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RESEARCH **Open Access**

Effectiveness of lime kiln dust on swelling of subgrade expansive soil

Mennat-allah Eid[1*], Youssef Gomaa[1] and Sameh Galal[1]

Abstract

Background The structure of flexible or rigid pavement built on expansive subgrade soil that has a volumetric change is vulnerable to many problems that might cause failure. Pavement and construction became more durable and economical by enhancing the quality of subgrade expansive soil. Solid waste recycling has become very popular recently as a means of attaining sustainable waste management, so using lime kiln dust (LKD), which is a by-product of quick lime production, to treat expansive soil in pavement subgrades. This research describes the effect of LKD on the chemical composition, strength, and swelling of high and low-plastic clay that were extracted from two sites. The minimum LKD required for treating expansive soils was determined by using the Eades and Grim pH test. From tests, it was found that the addition of LKD increased the shrinkage limit by a range (250–500)% and decreased the plasticity and swelling potential by between (50 and 100)% of expansive subgrade soils. The strength according to CBR, increased approximately by 150% for CL soil and 800% for CH soil.

Results The optimal percentage of LKD for CH soil is 6%, and for CL soil, it is 2%. The plastic limit increased by 50% for CH soil at 6% LKD. On the other hand, CL soil became non-plastic at 4% LKD. With an increase in the percentage of LKD, it led an the increase in the shrinkage limit by 500% in CH soil and 250% in CL soil. The free swell decreased by 50% in CH soil and 100% in CL soil. The swelling pressure decreased by 50% for two expansive soils. CBR increased by 800% in CH soil and by 150% in CL soil.

Conclusion This work found that the addition of LKD improves the physical, chemical, and mechanical properties of expansive subgrade soil.

Keywords Expansive soil, Stabilization, Swelling, Chemical treatment, Lime kiln dust, Atterberg limits, Pavement subgrade

1 Background

One of the most problematic and commonly encountered soils for a geotechnical engineer is expansive soil. It is greatly expanded when exposed to water and contracts when the water is removed from the soil. It presents a significant challenge to civil engineers worldwide as they severely degrade structures built on them, including pavement distortion and cracking.

In road construction, it is expensive to replace large volumes of expansive soil with more suitable soil or material, especially if the desired soil needs to be imported. To prevent deflection that could cause fatigue cracking in the layers above, the layers under the pavement must have the minimum specified structural quality to support and distribute the traffic loads.

Due to increased waste products and widespread manufacturing after the Industrial Revolution, the generation of by-product waste was an unfortunate side effect of industrialization. Consequently, there were problems with pollution, disposal, and management [1]. There has been a lot of research done recently on the use of industrial wastes in soil engineering, particularly in soil

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stabilization [2]. LKD is a solid waste that is produced from manufacturing quick lime. A lime kiln produces gases and dust during the process of turning limestone into lime. The gases are then released into the atmosphere, while the dust is collected [3].

LKD has been utilized as an additive in some states, including Michigan, Illinois, Indiana, and Kansas, to improve the workability of clayey soils and stabilize subgrade. After three days of compaction, the CBR values of the treated subgrade increased by approximately 125% when compared with the untreated soil [4, 5]. It was found that 5% LKD reduced the plasticity of five soils used in this study [4]. LKD had very little effect on the liquid and plastic limits on the test soil [5]. An extensive field experiment was conducted to determine the characteristics of subgrade soils treated with LKD in pavements that had been in use for at least five years [6]. LKD reduced the plasticity and swelling potential of the treated soils and improved their durability against wet–dry conditions [7].

2 Research objective

This research aims to study the effect of LKD on two different types of expansive soil (high-plastic clay (CH) and low-plastic clay (CL)) and study the effect of LKD on the swelling and CBR values of two soil samples, and determine the optimum percentage that improves each type.

3 Methods

3.1 Experimental program

An experimental program was created to determine the optimum percentage of LKD to improve the geotechnical properties of soils. The experimental program for this study is shown in Fig. 1.

3.2 Materials properties

Expansive soils were extracted from two locations in Egypt from Beni-Suef and Fayoum. The first sample was extracted from 2 m below the ground surface, while the second sample was extracted from 3m. The natural samples are shown in Fig. 2. The index and physical properties of these soils are determined in Table 1. The tests performed in this paper are included in Table 2 with their standard codes. The chemical properties of the two soil samples and LKD are shown in Table 3. Figure 3 shows the LKD that was brought from Suez, Egypt. The properties of LKD are (specific gravity is 2.81 according to (ASTM D854-14), Ph is 12.6, and color is white). Figures 4 and 5 show the grain size distribution of fine-grained soils and LKD.

3.3 Test specimens preparation

The laboratory tests were performed on samples taken from the field, such as the natural moisture content, modified proctor test, sieve analysis, Atterberg limits, CBR test, and swelling pressure. A pH meter was used to measure the pH of the soils with a percentage (soil: water ratio (1:10)). The results of these preparation tests will be presented in Sect. 5.

3.4 Scanning electron microscope (SEM) of soils and LKD

SEM allows us to show a detailed understanding of the morphology of clay particles by producing tiny surface pictures of a soil specimen. In natural soil, there are three main categories of micro-fabric properties, according to Collins and McGown [8]: (1) Basic particle arrangements: This group includes interactions between small groups of clay platelets and coated silt and sand particles. (2) Particle assemblages: These are organizing units made of particles that have mechanical and physical properties. It consists of different arrangements of fundamental particles or small particle assemblies. (3) Pores, or voids, are the building blocks of basic particle arrangements and assemblages. SEM images of the fine-grained soils and LKD are presented in Fig. 6 which shows the categories of soils and the particle composition of LKD. EDX is a form of elemental spectroscopy that is used in conjunction with electron microscopy. Figure 7 shows EDX analysis for soil samples and LKD.

4 Testing procedures

The untreated soils are dried at approximately 100 °C for 24 h before all tests. Soil was molded in a mold of the modified proctor test at the optimum water content obtained from the test at all percentages of LKD before swelling pressure, the sample was extracted in the oedometer ring. Untreated soil and treated soil are tested to determine Atterberg limits, free swell, CBR value, and swelling pressure. Figure 8 shows the preparation of samples for tests. The percentage of LKD to be used for each soil sample has been determined based on the pH test according to Eades and Grim method [9]. The approximate (LKD) percentage for soil stabilization is 12.4 like lime, to satisfy all of the reactions. These reactions represent that the calcium will attack silica and alumina, which the calcium reacts to form calcium silicates, as long as a high alkaline condition is maintained.

5 Results

5.1 Effect of LKD on the plasticity of treated soils

Figure 9 shows the effect of LKD on the plasticity of stabilized soils. The addition of LKD improves sample plasticity but has a negligible change in the soils' liquid limit

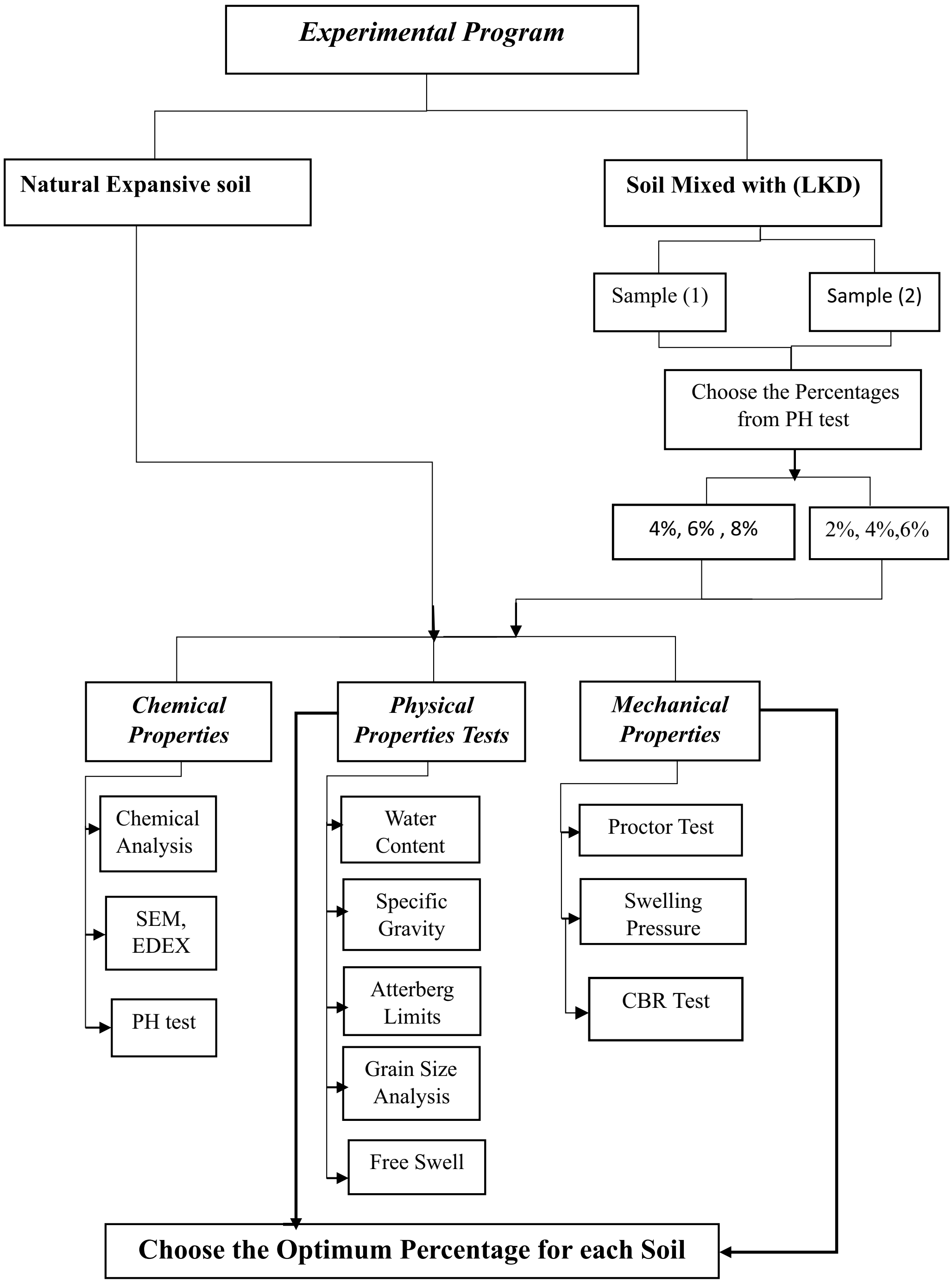


Fig. 1 Flowchart of experimental program

and a discernible change in their plastic limit. When 4% and 8% LKD are added to the sample (1), the liquid limit decreases negligibly from 63.6 to 59%. On the other hand, Sample (2) at a percentage of 4% took the behavior of sand; therefore, we couldn't calculate it. In the plastic limit, 6% increased the plastic limit to 38% from 26.5% in the sample (1), but it became non-plastic at a percentage of 4% in the sample (2).

Fig. 2 **a-1** Sample (1) at the site, **a-2** Sample(1) in laboratory after extracted, **b-1** Sample (2) at the site, **b-2** Sample (2) in laboratory after extracted

Table 1 Properties of material of expansive soil

Engineering properties for soils	Soil sample	
	Sample (1)	Sample (2)
	value	
Natural moisture content (%)	36.7	14.2
Liquid limit (%)	63.3	27
Plastic limit (%)	26.5	17
Plasticity index (%)	37	10
Shrinkage limit	3.8	13.93
Specific gravity	2.65	2.61
Maximum dry density (g/cm^3)	1.6	1.86
Optimum moisture content (%)	17.25	13
Bulk density (g/cm^3)	1.87	2.1
Free swell (%)	120	70
Passing #200 (%)	80	88
USCS classification	CH	CL
AASHTO classification	A-7-6	A-4
Swelling pressure (kg/cm^2)	4.5	2.6
PH value	8.4	7.8

Table 2 Tests method code

Test	Standard method code
Grain size analysis	ASTM D422
Atterberg limits	ASTM D 318
Shrinkage limit	ASTM D427
Free swell	IS 2720-40
Compaction (proctor test)	ASTM D1554
Swelling pressure	ASTM D4546
CBR test	ASTM D1883

Table 3 Chemical analysis of sample (1), sample (2) and LKD

Chemical composition	Percent of sample		
	Sample (1)	Sample (2)	LKD
SiO_2	50.13	12.96	4.70
Al_2O_3	13.45	3.68	0.13
Fe_2O_3	9.11	2.60	0.37
CaO	5.49	41.60	69.88
MgO	2.58	0.80	2.07
SO_3	0.26	1.02	0.55
K_2O_3	1.24	0.30	0.02
Na_2O	1.15	0.45	0.07
CL	0.04	0.05	0.05
LOI	13.35	35.19	21.88
Total	96.81	98.64	99.72
Moist	1.90	1.50	4.60

5.2 Effect of LKD on shrinkage limit of treated soils

The addition of LKD to soil increased the shrinkage limit of soils, irrespective of their plasticity characteristics. It indicates an improvement in the properties of the soil, as shown in Fig. 10. The increase is due to chemical changes in the composition of the soil. The shrinkage limit in the first sample (CH soil) increased from 3.7 to 26.4 at 5% LKD, but in the second sample (CL soil), it increased to 36.6% from 10%.

5.3 Effect of LKD on free swell of treated soils

The free swell decreased by increasing the percentage of LKD in two soils. It decreased from 120 to 40%, and the degree of expansion changed from high to medium in CH soil, but in CL soil, it changed from medium to low expansion at 2% LKD, as shown in Fig. 11.

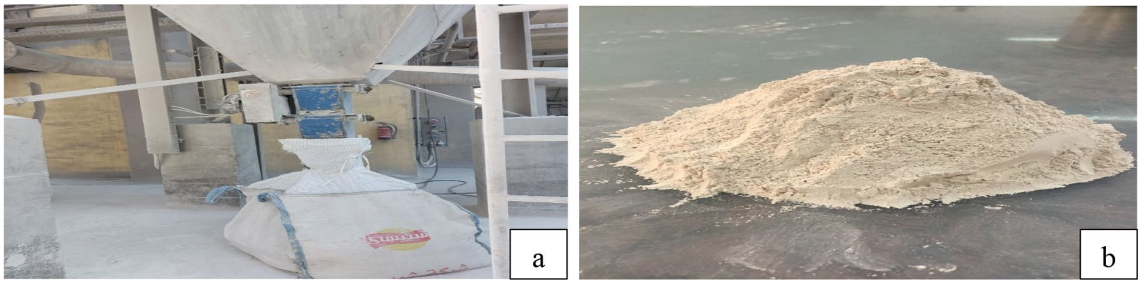


Fig. 3 **a** LKD collected in bags in factory, **b** sample of LKD in Lab

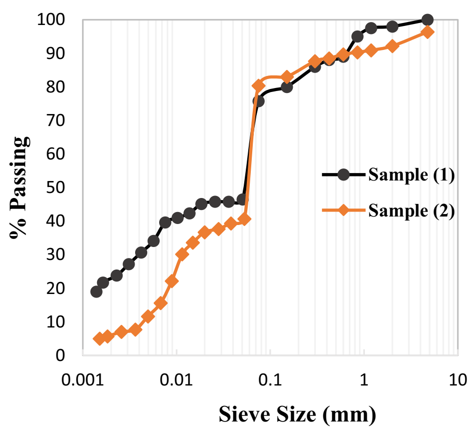


Fig. 4 Grain-size distribution curve of natural expansive soils

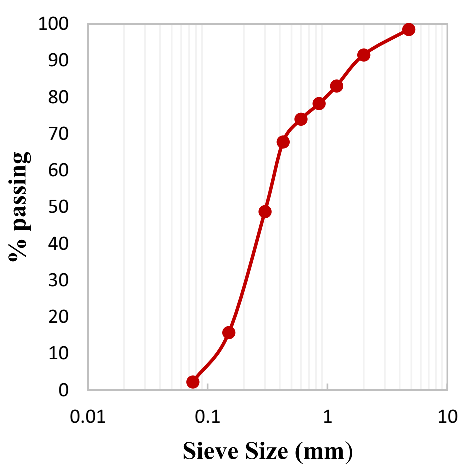


Fig. 5 Grain-size distribution curve of LKD

5.4 Compaction characteristics of treated Soils

The modified Proctor compaction test is used to determine the effect of LKD on optimum moisture content (OMC) and maximum dry density (MDD). The compaction test was executed using an automatic compactor apparatus according to ASTM D1557 specifications. As the percentage of LKD increased from 0 to 8% in CH soil, the optimum moisture content increased from 17 to 25%, and the maximum dry density decreased from 1.6 to 1.5 g/cm^3 as shown in Fig. 12. In CL soil, the optimum moisture content increased from 13 to 20% and maximum dry density decreased from 1.85 to 1.55 g/cm^3. The Compaction results of the treated soils at different LKD contents are presented in Fig. 13.

5.5 Effect of LKD on swelling pressure

Swelling pressure is measured in the laboratory with a one-dimensional consolidation (free swell oedometer test) according to ASTM D4546. After the soil sample is put inside a metallic ring, porous stone discs are positioned on top and bottom of the sample. At first, we let the specimens swell freely with an applied stress of 0.125 kg/cm^2 for one day to replicate the small building in the field. The normal stresses used are 0.25, 0.5, 1, 2, 4, 8, and 16 kg/cm^2 after the sample has been given time to consolidate under various vertical stress increments. Swelling pressure is the pressure corresponding to the zero-volume change of the sample.

In this study, soil was compacted at optimum moisture content to prepare each sample for the test. From the curves in Figs. 14 and 15, in CH soil: 8% (LKD) is the optimal quantity because the difference is insignificant, as shown in Fig. 14. It decreased from 4.5 to 2 kg/cm^2 at 8%. In CL soil, it decreased from 2.6 to 1.35 kg/cm^2, as shown in Fig. 15. Swelling pressure decreased by 50% in two soils.

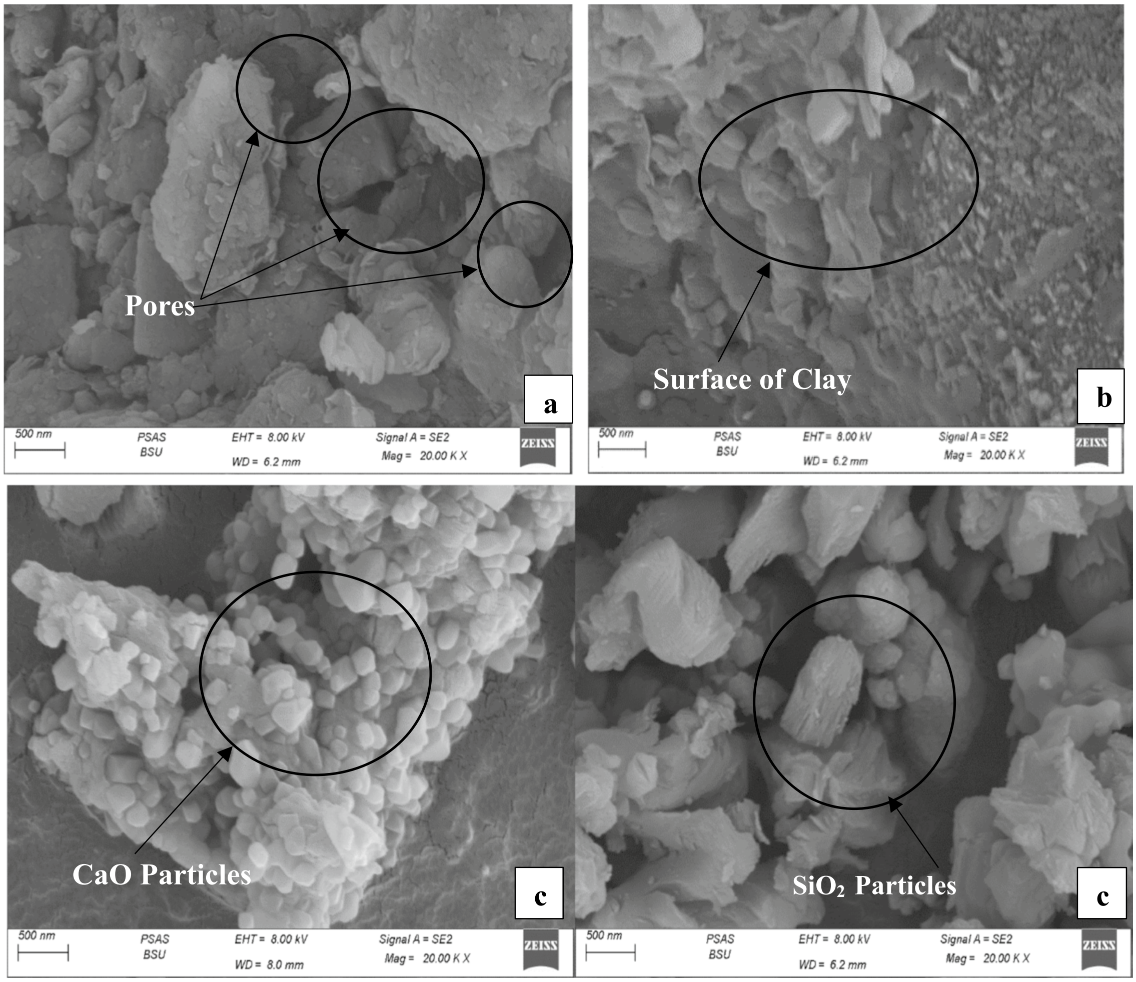


Fig. 6 SEM images for **a** first soil sample, **b** second soil sample, **c** LKD

5.6 Effect of LKD on CBR ratio

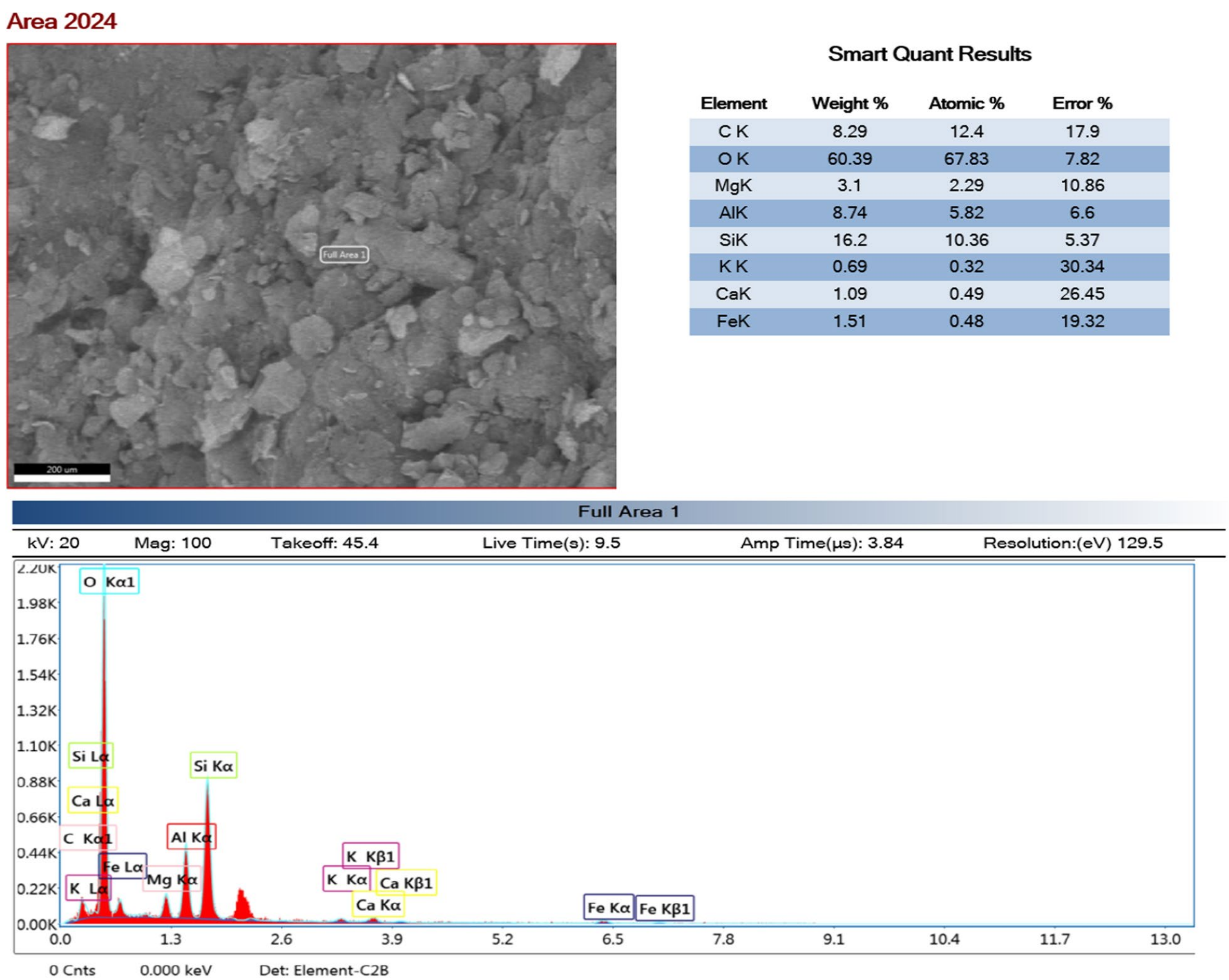
CBR is defined as the ratio of the force per unit load required to penetrate 0.1 inch and 0.2 inch to the force per unit load required to penetrate a standard material. The ASTM D1883 method is used for the estimated CBR value. The bearing capacity of subgrade is an important factor in the design of roads. The CBR value is commonly used to evaluate the quality of road materials. (LKD) was mixed with expansive soil to enhance the strength of the soil. (LKD) was mixed with soils at optimum water content. CBR tests were carried out to evaluate the strength of the soil. Figure 16 shows that the optimal quantity in CH soil is 6% (LKD), but in CL soil it is 2% (LKD). CBR increased by 800% in CH soil and 150% in CL soil.

5.7 Effect of LKD on treated soils under microscope imaging (SEM)

Figure 17 displays the SEM of 6% LKD on CH soil and 4% on CL soil after 14 days of cure. The natural sample of dredged material in SEM testing identified the existence of loose flaky particles in deflocculated form with clear open spaces and weak inter-particle linkages, resulting in a dispersed structure. The dispersed and deflocculated structure of the soil mass is indicative its poor strength characteristics. It also produces an increase in the pH of the pore water in the soil, allowing the clay minerals' alumina and silica dissolve and react with the calcium from the added LKD to form pozzolanic compounds like calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). The pozzolanic compounds have cementing effects as they bind the soil structure together, and so the strength and/or stiffness of the soil increase [10]. Silicate gel was covering and enclosing clay lumps as the process of aggregation began to take place. The gels joined the little pieces together to create aggregated crumbs, which made the overall soil mass permeable. Micrographs show that the new phase is made up of a network of crystals that resemble needles. An interconnecting network forms between surrounding soil particles after a year of curing. These continuous networks of interlocking-like crystals have grown into interstices.

6 Discussion

After analysis of test results of different physical, chemical and mechanical properties of treated soil. In CH soil, there was a little decrease in the values of the



Element	Weight %	Atomic %	Error %
C K	8.29	12.4	17.9
O K	60.39	67.83	7.82
MgK	3.1	2.29	10.86
AlK	8.74	5.82	6.6
SiK	16.2	10.36	5.37
K K	0.69	0.32	30.34
CaK	1.09	0.49	26.45
FeK	1.51	0.48	19.32

a) EDX for Sample (1)

Fig. 7 **a** EDX for sample (1), **b** EDX for sample (2), **c** EDX for LKD

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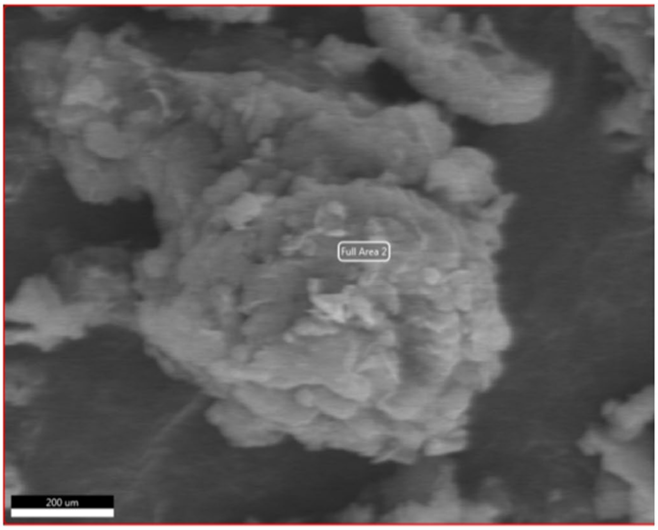
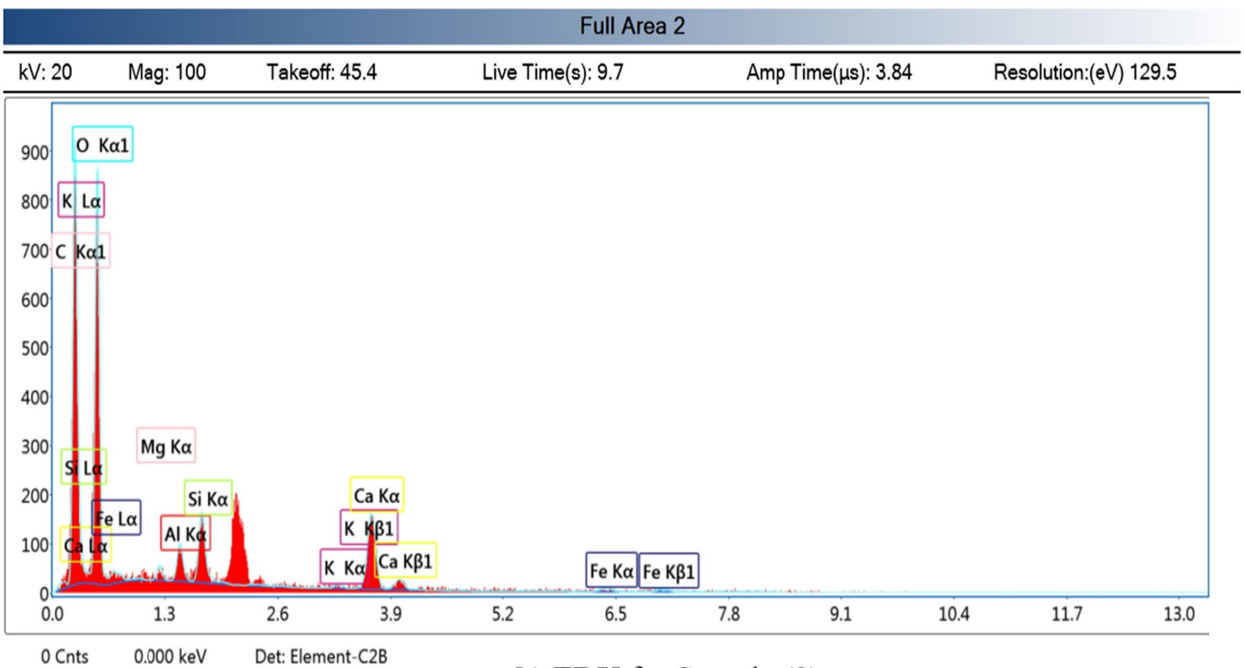


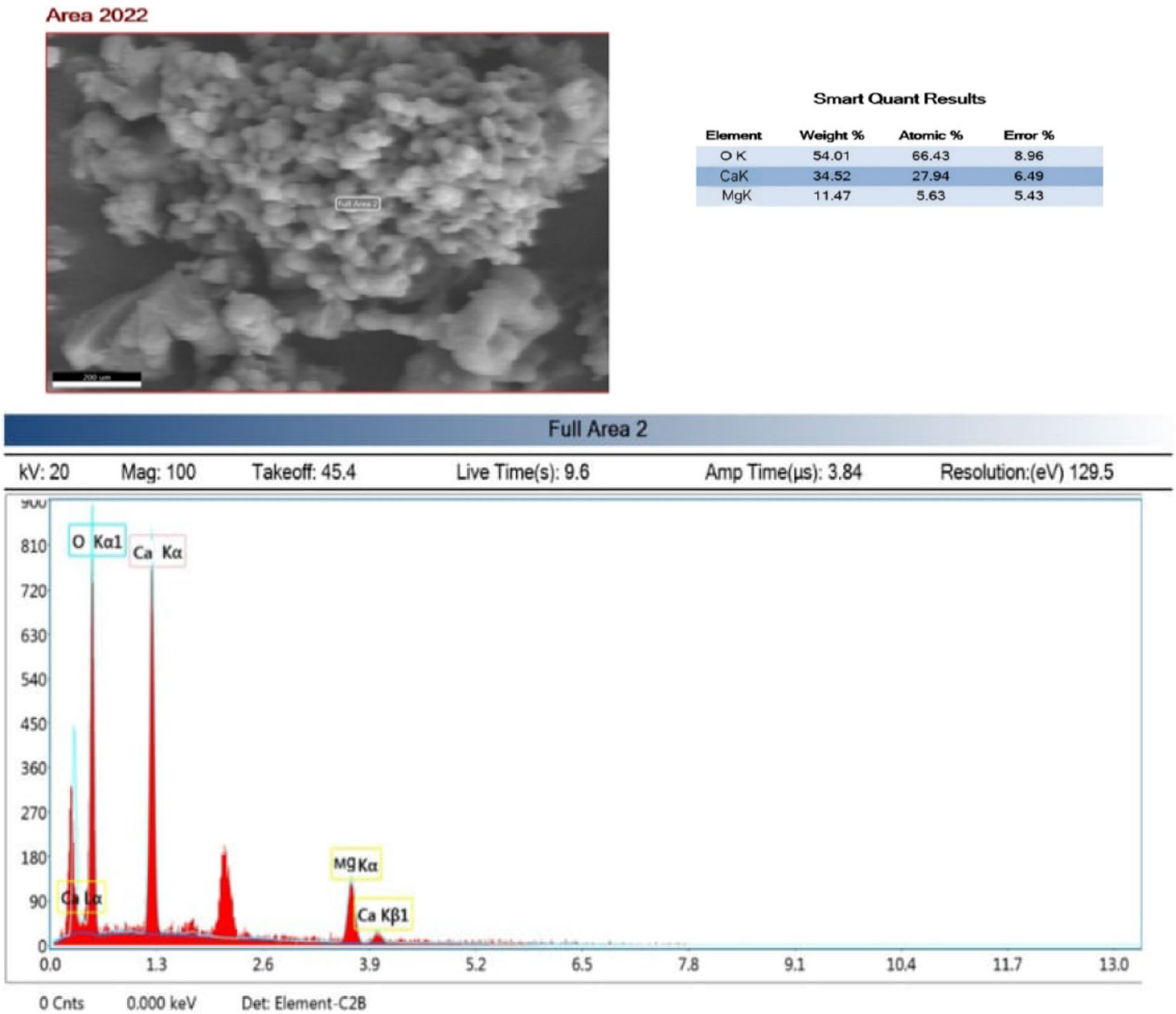
Smart Quant Results

Element	Weight %	Atomic %	Error %
C K	38.74	48.76	8.32
O K	48.14	45.49	10.64
MgK	0.7	0.43	25.35
AlK	1.56	0.87	11.7
SiK	2.69	1.45	8.42
K K	0.31	0.12	65.51
CaK	7.04	2.66	5.63
FeK	0.82	0.22	32.35



b) EDX for Sample (2)

Fig. 7 continued



c) EDX for LKD

Fig. 7 continued

liquid limit and a high increase in the plastic limit and plasticity index as the LKD content increased, but in CL soil, it became non-plastic at 2% LKD. There were an increase in the shrinkage limit and a decrease in swelling potential of expansive soil. It may be due to the different structural units of soil minerals, which are composed of calcium elements when water enters between minerals. According to flocculation and agglomeration, the initial reactions between LKD and soil are most likely what caused the decrease in the maximum dry unit weight [11]. The hydration of LKD may be the cause of the OMC increase with increasing LKD content. Additionally, the cementitious matrix is formed by the pozzolanic interactions between LKD and soil. This process usually occurs after a long enough period, which increases the soil's resistance to

Fig. 8 **a** Sieve analysis and hydrometer test, **b** determining liquid limit, plastic limit and shrinkage limit, **c** Free swell test, **d** Proctor test, **e** swelling pressure test, **f** CBR test

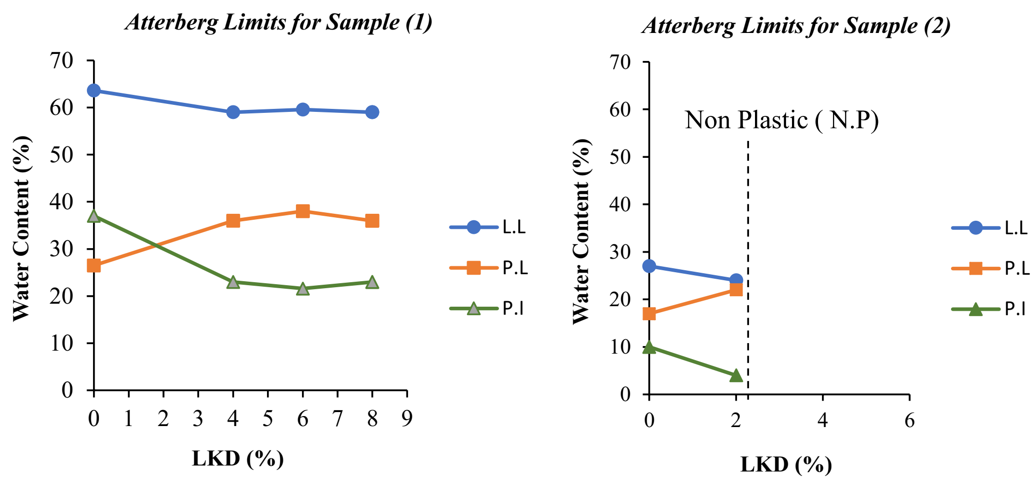


Fig. 9 Effect of LKD on Atterberg limits

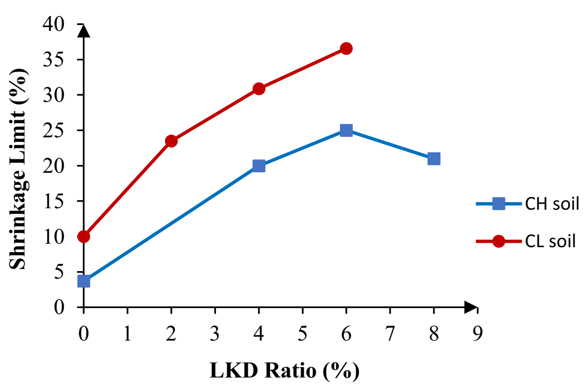


Fig. 10 Effect of LKD on shrinkage limit of soils

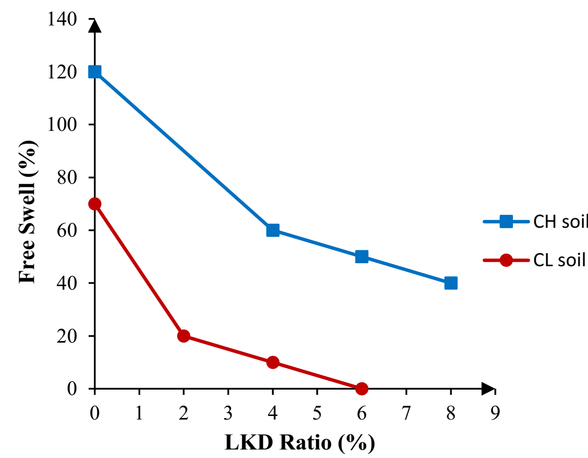


Fig. 11 Effect of LKD on free swell of soils

volumetric expansion to a significant degree. When LKD is added to soil, clay particles clamp together and form an aggregate with larger clay particles [12, 13]. Simply, we can say that the LKD fills the small pores of the mineral and allows less water to penetrate and be absorbed by soil particles, which led to a significant reduction in the swelling potential of the soil.

7 Conclusions

The conclusions of the research are summarized as follows:

1. The addition of LKD has a negligible effect on the liquid limit but increases the plastic limit of CH soil by 50%, so the plasticity index of soil is decreased by the same percentage and CL soil becomes non-plastic soil.
2. An increase in the percentage of LKD led to an increase in the shrinkage limit by 500% in CH soil and 250% in CL soil.

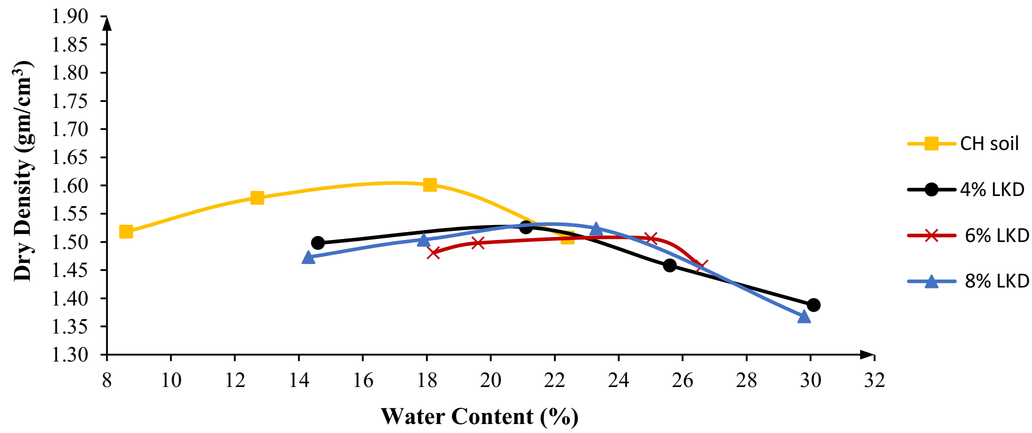


Fig. 12 (MDD and OMC) for untreated and treated CH soil

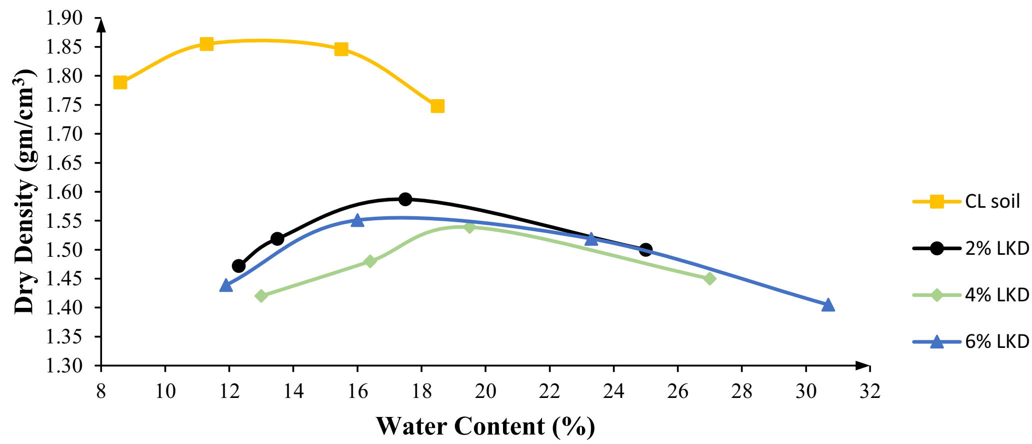


Fig. 13 (MDD and OMC) for untreated and treated CL soil

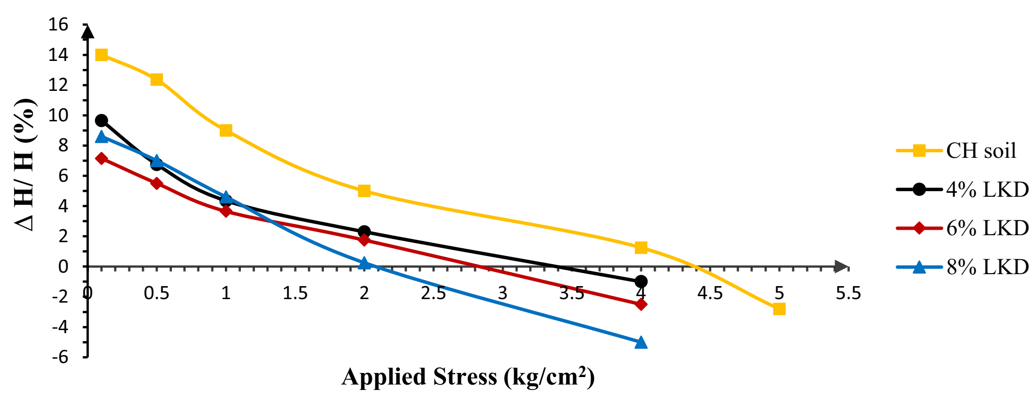


Fig. 14 Swelling pressure of untreated and treated CH soil

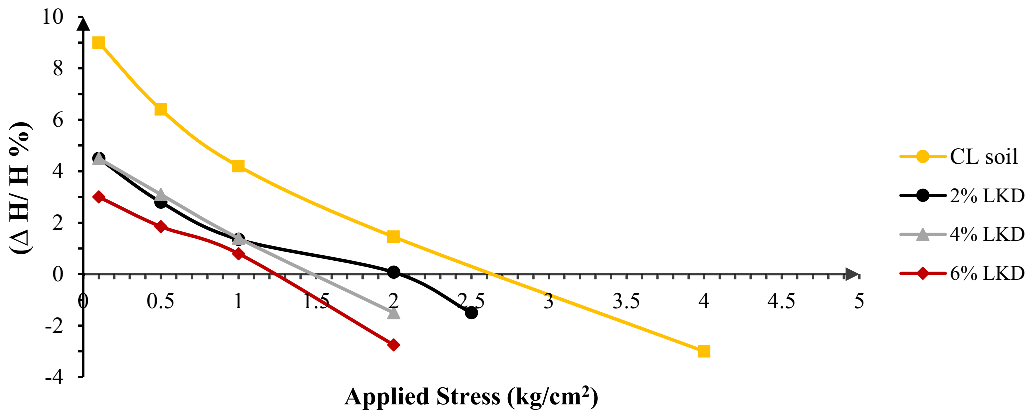


Fig. 15 Swelling pressure of untreated and treated CL soil

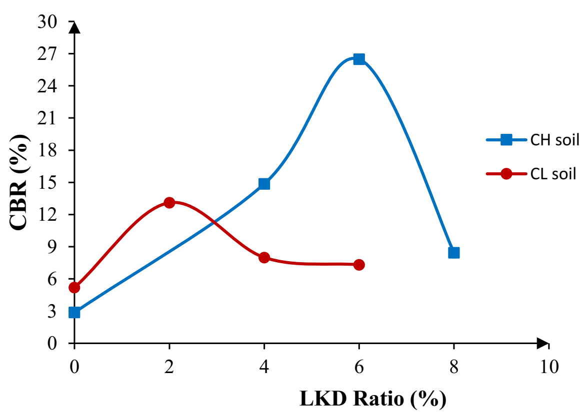


Fig. 16 Effect of LKD on CBR of soils

3. The MDD decreases by a range of (5–15%), and the OMC increases by 50% with the addition of LKD in soils.
4. The free swell index of soils decreases by 50% in CH soil and 100% in CL soil with an increase in LKD percentage.
5. The swelling pressure values decreased by 50% in two soil types. This has a high effect on the swelling properties of the subgrades. These effects are due to calcium ions being introduced between the silicate sheets to start the interaction between LKD and the clay, and this led to collecting pieces together to create aggregated crumbs, which made the overall soil mass permeable. These cementitious phases induced significant improvements in engineering properties such as strength, shrinkage, and swelling.
6. The increase in CBR value indicates a significant improvement in the pavement subgrade soil's qualities and increases its capacity to withstand heavy traffic loads. As a result, the thickness of the pavement is much reduced, which in turn reduces the cost of construction.

8 Recommendation

Based on the findings presented in this study, LKD is a soil stabilization additive that works well, and using it as a substitute for other soil stabilizers in the stabilization of subgrade soils is advised. The following are suggestion for additional research based on the study's findings:

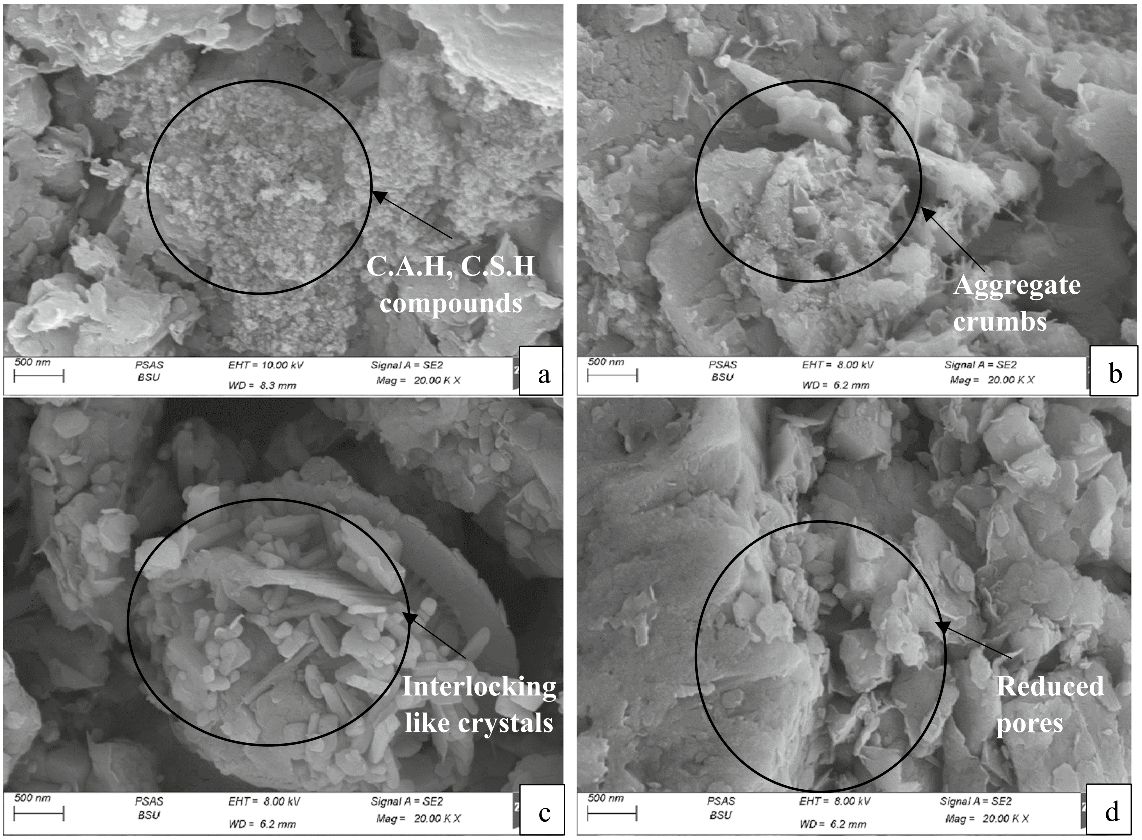


Fig. 17 SEM of treated soil **a**, **b** CH soil with 5% LKD **c**, **d** CL soil with 4% LKD

1- Examine the cost analysis of treated soil utilizing LKD compared with natural soil.
2- Trial pavement sections can be built in the field on an expanding subgrade that has been treated with LKD. Then, the sections' performance can be assessed repeatedly for rutting and fatigue distress.

Abbreviations

LKD	Lime kiln dust
CH	High-plastic clay
CL	Low-plastic clay
SEM–EDX	Scanning electron microscopy (SEM) with energy-dispersive X-ray analysis (EDX)
L.L	Liquid limit (%)
P.L	Plastic limit (%)
P.I	Plasticity index (%)
Sh.L	Shrinkage limit (%)
MDD	Maximum dry density (g/cm^3)
OMC	Optimum moisture content (%)

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Author contributions
Menna Eid did the experimental work and wrote the research. Youssef Gomaa reviewed the research. Sameh Galal reviewed the research. All authors read and approved the final manuscript.

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Availability of data and materials
All data used are mentioned in the paper.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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