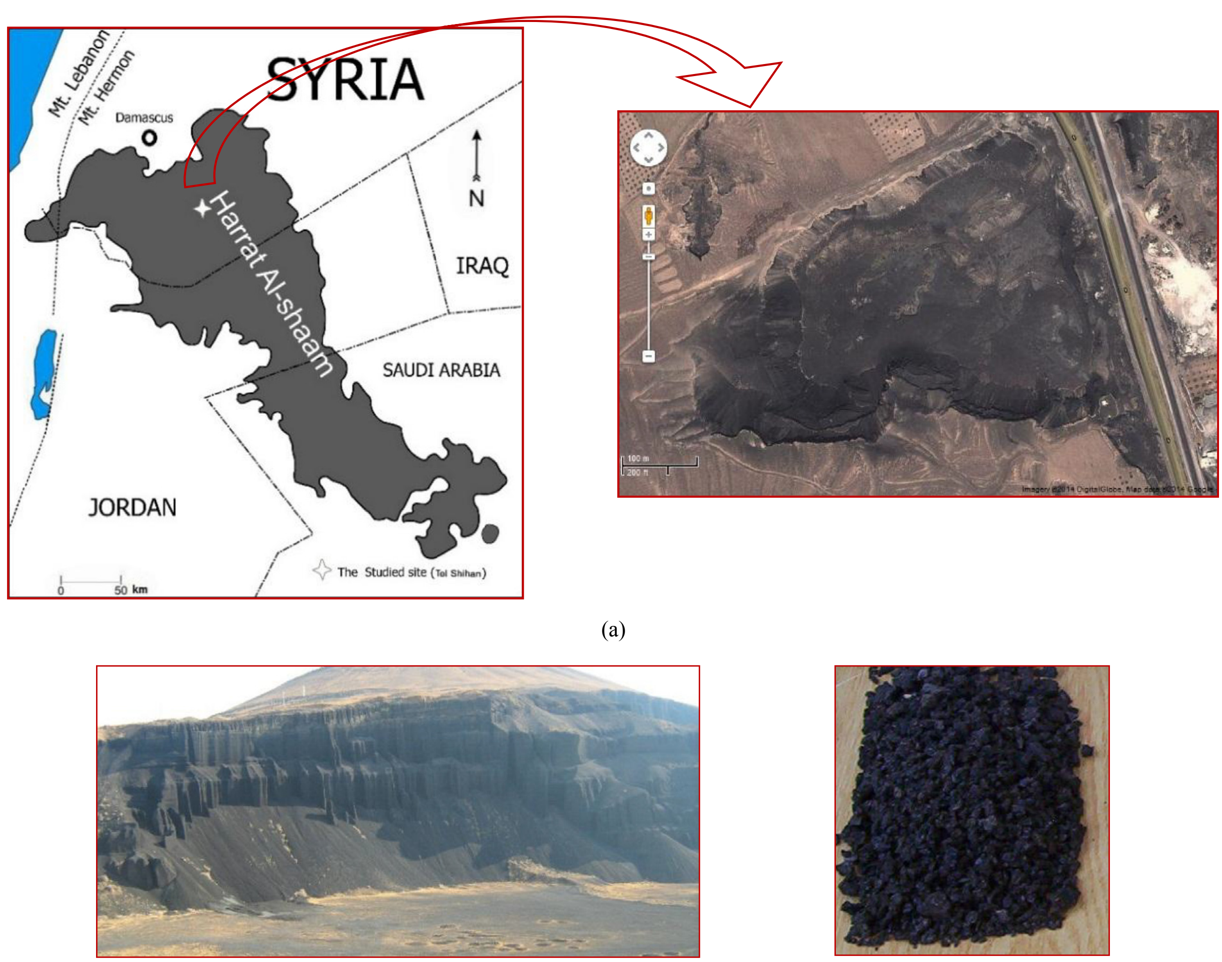

Fig. 1. (a) Map of Harrat Al-Shaam with a satellite view of the studied area. (b) Photo of studied natural pozzolana quarry. (c) Photo of studied natural pozzolana aggregate.

The clayey soil was extracted at a depth of about 1 m. Laboratory tests have been carried out to classify the soil. Particle size distributions of the studied soil conducted by "Horiba laser analyzer LA-950" are plotted in Fig. 2a. The gradation of soil revealed percentage passing No. 200 sieve (<0.075 mm) as 95%. Fig. 2b shows a micrograph of the studied clayey soil. The XRD analysis showed that the studied clay consists of clay and non-clay minerals. The clay minerals are kaolinite, illite and montmorillonite, with the percentages of 23%, 14% and 7%, respectively. The main non-clay minerals are quartz, feldspar and calcite, as shown in Fig. 3. The basic properties of the clayey soil are presented in Table 1. The liquid limits (LLs) greater than 50% confirmed the results obtained from X-ray diffraction which indicated the presence of montmorillonite and illite. The studied soil is classified as CH soil (fat clay) according to the unified soil classification system (USCS).

2.1.2. Lime

The lime used was a quick lime. It was quarried from Hama Governance at about 200 km north of Damascus, and then calcined at 950 °C. The chemical composition and some physical properties of lime are presented in Table 2. The particle size distribution of the lime is illustrated in Fig. 2a.

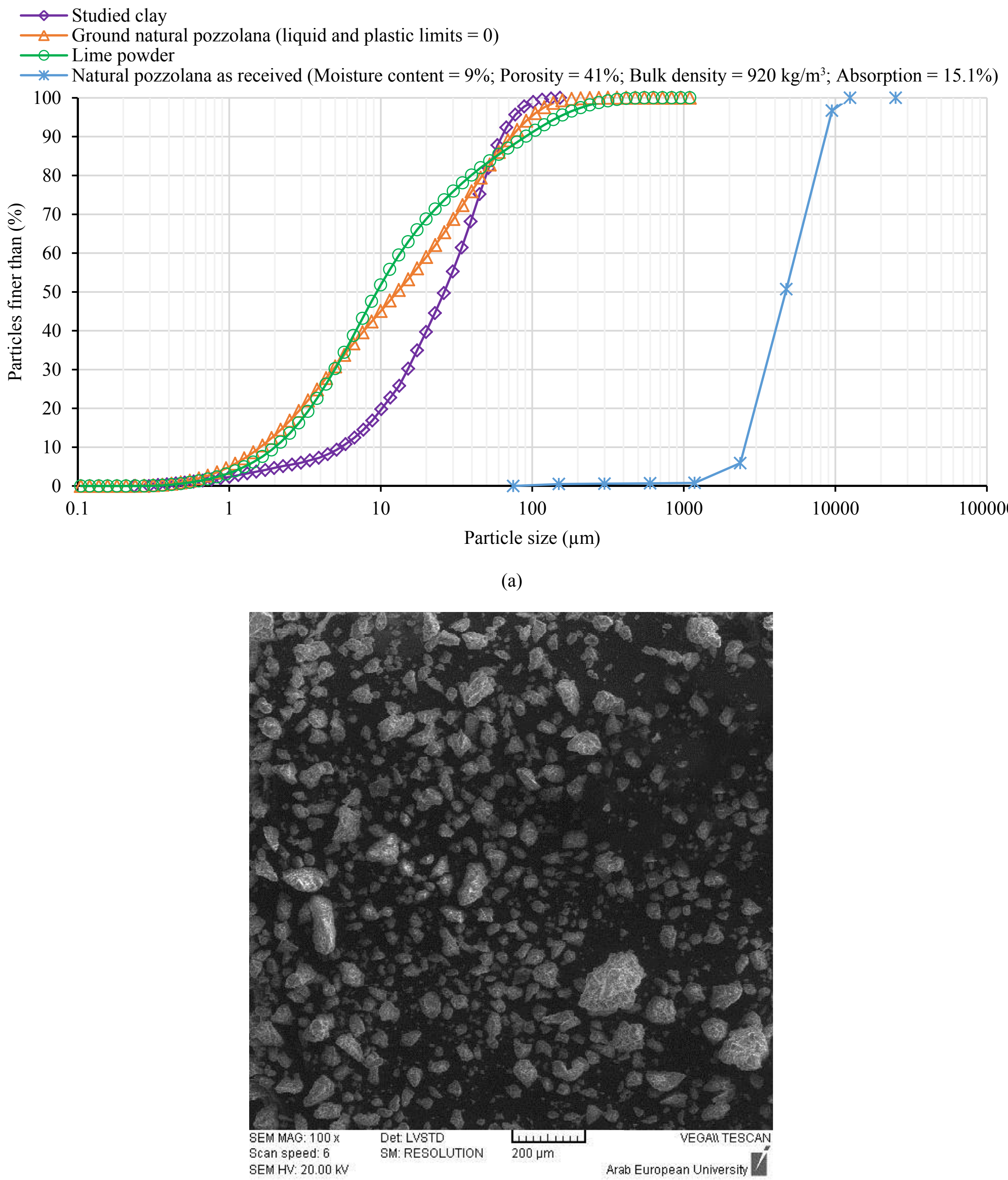

Fig. 2. (a) Particle size distribution of the studied materials and (b) a micrograph of the soil.

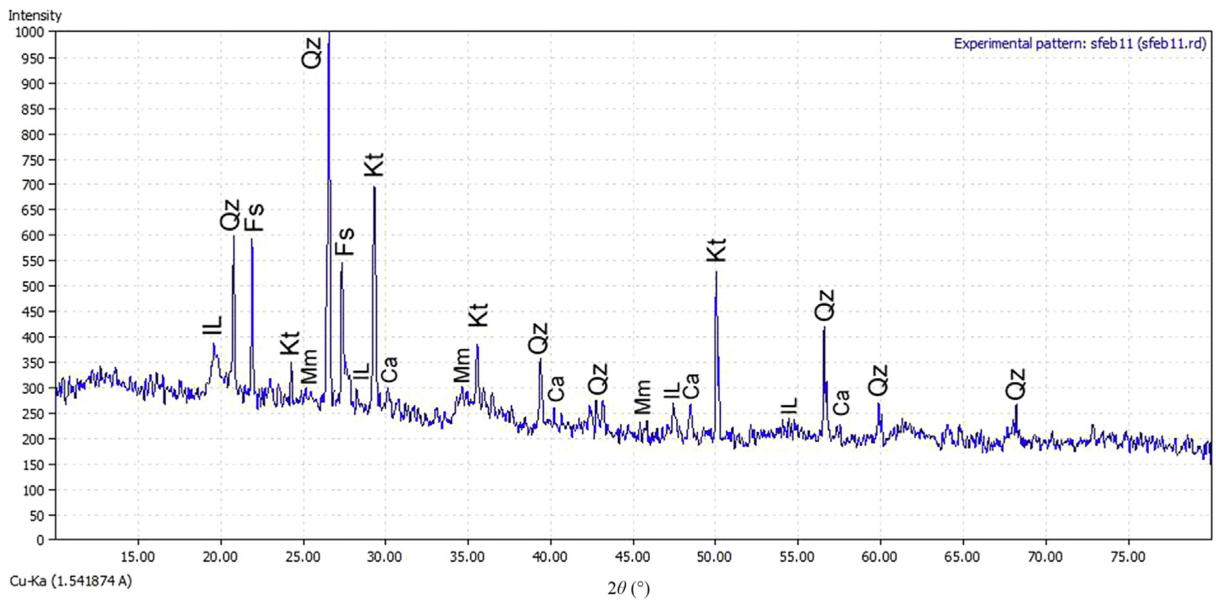

Fig. 3. XRD pattern of soil sample. Kt: kaolinite; Qz: quartz; IL: illite; Mm: montmorillonite; Fs: feldspar; Ca: calcite.

Table 1
Basic properties of the studied clayey soil.

Color	Depth (m)	Specific gravity	Passing 75 μm (%)	Median particle size (μm)	LL (%)	PL (%)	PI (%)	Classification (USCS)	Optimum moisture content (OMC) (%)	Maximum dry density (MDD) (kN/m^3)	CBR of soaked sample (%)	CBR of non-soaked sample (%)	Swelling using CBR mold (%)
Brown to red	1	2.68	95	27	58.8	30	28.8	CH	27	14.8	2.89	6.38	7.41

Table 2
Chemical composition and some physical properties of lime and natural pozzolana.

Type	Chemical composition (%)									Physical properties			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	Loss on ignition (LOI)	Blaine fineness (cm^2/g)	Specific gravity	Pozzolana activity index (%) (ASTM C618, 2003)
Lime	–	–	0.47	93.7	0.53	1.2	–	–	–	3.9	4000	2.2	–
Natural pozzolana	46.5[a]	19.28	11.22	8.5	5.48	0.14	2.7	3.61	1.88	0.6	3800	2.85	78 (at 7 d), 90 (at 28 d)

[a] $SiO_{2\ reactive}$ content in the studied natural pozzolana = 42.66% (determined in accordance with EN 196-2 (1989)).

2.1.3. Natural pozzolana

ASTM C125 (2003) describes pozzolana as a siliceous or silicious and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. The natural pozzolana used in the experiments was collected from a Tal Shihan's quarry, about 70 km southeast of Damascus, as shown in Fig. 1. The petrographical examination showed that the natural pozzolana consists of amorphous glassy ground mass, vesicles, plagioclase, olivine and pyroxene with the percentages (based on an optical estimate) of 20%, 30%, 20%, 15% and 15%, respectively. The natural pozzolana is dark black to blackish-grey in color with some red-brown spots, mostly due to its iron oxides content. Fig. 4 shows a thin section of the natural pozzolana used. The chemical analysis of natural pozzolana used in the study with some physical and mechanical properties is summarized in Table 2. This analysis was carried out by means of wet chemical analysis specified in EN 196-2 (1989). Some further physical properties of the added natural pozzolana with the particle size distribution are also displayed in Fig. 2a.

2.2. Methods

A series of laboratory tests consisting of initial consumption of lime, Atterberg limits, compaction, CBR and linear shrinkage tests was conducted on the clayey soil. The percentages of natural pozzolana used in the mixtures were 0%, 10% and 20%, while the percentages of lime were determined depending on the initial consumption of lime tested. All replacement levels were made by mass.

2.2.1. Initial consumption of lime (ICL)

The initial consumption of lime (ICL) was conducted in accordance with BS 1924 (1990). ICL gives an indication of the minimum quantity of lime that must be added to a material to achieve a significant change in properties. During lime stabilization reactions, the highly alkali soil pH value (12.4) promotes dissolution of siliceous and aluminous compounds from the clay mineral lattice. The

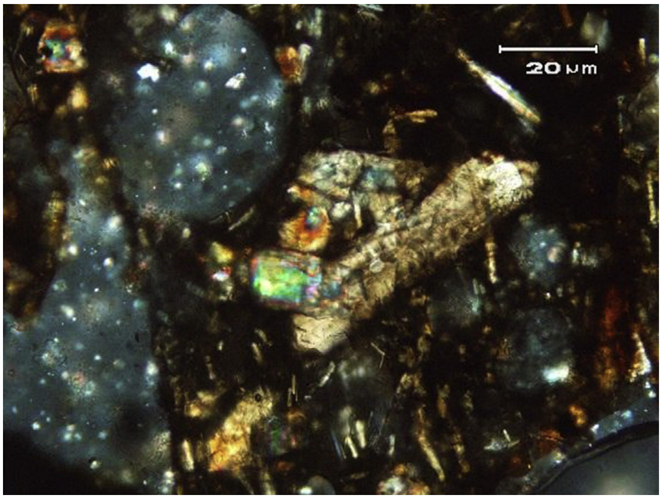

Fig. 4. Microphenocrysts of olivine, pyroxene and elongated plagioclase in volcanic glass matrix with vesicles, some of which are filled with white minerals.

compounds dissolved from the clay mineral lattice react with calcium ions in pore water to form calcium silicate hydrate (C–S–H) and calcium aluminum hydrate (C–A–H) gels, which coat the soil particles and subsequently crystallize to bond them. Stabilizing the clayey soil with lime contents greater than its ICL value thus ensures occurrence of cementitious pozzolanic reactions in the clayey soil.

The plot of pH values corrected at 25 °C versus lime content is illustrated in Fig. 5. The pH value of 8.01 puts the studied clayey soil in the slight alkaline range. At 8% lime content, the pH value of the treated soil increases to 12.63. The 4% lime content has pH value (12.46) of more than 12.4 which is necessary for pozzolanic reaction to occur. At this point, the silica and alumina components in the clayey soil are dissolved out of the soil and make it available to react with Ca^{2+} to form cementing products of calcium silicates and aluminates. Based on the test results, three percentages of the lime were employed (0%, 4% and 8%). A total of nine combinations, as shown in Table 3, thus were studied.

2.2.2. Atterberg limits tests

The PL, LL and PI were obtained following the method given in ASTM D4318 (2000). Variations in the PI of untreated and treated clayey soils were then studied. The PL tests were performed on material prepared for the LL test. Both PL and LL tests were conducted at room temperature.

2.2.3. Compaction test

The standard Proctor compaction tests were conducted in accordance with ASTM D698 (2000). This method was adopted to determine the MDD and OMC of the investigated soils. The air-dried clayey soil was mixed with different percentages of lime and natural pozzolana. Distilled water was added to the soil mixture. The quantity of lime and natural pozzolana added to the soil was taken as a percentage of dry weight of soil. The soil mixtures, with and without additives, were thoroughly mixed for 1 h prior to compaction. The first series of compaction tests was aimed at determining the compaction properties of untreated soils. The second series was carried out to determine the Proctor compaction properties of the stabilized soils with varying amounts of lime and natural pozzolana.

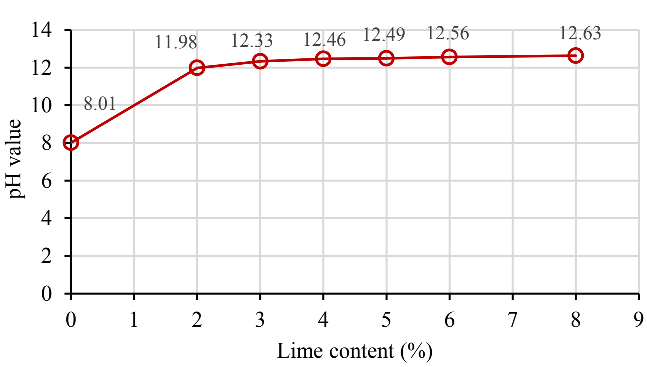

Fig. 5. Effect of lime content on pH value of lime-treated soil.

Table 3
Mixtures used for stabilized soil.

Soil mixture	Percentage (%)		
	Clayey soil	Lime	Natural pozzolana
0% Natural pozzolana and 0% lime (control)	100	0	0
0% Natural pozzolana and 4% lime	96	4	0
0% Natural pozzolana and 8% lime	92	8	0
10% Natural pozzolana and 0% lime	90	0	10
10% Natural pozzolana and 4% lime	86	4	10
10% Natural pozzolana and 8% lime	82	8	10
20% Natural pozzolana and 0% lime	80	0	20
20% Natural pozzolana and 4% lime	76	4	20
20% Natural pozzolana and 8% lime	72	8	20

2.2.4. California bearing ratio test

The CBR value is widely used in the design of pavement courses. It is one of the common tests used to evaluate the strength of soils. The CBR test was carried out in accordance with ASTM D1883 (1999). Three samples from each soil mixture have been tested after being soaked in water for 96 h. The soaked condition simulates the behavior of subgrade under heavy rainfall or flooded situations. In this research, samples were compacted to a MDD at the OMC determined by standard Proctor tests.

2.2.5. Determination of linear shrinkage

The bar linear shrinkage test is one of the most commonly used test methods for determining the shrinkage strain potential. This test was carried out in accordance with BS 1377 (1990). About 150 g of the soil sample passing No. 40 sieve was mixed with distilled water; approximately 2% of the soil above the LL and the soil paste were left to stand for a sufficient time (24 h) to allow the moisture to permeate throughout the soil mass. The thoroughly mixed soil-water paste was placed in the shrinkage mold, and then gently jarred to remove any air pockets in the paste. The soil was leveled off along the top of the mold with the palette knife. Drying mold first started at a temperature of 60 °C–65 °C until shrinkage has largely ceased and then was completed at 105 °C–110 °C. The linear shrinkage index (*LSI*) of the soil was calculated by

$$LSI = 1 - L_{avg}/L_0$$

where L_{avg} is the average length of soil (mm), and L_0 is the original length of brass mold (mm).

3. Results and discussion

3.1. Atterberg limits

Table 4 presents the results of Atterberg limits determined under different additive contents. The PI variations for both untreated and treated soils are shown in Fig. 6. The decrease in PI indicates an improvement in the workability of the soil. The higher the PI is, the greater the quantum of water that can be imbibed by the soil is, and

Table 4
Atterberg limits of the studied mixtures. All LL, PL and PI values are in percent.

Soil mixture	LL	PL	PI
0% Natural pozzolana and 0% lime (control)	58.8	30	28.8
0% Natural pozzolana and 4% lime	50.8	44.75	6.05
0% Natural pozzolana and 8% lime	49.9	44.11	5.79
10% Natural pozzolana and 0% lime	57	34.23	22.77
10% Natural pozzolana and 4% lime	47	42.21	4.79
10% Natural pozzolana and 8% lime	48	43.56	4.44
20% Natural pozzolana and 0% lime	56.1	34.86	21.24
20% Natural pozzolana and 4% lime	43.2	40.24	2.96
20% Natural pozzolana and 8% lime	44.4	41.53	2.87

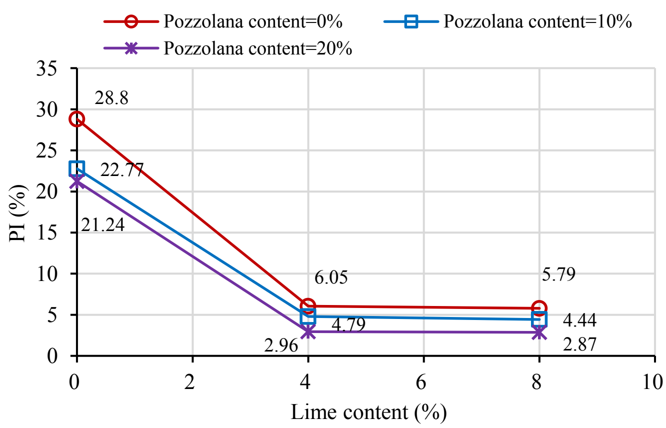

Fig. 6. Effect of natural pozzolana on PI of lime-stabilized clayey soil.

hence the greater its swell potential would be (Rao, 2006). The soil showed an immediate decrease in PI upon the addition of lime. It is obvious that an addition of 4% of lime was sufficient to enhance the workability of the soil by reducing the PI from 28.8% to 6.05%. Increasing the lime content beyond 4% had a marginal effect on reducing the PI. Similar behavior was found by several researchers for soil classified as CH class clay (Nalbantoglu, 2006; Harichane et al., 2011). This can be attributed to the chemical reactions between lime and soil including ion exchange and associated flocculation reactions (Puppala et al., 2006). The addition of lime to plastic soils causes a colloidal reaction which includes a replacement of naturally carried cations on clay surface by Ca^{2+} cations, an increase in pH value and a reduction in double layer water. This helps in flocculation and aggregation of colloidal clay particles, making them less plastic (Samantasinghar, 2014).

The addition of natural pozzolana alone enhances the workability as a result of a reduction in the plasticity of the soil. A reduction of the PI from 28.8% to 22.77% and 21.44% was observed for 10% and 20% pozzolana contents, respectively. The addition of natural pozzolana alone had reduced the PI by about 20% and 30% when added at percentages of 10% and 20%, respectively. A similar trend was observed by Parsons and Kneebone (2005) and Harichane et al. (2011) when they used natural pozzolana and fly ash, respectively. However, the combination of 20% natural pozzolana and 8% lime exhibited the highest effect on reducing the PI. The PI decreased from 28.8% to 2.87% when the “control” and 20% natural pozzolana and 8% lime mixtures were used, respectively.

The Atterberg limits test results are plotted on the Casagrande plasticity chart in order to determine the soil classification in accordance with the USCS, as shown in Fig. 7. It is clearly seen from Fig. 7 that the soil is classified as CH class clay. After the addition of natural pozzolana alone, the soil falls in the class of MH soil. However, the only 8% lime content makes the soil fall in ML class. On the other hand, all mixtures containing both natural pozzolana and lime moves the soil class from CH to ML. This renders the soil satisfactory for most construction operations even under severe environmental conditions.

3.2. Compaction properties

The compaction test was used to determine the effect of natural pozzolana on OMC and MDD of the studied clayey soil. Fig. 8 shows the effect of the addition of natural pozzolana, lime and their combinations on the compaction properties of the soil tested. It can be clearly seen that adding lime alone increases the OMC and decreases the amount of MDD with increasing lime content. Adding 4% lime has increased OMC from 27% to 31% and decreased the MDD from 14.8 kN/m^3 to 14.1 kN/m^3 when compared to 0% lime added. Similar behavior was also observed in the literature in the case of lime-stabilized clayey soils (Rahman, 1986; Bell, 1996;

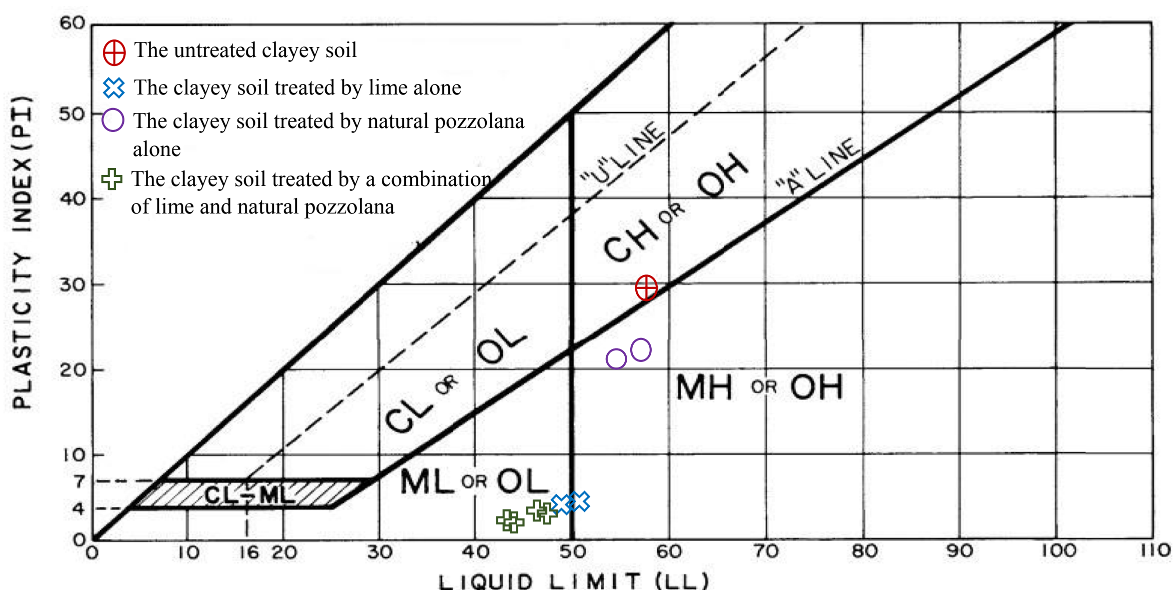

Fig. 7. Location of untreated and treated clayey soils in the Casagrande plasticity chart.

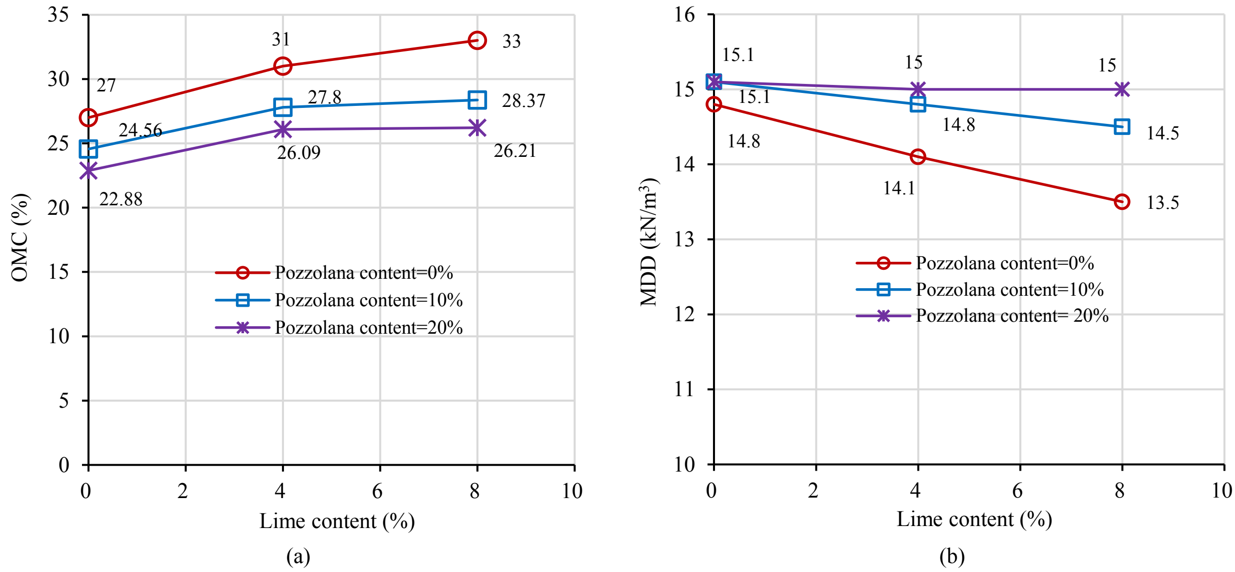

Fig. 8. Variation in compaction properties of lime-stabilized clayey soil with varying amounts of natural pozzolana. (a) OMM; (b) MDD.

Hossain et al., 2007; Kavak and Akyarli, 2007; Manasseh and Olufemi, 2008; Harichane et al., 2011). The explanation of this behavior is probably a consequence of the following reasons: (1) the lime causes 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 soil tested; (3) the pozzolanic reaction between the clay present in the soil and the lime is responsible for the increase in OMC (Harichane et al., 2011).

By adding natural pozzolana alone as stabilizer, the OMC decreases and the MDD increases, as shown in Fig. 8. It is clearly seen from Fig. 8 that the OMC decreases from 27% to 22.88% when the natural pozzolana content increases from 0% to 20%. This decrease in OMC could be attributed to the lower affinity of natural pozzolana to water. The MDD amount increases from 14.8 kN/m^3 to 15.1 kN/m^3 when the natural pozzolana increases from 0% to 20%. The increase in MDD is an indicator of soil properties improvement. A similar trend has been observed by Hossain et al. (2007) and Harichane et al. (2011) when natural pozzolana of similar contents was used. This increase in MDD is probably a result of the higher specific gravity of the natural pozzolana used. It is interesting to note from Fig. 8b that the significant reduction in MDD with 8% lime has been compensated by adding 20% natural pozzolana. The MDD increases from 13.5 kN/m^3 to 15 kN/m^3 with adding 20% natural pozzolana.

One can see from Fig. 8a that the increase in OMC has been compensated as well with adding 20% natural pozzolana. It decreases from 33% with 8% lime to 26.21% with 20% natural pozzolana. By comparing the relationship between OMC and MDD with the equation developed by Di Matteo et al. (2009), as shown in Fig. 9, it is apparently seen that the results of the studied soil samples are in good agreement with those predicted by the model developed by Di Matteo et al. (2009). The equation developed in the study is similar to that developed by Di Matteo et al. (2009) with a regression coefficient (R^2) of 0.86. According to Montgomery and Peck (1982), a regression coefficient, R^2, of more than 0.85 indicates an excellent correlation between the fitted parameters.

3.3. California bearing ratio

CBR values are closely related to both compressive strength and the bearing capacity of compacted subgrade. Therefore, this test is

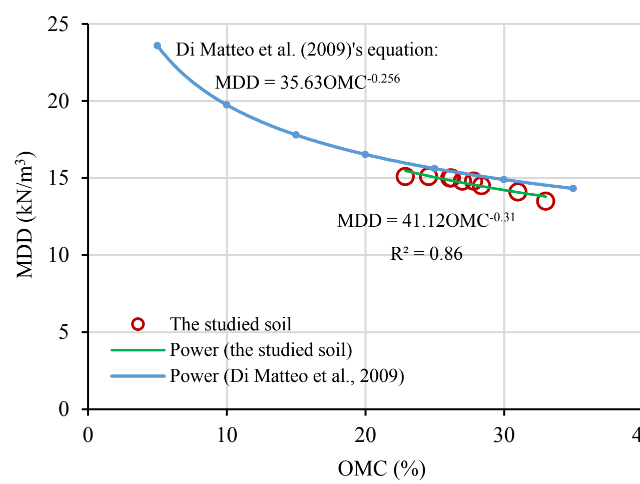

Fig. 9. Relationship between MDD and OMC for the soil tested.

most appropriate to quantify the suitability of any compacted subgrade (Indraranta, 1994). The results obtained from the CBR test carried out on both the unstabilized and stabilized clayey soil samples are shown in Fig. 10. The results show that the CBR increased from 2.89 to 55.76 and 66.02 with an increase in lime content from 0% to 4% and 8%, respectively. The increment in CBR may be attributed to the gradual formation of cementitious compounds in the soil as a result of the pozzolanic reaction between lime and clayey soil.

The natural pozzolana alone has increased the CBR value from 2.89 to 22.34 with an increase in pozzolana content from 0% to 20%. It should be noted from Fig. 10 that a 15% minimum CBR value required for pavement subgrades was thus attained by all treated soil samples except that of 10% natural pozzolana content. The lime when added alone enhanced the CBR more effectively than natural pozzolana. However, the enhancement by adding lime alone reached only a 66% CBR value at 8% lime content. The highest soaked CBR value of 90% (a value that normally characterizes an excellent compacted pavement subgrade (Hossain et al., 2007)) was attained when adding 20% natural pozzolana to 8% lime-treated soil

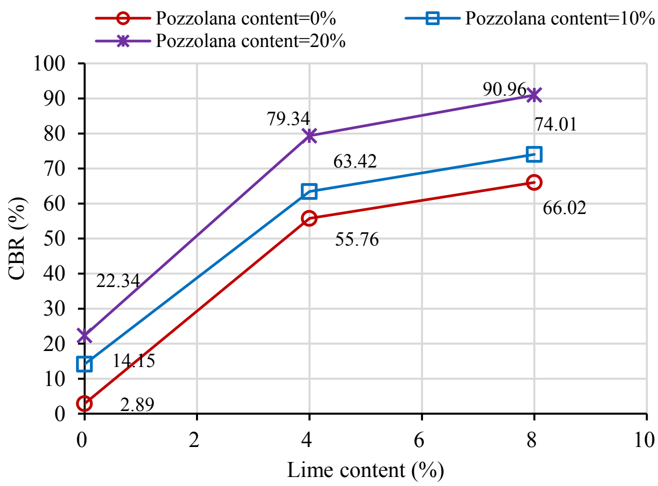

Fig. 10. Variation in CBR values of lime-treated soil with varying amounts of natural pozzolana.

sample. According to Emesiobi (2000), the improved soaked CBR value of up to 90% is a very stable material for subgrade. The increment in CBR value at 20% natural pozzolana and 8% lime may be attributed to the pozzolanic properties of the used natural pozzolana ($SiO_{2\ reactive}$ = 42.66%) and the gradual formation of cementing compounds between lime, natural pozzolana and clay.

3.4. Linear shrinkage index

Linear shrinkage index is defined as the ratio of decrease in linear dimension of a specimen to its initial dimension, expressed in percent and is given by the nearest whole number (Rao, 2006). The linear shrinkage test measures shrinkage strain of elongated soil specimens placed in a brass mold and subjected to drying in an oven for 24 h.

Fig. 11 shows the variation in linear shrinkage value for untreated and treated soils. The addition of lime to the clayey soils showed a reduction in shrinkage with increasing lime content. This reduction can be due to chemical reactions between lime and clay which result in reduction in plasticity properties and related shrinkage strain (Kariuki et al., 2006). The addition of natural pozzolana alone had an insignificant effect on the linear shrinkage of clayey soil. The 20% natural pozzolana-treated clayey soil showed a linear shrinkage strain of 13.25%, in contrast with 6.04% at 4% lime content. Lime treatments were more effective in reducing linear shrinkage strains than natural pozzolana treatment alone. However, when 20% natural pozzolana was added to 8% lime-treated soil sample, the lowest shrinkage strain (4.17%) was attained. These reductions are quite significant since expansive soils with such low shrinkage strains are considered non-problematic and they do not undergo any desiccation cracks (Kariuki et al., 2006).

3.5. Microstructure observations of treated clayey soil

SEM study was conducted on three paste specimens, i.e. untreated clayey soil, 8% lime-treated clayey soil, and 20% natural pozzolana and 8% lime-treated clayey soil. Furthermore, EDX spectrum was used to monitor the changes occurring in the chemical composition at selected locations within the investigated clayey soil before and after treatment. Fragments of these 7-d cured paste specimens dried, broken off and washed with acetone were examined and analyzed by SEM and EDX techniques. Figs. 12–14 show the SEM micrographs and EDX analysis at different locations of the examined specimens.

It is clearly seen from Fig. 12 that the untreated clayey soil has a discontinuous structure, where the pores are more visible as no hydration products exist. The EDX results showed majority of Si and Al and traces of Ca, Fe, K, Na in the untreated clayey soil.

Figs. 13 and 14 show significant changes in the microstructure of the clayey soil when mixed with either lime or lime-natural pozzolana and cured for 7 d. It could be observed in Fig. 13 that the clayey surface is covered with cementitious reaction products such as C–S–H and calcium aluminum silicate hydrates (C–A–S–H) which contain distinct peaks of Ca, Si and Al elements based on the EDX analysis. This observation is consistent with that reported by Chaunasli and Peethamparan (2010). The Ca/Si ratio was found to vary between 0.75 and 1.2. In addition, as a result of cation exchange of calcium ions (Ca^{2+}), a better flocculation of clayey particles is also evident from Fig. 13. Thus, changes in the plasticity properties of clay and a reduction in linear shrinkage values could be expected.

Cementing materials such as C–S–H and C–A–S–H were also detected in natural pozzolana-lime-treated clayey soil, as clearly seen in Fig. 14, indicating that a pozzolanic reaction had taken place

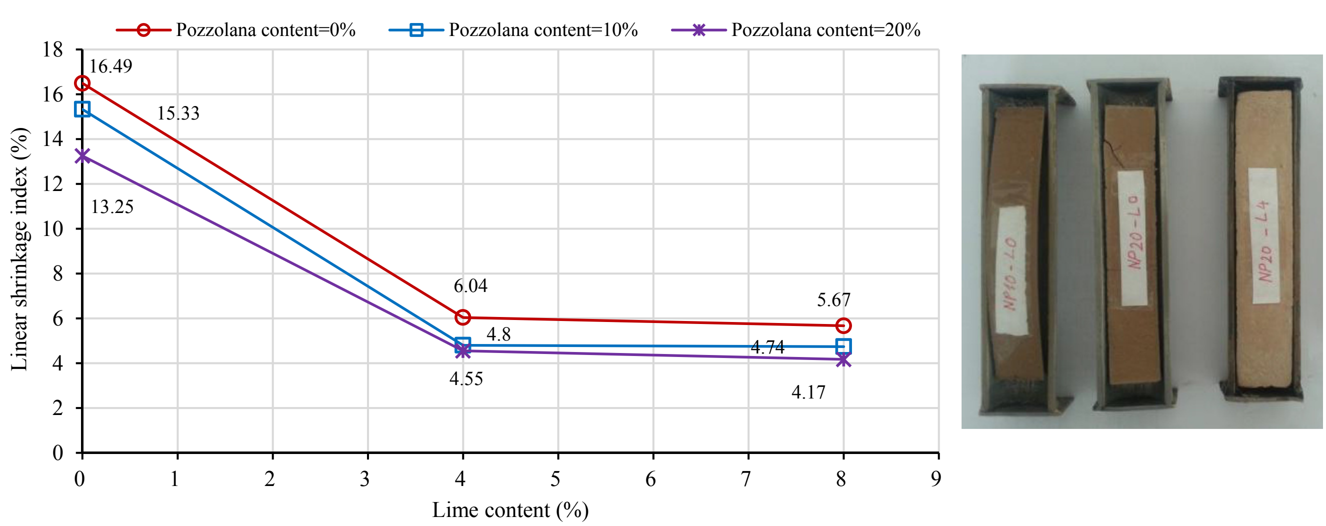

Fig. 11. Variation in linear shrinkage of lime-treated clayey soil with varying amount of natural pozzolana.

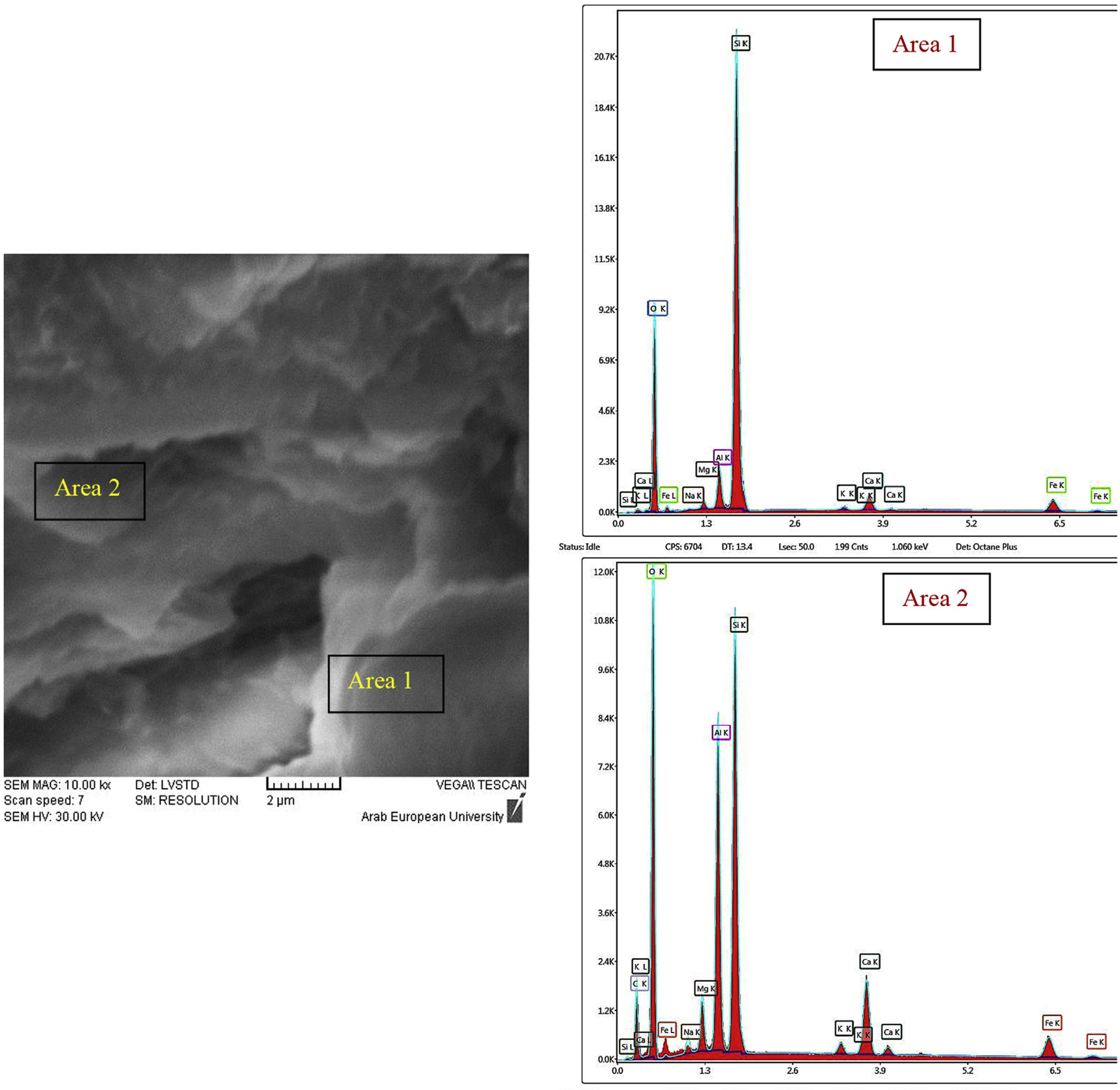

Fig. 12. SEM micrograph and EDX spectra of untreated clayey soil paste specimen cured for 7 d.

in the treated clayey soil between CaO present in lime and SiO_2 and Al_2O_3 in the soil and natural pozzolana. These cementitious compounds produced are characterized by their high strength (Lav and Lav, 2000) and low volume change. The Ca/Si ratios in C–S–H and C–A–S–H phases formed in the 20% natural pozzolana and 8% lime-treated clayey soil were higher compared with those obtained when the lime has solely been added. They ranged from 0.9 to 3.1, which give an indication of the formation of additional new cementing phases when natural pozzolana was added. Additionally, the pores in the untreated clayey paste specimens have been filled with such cementing materials. Hence, improved properties exhibited by treated clayey soil could be mainly attributed to the aforementioned cementing materials.

4. Conclusions

This study presents the effect of natural pozzolana on consistency, compaction, CBR and linear shrinkage of lime-stabilized clayey soil. On the basis of the test results, the following conclusions can be drawn:

(1) The PI of lime-treated clayey soil decreased with increasing natural pozzolana. Reduction of this index is an indicator of improvement which can be correlated with an increase in the strength and a reduction in swelling and compressibility. The use of natural pozzolana alone and 4% lime content transformed the studied clayey soil from CH into

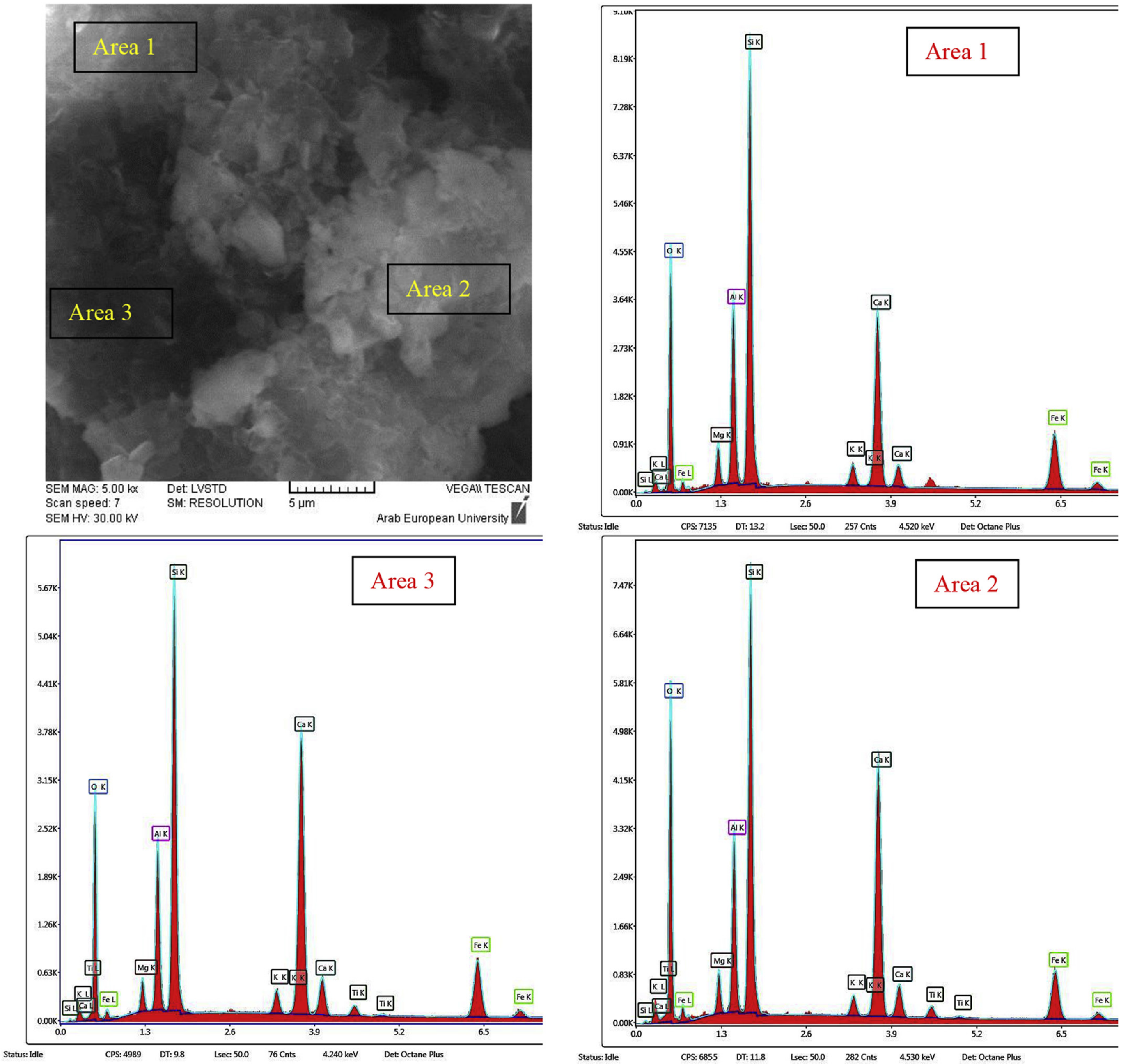

Fig. 13. SEM micrograph and EDX spectra of 8% lime-treated clayey soil paste specimen cured for 7 d.

MH class soil. However, adding natural pozzolana to lime-stabilized clayey soil moved the studied soil to ML class soil.

(2) The MDD of lime-stabilized clayey soil was significantly affected by adding natural pozzolana. The appreciable drop in MDD obtained at 8% lime content has been compensated with adding 20% natural pozzolana. On the other hand, the OMC was also reduced when adding 20% natural pozzolana to 8% lime-stabilized clayey soil.

(3) Adding natural pozzolana has a beneficial effect on the bearing capacity of lime-treated soil. It has the potential to significantly increase the CBR value up to 90% (a value that normally characterizes an excellently compacted pavement subgrade).

(4) Although linear shrinkage strains of lime-treated clayey soil samples have considerably been reduced with increasing lime content when compared to untreated soil, further reductions were noted with adding natural pozzolana.

(5) Microscopic analyses confirmed that the addition of lime or lime and natural pozzolana to the investigated clayey soil has caused a marked change in morphology. The SEM and EDX results showed presence of C–S–H and C–A–S–H in both lime- and natural pozzolana-lime-treated clayey soils. These cementitious phases induced significant

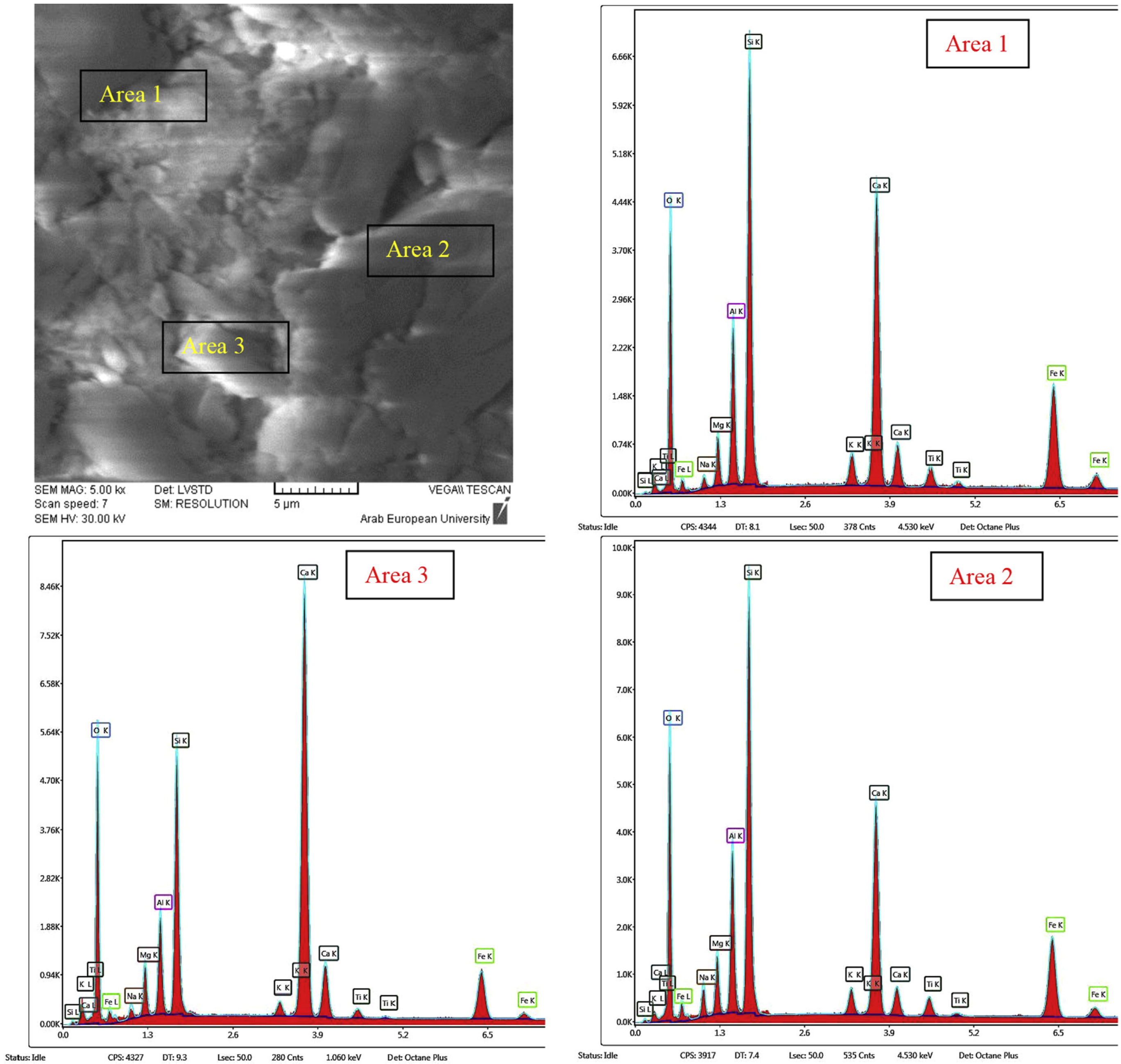

Fig. 14. SEM micrograph and EDX spectra of 20% natural pozzolana and 8% lime-treated clayey soil paste specimen cured for 7 d.

improvements in the engineering properties of the investigated clayey soil, such as workability, compaction, strength and shrinkage.

(6) The higher Ca/Si observed in the microstructure of the natural pozzolana-lime-treated clayey soil could be due to further pozzolanic reactions occurring when natural pozzolana was added. Hence, further improvements could be expected with adding natural pozzolana to lime-treated clayey soil, particularly with a longer curing time.

From the foregoing investigation, it would appear that natural pozzolana performs satisfactorily and is recommended for using with lime-stabilized subgrade clayey soils in road construction. Using natural pozzolana is considered to be an economic and ecological practice, because of the low cost of natural pozzolana and the reduction of CO_2 emissions when compared to other practices.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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