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Cement Kiln Dust for Improving Properties of Soil

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ABSTRACT

Globally, most of the factories have some waste that can be regularly produced. Cement factories generate cement kiln dust (CKD) waste, releasing large plumes into the air. Accumulation of factory waste, such as CKD, is a serious issue that has been considered in much research for some time to find the best cost-effective methods to utilize CKD for various purposes in construction projects. In this study, clay soil (CL) that covers most of north Iraq is considered to characterize its geotechnical characteristics in the *in-situ* condition and as a soil-CKD mixture. CKD was utilized with percentages of 10%, 20%, 30%, and 40% as an additive to replace the dry mass of the *in-situ* soil sample. The study's experimental program involves conducting geotechnical experiments to determine compression index, expansion index, standard proctor compaction, compressibility, and hydraulic conductivity. CKD improved the compaction characteristics, increasing the maximum dry density (MDD) after adding 10% CKD, and the optimum moisture content (OMC) linearly rose. The reduction in the porosity value was noticed particularly after 20% addition of CKD. Compressibility parameters, compression index (Cc) and expansion index (Ce), settlement, and swelling were also enhanced for stabilization and their reductions were significantly noticed. CKD successfully reduced the hydraulic conductivity values of soil-CKD mixtures. The study indicates that CKD is a significant soil stabilizer, suggesting that its removal and use for soil stabilization could have positive environmental consequences.

Keywords: CL soil, Cement kiln dust, Compaction, Compressibility, X-ray fluorescence.

INTRODUCTION

Cement production is growing very fast, globally, amounting to about 4 billion metric tons annually, as shown in Figure (1), due to rapid urbanization and the use of cement as the main raw material in the building-construction processes (Garside, 2020). CKD is a by-product, amounting to about 1% of cement production, is released in thousands of tons into farmland and air, altering topsoil properties and causing environmental damage by creating a thin flame above topsoil and vegetation covers (Al-Bakri et al., 2022), as shown in Figure (2). The cement kiln dust (CKD) leads to changes in the soil's chemical, physical, and mechanical properties (Al-Naje et al., 2020). The most popular beneficial use of CKD is as a stabilizing agent for red mud, mining tailings, dredged materials, municipal sludge, and other similar materials, because of the generally higher amounts of alkalis, CaO, and sulfates (Yamagoshi et al., 2015). The high concentration of lime (CaO) which causes decreasing swelling in soil (Diler, 1959; Naik et al., 2003), made the CKD more cementitious; as a result, the CKD is used for soil stabilization due to its effective impact on the mechanical properties of soil, such as compaction (MDD, OMC), consistency (LL, PL, PI), and compressibility (Cc, Cr, Mv, S_w, S) (Albusoda et al., 2012; Imoh et al., 2023). The mechanical and physical properties that were studied and tested in detail include maximum dry density (MDD), optimum moisture content (OMC), liquid limit (LL), plasticity index (PI), compression index (Cc), expansion index (Ce), volumetric strain index (M_v), and swelling. In this study, soil is replaced with 10%, 20%, 30%, and 40% of CKD to form four distinct mixtures. This study's primary goal was to investigate how CKD affected the topsoil's mechanical characteristics, such as compaction, consistency, and compressibility. The second goal is to employ CKD as an environmentally friendly soil stabilizer, which is crucial given the volume of soil that is now available (Paleogene deposit). The final and the most important goal of this study stems from the unique and concerning situation of having four cement factories concentrated within a mere 10 km² in a region designated as the 'food basket' of northern Iraq. This unprecedented industrial density raises critical questions about the impacts of cement kiln dust (CKD) and airborne dust plumes on the area's topsoil, agricultural productivity, and overall environmental health.

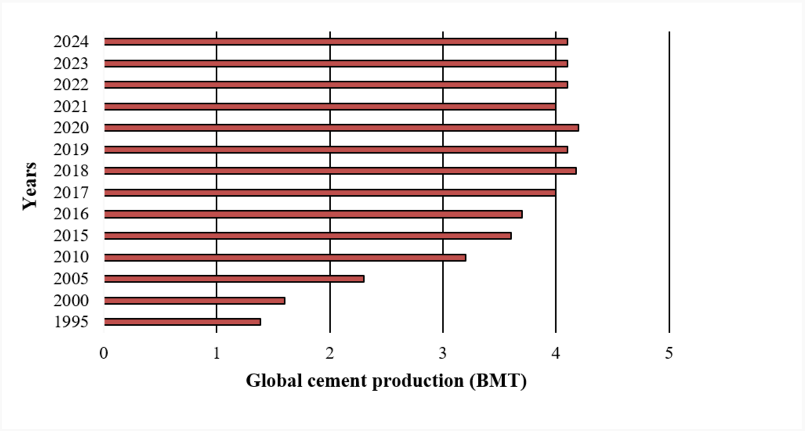

Figure (1): Global production of cement products for various years (1995-2024) after Garside (2020)

Figure (2): Effect of cement kiln dust on the plant's leaves in Baziyan area, northern Iraq close to the places of existing cement factories

Figure (3): (A) Fine-grained clayey soil used in the study, (B) CKD from a cement factory in the Baziyan area, north Iraq

MATERIAL AND METHODS

Soil Site Location

Baziyan, the selected study area, is about 22 km west of Sulaimani city, northern Iraq, see Figure (4). The region is characterized by deep red clay loam sediments from the Paleogene to the present and abundant well-bedded limestone of high calcium carbonate of Sinjar formation. The region has facilitated the construction of thirty-one cement factories (Ali & Al-Kaabi, 2024; Al-Naje et al., 2020; Jassim & Goff, 2006). Three cement factories in the area produce a significant quantity of CKD, as shown in Figure (3B), as a by-product each year. The topsoil in the study area appears as a flame-coated soil, which has an impact on the mechanical qualities of the soils and plants of available farms in the area, in addition to negative impacts of carbon dioxide on the environment, such as the health of vegetation covers.

Materials

The Selected *In-situ* Soil

The required samples of the selected soil were collected from the site close to a cement factory, nearly 100m north-west of the factory. With an elevation of (894) meters a.s.l., the cement factories are situated at latitudes (35°37'39"N) (35°38'45"N) and longitudes (45°05'14"E) (45°03'46"E). After the upper organic part was removed, the extraction and collection of the required soil samples were conducted from 0-5 cm and 5-40 cm underneath the natural ground surface. Six locations sequentially far from the factories that coincided with the wind direction were utilized to obtain the required soil samples. Then, the cement factory is roughly 7.0 kilometres away from the last location of soil sampling. To establish a baseline for comparison, a control soil sample was collected from a location unaffected by cement kiln dust.

Cement Kiln Dust (CKD)

Cement kiln dust (CKD) is considered an industrial by-product that is produced during the process of cement manufacturing. Normally, CKD is frequently dumped in the existing landfills. Similar to ordinary Portland cement, CKD is a fine and almost powdery material (Albusoda et al., 2012; Arulrajah et al., 2017). Therefore, the required samples of CKD were collected from the Baziyan cement factories. These factories usually produce about 2.5 million tons of cement yearly. Importantly, about 1% of the CKD was generated inside, or locally around these factories. Notably, one ton of cement production yields about 0.06-0.07 tons of CKD. The CKD amount utilized in the current study was evaluated and chemically analyzed for mineral oxide components, and showed significant contents of CaO and SiO_2, at about 77%.

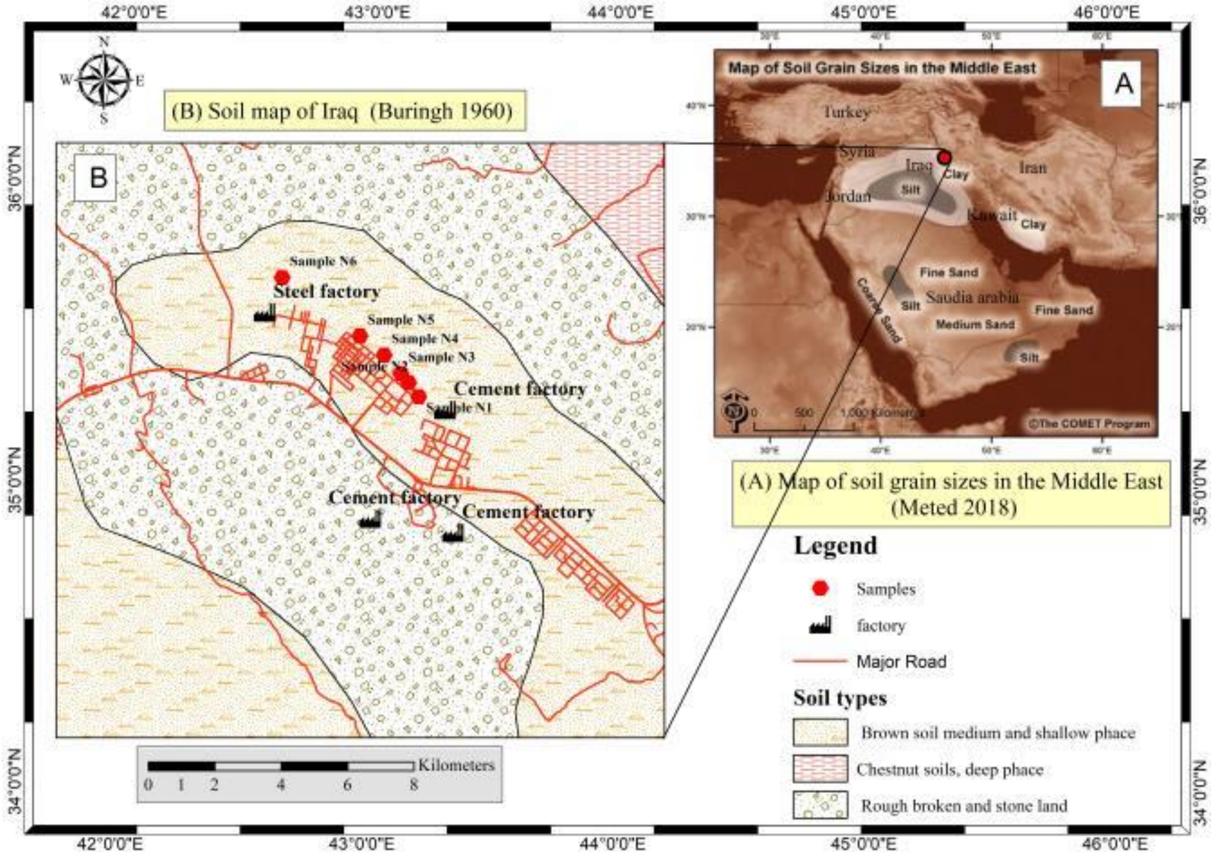

Figure (4): A. Soil size distribution in the Middle East, and B. Soil map of the basin after Buringh (1960)

Testing Methodology

In the present study, many samples of *in-situ* CL soil, as shown in Table 1, were placed in the tray in a dry state, and the 105ºC oven-dry soil was carefully hand-mixed with 10%, 20%, 30%, and 40% CKD stabilizers. A mixture was made for five minutes to conduct the mixing process for the prepared materials and water to obtain a homogeneous mixture. After that, the prepared mixture was put in plastic bags to be turned over, which lasted for five minutes, followed by squeezing out the air. The water content and CKD were measured in the current investigation using the dry mass of the *in-situ* soil sample. Standard proctor compaction, compressibility, and permeability tests were conducted for the prepared mixtures, as shown in Table 2. The electric conductivity (Ec) and the power of hydrogen (pH) value, as shown in Table 1, are also calculated to determine the nature of the chemical reaction of CKD with soil particles. The goal is to maximize the quantity of waste material that can be used to stabilize clayey soil and improve its geomechanical characteristics, such as porosity, compaction, and compressibility.

Table 1. Presentation of the experimental plan that was considered in this study

Natural soil (%)	CKD (%)	Parameters	Soil class	OMC (%)	Curing period	Ec 25ºC (µS/cm)	pH
100	0	n, Ac, MDD, OMC, C_c, C_e, Mv, S, Sw and Hc	CL	14	0, 3, 7, 14, 28	541	7.54
90	10		CL	17.8		334	7.51
80	20		CL	19.8		342	7.86
70	30		CL	22		331	7.74
60	40		CL	27.7		344	7.93

n = porosity, Ac = activity of clay, MDD = maximum dry density, OMC = optimum moisture content, Cc = compression index, Ce = expansion index, Mv = volumetric strain, S = settlement, Sw = swelling, Hc = hydraulic conductivity.

Table 2. Engineering characteristics of the used *in-situ* CL soil and CKD samples

Engineering Characteristics	Values (Soil)	Values (CKD)
Soil color (according to Munsell Color Chart)	Light brown	Brownish-yellow
Natural water content (W%)	14.12%	16.2
Specific gravity (G_s)	2.61	2.22
Liquid limit, LL (%)	47.1%	-
Plastic limit, PL (%)	26.11%	-
Plasticity index (PI)	20.99	-
Shrinkage limit, SL (%)	15.88%	-
Soil type (according to USCS)	CL	-
Optimum moisture content (OMC)	13.52%	-
Maximum dry density, MDD (g/cm^3)	1.65	-
Swelling percent Sw (%)	9.54	7.15

RESULTS AND DISCUSSION

Importantly, the aim of the current study is to investigate the role of CKD in improving some of the geotechnical characteristics of CL soil. Utilization of CKD caused significant changes in the examined geotechnical characteristics of the CL soil sample. The obtained outcomes are supported by the conducted experimental scenario, which presents the capability of CKD to stabilize some of the undesired geotechnical characteristics and enhance the suitability of the selected soil for various construction projects. The achieved stabilization level yielded that CKD is a significant material to enhance the capability of CL soil for more resistance to various risky conditions.

Effects of CKD on Index Properties and Mineralogical Composition of the *In-situ* Soil Sample

X-ray fluorescence of CKD and mixed soil with CKD showed that the main constituents of samples are calcium oxide (CaO), quartz (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and magnesia (MgO), as presented in Table 3. To obtain the used soil name, according to the Unified Soil Classification System (USCS) considering the ASTM D 2487-93 standard, the soil type is CL (clay loam). All CKD particles were less than 425 micrometers in size, passing through a No. 40 sieve. CKD has no impact on the *in-situ* soil sample type which is CL type of soil, whereas it has notable influences on the chemical changes of each of the utilized mixtures, as presented in Table 3. CaO percentages in each of the CKD and *in-situ* soil samples are 45.4% and 8.7%, respectively. The addition of CKD in percentages of 10, 20, 30, and 40% caused the CaO content of the mixtures to be increased to 19.5, 20.5, 24.5, and 28.3%, respectively. The high calcium content of CKD is the primary source of Ca ions, which leads to greater formation of cementitious compounds, resulting in higher compressive and shear strengths. Moreover, the pH value exhibited a slight increase, ranging from 7.54 to 7.93, indicating that the soil-CKD mixtures possess enhanced alkaline characteristics, particularly at a depth of 40cm. This phenomenon can be attributed to the leaching process, which has resulted in a higher concentration of Ca^{2+} ions derived from the incorporation of CKD. This high pH promotes the pozzolanic reactions between CaO and both SiO_2 and Al_2O_3 in the soil, leading to the formation of cementitious compounds (C-S-H, C-A-H). These cementitious compounds bind soil particles together, increasing strength and stiffness and reducing permeability. The involvement of magnesia (MgO) in cementitious reactions is acknowledged, yet its impact is generally not as pronounced as that of calcium. Although magnesia can facilitate strength enhancement, it may also promote the formation of undesirable phases. CKD contains soluble salts, including calcium sulfate (gypsum), which can manifest in various forms such as calcium sulfate dihydrate, hemihydrate, or soluble calcium sulfate anhydrite. These compounds contribute to elevated electrical conductivity (Ec), signifying a high salinity characteristic. Such high salinity levels can adversely impact the long-term durability of soil-CKD mixtures and hinder the soil's capacity to support plant growth. Therefore, CKD contributes positively to improving the undesired characteristics by creating more powerful attraction forces among the soil particles.

Figure (5) presents the influence of CKD on the porosity of the CL soil sample. The addition of CKD to the *in-situ* soil sample accumulates around the particles; this state increased the percent of available material (CKD) inside the existing pores and led to a decrease in the pore sizes, which significantly yielded smaller porosity percentages as the CKD content increased. Also, the addition of CKD that raised the CaO content helps the soil-CKD mixtures flocculate, driving the particles to be cumulative and linked tightly together and creating cementing bonds among the soil particles instead of being filled by either air and/or water (Salih et al, 2022). Moreover, after evaluating the soil-CKD samples, the results specified that the reduction in the porosity value is because of the existence of the free CaO and SiO_2 (around 77%), regularly causing denser packing and resulting in a notable reduction in the porosity value, therefore participating in the CL soil's stabilization.

Replacement of the *in-situ* soil particles by CKD particles means that the available percentage of clayey particles decreases, which causes the activity of the clayey particles to be decreased due to CKD-percentage increase, as shown in Figure (6). Moreover, the increase in the CaO content in the soil-CKD mixes absorbed the moisture content and gave the soil mixes more capability and stiffness than the *in-situ* soil sample.

Table 3. Chemical composition of the use of *in-situ* soil sample, CKD sample, and CKD mixed with the soil

Oxides	Control soil	CKD	S1(10%CKD)	S2(20%CKD)	S3(30%CKD)	S4(40%CKD)
Silica (SiO_2)	55.5	31.9	48.8	46.5	44.6	42.2
Calcium oxide (CaO)	8.7	45.4	19.5	20.5	24.5	28.3
Alumina (Al_2O_3)	17.0	9.4	15.2	15.4	14.6	13.6
Iron oxide (Fe_2O_3)	9.9	5.9	7.9	8.6	7.1	7.3
Magnesia (MgO)	4.8	5.1	4.5	5.0	4.6	4.9
Potassium oxide (K_2O)	2.3	1.2	2.4	1.9	2.2	1.9
Titanium dioxide (TiO_2)	1.0	0.5	1.0	0.9	1.0	0.9
Sodium oxide (Na_2O)	0.5	0.2	0.4	0.4	0.4	0.5
Sulfur trioxide (SO_3)	0.1	0.2	0.2	0.5	0.4	<0.0100
Manganese oxide (MnO)	0.2	0.1	0.2	0.2	0.2	0.1
Phosphorus pentoxide (P_2O_5)	0.0	0.1	0.0	0.2	0.3	0.2

Table 4. The results of chemical analysis regarding ion concentrations of the samples based on variations in depth

Locations	Samples	Depth (cm)	pH	ECe (μS/cm)	EC_{25}ºC (μS/cm)	TDS (ppm)	HCO_3^- (ppm)	Na_+ (ppm)	Ca+ (ppm)	Mg (ppm)
N1	A_1	0-5	7.22	1007	1357	869	146.4	22.39	195.20	19.68
	B_1	5-40	8.06	299	406	260	219.6	13.63	60.00	18.72
N2	A_2	0-5	7.5	973	1405	899	463.6	20.44	214.80	18.24
	B_2	5-40	8.12	462	657	420	219.6	16.55	100.00	10.08
N3	A_3	0-5	7.86	1296	1814	1161	805.2	17.52	304.00	21.36
	B_3	5-40	7.97	750	1037	663	488.0	14.60	164.80	11.52
N4	A_4	0-5	7.74	472	641	410	219.6	15.57	86.00	18.48
	B_4	5-40	8.02	667	957	613	219.6	14.60	134.40	23.28
N5	A_5	0-5	7.57	6730	9422	6030	219.6	59.38	1336.0	82.32
	B_5	5-40	7.93	719	1028	658	170.8	15.57	94.40	31.68
N6	A_6	0-40	8.06	541	773	495	292.8	17.52	126.80	5.04

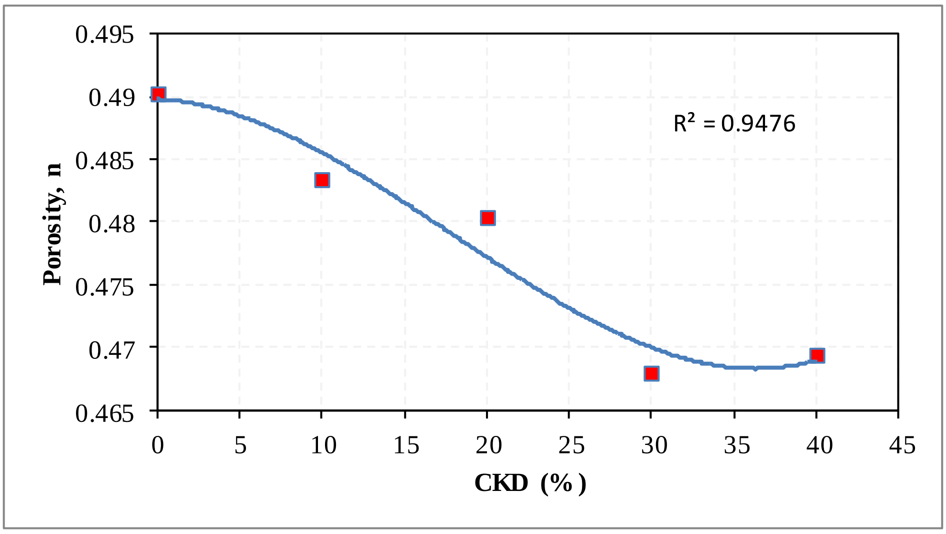

Figure (5): Variation of porosity of the soil-CKD mixtures with different percentages of CKD

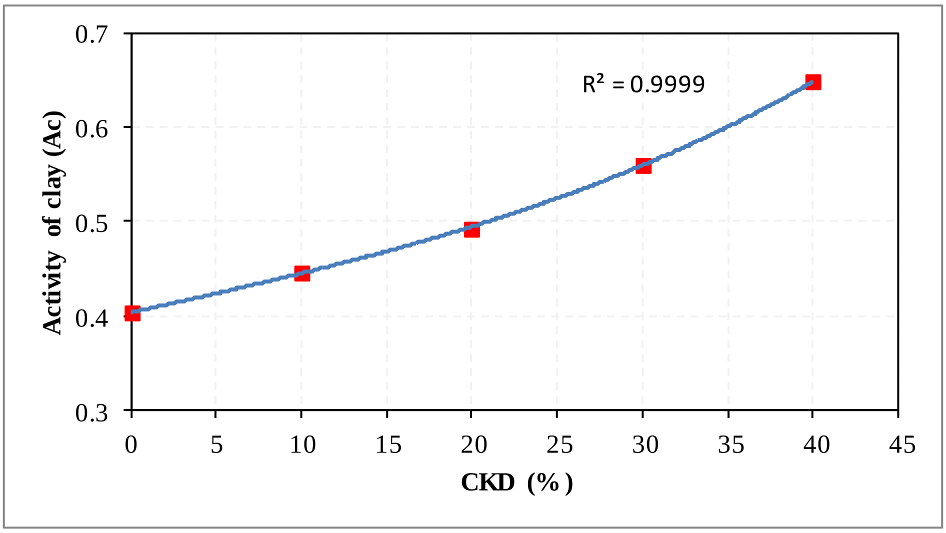

Figure (6): Variation of the activity of clay of soil-CKD mixtures with different percentages of CKD

Effects of CKD on Compaction Parameters

The soil-CKD mixtures were compacted with four different percentages of CKD (10%, 20%, 30%, and 40%) according to ASTM standard (D698-12) to determine the effect of CKD on the maximum dry density (MDD) and the optimum moisture content (OMC). Figure (7) shows the influences of CKD on MDD values. Upon the addition of 10% CKD, a notable decrease in MDD value was noticed compared to the MDD value of 0% CKD. After that, the MDD values were significantly raised when the CKD percentages were more than 10%. Compared to the related literature, some previous studies showed that the dry density of the stabilized soils by cement has increased by more than 4% (Anwar Hossain, 2011; Bahar et al., 2004; Rahman, 1986). Moreover, CL soil's MDD was reduced due to the early reaction with the added 6% lime kiln dust, which resulted from the process of flocculation and agglomeration (Eid et al., 2024; Jjuuko et al., 2024).

The original characteristics of the used soil and CKD influence the compaction process of the prepared mixtures; for instance, specific gravity, and grain-size distribution. In the early stage of the stabilization process, CKD coats the mixed soil grains, resulting in larger aggregation conditions, which reduces the available void sizes. CKD particles at the early stage tend to reduce the mixture dry density, as these particles are quite small in size. This state continues until the CKD particles reduce the spaces/voids by flocculation more in the free spaces, resulting in enhancing the mixture dry density to be increased. Figure (8) shows the changes happening in the OMC values with an increase in the content of CKD. This figure demonstrates that when CaO content increases, the water needs to increase, which results in the OMC value to increase sharply to 40%. So, increases in CaO content (8%-28%), caused by the utilization of 40% CKD, resulted in the OMC value of the used CL soil notably to increase (14% - 29%). The CKD filled the pores among soil particles and occupied 40 percent of the soil sample. This state led to an increase in the absorption of water more than the normal condition due to the need for water for the chemical process of stabilization by CKD.

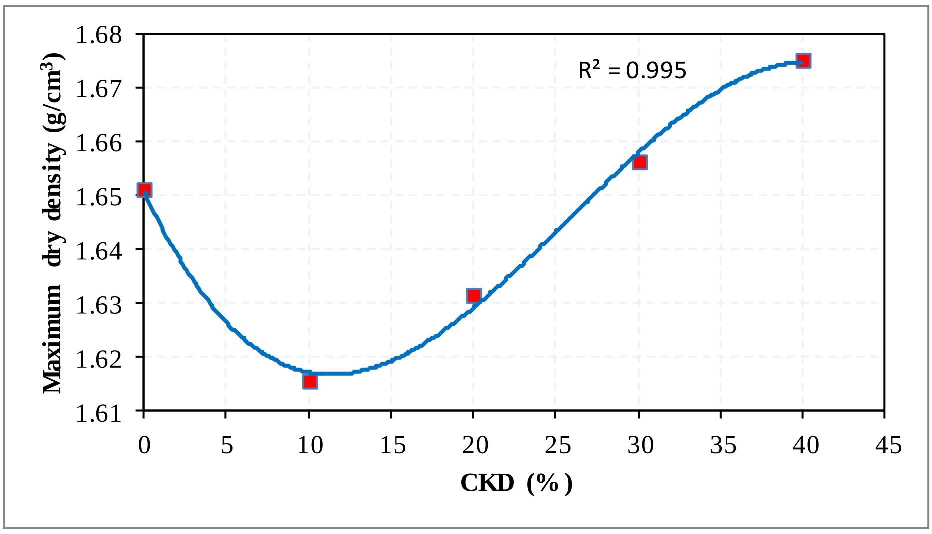

Figure (7): Variation of the MDD of the soil-CKD mixtures with the used percentages of CKD

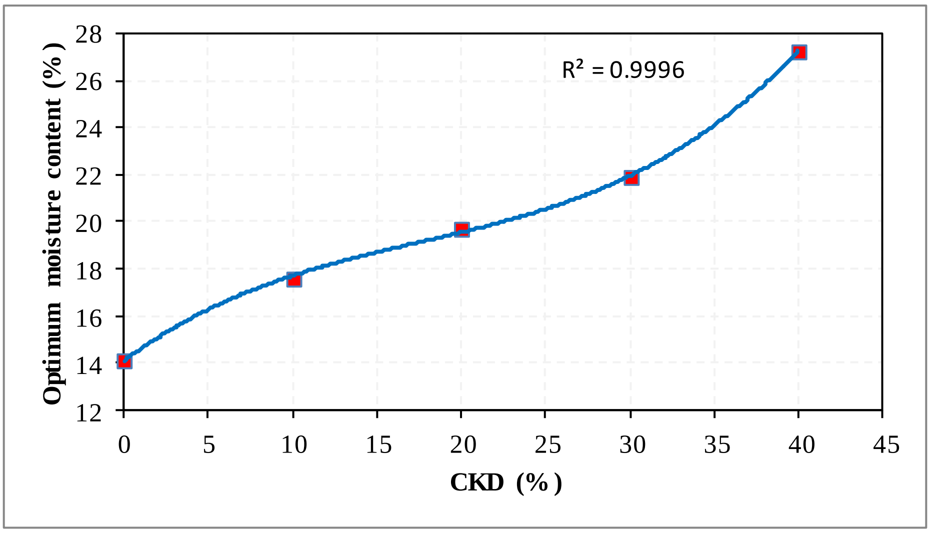

Figure (8): Variation of the OMC of the soil-CKD mixtures with the used percentages of CKD

Effects of CKD on Compressibility Parameters

The compressibility of soil samples after adding different percentages of CKD (10, 20, 30, and 40%) was assessed based on the Cc index, as shown in Figure (9). The results reveal that 20% of CKD gives maximum Cc, which is related to the pore and water content of the soil sample. When CKD exceeds the perfect permeability of soil, the particle contact causes the soil particles to move far away from each other, which leads to a decrease in the grain contact and decreases the compressibility (Mohamed et al., 2024). Based on Figure (9), CKD has no positive effect on improving the Cc of the CL soil, while its effects negative and increases compressibility at 20% of CKD. After that, Cc started to decrease until the added percentage of CKD was 40%. This state is due to the particle size of the CKD being quite small, and in some way closer or smaller than clay particle size, which makes the soil-CKD mixture more prone to compressibility as both grains of either the soil sample or the CKD are small and not capable of resisting the forces, which resulted in more compressibility. After 20% of added CKD, the soil-CKD mix starts to decrease in terms of Cc, which may be due to the decrease in the soil's dry mass; in other words, the clayey particle percentage is decreased, and that reduces the compressibility issue.

Regarding the presented results in Figure (10), the expansion index (Ce) is at a maximum level when the added CKD percentage is 30%, but the minimum expectation is when CKD is 10%, 20%, or 40 %, which is related to the permeability of the soil sample when exceeding the permeability level, where it starts more expanding, while in 40% of CKD, the coated soil sample is governed by CKD instead of clay content, which leads to an increase in the value of Ce. Significantly, Figure (11) shows the role of CKD in changing the behaviour of CL soil's Mv, which is notably decreased, especially for 30% and 40% added CKD. Almost all the soil-CKD mixtures exhibited reductions; however, both 10% and 20% added CKD caused the soil to behave similarly to the *in-situ* soil state. Importantly in Figure (11), the soil-CKD mixtures (30% and 40% added CKD) changed their style of change which is significantly different from the *in-situ* soil sample and the other soil-CKD behavior. As much as CKD was added, as significant as reduced and changed the soil-CKD mixtures' coefficient of soil volume compressibility. Similarly, the measured settlement values, which are presented in Figure (12), have decreased significantly. Replacement of clayey particles with CKD reduced the agents that generate settlement and cause volume changes, as the CKD particles behave differently from the common clayey particles. The remaining clay particles in the soil-CKD mixtures are coated with the CKD, resulting in more cementing agents among clayey particles, which bond them causing the visible reductions in the values of volumetric strain and settlement of the soil-CKD mixtures. Finally, CKD percents beyond 20% are more efficient for CL soil's compressibility characteristics.

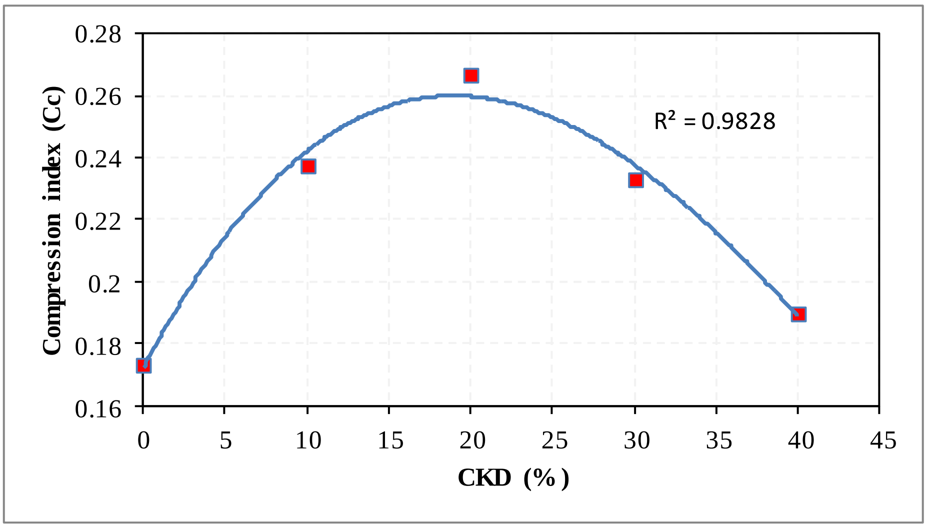

Figure (9): Variation of the compression index of the soil-CKD mixtures with the used percentages of CKD

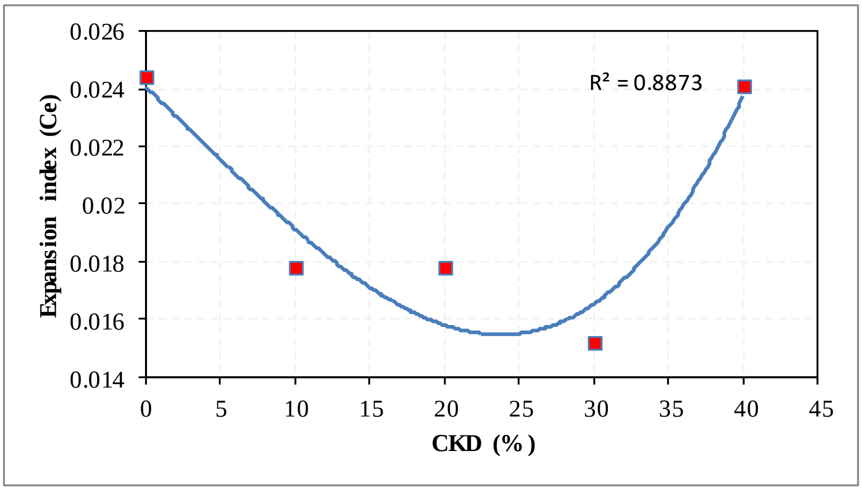

Figure (10): Variation of the expansion index of the soil-CKD mixtures with the used percentages of CKD

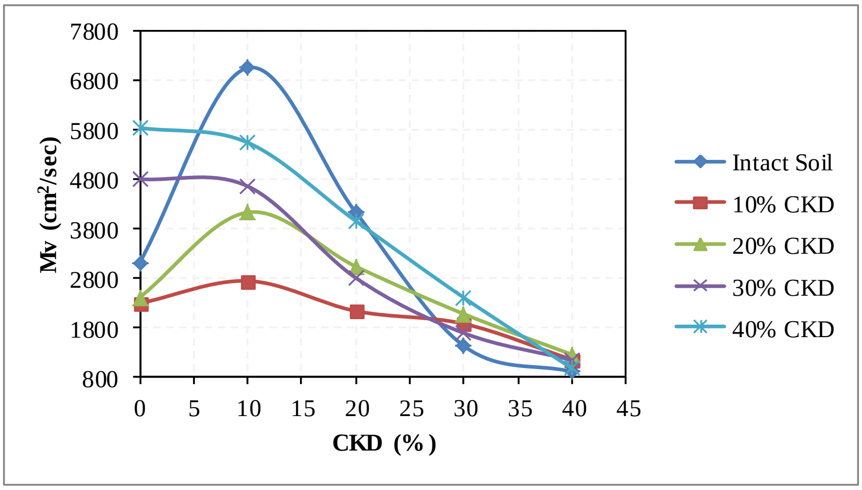

Figure (11): Variation of the volumetric strain of the soil-CKD mixtures with the used percentages of CKD

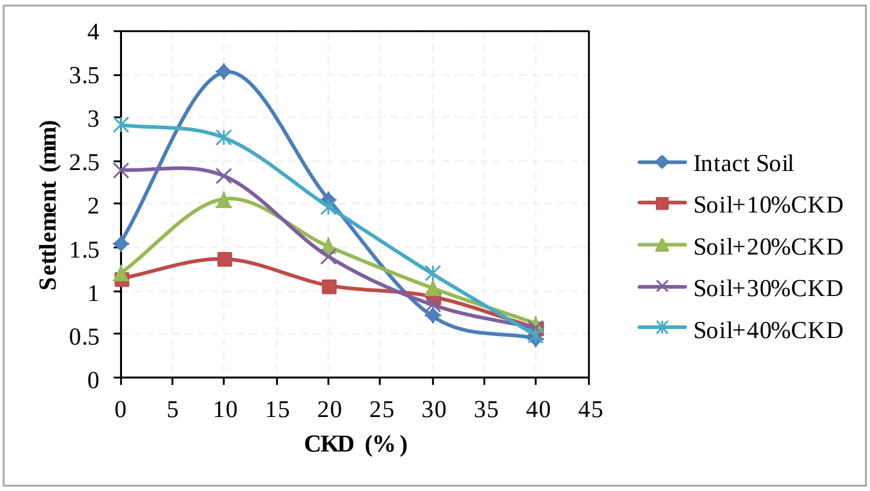

Figure (12): Variation of the measured settlement for the soil-CKD mixtures with the percentages used of CKD

Effects of CKD on Swelling

The laboratory results reveal that with increasing the CKD percentage, the swelling percent of the soil-CKD mixtures decreases due to the high concentration of CaO which changes the pH value of the mixtures, the Ec value, and the chemical reaction condition between the clay oxides and the CKD oxide. The C_a^{+2} ions coated the clay particles causing more absorption of water and stopping the strain reaction between the clay particles and the other soil particles. As a result, the solidification increased, making the soil-CKD mixtures more capable of resisting any swelling forces. In addition, CKD works more as a cementing bond among soil particles of the CL soil sample, which ties the clay particles more together and reduces the clay minerals' capability to swell, as shown in Figure (13). The findings are consistent with those of (Jain, 2024), who claimed that electrostatic force causes cations to adhere firmly to the clay surface.

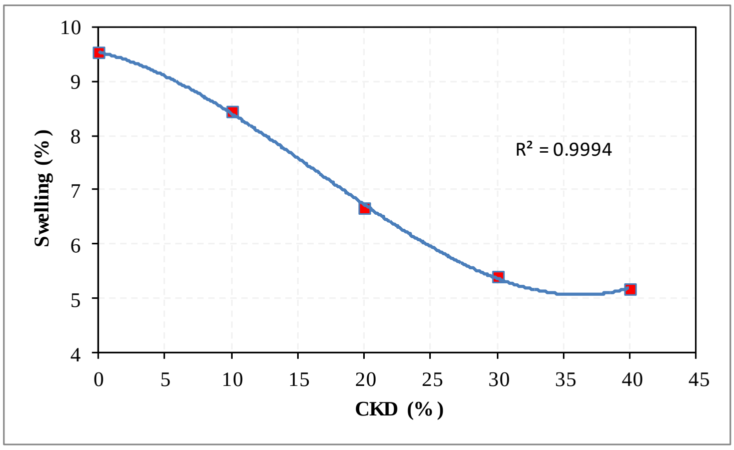

Figure (13): Variation of swelling with the percentages used of CKD

Effects of CKD on Hydraulic Conductivity

In the current study, Figure (14) presents the relationship between the soil-CKD mixtures' hydraulic conductivity (HC) and the used CKD percentage. Notably, H_C is influenced by the percentage of the added CKD and the main composition of the used CKD, which means that the decrease happens in the amount of the dry mass of the *in-situ* soil sample that exhibits permeability issues. From the mentioned figure, it can be noticed that with the CKD percent increase, the H_C value notably decreased. This is because the addition of CKD raised the alkalinity character of the soil-CKD mixtures. Alkalinity-character increase causes the endorsement of the pozzolanic reaction, which makes the particles of the used CKD more capable of working as a cementing binder (cementing bonds increase). The binder percentage increase caused by CKD can significantly increase the solidification of the soil-CKD mixtures, which may work essentially or at least auxiliarily to progressively reduce the size of the initial voids existing in the *in-situ* soil sample. The obtained reductions in the values of the H_C are in line with the outcomes of related studies, such as (Al-Refeai & Al-Karni, 1999; Moses & Saminu, 2012; Osinubi, 2012).

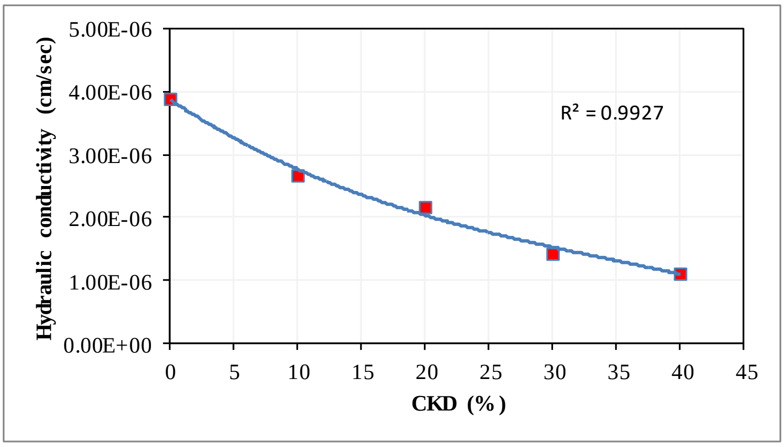

Figure (14): Variation of hydraulic conductivity of the soil-CKD mixtures with the various percentages of CKD

STATISTICAL ANALYSIS

The statistical assessment of the impact of cement kiln dust percentage on mechanical properties was conducted through the analysis of means, standard deviations, and correlation coefficients, see Table 5. This evaluation, carried out on samples prepared in accordance with ASTM standards, was validated by comparison with established procedures, thereby affirming the influence of the dust.

$$\text{Mean} = (x) = \frac{\sum_i^n 1^{xi}}{n}) \qquad (1)$$

Xi Variable, n number of samples

$$\text{Standard deviation SD}= \sqrt{\frac{\sum(xi-Mean)^2}{n}} \qquad (2)$$

Pearson's correlation coefficient which measures the linear relationship between two variables (Cement Kiln Dust % *vs*. Parameters)

$$r = [\, n(\sum xy) - (\sum x)(\sum y) \,] / [\, \sqrt{[\, n(\sum x^2) - (\sum x)^2 \,]} * \sqrt{[\, n(\sum y^2) - (\sum y)^2 \,]} \,] \qquad (3)$$

r = Pearson's correlation coefficient, n = number of pairs of data points, $\sum xy$ = sum of the products of paired data points, $\sum x$ = sum of all x values, $\sum y$ = sum of all y values, $\sum x^2$ = sum of the squared x values $\sum y^2$ = sum of the squared y values.

Table 5. Statistical analysis between cement kiln dust and geotechnical parameters

Variables	**Mean (x)**	**Standard Deviation (SD)**	**Correlation Coefficient (r)**
Pressure, P (kPa)	155	158.11	-0.92
Void ratio, e	0.55	0.076	-0.98
Maximum dry density, MDD (g/cm^3)	1.58	0.058	-0.85
Optimum moisture content, OMC (%)	19.92	5.07	0.95
Specific gravity, G_s	2.375	0.104	-0.89
Porosity, n (%)	47.82	0.923	-0.96
Compression index, Cc	0.22	0.036	0.78
Expansion index, Ce	0.019	0.004	-0.65
Volumetric strain, Mv (cm^2/sec)	3299	2382	-0.93
Settlement, S (mm)	1.65	1.239	-0.94

The addition of cement kiln dust led to a denser material, as evidenced by decreases in void ratio, porosity, and dry unit weight. Additionally, the material's water-retention capacity was enhanced, indicated by a rise in optimum moisture content. While there was a moderate increase in compressibility associated with the addition of cement kiln dust, the material demonstrated a marked improvement in stability, as reflected by diminished settlement and volumetric strain.

Importance of Study Outcomes

From our study conducted on the role of CKD for soil-stabilization purposes, we have also considered more related purposes. After achieving the essential understanding from the obtained experimental set of data, CKD is a robust waste for soil-stabilization work, especially CL soils. CKD purely improved CL-soil characteristics, such as porosity, activity of clay, compaction and compressibility parameters, and hydraulic conductivity. With the obvious outcomes, CKD works chemically to coat the soil grains and tie them together. CKD's capability to generate bonds among soil grains is significant. Thus, CKD behaves as a barrier to prevent direct water contact for the soil grains, a cementing bond creator, and a filler for the initial excising voids. Also, CKD increased the percentage change of the CL-soil reactions for external actions, such as settlement record, porosity control, water-infiltration process *via* hydraulic-conductivity control, solidification process, and mechanical response for compressibility forces. From the experimental achievements, any decision on using CKD for soil-stabilization purposes is fruitful. Outstandingly, and as a comparison with the global work of other researchers who utilized CKD, this study thoroughly demonstrated the accurate character of CKD to amend the undesired parameters of CL soil within short-term laboratory testing. CKD is one of the best waste types to be used for CL soil-stabilization purposes.

CONCLUSIONS

After the successful conduction of the study experimental program, the following conclusions can be drawn

1. Utilization of CKD leads to a significant reduction in the porosity percentage of CL soil, specifically beyond 20% of CKD. The best percent is 30% of CKD for porosity and 40% of CKD for the activity of clay improvement.
2. The addition of CKD significantly improves CL soil's MDD. 40% of CKD is the best percent to obtain the best improvement of MDD. OMC values increased sharply for all the added percentages of CKD.
3. The addition of CKD is not improving the Cc value of CL soil, while it works positively to control and reduce the Ce value. The best percentage of CKD is 30% for the improvement of CL soil's expansion index (Ce).
4. Utilization of CKD causes a notable reduction in the CL soil's swelling percentage. The optimum percentage is 40%, which resulted in an almost 50% reduction in the swelling percentage of the CL soil.
5. The addition of CKD has considerably reduced the hydraulic conductivity of CL soil. At 40% CKD, the hydraulic conductivity dropped by 39%.

Recommendations

To comprehensively evaluate the impact of CKD on soil mechanical properties, we recommend a detailed examination of chemical and mineral oxide analyses, coupled with the exploration of diverse CKD sources. Triaxial testing is essential for a more thorough assessment of geotechnical parameters. In the specific context of this study area, the presence of three cement factories within 20 km^2 has negatively impacted topsoil, resulting in increased compressive strength. While this may incidentally improve soil stability, but as long-term effects on soil health and plant growth, it can hinder vegetation root growth and agricultural ploughing. Therefore, we recommend the implementation of plastic greenhouses across all farmlands to mitigate soil-quality degradation. Additionally, further research should investigate the long-term effects of CKD on soil health and plant growth, considering the specific chemical composition of locally sourced CKD.

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