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Influence of sodium chloride on cement kiln dust-treated clayey soil: strength properties, cost analysis, and environmental impact

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Abstract

This research investigates the microstructural and geotechnical properties, environmental impact, and economic benefit of cement kiln dust (CKD)-treated kaolinite clay with the addition of sodium chloride (NaCl). As a chemical admixture, NaCl is expected to enhance the strength properties of the clay soil stabilized by CKD. To verify this issue, the geotechnical characteristics of CKD-treated soils with different contents of NaCl (2.5, 5, and 10%) were examined. To this end, the Atterberg limits, standard Proctor, unconfined compressive strength and California bearing ratio (CBR) tests were conducted. Besides, scanning electron microscopy (SEM) analysis was used to observe the microstructural changes resulting from using additives. It was found that the addition of NaCl to the CKD-stabilized clay caused the maximum dry density to increase and the optimum moisture content to decrease. 10% NaCl enhanced the unconfined compressive strength of the CKD-treated soil to 18.7% and 8% higher than that of the NaCl-free specimen during 7 and 28 days of curing, respectively. These results were in accordance with the consequences extracted from the CBR behavior diagram. Moreover, cementitious compounds products in the mixtures were presumed to be the significant factor contributing to strength improvements based on the SEM results. The stabilized clayey soil with 15% CKD and 10% NaCl as environment-friendly method could significantly reduce energy consumption, e-CO_2 emission, and cost of soil stabilization.

Keywords Soil stabilization · Cement kiln dust (CKD) · Sodium chloride (NaCl) · Cement · Strength · Environmental impact · Cost analysis

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1 Introduction

Based on the increasing usage of resources and population growth, the soil with suitable properties for civil engineering projects such as pavement construction is not available. Low shear strength, low bearing capacity as well as high compressibility and excessive settlements can cause the inappropriate geotechnical characteristics of soils for constructing roads/railway embankments and building foundations. Therefore, increased public expectations for long-lasting poor soils under extreme environmental conditions require enhancement of their properties. Therefore, the improvement of local soils properties would be of immense concern.

Soil improvements can be classified into two main processes. First, the soil modification that leads to change the texture and moisture sensitivity of the soil, usually by a change in its plasticity. Second, increase the long-term strength of the compacted soil through the addition of stabilizers, which may occur in addition to the modification (Parsons et al. 2001; INDOT 2015). To enhance the performance properties of clayey soils, cement has been employed as commonly used stabilizers. Concerning the stabilizing the soil with cement, it has been demonstrated that addition of cement to clay soils reduces the plasticity index and increases unconfined compressive strength (Basha et al. 2005; Al-Rawas et al. 2005; Sariosseiri and Muhunthan 2009; Asgari et al. 2013).

Regardless of the enhancement of soil properties, the cement can cause the destruction of environmental. As stated in the previous studies, the cement considered as the global anthropogenic e-CO_2 emissions through the more than 5–7% of CO_2 emission and utilizing a significant amount of energy by cement industry (Rashad 2015; Feiz et al. 2015). Not only CO_2 releases from cement plants but also SO_2 (sulfur dioxide) and NO_x (nitrous oxides) contribute to the greenhouse effect and acid rain. Furthermore, about 1.5 tons of raw materials along with 3000–4300 MJ of fuel energy and 120–160 kWh of electrical energy is needed for producing each ton of cement (Feiz et al. 2015). Based on the aforementioned concepts, utilizing some strategies to reduce cement consumption should be of concern. This preserves the environment, raw materials, fuel and energy with the reduction in pollution emitted during the process of cement production. To this end, the researchers have been interested in utilizing the waste materials and by-products of industries as the cement replacement (Basha et al. 2005; Siddique 2008; Moghadas Nejad et al. 2017; Ghavami et al. 2018).

It has been shown that the cement kiln dust (CKD) has a potential capability as a soil stabilizer to replace the cement (Sariosseiri and Muhunthan 2008; Sariosseiri et al. 2011; Yoobanpot et al. 2017). As inferred in previous research, the free lime (CaO), high alkali content, and the large fineness of CKD make it as a potential candidate to improve the soil properties (Peethamparan 2006). In this regard, it has been revealed that CKD significantly increased the unconfined compressive strength (UCS) of different soils (Miller and Azad 2000; Peethamparan 2006; Sariosseiri and Muhunthan 2008; Sariosseiri et al. 2011; Yoobanpot et al. 2017; Sharma 2017). Sariosseiri and Muhunthan (2008) indicated that the addition of 15% CKD to low plasticity clay enhanced the soils UCS five time more than that of raw soil. Also, the stabilizing of clayey soil with CKD led to the improvement in soaked California bearing ratio of the soil in order to utilize it as a flexible pavement subgrade)Sharma 2017). Regarding the soil stabilization, it is worth mentioning that enhancement of soil UCS and modulus of elasticity with CKD was lower than that of cement as a stabilizer (Sariosseiri and Muhunthan 2008; Sariosseiri et al. 2011).

Based on the aforementioned concepts, finding a method in order to improve the effectiveness of CKD on the clayey soil characteristics should be of concern. Given the findings in previous researches, addition of chemical admixtures (e.g., sodium chloride (NaCl), calcium chloride ($CaCl_2$) and sodium hydroxide (NaOH)) into the clay soil stabilized by cement causes the UCS to increase (Moh 1962) and the liquid limit and spacing between aggregations to decrease (Modmoltin and Voottipruex 2009). Also, the improvement of the soils UCS increases as the admixture content increases through the setting and the hardening of the hydrated cement (Modmoltin and Voottipruex 2009). Furthermore, in the case of lime-treated soils, it has been postulated that the UCS (Mohd Yunus 2007; Davoudi and Kabir 2011) and undrained shear strength (Mohd Yunus et al. 2012) increased through the addition of salts as chemical admixtures. Therefore, the addition of chemical additives to soil stabilized with CKD might be an effective way to enhance its impacts.

There are plenty of soils in the nature that sodium chloride (NaCl) is a part of their constituent materials, or they are affected by sodium chloride due to the proximity to saline water sources. Based on the aforementioned research studies, it can be concluded that NaCl is a potential candidate to intensify the strength enhancement of soil stabilizing by cementation agents (e.g., CKD). However, there remains a real need for a thorough understanding of the effects of NaCl on the characteristics of clay soil stabilized with CKD. Consequently, the objective of this study was to examine the effects of NaCl on microstructural and geotechnical properties, cost analysis, and environmental impact of the kaolinite clay as a poor soil (Alrubaye et al. 2016) which is stabilized with CKD. To this end, Atterberg limits, compaction, unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were conducted on the stabilized soil. Moreover, scanning electron microscope (SEM) also was employed to identify the microstructural modification. Furthermore, the environmental impacts and economic benefits of stabilized soil are analyzed and compared with cement-treated soil.

2 Experimental and test methods

2.1 Materials

In this study, the commercial kaolinite clay which engineering properties based on the ASTM standards are presented in Table 1 was utilized. Moreover, the particle size distribution curve of the soil in accordance with ASTM D422-63 (2007) is shown in Fig. 1.

Table 1 Engineering properties of the soil

Properties	Value	Standard
Liquid limit (LL) (%)	29.5	ASTM D4318 (2005)
Plastic limit (PL) (%)	21.5	ASTM D4318 (2005)
Plasticity index (PI) (%)	8	ASTM D4318 (2005)
Unified soil classification system (USCS)	CL	ASTM D2487 (2011)
Specific gravity	2.65	ASTM D854 (2002)
Maximum dry density (MDD) (kN/m^3)	17	ASTM D698 (2000)
Optimum moisture content (%)	16.2	ASTM D698 (2000)
Unconfined compressive strength (UCS) (kPa)	129	ASTM D2166/D2166M (2013)

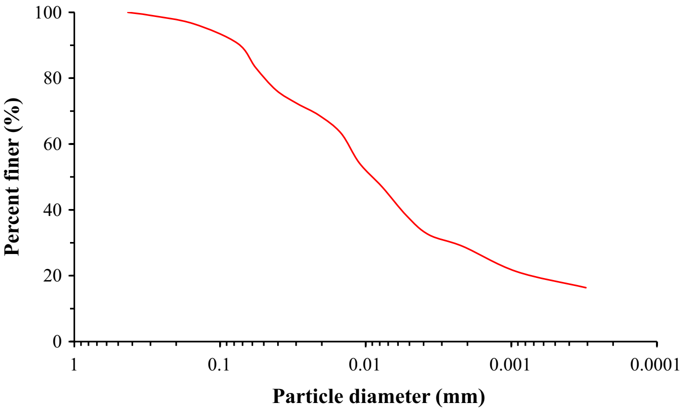


Fig. 1 Grain size distribution of the kaolinite clay

The soil is classified as clay with low plasticity (CL) based on the Unified Soil Classification System (USCS). Table 2 also represents the chemical composition of the soil through X-ray fluorescence (XRF) spectrometer.

To fabricate the stabilized soil, cement kiln dust as a by-product of the Shahroud cement factory was employed. The chemical properties of CKD used in this research are shown in Table 2. Regarding the Kamon and Nontananandh (1991) findings, the ratio of the amount of CaO to the total amount of SiO_2, Al_2O_3, and Fe_2O_3 of the stabilizers must be at least 1.7 in order to take place the effective stabilization reactions. The used CKD with an approximate specific gravity of 2.70 also meets this requirement through the results of Table 2.

The non-iodized commercial grade of sodium chloride as a chemical additive was utilized. It is white and has a crystalline structure, in which each Na^+ ion is surrounded by six chloride ions in an octahedral geometry. The salt NaCl was of analytical grade, corresponding to a purity of 99%.

2.2 Cement kiln dust percentage

As stated in the previous section, cement kiln dust was employed as a cement replacement. The main feature of using cementation materials as a cement replacement in soil

Table 2 The chemical composition of kaolinite clay and cement kiln dust

Compound	Soil	CKD
SiO_2	72.5	6.7
Al_2O_3	18.07	1.3
Fe_2O_3	0.36	2.2
CaO	1.15	67.9
MgO	0.61	1.1
SO_3	0.06	1.6
K_2O	0.39	4.4
Na_2O	0.25	0.48
Other	0.61	2.84
Loss on ignition	6.0	11.3

stabilizing is the capability of improving strength. In this section, the effectiveness of CKD to enhance the mechanical properties of the kaolinite clay was investigated. To this end, the unconfined compressive strength of the soil after 7 and 28 days of curing was carried out. Concerning the finding of previous research, the 9% cement by dry weight of the soil was selected through the Air Force Manual NO. 32–1019 (1994). Accordingly, unconfined compressive strength test was performed after 7 and 28 days curing on soil stabilized with 9% Portland cement that was prepared at their optimum moisture content (OMC = 19.2%) and compacted to 100% of maximum dry density (MDD = 16 kN/m^3). Three different percentages of CKD (e.g., 5, 10 and 15%) were also used. Unconfined compressive strength of specimens after 7 days of curing was obtained as 370.5, 577, 795 kPa for 5, 10 and 15% CKD, respectively, and 812 kPa for 9% cement. Also, compressive strength of the soil stabilized with 15% CKD and 9% cement at 28 days was 2122 and 2140 kPa, respectively. Accordingly, 15% CKD by dry weight of the soil was utilized for stabilization of kaolinite clay in this research. In addition, it has been inferred that this content of CKD is a practical upper limit for the cost-effective stabilization (Miller and Azad 2000; Solanki et al. 2007; Sariosseiri and Muhunthan 2008).

2.3 Mixing and sample preparation

Previous studies demonstrated that 10% sodium chloride (by dry weight of the soil) could effectively improve the strength of soil stabilized by lime or cement (Mohd Yunus 2007; Modmoltin and Voottipruex 2009). Moreover, it has been indicated that the existence of high content of salt in the soil results in the higher stabilizer contents to need and also pretreatment with lime (Jones et al. 2010). Therefore, to examine the influence of NaCl on CKD-treated soil, 15% of CKD in conjunction with 2.5%, 5%, and 10% (by dry weight of the soil) of salt (NaCl) were employed in the research. Table 3 presents the raw and treated soils. To fabricate the treated soils, the premeasured amounts of CKD and NaCl were added to the soil and dry-mixed by hand. Mixing of the dry materials was continued until a uniform color was obtained. Then, the required amount of water was added to the mixture. Again, mixing was performed until a homogeneous mixture was gained. The specimens for Atterberg limits tests and proctor compaction test were prepared through the ASTM D4318 (2005) and ASTM D698 (2000), respectively. Cylindrical specimens with 38 mm diameter and 76 mm height for the unconfined compressive strength tests were prepared at their optimum moisture content and compacted to 100% of maximum dry density. After compaction, the specimens were taken out of the mold and were wrapped in plastic bags individually so that no moisture would be lost for 7 and 28 days before being loaded in compression. Specimens for soaked California bearing ratio tests were cast into the CBR mold with the same compaction energy per volume as in Proctor compaction test. Finally, prepared specimens were cured inside the plastic bag for 7 days to prevent moisture loss.

Table 3 Evaluated treated soil types

Soil code	S	SC	SC-2.5N	SC-5N	SC-10N
Raw soil		Commercial kaolinite clay			
Type of stabilizer (%)	–	CKD	CKD, NaCl	CKD, NaCl	CKD, NaCl
Percent of stabilizer (%)	–	15	15, 2.5	15, 5	15, 10

2.4 Test methods

The main contribution of the soil stabilizing with CKD along with chemical agent (NaCl) is to enhance the geotechnical characteristics of the soil. However, the side effects of the impacts of NaCl on the performance of CKD treated the soil in addition to environmental impact, and economic benefit needs investigation using the microstructural and geotechnical testing. To elaborate the goals of research, the following tests were conducted:

- The Atterberg limits were examined through the ASTM D4318 (2005), which represent a methodology to obtain the liquid limit (LL), plastic limit (PL), and Plasticity Index (PI).
- The maximum dry density (MDD) and the optimum moisture content (OMC) were also tested based on the procedures outlined in ASTM D698 (2000).
- Unconfined compressive strength test was performed on the compacted cylindrical specimen after curing time, according to ASTM D2166 (2013).
- CKD- and NaCl-treated soils specimens were tested following ASTM D1883 (1999) test procedure to calculate the California bearing ratio after 7 days of curing.
- The effectiveness of the soil treated by CKD as well as soil treated by CKD salt was evaluated by scanning electron microscopy (SEM).

2.5 Statistical analysis

In this study, the statistical analysis is performed to study if the addition of chemical agent (NaCl) is statistically significant in strength characteristics of CKD-treated kaolinite clay. For this purpose, multi-way analysis of variance (ANOVA) with replication was assessed through the Minitab 2018 software. The statistical analysis was done on the results of UCS at 7 and 28 days curing time along with CBR at 7 days curing time. In addition, the commonly used significance level ($\alpha = 0.05$) was selected to examine the null hypothesis, which states that all the treatment means are statistically the same. Furthermore, based on the objectives of this research, the Tukey–Kramer method was employed to compare all possible pairs of means and find the means that are significantly different from each other.

3 Results and discussion

3.1 Geotechnical characteristics

This section investigates the effect of different percentages of chemical agent (NaCl) with cement kiln dust on the mechanical properties of the stabilized clayey soil. To this end, Atterberg limits, compaction characteristics, unconfined compressive strength (UCS), California bearing ratio (CBR), and scanning electron microscopy (SEM) analysis were conducted to assess the geotechnical properties and the microstructural characteristics of the treated soil.

3.1.1 Atterberg limits

Figure 2 displays the mean liquid limit (LL), plastic limit (PL), and the plasticity index (PI) for three replicates of raw and stabilized soil with different percentages of stabilizers. The addition of 15% CKD leads to increase in the LL and PL of the soil. It can be attributed to the increase in CKD fines and the accompanying increased affinity for water. As stated in the previous study, the liquid limit of the soil is more sensitive to cations present in clay than the plastic limit (Diamond and Kinter 1965; Marks 1970; Miller and Azad 2000). From this, it was expected that addition of CKD to the soil affects its LL more than PL. Therefore, the plasticity index of kaolinite clay increased due to the addition of CKD.

Taking into account the impacts of chemical agent (NaCl), the LL, PL, and the PI of CKD-treated kaolinite clay followed a decreasing trend as NaCl content increased. Regarding this issue, it can be explored that increasing the NaCl resulted in the reduction in the thickness of the diffused double layer leading to the replacement of the univalent alkali ions that generally attracted to the negatively charged clay particles with dissociated bivalent calcium ions in the pore water. Furthermore, adding the NaCl to the CKD-treated soil causes the ions tend to depress the double layer around the particles, and clay particles are attracted to one another to form flocs. Based on the concepts mentioned above, the particles become free to move at lower water contents leading the liquid limit to decrease. As the results of Fig. 2 show, the plasticity index is reduced by about 57% when the NaCl content is 10% compared to the CKD-soil mixture. The flocs behave as silt particles which are least plastic. That is why a reduction is observed in the plasticity Index.

3.1.2 Compaction characteristics

The results of the compaction tests performed to assess the optimum moisture content (OMC) and maximum dry density (MDD) of treated soils are given in Fig. 3. Based on this figure, it can be inferred that the MDD of clayey soil obviously decreases after the addition of the CKD. Also, stabilizing the soil with CKD causes the OMC to increase from 16.2 to 21%, compared with the raw soil. This observation can be explained with the hydraulic (water-loving) nature of the calcium oxide in the CKD. Moreover, the aggregation of

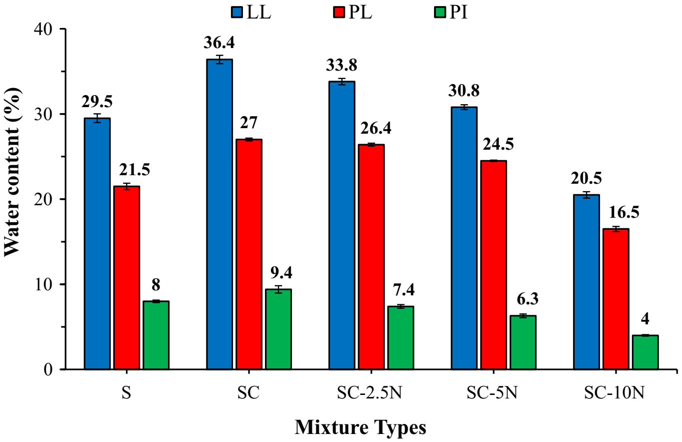


Fig. 2 Variation of LL, PL, and PI of specimens

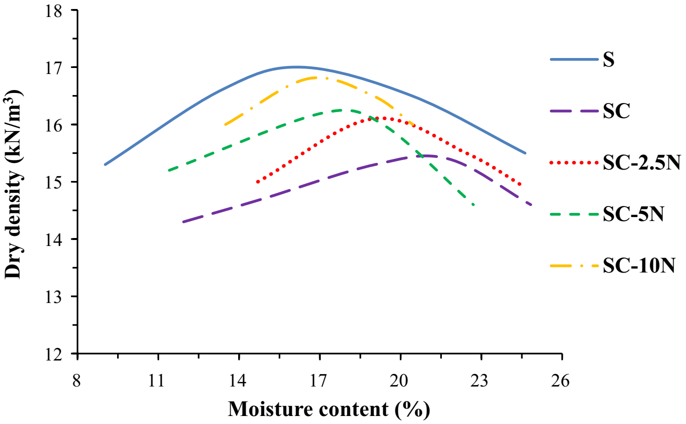


Fig. 3 Moisture-density relationships of specimens

particles due to the addition of CKD can make larger macropores within the soil which causes the lower MMD.

As can be depicted in Fig. 3, the maximum dry density increased, and the optimum moisture content decreased as the salt content became higher. The OMC and MDD of SC-10N are 20 and 8% more than those of the CKD-treated soil, respectively. This observation can be explained by the formation of salt flocculation in the soil structure, which intensifies with increasing the salt content. The lower OMC of CKD of the treated soil with salt can be explained by the higher face-to-face flocculation made in soil structure after addition of NaCl causing the reduction in water is needed to lubrication.

3.1.3 Unconfined compressive strength (UCS)

The effect of CKD as stabilizers and NaCl as a chemical agent on the UCS of the soil at curing periods of 7 and 28 days is shown in Figs. 4 and 5, respectively. These figures show the average UCS for three replicates of each treated soil type. As depicted in these figures, the untreated soil had a UCS strength of 129 kPa. After treating the kaolinite clay with CKD, the UCS increased to reach the values of 795 and 2122 kPa after 7 and 28 days curing, respectively. Regarding the reaction between dissolved silica and alumina from the clay and calcium hydroxide of the CKD, the cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels are formed leading to reduction in the volume of the void spaces and make the soil particles to join. These crystalline hydration products that are shown below are presumed to be the major factor contributing to strength improvements.

$$Ca^{2+} + 2(OH)^{-} + SiO_2 \rightarrow \text{Calcium silicate hydrate}$$

$$Ca^{2+} + 2(OH)^{-} + Al_2O_3 \rightarrow \text{Calcium aluminate hydrate}$$

As depicted in Figs. 4 and 5, the addition of NaCl resulted in the maximum stress of the CKD-treated soils to increase. This can be related to the formation of the continuous

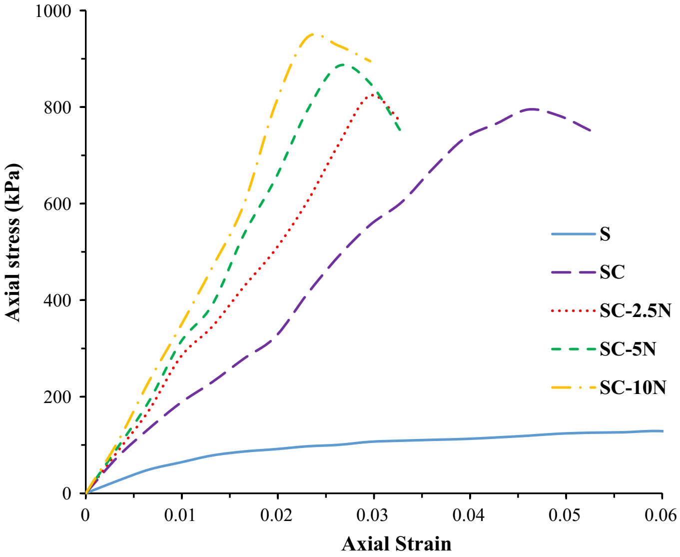
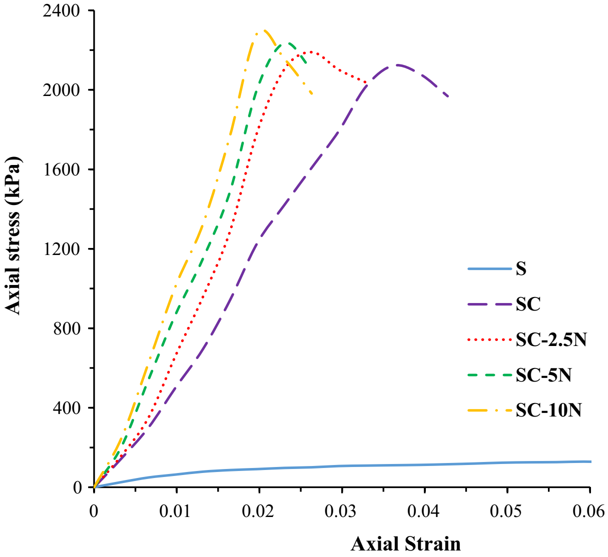


Fig. 4 Effect of stabilizers on the stress–strain curves at 7 days of curing

Fig. 5 Effect of stabilizers on the stress–strain curves at 28 days of curing



pozzolanic reaction during the curing period. By adding 10% NaCl to the CKD-treated kaolinite clay, the maximum compressive strength is 18% higher than that of the NaCl-free specimen during 7 days of curing. The dissolved silicate of the clay structure combines with CKDs calcium producing the calcium–sodium silicate gel in the presence of NaCl. This can cause the improvement of treated soils strength gain. Furthermore, the strain corresponding to peak axial stress of stabilized soil with CKD decreased after the addition of NaCl making the treated soil to behave more brittle compared to non-salt soil.

Table 4 Statistical analysis of UCS test results

Test	ANOVA test results					Tukey–Kramer test grouping results					
	Factor	Adj. MS	*F* value	*P* value	*T* value						
UCS-7	Stabilization	331,355	2343.37	0.000		SC-10N	A				
			SC	0.000	12.93	SC-5N		B			
			SC-2.5N	0.000	17.65	SC-2.5N			C		
			SC-5N	0.000	27.59	SC			C		
			SC-10N	0.000	37.19	Raw				D	
UCS-28	Stabilization	2,601,551	63,762.46	0.000		SC-10N	A				
			SC	0.000	99.92	SC-5N		B			
			SC-2.5N	0.000	120.54	SC-2.5N			C		
			SC-5N	0.000	134.18	SC				D	
			SC-10N	0.000	149.34	Raw					E

In order to assess the impact of stabilizers on the strength of kaolinite clay soil, the statistical analysis was carried out. Based on the results obtained through the statistical analysis presented in Table 4, the NaCl as chemical agent accordingly improved the unconfined compressive strength of the CKD-treated soil at the significance level of 0.01. As Tukey–Kramer statistical test says, the strength parameters of treated soils are significantly higher than that of the raw soil. About the comparison between different mixtures, it can be concluded that there is no significant difference between SC and SC-2.5N based on the test results from 7-day curing time which these soils were ranked similarly (Group C). However, the addition of 2.5% NaCl considerably affects the unconfined compressive strength of kaolinite clay after 28-day curing period. This can be attributed to a considerable contribution of salt to the compressive strength of the soil at later ages. The examined treated soils in this research after 28 days of curing have been ranked into different groups, which indicated the effectiveness of chemical additive addition into the CKD-stabilized soil.

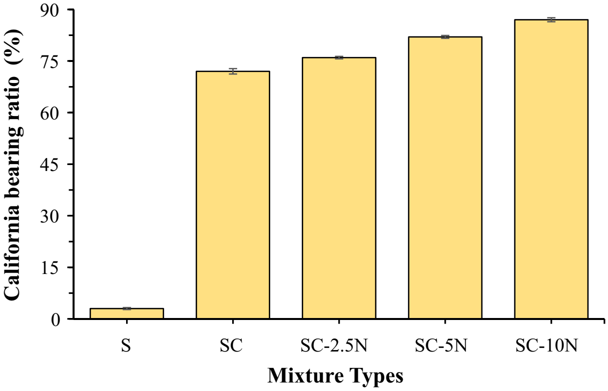


Fig. 6 CBR values of CKD-soil mixture with varying NaCl contents

3.1.4 California bearing ratio (CBR)

Regarding the investigation of the treated soils bearing capacity, the soaked CBR test was conducted on the soil samples after 7 days of curing time. The results of three replicates for each sample were averaged out and are presented in Fig. 6. The kaolinite clay had a CBR value of 3% which categorizes as weak soils. After stabilizing the raw soil by the CKD, this treatment increased the CBR value of the soil about 24 times more than that the untreated soil. This strength improvement can be related to made cementitious compounds between the soil and CKD particles.

Concerning the effect of NaCl as a chemical agent, it can be inferred that the salt leads the CBR value of CKD-stabilized soil to enhance. The addition of salt in 2.5, 5, and 10% leads to increase the CBR value of CKD-treated soil after 7 days of conditioning from 72 to 76%, 82 and 87%, respectively. These consequences were in agreement with the results of the UCS test on the evaluated soils. Through the impact of salt on the strength gain of the CKD-stabilized soil, it can be postulated that the addition of NaCl makes higher silicate dissolution and therefore improves the pozzolanic reaction in CKD-soil mixture.

The consequences of the statistical analysis of the CBR results are shown in Table 5. As mentioned before, three replicates were tested, and the results were averaged out and presented in the figure. These replicate data were used to perform statistical tests. As the *P* values in Table 5 inferred, CBR test results were affected by stabilization. Concerning the Tukey–Kramer statistical test says, the CBR values of treated soils after 7 days of curing period are significantly higher than that of the raw soil. Furthermore, since the treated soils are ranked in different groups, it can be concluded that the NaCl as a chemical agent significantly improved the CBR value of the CKD-stabilized soil. Moreover, the consequences of statistical analysis revealed that CBR and UCS test results were consistent.

3.1.5 SEM analysis

The impact of soil stabilization by CKD and salt on the microstructural and morphological changes in the compacted kaolinite clay after 28 days curing time were examined using scanning electron microscope (SEM) at magnifications of 2000 times. Energy-dispersive X-ray spectroscopy (EDS) analysis was performed to show any changes in the elemental chemical compositions of the soil and stabilized the soil. Figure 7a shows SEM micrographs of the compacted kaolinite clay at high magnification and a typical EDS pattern collected from a point on soil (position is marked as “A”). It shows hexagonal clay flakes with a discontinuous structure and large voids are exist in the raw soil. The EDS pattern

Table 5 Statistical analysis of CBR test results

Test	ANOVA test results					Tukey–Kramer test grouping results					
	Factor	Adj. MS	*F* value	*P* value	*T* value						
CBR-7	Stabilization	3607.19	8928.69	0.000		SC-10N	A				
			SC	0.000	23.82	SC-5N		B			
			SC-2.5N	0.000	37.53	SC-2.5N			C		
			SC-5N	0.000	55.21	SC				D	
			SC-10N	0.000	69.83	Raw					E

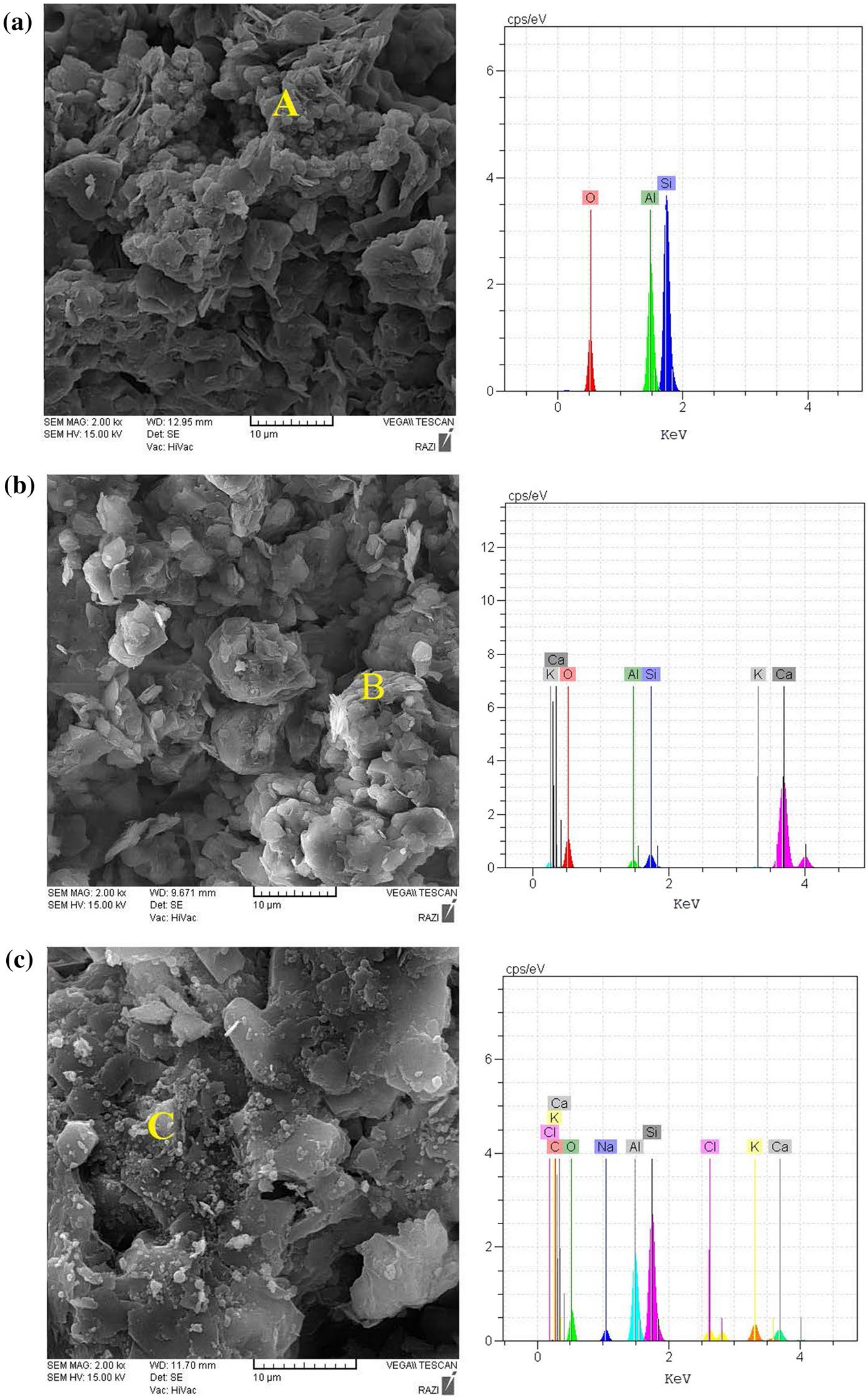


Fig. 7 Scanning electron micrograph of specimens **a** kaolinite clay **b** kaolinite clay + 15% CKD **c** kaolinite clay + 15% CKD + 10% NaCl

indicates peaks for oxygen (O), aluminum (Al) and silica (Si). The micrograph of the CKD-treated soil is depicted in Fig. 7b. It can be seen in the EDS spectrum corresponding to point “B” calcium (Ca) peak appears. Because of the high amount of Ca at this location, it could be possible that C–S–H is present at this point. The formation of cementitious compounds as a pozzolanic reaction product filled pore space of clay particle. These hydration reaction products have improved the geotechnical properties and strength of the soil such as unconfined compressive strength. Figure 7c presents the SEM images of CKD-stabilized kaolinite clay with the addition of 10% sodium chloride. Regarding the effect of NaCl, it can be stated that 10% salt causes the silicate dissolution for reacting with calcium through the presence of Na^+ ions (see EDS pattern collected from point “C”) leading to accelerate the pozzolanic process and produce cement. This cemented structure bridges the aggregates and improves the strength of CKD-treated soil.

3.2 Environmental impacts and cost analysis

Through the overuse of resources in order to construct the civil engineering infrastructure such as pavement construction and building foundations, the treatment of poor soils as one of the predominant part of civil construction components need to be taken into consideration. As stated in the introduction section, cement as a commonly used stabilizer has captured numerous attention by researches as a capable treatment additive for clayey soils with poor geotechnical characteristics. However, Approximately 5% of global air pollution around the world are pertinent to the manufacturing of the cement. Moreover, through using 2.5 billion ton of the raw material for 1.6 billion tons of cement produced annualy and emmision about 1 ton of greenhouse gases per ton of cement production, the cement, and concrete industries is considered as one of the three energy consumer industries in the world (Siddique and Rajor 2012). Furthermore, about 811 Megajoule of energy consumption is caused by cement manufacturing (Wilson 1993). It should be worth mentioning that replacing the 15 and 50% of cement usage worldwide by supplementary cementitious materials (SCM) leads the 250 and 800 million tons of CO_2 emissions to decrease (Siddique and Rajor 2012). Therefore, by utilizing the SCM such as cement kiln dust, the pollution generated by the cement industry can be decreased considerably, and it helps the agencies to promote the sustainability of the environment.

Cement kiln dust (CKD) is a fine powder that is generated during the cement manufacturing process, then carried off in the flue gases, and subsequently collected in baghouses or electrostatic precipitators (Khanna 2009). Approximately 4.3 million tons of CKDs is to be stockpiled or deposited in landfills (Peethamparan et al. 2008). In addition to the environmental problems caused by these landfills, the cost for disposal of CKD in designed landfill falls between \$5 and \$14 per ton (Schreiber and Riney 1995). Considering the vision of a sustainable environment, the potential utilization of cement kiln dust has become imperative. Huntzinger and Eatmon (2009) conducted a life-cycle assessment (LCA) of Portland cement manufacturing to evaluate the environmental impact of four cement manufacturing processes: (1) the production of traditional Portland cement, (2) blended cement (natural pozzolans), (3) cement where 100% of waste CKD is recycled into the kiln process, and (4) Portland cement produced when CKD is used to sequester a portion of the process-related CO_2 emissions. Based on stoichiometry and material composition, it is considered that CKD can capture 0.4 ton of CO_2 per ton of CKD (Huntzinger 2006). Results indicated that utilization of CKD for CO_2 sequestration decreased cement’s environmental impact score of approximately 5%, which was the best of the choices. The recycling of CKD back into the kiln feed has little to no effect on reducing carbon emissions or energy required in pyroprocessing. Therefore, utilizing this by-product as construction material such as improving the properties of poor soil supports sustainable construction and helps in preserving the environment.

In this study, utilizing CKD in accordance with NaCl as cement replacement in soil stabilization was assessed. The findings of previous parts demonstrated that the treatment of clayey soil with CKD and NaCl could effectively improve geotechnical characteristics of soil specially unconfined compressive strength. As stated in Sect. 2, the compressive strength of clay soil with 15% of CKD was approximately equal to treatment of the soil with 9% of cement. Therefore, in this section, all the examined soil in this research in addition to treated soil with 9% of cement (C9) are compared base on the amount of greenhouse gas emission, energy consumption and cost to find eco-friendly green soil stabilization.

Regarding the comparison of the environmental value of studied soils, the energy consumption and the e-CO_2 emission of materials and in-place stabilization process have been extracted from the previous research studies, which are shown in Tables 6 and 7, respectively. It should be revealed that since CKD is a by-product, it would not bring additional environmental impacts to producers. Furthermore, through the existence of soil in situ, there are no environmental impacts in order to excavation and transportation of the clayey soil. Considering the weight of materials used in soil stabilization process, the energy consumption and CO_2 emission of examined soils are measured and are depicted in Figs. 8 and 9, respectively.

Table 6 The energy consumption of materials used in soil stabilization

Materials and process	Energy consumption (MJ/Ton)	Source of data
Clayey soil	0	–
Cement	4976	Omrani and Modarres (2018)
Water	5.74	Chiaia et al. (2014)
Cement kiln dust	0	El-Attar et al. (2017)
NaCl	90	Chadwick (1988)
Material transportation	1.25	da Rocha et al. (2016)
In place stabilization	15	Omrani and Modarres (2018)

Table 7 Greenhouse emission of materials used in soil stabilization

Materials and process	e-CO_2 emission (Kg/Ton)	Source of data
Clayey soil	0	–
Cement	980	Omrani and Modarres (2018)
Water	0.318	Chiaia et al. (2014)
Cement kiln dust	0	El-Attar et al. (2017)
NaCl	0.2	Lamsairhri (2017)
Material transportation	5.18[a]	El-Attar et al. (2017)
In-place stabilization	1.13	CCA (2005)

[a] The transportation distance for raw materials was assumed to be 100 km

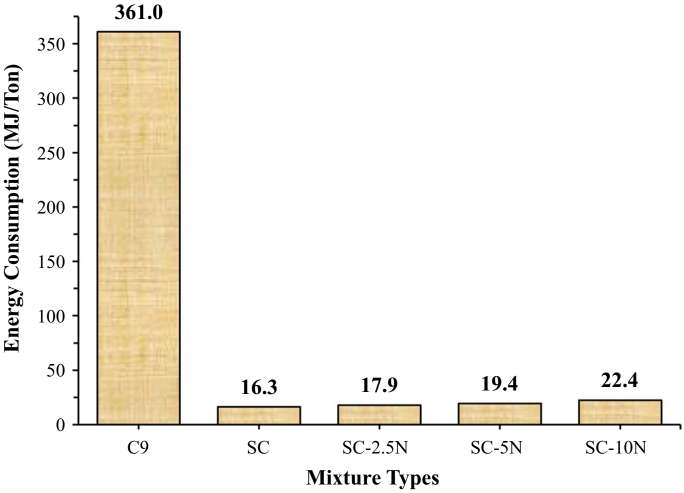


Fig. 8 The energy consumption of various stabilized soils

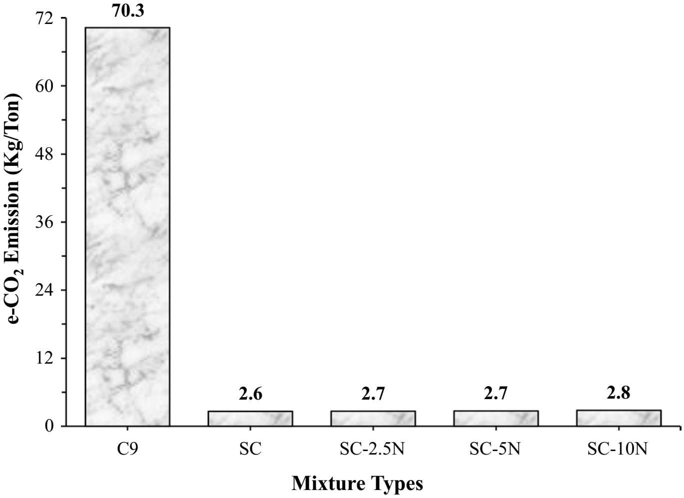


Fig. 9 The e-CO_2 emission of different treated soils

Based on the results of Fig. 8, it can be inferred that CKD leads a considerable decrease in energy consumption through the stabilization of clayey soil. By stabilization of soil with 15% CKD instead of 9% cement, the needed energy to soil treatment reduces considerably from 361 to 16.3 Megajoule (96% reduction). Furthermore, the addition of NaCl caused to increase the unit energy consumption, but this higher energy consumption is not considerable. The SC-10N which had highest unconfined compressive strength after 28 days of curing required 94% lower energy to treat the existing clayey soil rather than cement stabilization. Through the consequences presented in Fig. 9, the equivalent CO_2 emission followed a similar trend of energy consumption. Correspondingly, through the soil stabilization with

CKD and NaCl as chemical agent in different percentages, the amount of CO_2 emitted considerably reduced than cement stabilization (96% decrease). Similar to energy consumption, the increase in the NaCl percentage have a destructive role in the reduction in e-CO_2 emission. However, the amount of e-CO_2 increment by the addition of this material was negligible. Consequently, the environmental performance of the treated clayey soil with CKD and NaCl concurrently is marvelous, and it can opt for the greenest soil stabilization rather than cement treatment.

Based on the limited civil infrastructure construction and maintenance funds, finding a cost-effective method to construct civil substructure need to be considered. Therefore, the cost–benefit analysis as a dominant parameter to select an option among several alternatives was assessed to compare the proposed soil stabilization materials, which are introduced in this study with traditional soil treatment with cement. To this end, the accurate unit price of materials and their transportation in addition to in-place stabilization are extracted from the related research, which is shown in Table 8. With the results of this table, the stabilization process of clayey soil was calculated and is demonstrated in Fig. 10. As it is depicted in Fig. 10, all the soil treatment processes that included refined materials are more economical than the cement

Table 8 The unit price of materials and operations for soil stabilization

Materials and process	Unit price (USD ($)/Ton)	Source of data
Clayey soil	0	–
Cement	106	Assi et al. (2018)
Water	0.32	El-Attar et al. (2017)
Cement kiln dust	0	El-Attar et al. (2017)
NaCl	42	Kelting and Laxon (2010)
Material transportation	4[a]	Raballand and Macchi (2008)
In-place stabilization	3.34	Sheeler et al. (1957)

[a] The transportation distance for raw materials was assumed to be 100 km

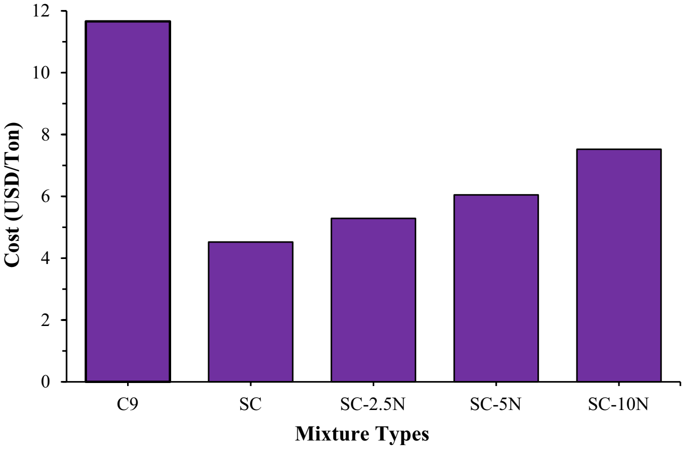


Fig. 10 The stabilization cost of different treated soils

stabilization. In detail, the treatment price of clayey soil with CKD is remarkably lower than cement stabilization (60% cost reduction). With the addition of NaCl as chemical additive, the price of stabilization process was increased, but it should be worth mentioning that the addition of NaCl to the CKD-treated soil leads the compressive strength to enhance. The SC-10N as the treated soil with most UCS reduces the unit price of stabilization from 11.7$ to 7.5$ per ton of materials. Accordingly, the SC-10N approximately has a 36% reduction in the cost of soil treatment. Therefore, it is not recommended to add more sodium chloride as chemical additive to the CKD-treated clayey soil.

4 Conclusions

The main purpose of this research was to investigate the effect of sodium chloride on the geotechnical properties of kaolinite clay that were treated with cement kiln dust. The Atterberg limits, standard Proctor, unconfined compressive strength, and California bearing ratio tests were conducted to examine the mechanical characteristics, and scanning electron microscopy (SEM) was employed in order to analyze the microstructural changes. The obtained results can be summarized as follow:

- The cement kiln dust had a beneficial effect on the clayey soil behavior used in this study. It also can be effectively utilized instead of cement leading the reduction in cement demand, decreasing the energy consumption and e-CO_2 emission as well as the cost of soil stabilization.
- The addition of NaCl decreased the liquid limit, the plastic limit, and the plasticity index of CKD-soil mixture.
- With increasing the salt content (NaCl), the maximum dry density (MDD) and optimum moisture content (OMC) increased and decreased, respectively, caused by more oriented clay particles in the presence of NaCl.
- The addition of NaCl led the unconfined compressive strength of specimens to increase. The highest unconfined compressive strength (UCS) achieved is 2285 kPa for clay stabilized with 15% CKD and 10% NaCl cured at 28 days.
- The CBR value of soil-15% CKD composite is 72%, which increases to 87% at 10% NaCl content. The results from the CBR test are in line with those of the uniaxial compressive strength test.
- The SEM micrographs inferred that NaCl could change the microstructure of CKD soil and improve the formation of cementing compounds causing the unconfined compressive strength to enhance.
- The stabilized clayey soil with 15% CKD and 10% NaCl as environment-friendly method reduced 94% energy consumption, 96% e-CO_2 emission, and 36% of the cost rather than treatment the soil with 9% of cement.

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Compliance with ethical standards

Conflict of interest The author declares that they have no potential conflict of interest.

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