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CEMENT KILN DUST (CKD) AS A POTENTIAL STABILIZER TO MITIGATE THE SWELLING OF CLAYS

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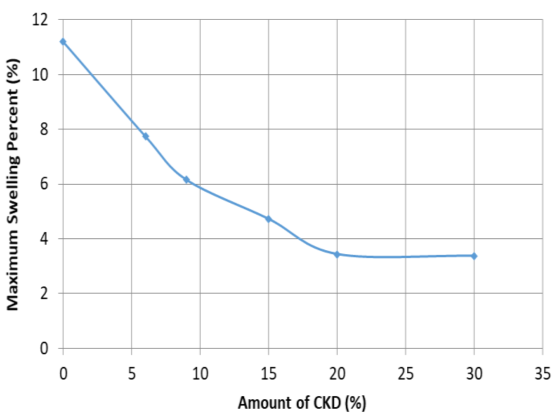
Graphical abstract



Abstract

Utilizing industrial waste, like CKD (cement kiln dust) to stabilize expansive soils is of paramount importance in reducing the environmental impact of waste and in alleviating the expansive soil-induced structural damage. More studies are needed to demonstrate that CKD is beneficial in lowering the potential of expansive soils to swell. Therefore, this paper investigates how CKD affects the swelling of the CKD-treated soil as well as other engineering properties like compaction, Atterberg limits, mineral compositions, and microfabric. Soil stabilization was achieved by adding CKD in amounts of 6 to 30% of soil mass. The study revealed that CKD reduced the liquid limit from 85 % to 75 % and the plasticity index from 46 % to 16 % and thus, improved the plasticity and workability of the soil. Moreover, CKD decreased the swelling potential from 11.2 % to 3.4%, and the swelling pressure from 108 kPa to 17.5 kPa. XRD patterns demonstrated the usefulness of CKD for reduction in the intensity of palygorskite, montmorillonite, and illite swelling minerals. The success of the stabilization mechanism was also confirmed by the SEM micrographs where condensed soil particles with a few numbers of small pores were observed.

Keywords: CKD, expansive clays, swelling pressure, stabilization, waste

1.0 INTRODUCTION

Utilizing industrial by-products, like CKD, in improvement of expansive soil is of paramount importance in reducing the environmental impact of waste by minimizing the need to dump these wastes in landfills. CKD is beneficial in lowering the cost associated with expansive clay-induced damage to infrastructures. Industrial wastes such as (CKD) provide a cheaper and environmentally friendly alternative to lime and cement stabilizers [1-8]. Because of its high amount of calcium oxide, CKD was successfully utilized to stabilize expansive clays [6, 8-21].

Zaman and Laguros, 1992 [14] added up to 25% of CKD to a highly swelling clay and found that swelling potential and the plasticity index were reduced and strength and CBR were increased. Almuaythir and Abbas, 2023 [9] reported that even a CKD content of 8% reduced the swelling potential to insignificant values and the strength was substantially increased.

Cui *et al*., 2018 [15] reported for a CKD content of 18%, the swelling pressure decreased exponentially to a small value. Further, CKD improved the long-term shear strength. According to Miller and Azad, 2000 [22], CKD addition increased the soil strength; however, the stabilization is significant for low-plastic soils. Studies have also shown the suitability of CKD-treated expansive soil for use as a subgrade in pavements [10, 12, 19].

Most of the studies outlined above focused on how CKD affected soil strength. Few studies dealt with the measurements of the percentage of swelling and associated pressure after CKD stabilization to quantify the reduction in these quantities. Therefore, this study's goals are to present the measured values of the swelling parameters for untreated soils and CKD-treated soils. Additionally, a comparison is made between the measured values and those reported in the literature. Finally, changes in minerals of CKD-treated soil are investigated using XRD, and the SEM micrographs are used to study the resulting structure and fabric. This study provides more data for the CKD-stabilized expansive soils and also proposes predictive models for the effects of CKD on swelling parameters.

2.0 MATERIALS AND TESTS

Soil

The study area is situated in Adam City, approximately 200 km from Muscat, Oman. Expansive soils in this region have caused significant damage to pavements and buildings. The soil was obtained from an area where buildings experienced cracks in the walls and heave of floors. Samples of soil were obtained from the bottom and sides of a trial pit that was dug down to a 3 m depth. Collected samples of soil were thoroughly mixed to make a homogeneous material and then sieved to remove the oversized particles.

The soil's characteristics are listed in Tables 1 and 2. The fine content in the soil is about 59%. Liquid (LL) and plastic (PL) limit tests performed on soil passing sieve # 40 (size 0.425 mm) gave LL = 82%, PL= 36%, PI = 46%, and linear shrinkage = 12%, indicating highly plastic clay (CH).

Free swell ratio (FSR) and free swell index (FSI) were found to be 1.65, and 65%, respectively indicating this soil has medium swell potential [23, 24].

XRF results are displayed in Table 2 and the table shows that the dominant oxides are SiO_2, Al_2O_3, CaO, and Fe_2O_3. The XRD analysis showed montmorillonite, palygorskite, illite, kaolinite, quartz, calcite, and gypsum. Montmorillonite mineral is also confirmed using Prakash and Sridharan's, 2004 [23] classification scheme, which is based on FSR.

CKD

The chemical properties of CKD, obtained from a nearby site, are summarized in Table 2 and Figure 1 shows a photograph of the CKD. The abundant lime shown in the table can accelerate chemical and hydration processes. The minerals present in CKD are larnite (calcium silicate Ca_2SiO_4), portlandite ($Ca(OH)_2$), and calcite ($CaCO_3$), which are typical for CKD [17]. CKD has a specific gravity of 2.35 and it is similar to the values obtained by others [25, 26].

Figure 1 Cement Kiln Dust (CKD)

Table 1 Soil physical and mechanical characteristics

Parameter	Value	Standard
Fines (< 0.075 mm) (%)	59	Sieve Analysis ASTM D6913–17
Clay (< 0.002 mm) (%)	26	ASTM D7928-21 (Hydrometer on fraction < 0.075 mm)
Gs	2.74	ASTM, D854-14
Atterberg Limits (LL, PL, PI) (%)	82, 36, 46	ASTM D4318-17 (on fraction passing sieve No. 40 (size 0.425 mm)
Shrinkage percent (%)	12	
USCS classification	Clay with high plasticity (CH)	
MDUW (KN/m3)	15.5	ASTM D698-12 and ASTM D558-19
OWC (%)	24	
FSI (%)	65	IS:2720, Part-40, 1977
FSR	1.65	
Minerals	Kaolinite palygorskite, montmorillonite, illite.	

Table 2 Major oxides for CKD and soil

Oxide	%	
	Soil	CKD
SiO_2	51.3	10.3
Al_2O_3	20.3	3.4
CaO	13.7	49.2
Fe_2O_3	8.2	2.9
MgO	3.1	1.2
TiO_2	1.2	0.2
Na_2O	1.1	0.8
K_2O	1.1	3.5
MnO	0.1	0.1
P_2O_5	0.1	0.02
SO_3	-	3.3
LOI	-	24.5

Specimen Preparation

Dry soil and CKD were thoroughly mixed to prepare a homogeneous mix. Further, the mixing process was enhanced by the addition of an amount of water equal to OWC. Large amounts of the mixture were prepared, and duplicate samples were tested for each CKD content to ensure repeatability of the results.

Testing

Specific gravity, gradation, Atterberg limits, and compaction were conducted to characterize the soil before and after treatment following ASTM standards [27-32] as shown in Table 1. Indian Standard (IS:2720, Part-40, 1977) [33] was followed for the free swell index. ASTM D4546-21 [34] was followed for swelling potential. Also, XRD, XRF, and SEM tests were conducted.

Swelling Test

The oedometer apparatus was used to carry out swelling tests (ASTM D4546-21, Method A) [34]. This test method gives the swelling percent under a load and the magnitude of the swell pressure. Samples with a diameter of 75 mm diameter and thickness of 20 mm were prepared in the consolidation ring. Dry porous disks were placed below and above the ring. Then, after applying a token load of 1 kPa to the sample, the deformation under this load was recorded. Subsequently, water was added to saturate the sample, and the swelling deformations were recorded until the swelling seizes. The process was repeated for other seating pressures. In this study, seating pressures between 1 and 133 kPa were applied to the samples. Seating pressure that prevents any swelling is the swelling pressure.

3.0 RESULTS AND DISCUSSION

CKD Effects on Atterberg Limits

CKD gradually reduced the liquid limit to 85, 80, 76, and 75% when the content of CKD is 9, 15, 20 and 30%, respectively (Figure 2). Conversely, the figure shows a gradual increase in PL from 36% for pure soil to 48, 53, 56, and 55% for CKD contents of 9, 15, 20, and 30%, respectively (Figure 2). CKD decreased PI from 46% for pure soil to 16 and 19% for CKD contents of 20 and 30%, respectively. CKD substantially decreased the shrinkage percent to only 2% with a CKD content of 20%. The improvement of plasticity of soil is a result of lime hydration, flocculation, agglomeration of clay grains to form silt grains, and cation exchange reaction [9, 21, 35].

Compaction Parameters of CKD-Soils

Table 3 and Figure 3 display specific gravity (G_s), optimum water content (OWC), and maximum dry unit weight (MDUW) for different mixtures of CKD-soil. The figure and the table revealed that CKD decreases MDUW and increases OWC. These effects of CKD on compaction parameters were observed before [9, 10, 19, 21, 22, 35, 36]. With the addition of CKD, the void ratio increased due to particle flocculation and aggregation and therefore, resulting in a reduction of MDUW [10, 35]. Table 3 shows as the CKD increases there is a continuous reduction in the G_s from 2.74 to 2.64 for 30% CKD, hence a reduction in MDUW. On the other hand, CKD increases in the OWC of the mixture because of the need for CaO to water during cation exchange reaction [9, 11, 35].

Some studies showed a different trend where CKD increases the MDUW [11, 26, 36-39]. Some researchers linked this trend to the type of soil, the type of CKD, and the difference in compaction techniques [9, 22].

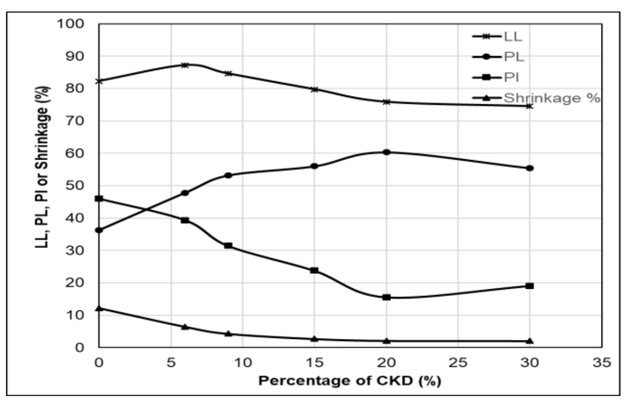


Figure 2 Atterberg limits of CKD-soil

Table 3 Summary of compaction parameters for different CKD-soil mixtures

CKD %	0	6	9	15	20	30
Max. dry unit weight (kN/m^3)	15.50	15.48	15.25	15.18	15.08	14.45
Optimum water content (%)	24	24	24.5	25.5	26	27.5
Specific Gravity* ($G_{s\text{-}CKD}$)	2.74	2.71	2.70	2.68	2.67	2.64

$$* G_{s-CKD} = \frac{G_s G_{CKD}(1+c)}{(G_{CKD} + G_s c)}$$; c is the CKD content as a ratio; G_s = 2.74; G_{CKD} = 2.35

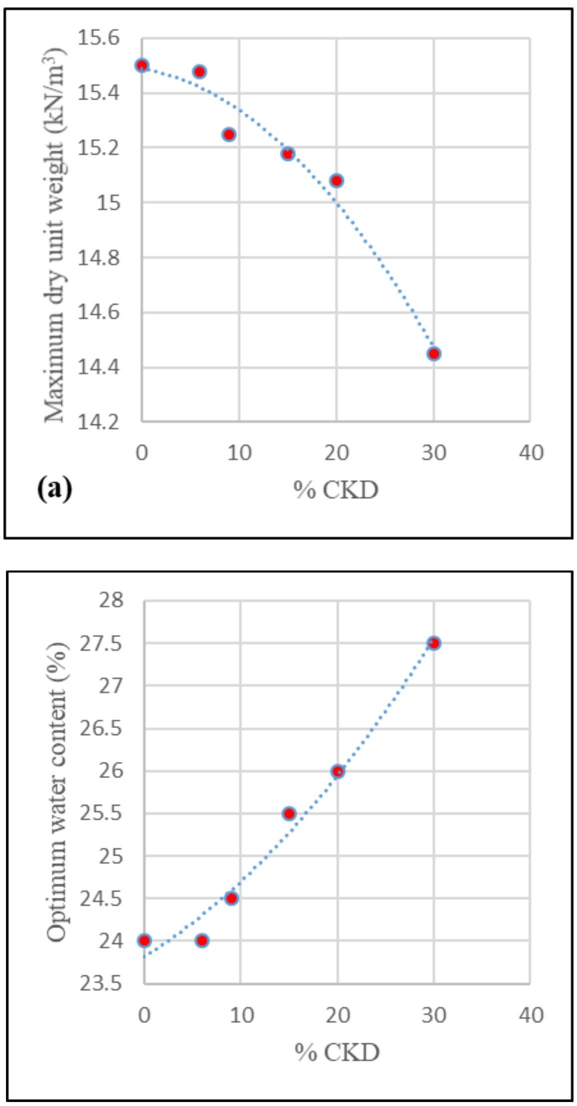


Figure 3 MDUW and OWC for different CKD-soil mixtures

Swelling Percent

Figure 4 depicts the time-rate curve for soil for different seating pressures. The swelling starts slowly for the first few hours and then increases rapidly before it becomes constant within 3 to 4 days indicating the completion of the swelling. In addition to time, the swelling percentage also depends on the seating pressure (Figure 5). The seating pressure substantially reduced the swelling percentage. The swelling percent (S, in %) can be related to the seating pressure (σ, in kPa) by an exponential regression equation (R^2=0.99) as:

$$S\,(\%) = 11.634e^{-0.028\sigma} \quad ; S > 0 \qquad [1]$$

This equation is important because it gives the swelling percent under a token seating pressure and hence the swelling potential. The value of this seating pressure differs from one standard or classification scheme to another. For example, ASTM D4546-21 [34] specifies a value of 1 kPa for token pressure to determine free swell value. The classification of the expansive soil system proposed by Seed *et al.*, 1962 [40] specifies a token pressure value of 7 kPa to obtain the swelling percent. In addition, some studies for measurement of the swelling of CKD-soil mixtures used different seating pressures. For example, seating pressures of 4, 9.5, 25, and 50 kPa were used by Sreekrishnavilasam *et al.*, 2007 [41], Zaman *et al.*, 1992 [14], Taha *et al.*, 2001 [21] and Almuaythir and Abbas, 2023 [9], respectively. Thus, Equation 1 would allow for evaluation and comparison of the data for swelling percent presented by different studies.

Figure 5, the measured swelling pressure of this soil is about 108 kPa (ASTM D 4546-21 [34]). A comparison was made between the measured swelling pressure and those predicted by empirical models [42-46] as shown in Table 4. These models use one or more of the basic properties of soil: initial moisture content (w_i), the content of clay (C), dry density (ρ_d), dry unit weight (γ_d), Atterberg limits and indices (i.e. LL, PL, PI, LI) and free swell to predict swelling pressure (P_s). Table 4 shows the prediction capabilities of these models where the errors of prediction ranged from -71% to 86%. The best predictions are given by the models of Sabtan, 2005 [42] (error =26%) and Jeevanantham *et al.*, 2022 [43] (error = 35%). There are several reasons for this variation in the predicted swelling pressure as the prediction models are based on limited data for soils from different regions, varying soil minerals and properties, and different methods are used for measuring the swelling pressure. For example, swelling pressures measured using the consolidation-swell method (ASTM D4546-21 [34]) are higher than those measured using the constant volume methods [47]. Thus, there is a need for more standardization of the procedures for measuring swelling pressure.

Swelling of CKD-Soils

Swelling Percent

Figure 6 shows the swelling rate for treated soils and for comparison purposes the behavior of untreated soil is also shown in the figure. The figure shows the variation of swelling with time for a seating pressure of 1.1 kPa. The trend is similar to that of untreated soil, albeit the maximum swelling percent is much smaller. The figure also indicates that the swelling process starts earlier in the cases of treated soils, but it takes slightly longer time to reach the maximum swelling percent. The curves become flatter as the amount of CKD increases. The trend is also similar for other seating pressures with the maximum swell percent decreases with the increase in the seating pressure and the amount of CKD.

Figure 7 illustrates that CKD decreases the swelling percentage substantially. For example, for 15% CKD, the swelling percent is only about 40% of its original value. Beyond 15% CKD, the reduction in swelling percent is not significant, and basically no change after 20 % CKD.

Swelling Pressure

The swelling pressure for CKD-soil mixtures is displayed in Figure 8. CKD substantially decreases the swelling pressure from 108 kPa for untreated soil to 35.5, 20.5, and 17.5 kPa for soil treated with 15, 20 and 30% CKD, respectively. These values correspond to reductions in swelling pressure of 67, 81 and 84%, respectively. A polynomial curve that models the dependency of pressure (P_s) on CKD percentage (c %) is proposed

$$P_s = 0.1415c^2 - 7.054c + 103.42\,; \quad (R^2 = 0.98) \qquad [2]$$

The percent reduction (R) in swelling pressure can be defined as:

$$R\ (\%) = \frac{(P_{si} - P_{sf}) \times 100}{P_{si}} \qquad [3]$$

Where: P_{si} and P_{sf} are swelling pressures of untreated and treated soil respectively.

Figure 7 shows that the reduction percent reached 81% at a CKD amount of 20% and became constant after that. For comparison purposes, the figure also shows the reduction in swelling pressure reported by others who used CKD to stabilize expansive soil. There is a close agreement in values and trends between the results obtained in the current study and the results by Cui *et al.*, 2018 [15]. The reduction values from other studies show some scatter because of the differences in CKD and soils and also because different methods are used for measuring the swelling pressure.

Table 4 Predictions of empirical models

	P_s (kPa)	% Error	Ref.
$LogP_s = 0.0276\,PI - 365.2188\gamma_d^{-2.4616} - 0.0032 w_i + 2.2292$	200.4	86	[44]
$P_s = 0.0035817\,PI^{1.12}\,(\frac{C}{w_i})^2 + 3.7912$	47.2	-56	[45]
$P_s = 3.576\,PI - 18.73$	145.8	35	[43]
$LogP_s = -5.197 + 0.01457\,PI + 2.408\,\rho_d + 5.819\,LI$	31.5	-71	[46]
$P_s = 135 + 2(C + PI - w_i)$	136.0	26	[42]

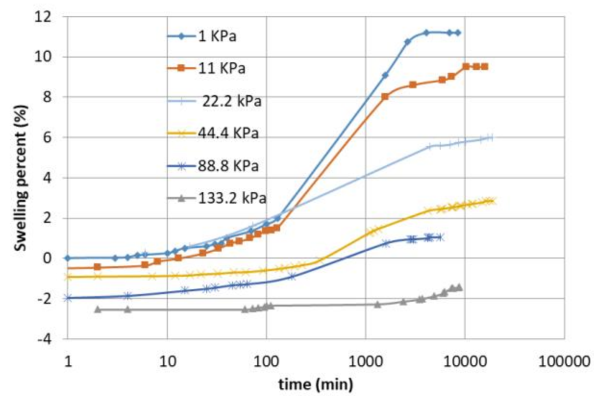


Figure 4 Time rate of swelling of untreated soil

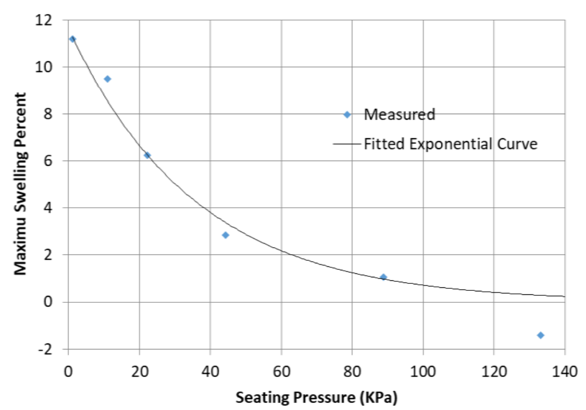


Figure 5 Swelling percent versus seating pressure for untreated soil

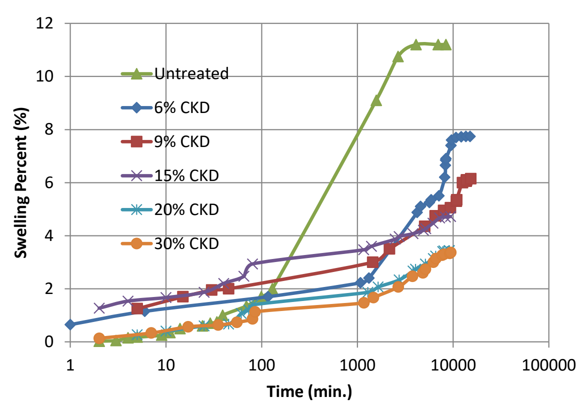


Figure 6 Rate of swelling percent for untreated and soil with CKD (seating pressure =1.1 kPa)

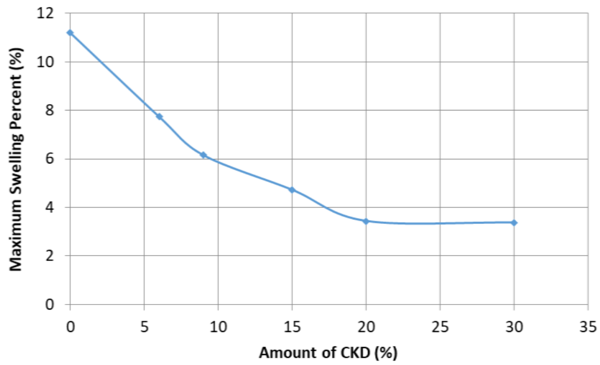


Figure 7 CKD effect on swelling percent (seating pressure = 1 kPa)

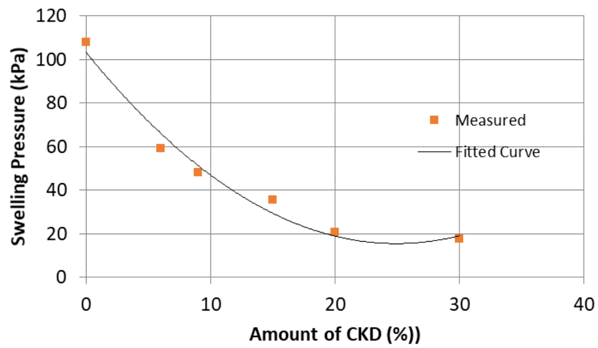


Figure 8 Swelling pressure of CKD-soil mixtures

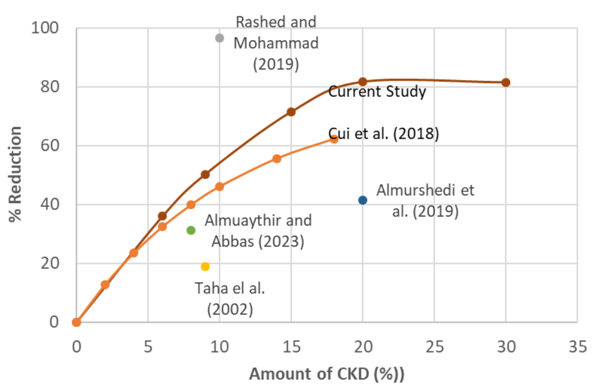


Figure 9 Percent reduction of swelling pressure

Effect of CKD Minerals after Stabilization

Figure 10 displays the XRD graphs for CKD, CKD-soil mixture, and soil. Swelling minerals such as palygorskite, montmorillonite, and illite are found in soil before stabilization. The graph also shows the presence of quartz, calcite, and gypsum.

The XRD graph for CKD shows larnite (calcium silicate Ca_2SiO_4), portlandite (Ca(OH)2), quartz, and calcite (CaO_3) minerals, which are typical for CKD [17].

The XRD graph for soil treated with 15% CKD shows that CKD reduced the peaks for swelling minerals and substantially increased calcite ($CaCO_3$) intensity. This confirms the effectiveness of CKD treatment. Soil stabilization with CKD involves several reactions as [13, 35, 48, 49] as shown in Table 5.

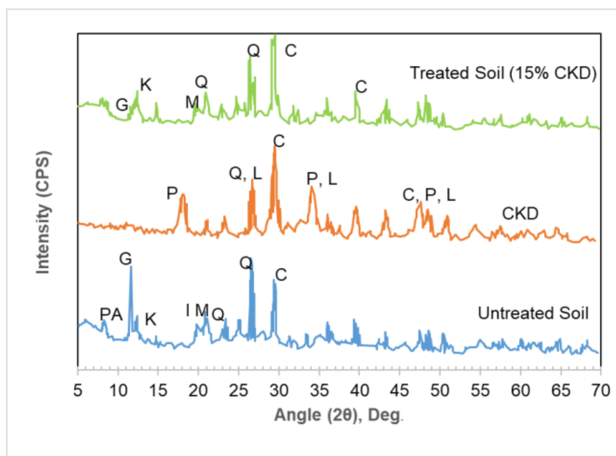
Table 5 Chemical reactions equations

$CaO + H_2O \rightarrow Ca(OH)_2$	[4]
$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^-$	[5]
$Ca^{2+} + 2(OH)^- + SiO_2 \rightarrow CSH$	[6]
$Ca^{2+} + 2(OH)^- + Al_2O_3 \rightarrow CAH$	[7]
$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$	[8]

Effect of CKD on Fabric and Structure of Treated Soil

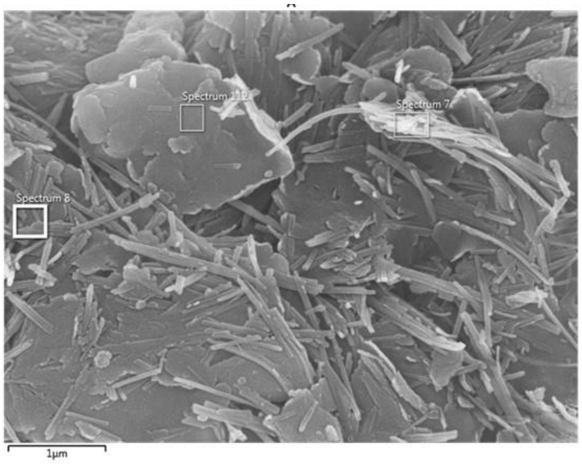
Figure 11a displays the fabric and structure for soil. The figure shows soil grains resembling the shape of rods and sheets [50]. Small to medium-size pores of different shapes are shown between the solid particles. The EDS spectrum for untreated soil (Figure 11b) indicates the dominant elements are silica, aluminum and oxygen and the minor elements are calcium, magnesium and iron similar to XRF results (Table 2).

For soil treated with 15% CKD, image of the fabric is presented in Figure 12a. The fabric and structure of the treated soil included dense clay structure (clay matrix) and minor pores or voids. Ettringite is present in few locations as indicated by needle particles [14, 51]. Figure 12b reveals that calcium is the dominant element in the treated soil which results from abundant CaO from CKD. Oxygen and carbon are also present in high concentration. Element with low concentration included silica, iron, aluminum and sulfar.

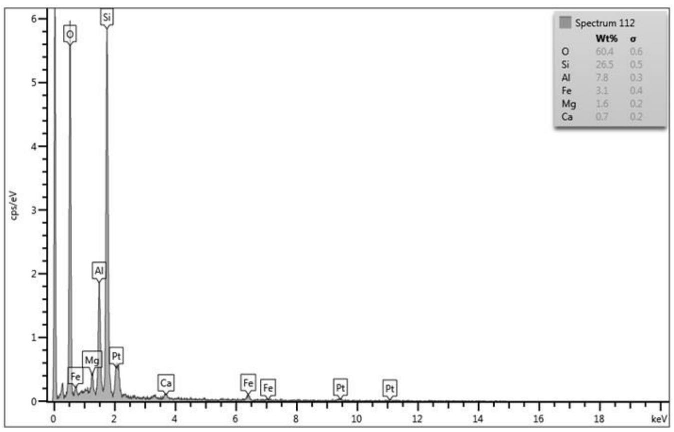


(Quartz (Q); Calcite (C); Gypsum (G); Portlandite (P); Larnite (L); PA = Palygorskite (PA); Montmorillonite (M); Kaolinite (K); Illite (I))nvironments condition for traffic monitoring

Figure 10 XRD patterns

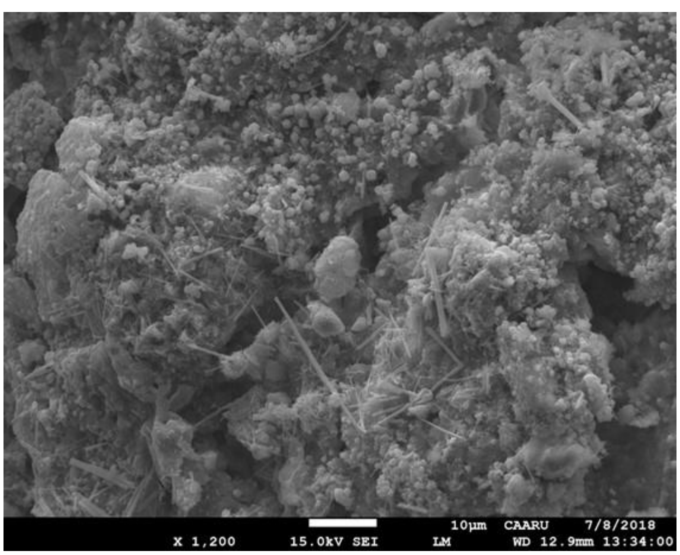


(a) SEM of untreated soil

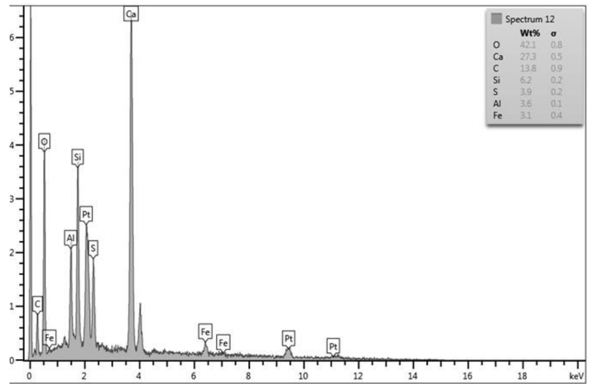


(b) Elements in soil

Figure 11 Fabric and elements in soil



(a) SEM of treated soil



(b) Element in EDS of treated soil

Figure 12 Fabric and elements in CKD-soil mixture

4.0 CONCLUSION

CKD effects on swelling, plasticity and compaction properties of expansive clay were studied. The amounts of CKD mixed with soil ranged from 6 to 30% of the dry soil's mass. The Measured swelling pressures were contrasted to published results and empirical prediction models. This study showed that CKD reduced the liquid limit of the soil from 85 % to 75 %, the plasticity index from 46 % to 16 % (a reduction of 65%), and the shrinkage from 20 % to only 2% (a reduction of 90%). Further, CKD diminished the percent of swelling from 11.2 % to only 3.4 % (a reduction of 70%), and the swelling pressure from 108 kPa to 17.5 kPa (a reduction of 84%). The efficiency of CKD is demonstrated by the reduction of the intensity of clay minerals such as palygorskite, montmorillonite, and illite. Also, the SEM showed that the CKD-soil mixture has a dense clay structure and few pores. Presence of ettringite in isolated locations was evidence from needle-shape particles. Direct comparison between different measured and predicted swelling parameters showed wide scatter because of the difference in testing methods for measuring swelling pressure and swelling percent. Finally, the study demonstrates the effectiveness of CKD in stabilizing expansive soils, however, further research is recommended to confirm the long-term durability (sustainability) of the treated soils.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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