Stabilization of Clayey Soil Using Cement Kiln Dust as Sustainable Material

Athraa M. J. Alhassani1,a,*, Sami M. Kadhim2, and Ali A. Fattah3
1Structures and Water Resources Department, University of Kufa, Iraq
2Senior Structural Engineer, Chief Engineer, Cameco Corporation, Canada.
3Sulamania Technical Institute, Sulamania, Iraq.
a*athraam.alhasani@uokufa.edu.iq
*Corresponding author

Abstract. One of the cornerstones of sustainability is reusing by-product waste materials that contribute to serious environmental problems. The current study presents the results of a series of laboratory tests using cement kiln dust (CKD) waste material as a soil stabilizer. A clayey soil was treated with four percentages of cement kiln dust (CKD) content of 5, 10, 15, and 20 by dry weight of the soil. To investigate the effect of the curing age on the behavior of the treated soil, different curing ages were considered such that; 1, 4, 7, 30, 60, and 90 day. The assessment of the improving rate of the treated soil was based on the outcomes of the compaction parameters, consistency limits, unconfined compressive strength, permeability, and durability (freezing-thawing and wetting-drying) tests. The results showed that the tested properties were improved substantially, and it is concluded that the optimum CKD content was 5% by dry weight of the soil. The unconfined compressive strength of treated soil samples with 5% CKD was increased by 43% for the age of one day and 238% after 90 days curing age compared with the untreated soil samples. The plasticity index was reduced by 7.9, 26.3, 43.1, and 57.9% for the soil treated with cement kiln dust (CKD) content of 5, 10, 15, and 20%, respectively. The coefficient of permeability of the treated soil was substantially reduced. Also, the findings show that the durability of the treated soil was improved appreciably, and this improvement is in proportion with increasing the percentage of CKD content for both (freezing-thawing) and (wetting-drying) tests.

Keywords: by-product waste, cement kiln dust, soil stabilization, curing age, durability tests.

1. Introduction
Cement is considered the most widely used material for building construction. The cement demand is increasing across the world, resulting in massive amounts of cement kiln dust as by-product wastes. In terms of sustainability, the cement industry poses a threat to the environment, whereby annually, many natural resources are exploited to provide the demand for cement, which results in a huge amount of CKD by-product waste being thrown out. In 2012, more than 3.4 billion tons annually and increased to 4.3 billion tonnes in 2014 [1-3]. It is found that about 0.6 to 0.7 tons of CKD are generated for every ton of produced cement [4-6]. Since a large amount of cement is manufactured each year, the generated global volume of CKD is about 2.4-2.8 billion tons annually. To tackle this problem, research is underway in various parts of the world to find effective ways to use cement dust for various purposes, such as soil improvement. It is discovered that the hydration products and the chemical reactions in CKD are similar to those observed in cement. Therefore, using CKD as a cement substitute for large-scale city or national projects is a viable option.
The physical and chemical composition of dust has governed the efficiency of using CKD involving clay and sand improvement. In practice, dust's mineralogical, chemical, and physical composition differ considerably, depending on the raw materials for feed, operation method of kiln, facility of collecting the dust, and the used fuel [7,8]. Baghdadi [9] investigated the ability of CKD to improve the bentonite and kaolinite clay soil materials that using for pavement construction, the study showed that using CKD as a stabilizer agent enhanced the properties of the treated soils. Also, it was found that stabilized soil's unconfined compressive strength (UCS) improved significantly compared with unstabilized soil and marked a reduction in plasticity indices. The shrinkage and swelling characteristics were also reduced.

McCoy et al. [10] were investigated different geotechnical properties for stabilized clayey soil by CKD. The study showed that using CKD for stabilization of the soil used as a subbase was a promising choice. Miller and Azad [11] conducted laboratory research to evaluate the soil stabilizer efficiency of cement kiln dust (CKD). The study reported that the addition of CKD increases UCS of the stabilized soil. It also showed that the amount of increase in unconfined compressive strength is inversely proportional to the plasticity index of untreated soil, and CKD treatment resulted in a significant reduction of plasticity index, especially that of high value. Mohie [12] stated that the compaction feature of sand was enhanced by CKD additive. In terms of the compressive strength and seepage control, sand stabilized by cement dust was showed a significant reduction in permeability and compressive strength.

Mohamed [13] carried out an experimental study to investigate the possibility of using cement dust to stabilize the arid soil to improve the mechanical and hydraulic properties. The stabilized soil's physical properties were estimated experimentally, and the optimal mixture ratio gives the highest shear strength and lowest permeability. According to the study, the optimum mix design of 6% by weight of CKD increases shear strength while lowering the permeability to less than $10^{-9}$ m/s. Thus, it is concluded that from the treated soil Mohamed [13]. In general, using CKD and the other additives is aimed to improve the strength and reduce the swelling characteristics of the treated soils. If the mixed additives contain free calcium hydroxide, plasticity of the soil reduces due to the action of the calcium, which flocculates the clay particles into a more sand-like structure [14]. Then, the shrink/swell of the treated soil character is reduced due to the plasticity reduction that is called the modification.

This research aims to investigate the efficiency of cement kiln dust for improving the engineering properties of clayey soils. A series of laboratory tests were carried out to explore some properties of the soil treated by different CKD content of 5%, 10%, 15%, and 20% by dry weight of the soil as well as for untreated soil as a control sample. The assessment of the efficiency of the CKD for soil improvement was based on results of the compaction parameters, consistency limits, unconfined compressive strength, permeability, and durability (freezing-thawing and wetting-drying) tests. The tests program has also involved the effect of different curing ages of; 1, 4, 7, 30, 60, and 90 day.

2. Experimental work

2.1 Materials

2.1.1 Used soil

The soil used in this study was classified as CL according to the Unified Soil Classification System. The specific gravity of the soil was 2.73. The properties of the used soil were shown in Table 1. The stabilized soil was specified by a grain size distribution curve shown in Figure 1.

| Property                                      | Value |
|-----------------------------------------------|-------|
| Specific gravity, Gs (ASTM D854-10)           | 2.73  |
| Soil classification (ASTM D2487)               | CL    |
| Liquid limit (%) (ASTM D4318-10)              | 38.0  |
| Plasticity index (%)                          | 19.0  |
| Max. dry unit weight (kN/m$^3$) (ASTM D698-07)| 16.45 |
| Optimum moisture content (%)                  | 20.50 |
2.1.2 Cement kiln dust CKD
A light brown cement kiln dust (CKD) used in this investigation was provided from Al-Kufa cement manufacturing plant in Kufa, Iraq. The specific gravity of the cement dust is 2.85 and is characterized by a grain size distribution curve shown in Figure 1. The chemical composition of the used cement dust was listed in Table 2.

![Grain size distribution curves of the used soil and CKD.](image)

Table 2. Chemical composition of the cement kiln dust (CKD).

| Compound | Composition (%) |
|----------|----------------|
| SiO₂     | 14.1           |
| Al₂O₃    | 4.70           |
| Fe₂O₃    | 1.97           |
| CaO      | 40.17          |
| MgO      | 2.79           |
| SO₃      | 5.85           |
| K₂O      | 3.13           |
| Na₂O     | 1.55           |
| Cl       | 1.83           |
| Loss on ignition LOI | 24.25 |

2.2 Methodology
The program of the experimental work was shown in Figure 2. It consisted of several tests for different soil properties such as; compaction parameters, plasticity indices, unconfined compressive strength (UCS), coefficient of permeability, and durability for both (wetting–drying tests) and (freezing-thawing tests). Different percentages of CKD content were added to clayey soil, that is 5, 10, 15, and 20% by dry weight of the soil. The maximum dry unit weight and optimum moisture content are determined using a standard Proctor compaction test for untreated soil samples and treated samples of all CKD additives content. To prepare the samples for each tested property, the required amount of soil and the required amount of CKD were weighted according to the volume of the using mold such that the corresponding maximum dry unit weight that earlier determined could be obtained.

Initially, the dry soil and the CKD additive were mixed thoroughly then the quantity of water respective to estimated optimum moisture content was added. The mixture was compacted statically to produce a homogenous sample. The tests program involves the investigation of the effect of the curing age on some studied properties. For this purpose, many samples were enclosed in plastic sheets and stored in a moist room with a temperature of about 21°C and relative humidity of 70% for the required age.
3. Test results and discussions

Laboratory tests of Compaction, Plasticity characteristics, unconfined compressive strength (UCS), permeability, and durability for both (freezing-thawing) and (wetting-drying) were carried out for treated and untreated soil to examine the feasibility of using the CKD for clayey soil improvement. Determination of each property was achieved for sets of samples (each set includes three samples). The results of investigated properties are as following:

3.1 Compaction Tests

Figure 3 shows the maximum dry unit weight variation with the percentage of CKD content for treated and untreated soil samples. From the figure, it is clear that the dry unit weight increased up to a value of around 5% CKD content as the CKD increased. Beyond this, the dry unit weight will be decreased. This could be attributed to the fact that; initially, the CKD amount is low and inadequate for bonding the soil particles, contributing to an increase in the maximum dry unit weight. As the amount of CKD increased, the soil particles are possibly cemented together, and the hydration products and the secondary reactions create a continuous structure with harder contacts. Consequently, the movement of the soil particles is restricted due to their fixation together, causing a reduction in maximum dry unit weight.

Whereas the optimum moisture content curve shows a reversible manner, as seen in Figure 4. With increasing CKD content, the curve dips initially, then increase. It is owing to the hydraulic (water-loving) aspect of the calcium oxide in the CKD. Also, from Figure 4, it can be concluded that the larger optimum moisture content corresponds to the higher CKD content.
3.2 Plasticity index tests

The effect of the CKD content on the plasticity index is shown in Figure 5. It is clear that the plasticity index of treated samples decreased significantly with increasing the percentage of the CKD content. The results showed that the plasticity index was reduced by 7.9, 26.3, 43.1, and 57.9% for CKD content of 5, 10, 15, and 20%, respectively. Little [14] reported that “When the additives containing free calcium hydroxide are mixed with the soil, the calcium causes the clay particles to flocculate into a more sand-like structure reducing the plasticity of the soil. Swell/shrinkage characteristics of the soil are reduced as a result of this decrease in plasticity”.

It was stated by different studies in the literature that the high percentage of CaO in the soil mixture is responsible for the reduction of the plasticity index due to cation ion exchange of Ca$^{2+}$, which caused a modification in clay minerals which is reduced the soil-water affinity [15]. Mosa et al. [16] reported that the reactivity of the CKD is affected by its fineness, as well as the existence of high alkali and sulfate content in addition to ion exchange. However, lowering the plasticity index is an evident indicator of soil improvement [17].
3.3 Unconfined compressive strength (UCS) tests

It is well known that the shear strength is considered an indicator of soil improvement. In this investigation, the unconfined compressive tests (UCS) were carried out to the compacted, cured samples to assess the efficiency of CKD for improving the shear strength of the soil. The tested samples were treated with different CKD content, 5, 10, 15, and 20%, and cured for different ages; 1, 4, 30, 60, and 90 days. The results of unconfined compressive tests are shown in Figure 6. This figure clarifies that the unconfined compressive strength of the treated soil was increased as the CKD content increased up to 5%. Beyond this, as the percentage of CKD content increases, the unconfined compressive strength decreases considerably. This behavior is similar for all curing ages. In addition, Figure 6 shows that if the curing age is increased for specified CKD content, the unconfined compressive strength increased significantly. Also, it can be seen that the results of the unconfined compressive strength are consistent with the results of maximum dry unit weight. In addition, it can be concluded that the optimum CKD content that improves the clayey soil's shear strength is around 5% by dry weight of the soil.

![Figure 6. Unconfined compressive strength vs. CKD content for different curing ages.](image)

3.4 Permeability tests

The coefficient of permeability of treated and untreated soil was determined using the falling-head permeability test. To investigate the effect of CKD additive on the coefficient of permeability of the treated soil, different cement kiln dust (CKD) content of 5, 10, 15, and 20% in addition to the untreated soil were considered. For each CKD additive content, the permeability coefficient was determined at different curing ages of 1, 4, 7, 30, 60, and 90 days.

Figure 7 displays the coefficient of permeability values of treated soil for different percentages of CKD contents compared with that of untreated soil (CKD=0%). It is obvious from figure 7 that treated the soil with CKD was reduced the coefficient of permeability considerably. It is also clear that increasing the CKD content by more than 15% has no effect on the reduction of the coefficient of permeability. As for curing age, Figure 7 shows that seven days of curing is sufficient to reduce the permeability of the treated soil to the lowest possible amount, after which no appreciable reduction is recorded. Therefore, it can be concluded that the value of the coefficient of permeability of CKD-treated soil seems to be CKD-content dependent rather than time-dependent.
3.5 Durability Tests

The assessment of the feasibility of any additive for soil improvement will be incomplete if the durability tests are not performed. To ensure the ability of the treated soils, which fulfill the requirements of the strength to withstand environmental conditions, they should pass the durability tests. In this study, a series of durability tests for both (freezing-thawing) and (wetting-drying) was conducted on the soil samples treated with different CKD content of 5, 10, 15, and 20% in addition to the untreated soil as reference samples. Twenty samples were prepared, half of them for (freezing-thawing) tests and the others for (wetting-drying) tests. For each CKD content, two samples of the mixture were prepared and tested.

The prepared soil samples for both durability tests were initially stored for a duration of 7 days in a humid chamber at 21°C and 70% humidity. Then according to the type of durability test, the samples were exposed to 12 cycles (each cycle takes 48 hours) of (freezing-thawing), or 12 cycles (each cycle takes 48 hours) of (wetting-drying) according to ASTM D560 – 96, and ASTM D559 – 03, respectively. The weight loss and volume change at the end of the cycles are used to express the effects of durability tests. The tests observation showed that, after 12 cycles of (freezing-thawing) or (wetting-drying), the samples were survived. The results of durability tests are shown in Table 3 and Figures 8 and 9. From Table 3, it is clear that the durability of the treated soil improved significantly for both types of durability tests and for weight loss and volume change determination. Also, the finding shows that increasing the percentage of CKD leads to better improvement for the treated soil, whether for (freezing-thawing) or (wetting-drying) tests.

**Table 3.** Results of durability tests.

| CKD, % | Freezing–thawing: (weight loss), % | Freezing–thawing: (volume change), % | Wetting–drying: (weight loss), % | Wetting–drying: (volume change), % |
|--------|----------------------------------|------------------------------------|-----------------------------|----------------------------------|
| 0      | 5.1                              | 1.6                                | 3.5                         | 0.9                              |
| 5      | 4.9                              | 1.3                                | 3.2                         | 0.7                              |
| 10     | 4.3                              | 1.0                                | 2.8                         | 0.3                              |
| 15     | 4.1                              | 0.8                                | 2.5                         | 0.2                              |
| 20     | 3.8                              | 0.6                                | 2.1                         | 0.2                              |
4. Conclusions

Based on the outcomes of the conducted tests, the following conclusions can be drawn:

- Cement kiln dust is an efficient choice for stabilization the clayey soil.
- The optimum CKD content that improves the shear strength of the clayey soil is around 5% by the dry weight of the soil.
- Adding 5% CKD to the clayey soil was improved the unconfined compressive strength up to 43% and 238% for samples cured for one day and 90 days, respectively.
- The results were showed that the plasticity index was reduced by 7.9, 26.3, 43.1, and 57.9% for the soil samples treated with CKD content of 5, 10, 15, and 20%, respectively.
- Adding CKD to the soil reduces the coefficient of permeability considerably.
- The durability of the treated soil was improved significantly for both types of durability tests (freezing-thawing) and (wetting-drying), and increasing the percentage of CKD leads to better improvement for the treated soil whether it is for (freezing-thawing) or (wetting-drying) durability tests.
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