Impact of Cement Kiln Dust on Soil Geotechnical Properties: A Case Study of Soils Surrounding Cement Factories in Bazian Area, Sulaimani Governorate, Iraq

Rozhgar A. Hasan[1†], Fahmy O. Mohammed[2] and Nihad B. Salih[3]

[1]Department of Natural Resource, Collage of Agriculture Engineering Science, University of Sulaimani, Sulaimani, Kurdistan region - F.R. Iraq

[2]Department of Earth Sciences and Petroleum, College of Science, University of Sulaimani, Sulaimani, Kurdistan region - F.R. Iraq

[3]Department of Water Resources Engineering, College of Engineering, University of Sulaimani, Sulaimani, Kurdistan region - F.R. Iraq

***Abstract*—As cement demand rises daily; kiln dust from cement-producing facilities is being collected in large quantities. This tiny dust poses a risk to the environment when it is disposed of. This study investigates the potential reuse of CKD as a stabilizing agent for expansive soils. The amount of CKD added to intact soil was 0%, 10%, 20%, 30%, and 40% of the dry mass of the soil. The liquid limit (LL) of the intact soil decreased after adding CKD from 47.7% to 43.7%, and the plastic limit (PL) from 26.97% decreased to 21.36%. A sharp decrease was observed in the consistency index (Ic) and toughness index (It), while the flow index (If), liquidity index (Li) and shrinkage index (Is) are noticeably increased. The unconfined compressive strength (qu), modulus of elasticity (E), and Resilient Modulus (Ur) increased for the samples cured for 7 days and 28 days; the rate of increase in the values of these parameters was observed to be higher in 28 days during the period compared to 7 days. Also, the shear strength and cohesion sharply increased after the soil was treated with CKD. The UPV also increased for both sets of prepared cylindrical soil samples. The CKD additives decreased the hydraulic conductivity of the soil and successfully improved the geotechnical characteristics of fine-grained soil. Thus, CKD can be repurposed as a sustainable soil stabilizer for slopes, subgrades, and foundations, providing a viable solution for its disposal and reducing environmental impact.**

***Index Term*—Cement kiln dust, Eco-friendly additive, Soil stabilizer, Swelling, Uniaxial compressive strength.**

I. Introduction

Portland cement, a fundamental building material, is primarily derived from abundant natural resources like limestone and chalk, both of which are rich in carbonates (Reid, 2024). Other key raw materials include ironstone and gypsum, alongside essential chemical compounds such as calcium oxide (CaO), aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), and iron (III) oxide (Fe_2O_3), (Bye, 1999). The initial stages of cement production, specifically the extraction and processing of these raw materials, carry substantial environmental and health implications (Huntzinger and Eatmon, 2009). Cement kiln dust (CKD) is the most harmful by-product of cement manufacturing, which is a fine particle generated in large quantities from kiln exhaust gases. The CKD constitutes 15–20% of the total cement clinker output, which is one of the most significant environmental, economic, and social problems nowadays that must be properly disposed of (Habert, 2014). In Iraq generally, and especially in the Bazian area four cement factories within 72 km^2 produce continuously (24 h/day), emit large volumes of CKD, forming persistent plumes over the region. Despite these concerns, CKD exhibits pozzolanic, cementitious properties and its cost-effective have led to it being used as a stabilizing agent more often recently, making it a useful stabilizer for specific soil types such as clayey soils including lean clays (CL) and lateritic soils (Amadi and Eberemu, 2013; Yamagoshi et al., 2015; Yin et al., 2025). CKD is a soil additive that improves mechanical and physical properties such as texture, strength, compressive and tensile strength, modulus of elasticity, and California bearing ratio CBR, as well as durability in terms of shrinkage, permeability, water resistance and reduces swelling of soil (Elbaz et al., 2019). The amount of free lime (CaO) play critical role pozzolanic reaction in CKD and determines whether it is suitable for stabilizing soil, and it can be added to poor soils to improve their geotechnical qualities (Miller and Azad, 2000; Sreekrishnavilasam et al., 2007; Al-Homidy, Dahim and Abd El Aal, 2017; Rimal, Poudel and Gautam, 2019). When CKD is added to the soil, the Unconfined compressive strength (UCS) increases significantly (Miller and Zaman, 2000). Using

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†Corresponding author's e-mail: rozhgar.hasan@univsul.edu.iq

CKD as a stabilizing factor for black cotton soil as a subgrade gives significant and long-lasting benefits (Ahmed, Jafer and Al-Kremy, 2024). Importantly, based on (Peethamparan and Olek, 2008a; Ismaiel, 2013; Amadi and Lubem, 2014; Rimal, Poudel and Gautam, 2019), the addition of cement dust affects the soil's plasticity index, maximum density, and optimum water content, potential of hydrogen value, shear strength, and California bearing ratio. One of the most harmful waste disposals besides the increasing trend towards cement production is the increasing quantities of CKD generated in Iraq and its underutilized potential, repurposing CKD for geotechnical applications offers an environmentally and economically sustainable solution to both waste management and soil improvement. This research aims first to evaluate and characterize the geotechnical properties of fine-grained soils when treated by CKD, to understand how the presence of CKD alters the inherent engineering characteristics of these soils. The second is to improve problematic soils found in the Sulaimani Governorate by using CKD as an additive by-product.

II. Materials and Methods

A. Geological Setting and Description of Study Area

The study area is located in Sulaimani governorate, about 32 km to the west of Sulaimani city. The main lithological rock units are the Sinjar Formation of the Eocene age (Jassim and Goff, 2006), which has great economic importance in the cement industry because of its enrichment with calcium carbonate, its thickness is more than 100–150 m (Buday, 1980). The quaternary deposit of about 40–30 m thickness of brown soil appeared as cultivated farmland (Buringh, 1960) as shown in Fig. 1, this Quaternary deposit is used in the cement industry as a soil source for cement (Mohammed and Al-Hazaa, 2025). The cement industry rapidly grew in the area and was represented by three factories within 50 km^2 of the area because the quarries are very close to the factories and farmlands.

B. Material

Soil

Soil samples (Thirteen) were taken from the vicinity of the Bazian cement factories, which are about 100 m–7 km m northwest of the facility. The factories are situated at latitudes (35°37'39"N) (35°38'45"N) and longitudes (45°05'14"E) (45°03'46"E) as shown in Fig. 1. Following the removal of the upper organic portion, soil samples were taken. Six sequential locations away from the factory that coincided with the direction of the wind were used to collect the soil samples. The cement facility is approximately 7.0 km away from the last soil sampling location. Since the soil at the final position is seldom impacted by cement dust, the last soil sample location point was chosen as intact soil and treated as a control soil sample evaluated.

C. CKD

CKD, a fine, powdery industrial by-product similar to Portland cement, is produced during the cement manufacturing process and is frequently dumped in landfills (Arulrajah et al., 2017; Al-Bakri, Ahmed and Hefni, 2024). CKD sample was taken from cement factories in the Bazian area. The average particle size of CKD is usually between 10 μm and 200 μm as shown in Fig. 2, which is a high-quality additive and compatible mixed materials and gives favourable compaction, permeability, and unconfined compressive strength values to clay (Gupta et al., 2012; Zhao et al., 2020). The production in Bazian cement factories reaches up to 2.5 million tons of

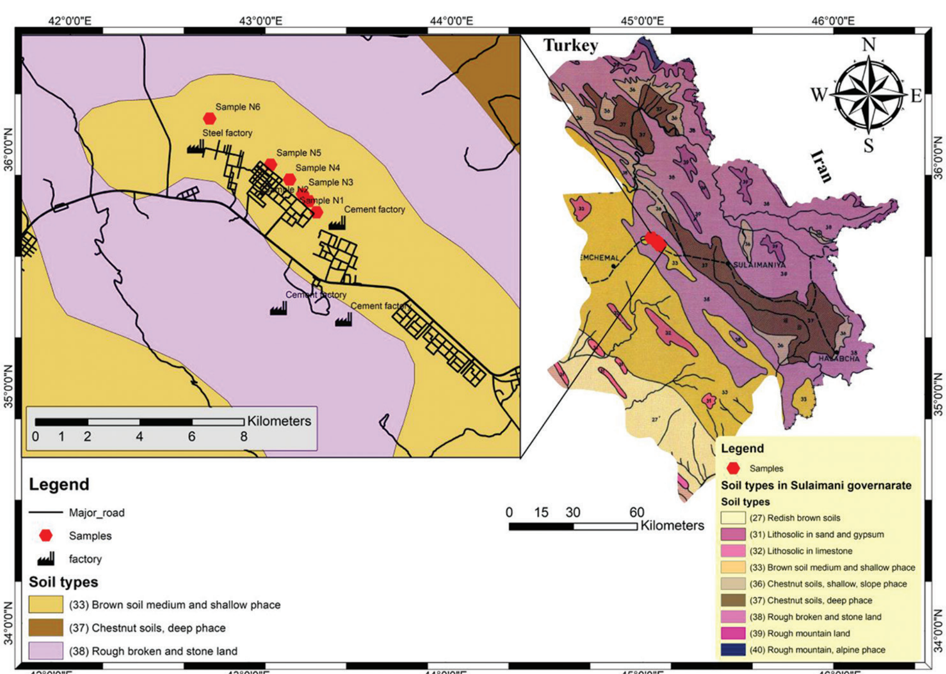

Fig. 1. Location of the study area and soil sampling after Buringh, 1960.

cement annually. Approximately 0.06–0.15 tons of CKD are generated as a by-product for every ton of cement produced (Anon., 1993; Elbaz et al., 2019). X-ray fluorescence (XRF) of CKD showed that the main constituent is CaO, quartz (SiO_2), Al_2O_3, Fe_2O_3 and magnesia with specific percentages Table I. Based on these results and typical mineralogical associations in cementitious materials, the primary constituents are identified as free lime (CaO), tricalcium aluminate ($_3CaO·Al_2O_3$), and calcium aluminoferrite ($_4CaO·Al_2O_3·Fe_2O_3$), along with minor alkali sulfates derived from (sulfur trioxide).

D. Specimen Preparation and Testing

First, in a huge tray in a dry state, the 105C° oven-dry soil was carefully hand-mixed homogeneously with each percentage (0%, 10%, 20%, 30%, and 40%) of CKD. After adding water to achieve the desired moisture content, the mixture was blended in a mixer for at least 5 min, then transferred to plastic bags where it was shaken, turned over for another 5 min, and manually squeezed out. The prepared soil sample was kept at room temperature until the tests were conducted. On the chosen clayey soil treated with different proportions and mixes of CKD, extensive laboratory tests were conducted on some of the geotechnical characteristics of the selected soil as shown in Table II. These tests assessed unconfined compressive strength and consistency indices. The percentages of CKD as an additive were 0, 10, 20, 30, and 40% of the mass of the dry intact soil. The standard Proctor compaction test was used to estimate the ideal dry density and moisture content for the soil with varying CKD percentages based on American Society for Testing and Materials (ASTM) D698–12 (D698 standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft^3 [600 kN-m/m^3]). Unconfined compressive strength (UCS) was measured using cylindrical specimens with a diameter of 38 mm and a length of 76 mm based on ASTM D2166 (standard test method for unconfined compressive strength of cohesive soil) as presented in Fig. 3. Hence, in an attempt to ascertain the stress-strain connection, the modulus of elasticity was calculated with loading at a constant rate of deformation of 0.64 mm/min after 7 and 28 days of curing periods. Liquid limit (LL), plastic limit (PL), and plasticity index (PI) were determined to use the Atterberg limit experiments following ASTM D4318-17 (standard test methods for LL, PL, and PI of soils) as shown in Fig. 4. The liquidity, toughness, consistency, and flow indices were then computed.

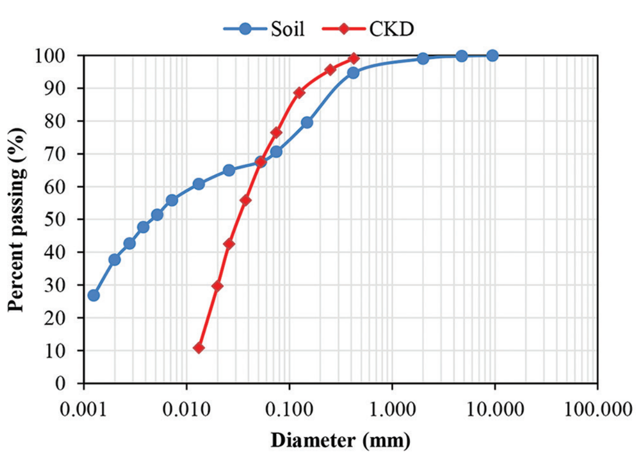

Fig. 2. Particle size distribution curves for the intact soil sample and cement kiln dust.

III. Results and Discussion

A. Consistency Limit

The fine-grained nature of the soil sample was demonstrated by its particle size distribution as in Fig. 2, where nearly 71% of the particles could be passed through a 75-μ sieve. At first, the soil's LL, which varied between 45% and 50%, suggested moderate compressibility. However, the A-line equation (0.73 [W.L.– 20]) yielded a PI of 20.22%, and the actual soil PI is closer which was 20.73% as shown in Fig. 4. Given that, this value is higher than the A-line PI, the soil is classified as intermediate compressible

TABLE I
Chemical Composition of CKD as Determined byXRF Analysis

Oxide and its chemical formula	Content %
Calcium oxide (CaO)	45.19
Silica (SiO_2)	31.73
Alumina (Al_2O_3)	9.3
Iron oxide (Fe_2O_3)	5.81
Magnesia (MgO)	5.1
Potassium oxide (K_2O)	1.21
Titanium dioxide (TiO_2)	1.01
Sodium oxide (Na_2O)	0.23
Sulfur trioxide (SO_3)	0.17
Manganese oxide (MnO)	0.16
Phosphorus pentoxide (P_2O_5)	0.03
*Loss of ignition (LOI)	3.8

*The loss on ignition (LOI) was measured by placing the sample in a muffle furnace at high temperatures (950C°) to quantify the weight loss due to volatile compounds.
CKD: Cement Kiln dust, XRF: X-ray fluorescence

TABLE II
Geotechnical Properties of the Used Clayey Soil and CKD

Parameters	Symbols	Values (Soil)	Values (CKD)
Soil color	-	Light brown	Tan-yellow
Natural water content	W%	14.12	16.2
Specific gravity	G_s	2.61	2.22
Liquid limit	LL (%)	47.7	34.45
Plastic limit	PL (%)	26.97	21.36
Plasticity index	PI (%)	20.73	13.09
Shrinkage limit	SL (%)	16.07	6.07
Consistency index	I_c	1.62	1.39
Flow index	I_f	16.65	15.32
Toughness index	I_T	1.24	0.85
Liquidity index	I_L	−0.62	−0.39
Shrinkage index	Is	10.9	15.29
Classification of soil	USCS	CL	-
Optimum moisture content	OMC (%)	13.52	16.1
Maximum dry density	MDD (g/cm^3)	1.65	1.76
Unconfined compressive strength	UCS (kPa)	128.6	101.7
Shear strength	τ (kPa)	192.9	152.6
Cohesion	c (kPa)	64.3	50.87
Ultrasonic pulse velocity	UPV (cm/sec)	38422.65	48407.64
Swelling	S (%)	9.54	7.15

CKD: Cement Kiln dust

Fig. 3. Soil samples under testing for consistency indices, UCS and ultrasonic pulse velocity.

CL clay in compliance with ASTM rules. The low specific gravity of CKD affects the soil consistency (Al-Rubaiee and Hussian, 2022), it can correlate with low consistent soil which may affect their liquid and PLs as shown in Fig. 5. The results of LL, PL, and PI with varying percentages of CKD are shown in Fig. 6. Figs. 5 and 6 show that LL and PL are decreased noticeably with a CKD increase. However, the PI was slightly decreased comparatively to LL when the percentages of dust increased (Peethamparan and Olek, 2008a; Ashwini and Ramesh, 2023). In addition, the reduction in PI makes the soil less prone to compressibility and swelling, making it more suitable for enhancing the soil subgrade. CKD sharply reduces soil swelling and shrinkage due to the pozzolanic reaction and flocculation between soil particles, which is caused by the high CaO concentration that results in interparticle cementation (Peethamparan and Olek, 2008b; Gilbert, 2025). Fig. 7 illustrates how CKD drastically lowers the shrinkage and swelling of the soil. This is because cement dust's binding qualities aid in moisture retention and soil structure stabilization. Therefore, it is important from the perspective of utilization in pavement application and foundation work. This observation is consistent with the findings reported by Sherwany, Kakrasul and Han, (2023), who highlighted the use of waste glass as an effective means to reduce the swelling behavior of fine-grained soils while also enhancing their strength properties. The consistency index and liquidity index of the soil suggest that the soil is very hard because the Ic value for the intact soil is 1.62 and

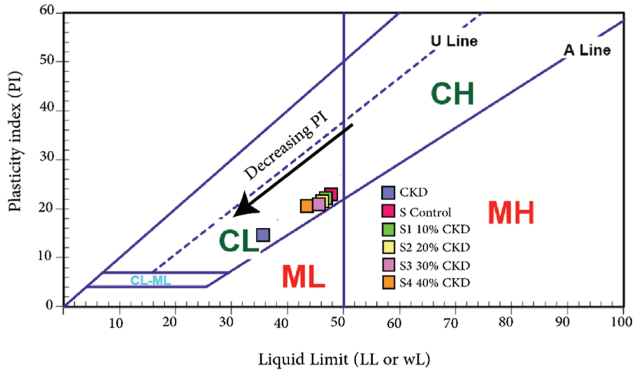

Fig. 4. Consistency limits variation with cement kiln dust percentages, where (CL) is low plasticity clay, (CH) is high plasticity clay, (ML) is low plasticity silt, and (MH) is high plasticity silt.

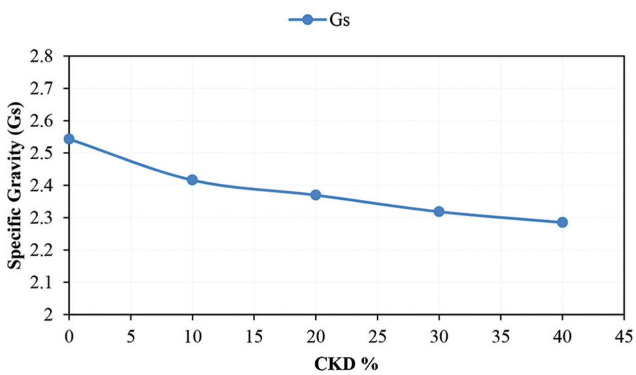

Fig. 5. Variation of specific gravity with different percentages of cement kiln dust.

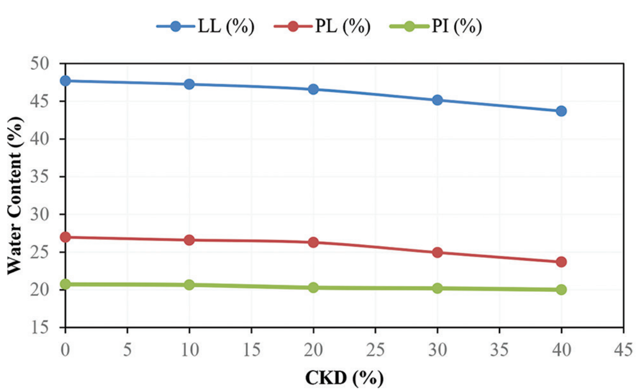

Fig. 6. Variation of consistency limits with different percentages of cement kiln dust.

the L_i value is <0, but the value for the CKD is somewhat lower, at 1.39 and −0.39, indicating that it is also very hard. However, when 40% of CKD was applied, the consistency index of the soil reduced to 0.82, and the liquidity index of the soil changed from hard to stiff as shown in Fig. 8. The flow index of the intact soil increased in proportion to the percentage of CKD. This indicates that the shear strength of the soil is reduced with the addition of CKD because the CKD's high dissolved CaO content causes more lubrication between the particles, lowering the soil's shear strength.

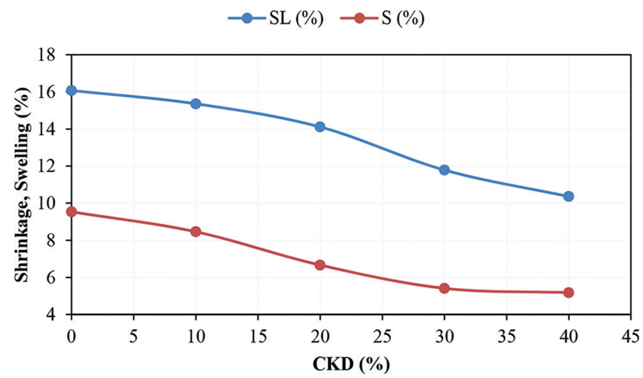

Fig. 7. Variation of shrinkage and swelling with different percentages of cement kiln dust.

The soil toughness index, which is the degree of durability of the soil at a PL, provides information on the soil's shear strength at the PL of the soil. Fig. 8 also shows how the soil's hardness index declined with CKD.

B. Unconfined Compressive Strength

Figs. 9 and 10 show the unconfined compressive strength values for the tested soils that were combined with additives at various curing times. It can be seen that all of the soil and CKD combinations became stronger with time. This conduct is in line with the research that was published by (Kumar and Singh, 2017). The utilization of CKD containing over 45% free CaO in ratios of 0–30% allowed for the observation of an increase in compressive strength in this study. Focusing on the mechanical characteristics of the intact soil and the treated soil by CKD, the addition of CKD does not notably change the style of behavior for all the added CKD percent, the style of mechanical behavior stayed in a brittle situation. However, 28 days of the curing period influenced the behavior of the samples treated to be close to a ductile state as shown in Fig. 9. Furthermore, the mixing of the samples investigated becomes more competent and stronger with the curing time as shown in Fig. 10., indicating that the high concentration of free CaO in the CKD acts as a cementing agent between the soil's particles, promoting better cohesion and interlocking. From 0% to 30% of CKD, the strength parameters qu, E, and Ur are shown in Figs. 11-13 enhanced the soil strength significantly. The qu-value increased from 128.6 to 181.23 KN/m^2 and from 264.1 to 567.83 KN/m^2 at 0–30% of CKD, respectively, when the curing time was extended from 7 to 28 days. The findings are consistent with (Miller and Zaman, 2000) demonstration that when 16% CKD is added at 28 days as a curing time, the UCS increases from 0.21 to 1.1 MPa. Fig. 14 illustrates how the addition of CKD enhanced the cohesiveness of the intact soil and how this increase grew dramatically over the course of the curing period. The ultrasonic pulse velocity (UPV) test, which was performed on all cylindrical soil samples presented in Fig. 15, also showed that after 28 days of curing, the pulse velocity waves through the soil samples were raised from 62295.08 cm/s to 93366.09 cm/s. The increased competency was provided by CKD, which gives the soil higher rigidity, properties, and improved strength because the CKD contain

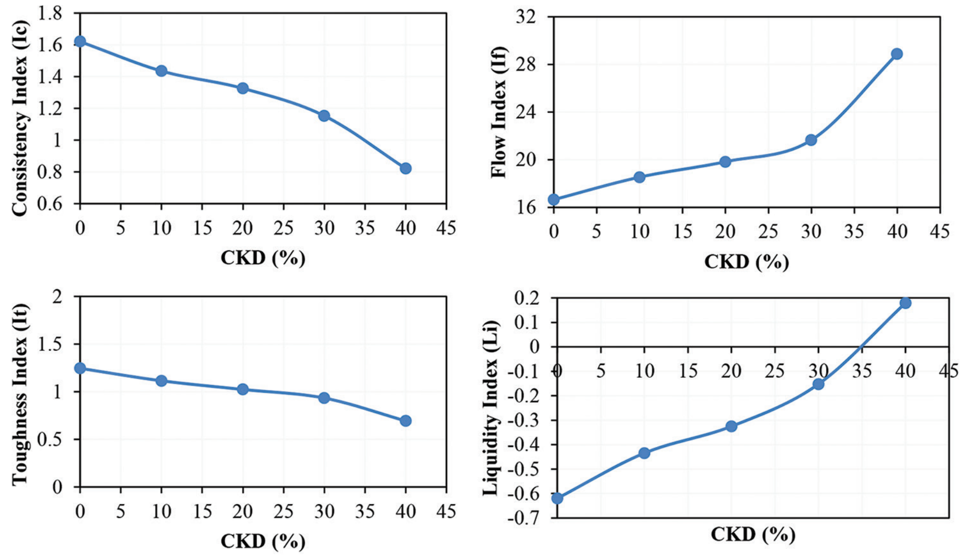

Fig. 8. Relation of consistency indices with percentages of cement kiln dust.

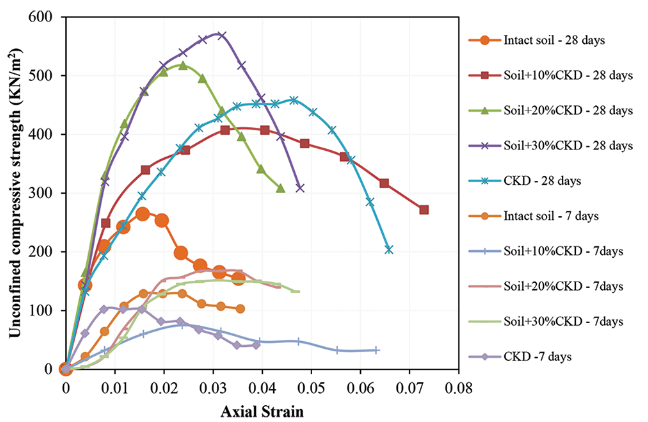

Fig. 9. Variation of UCS value with different percentages of cement kiln dust.

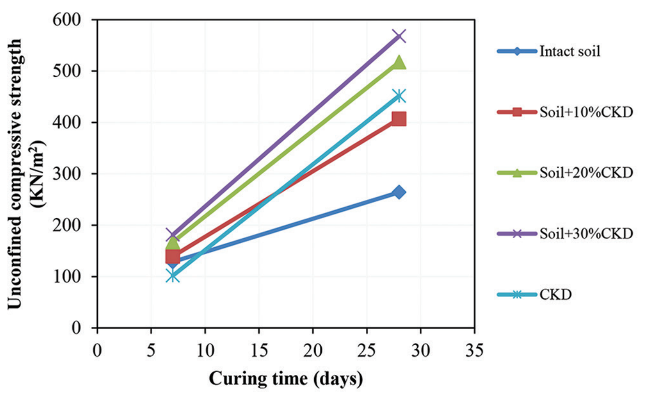

Fig. 10. Effects of curing time on UCS value for different percentages of cement kiln dust.

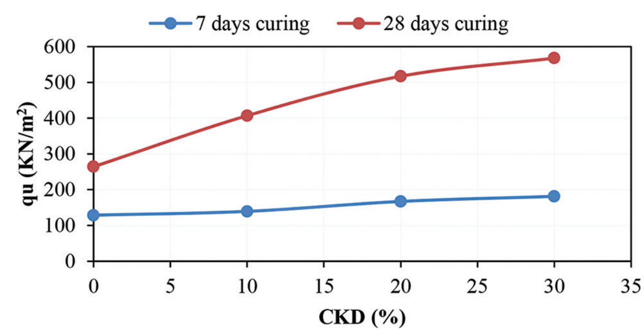

Fig. 11. Variation of maximum strength with different percentages of cement kiln dust.

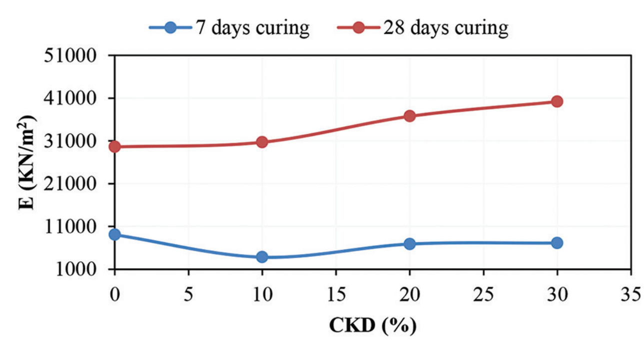

Fig. 12. Variation of modulus of elasticity with different percentages of cement kiln dust.

fine particles when it fills the voids between coarser particles of soil leading to denser and tight-packed structure as a result the increased packing improves inter-particle contact and friction, which directly increases rigidity (Amadi and Eberemu, 2013). Furthermore, the CKD effectively reduces the void ratio of the soil. A lower void ratio generally correlates with higher stiffness and strength, allowing waves to propagate more quickly. XRF results show that the CKD samples are rich in positively charged ions (cations) such as calcium, potassium, and iron as shown in Table I. These CKD cations can swap places with ions on the surface of negatively charged clay minerals in the soil (Bolt, Bruggenwert and Kamphorst, 1976). This exchange of ions then changes the clay's structure, making it less plastic and stiffer. This is in line with the findings obtained by Ismaiel in (2013).

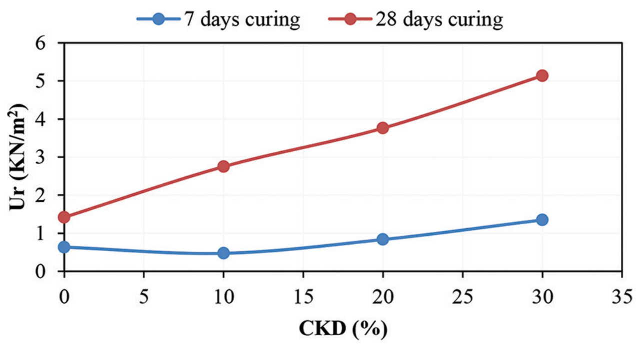

Fig. 13. Variation of resilient modulus with different percentages of cement kiln dust.

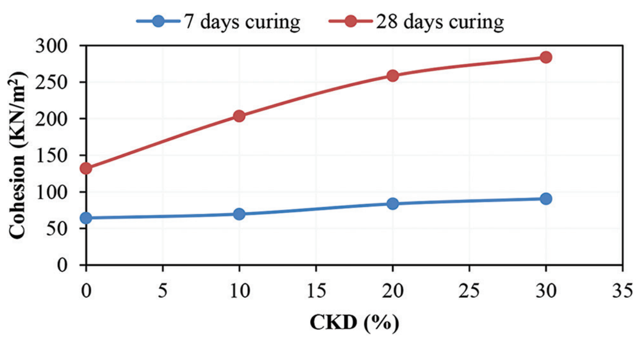

Fig. 14. Variation of soil cohesion with different percentages of cement kiln dust.

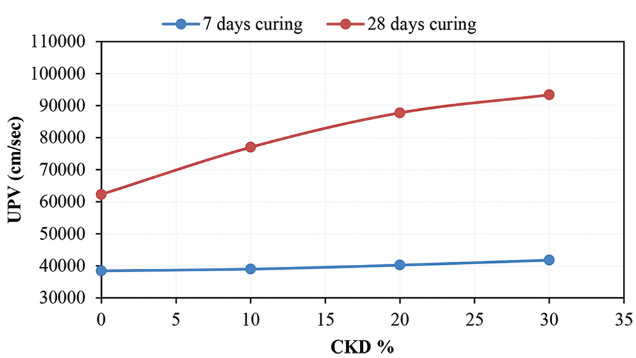

Fig. 15. Variation of ultrasonic pulse velocity with different percentages of cement kiln dust.

C. General Outcomes

The addition of CKD simply acts on the CL soil's behavior improvement, which showed consistency and shear strength characteristics changes in this study. CKD works more actively when cured for a period, which is closely similar to the cementing role of concrete. Thus, in this study, CKD worked greatly when left for 28 days as curing time. Furthermore, fine-grained soil's mechanical reaction is significantly affected by the curing period. For the experimental package considered in this study, CKD is very successful in improving soil's geotechnical characteristics. Importantly, and compared with other studies done on CKD, the current study comprehensively showed the exact role of CKD in improving CL soil within the short term, CKD is active to improve consistency and shear strength parameters. In the same manner, within the long-term action, CKD is more capable of changing the CL soil characteristics in terms of water–soil relations, and mechanical capability for the reaction of the applied forces (Figs. 5-15). Therefore, significantly, increasing CKD percentages that are added to soil by more than 30% change the behavior style of soil reaction for axial loading, and it is not preferable to use more than 30% CKD for CL soil stabilization.

IV. Conclusion

The conclusions drawn from this experimental-based study are summarized as follows:

1. The addition of different amounts of CKD to intact fine-grained soil lowers the Atterberg limits by 8.38% for the LL value, 12.16% for the PL value, and 3.47% for the PI values
2. Consistency index metrics such as Ic dropped by 49.34%, If raised by 73.39%, It dropped by 44.33%, and interleukins increased by 128.94%
3. The addition of CKD improved fine-grained soil shrinkage and swelling. The swelling and shrinkage of the soil treated with 40% of CKD decreased by 35.55%, and 45.7%, respectively
4. The addition of CKD has significantly increased the UCS value. The UCS of soil treated with 30% of CKD was increased by 114.77% after 28 days of curing period
5. Curing time significantly enhanced the CKD to improve CL soil's geotechnical characteristics
6. The result of the ultrasonic pulse velocity tests supports the increase in UCS values. The UPV increased for all treated CKD% and also proportionally with the curing time.

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