

Research

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Investigating the Influence of the Combination of Cement Kiln Dust and Fly Ash on Compaction and Strength Characteristics of High-Plasticity Clays

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ABSTRACT

An experimental study was conducted to determine the effect of cement kiln dust (CKD) and fly ash (FA) on compaction and strength characteristics of the high-plasticity clay obtained from a forest road in North of Iran. Accordingly, the soil was mixed with 15% CKD by dry weight the soil, and a partial replacement of the CKD with 10, 20, and 30% FA was applied to produce mixtures. The unconfined compressive strength tests were performed on specimens after a curing time 7 and 28 days. Also, the microstructures of untreated and treated specimens were examined using a scanning electron microscope (SEM). It was found that incorporation of CKD and FA leads to a decrease in the volume of pores in the soil matrix, which is due to the formation of calcium silicate hydrates and calcium aluminate hydrates gels. These cementitious compounds in the mixtures were presumed to be the significant factor contributing to strength improvements.

Keywords: Soil stabilization, Cement kiln dust, Fly ash, Compressive strength, High-plasticity clay

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1. INTRODUCTION

High-plasticity clays occur in many parts of the world and cause extensive damage to the structures and pavements resting on them due to their low bearing capacity [1, 2]. There are various techniques used for the improvement of the soil based on the construction activity and type of soil. Soil stabilization is a very common process for almost all construction projects, which is classified into two categories, i.e. mechanical stabilization and chemical stabilization [3]. Mechanical stabilization can be achieved through the physical process by changing the grading of the soil by either induced vibration or compaction or by adding fibrous and non-biodegradable reinforcement [4]. Chemical stabilization is associated with the modification of soil properties by the addition of chemically active materials, which can change the surface molecular properties of the soil particles and, in some cases, cement the particles together [3, 5]. Portland cement is a comprehensive chemical stabilizer widely used in ground improvement projects. However, cement stabilization is nowadays not desirable because of

environmental issues associated with the CO₂ emissions from the production of Portland cement, energy demand, resource conservation consideration, and economic impact due to the high cost of Portland cement production [6]. Accordingly, in recent years, a great effort has been done to develop alternative agents or non-conventional additives, especially those that are more effective and less costly, for a sustainable soil stabilization process [7-11]. Cement kiln dust (CKD) is a by-product of Portland cement manufacturing, which is composed of micron-sized particles collected from electrostatic precipitators during the production of cement clinker [12]. The presence of free-lime (CaO), the high alkali content, and the large fineness of CKD make it as a potential candidate to improve the engineering properties of different soils [13-15]. In addition, Ghavami et al. (2020) indicated that stabilized soil with 15% CKD as an environment-friendly method reduced 96% energy consumption and the equivalent CO₂ emission, and 60% of the cost rather than treatment the soil with 9% of Portland cement [16]. Fly ash

(FA) is a by-product of the combustion of pulverized coal in thermal power plants that have been pulled out of the boiler by flue gases and collected by electrostatic precipitators or filter bags. ASTM C618 categorizes fly ashes by chemical composition, according to the sum of the iron, aluminum, and silica content (expressed in oxide form). Class F fly ash consists of siliceous and aluminous materials and exhibits pozzolanic property but rarely, if any, self-hardening property. However, it chemically reacts with calcium oxide in the presence of moisture to form cementitious compounds. Lime-fly ash stabilizers were observed to be well suited for stabilizing expansive soils and significantly increased the strength and decreased

the swell potential of the soil [17]. Samanta (2017) indicated that cement stabilization improved the engineering behavior of class F fly ash, which may aid in their application as resource geomaterials in civil constructions [8]. The main objectives of this study are to determine the compaction characteristics and the strength of the stabilized clay using CKD and partially replacing the CKD with class F fly ash as pozzolanic material. To this end, standard Proctor compaction and unconfined compressive strength (UCS) tests were conducted on the stabilized soil. Moreover, the changes in the microstructural of the stabilized soil were observed using a scanning electron microscope (SEM).

2. MATERIALS AND METHODS

The soil used in this study was obtained from a forest road located approximately 7 km east of Nowshahr, Mazandaran province, North of Iran (Figure 1). The grain size distribution of the soil is illustrated in Figure 2. The soil was classified as clay with high plasticity (CH) according to the Unified Soil Classification System

(USCS). The chemical composition identification with X-Ray Fluorescence analysis for the soil showed that it consisted primarily of SiO_2 , Al_2O_3 , and Fe_2O_3 . Table 1 presents a summary of the geotechnical properties of the soil.

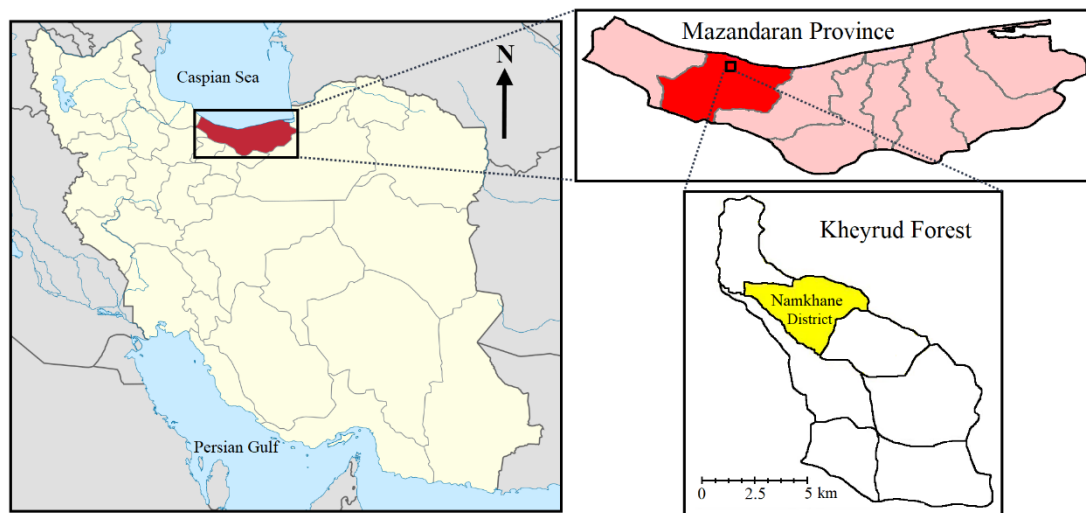


Figure 1. Site where the soil specimen was obtained

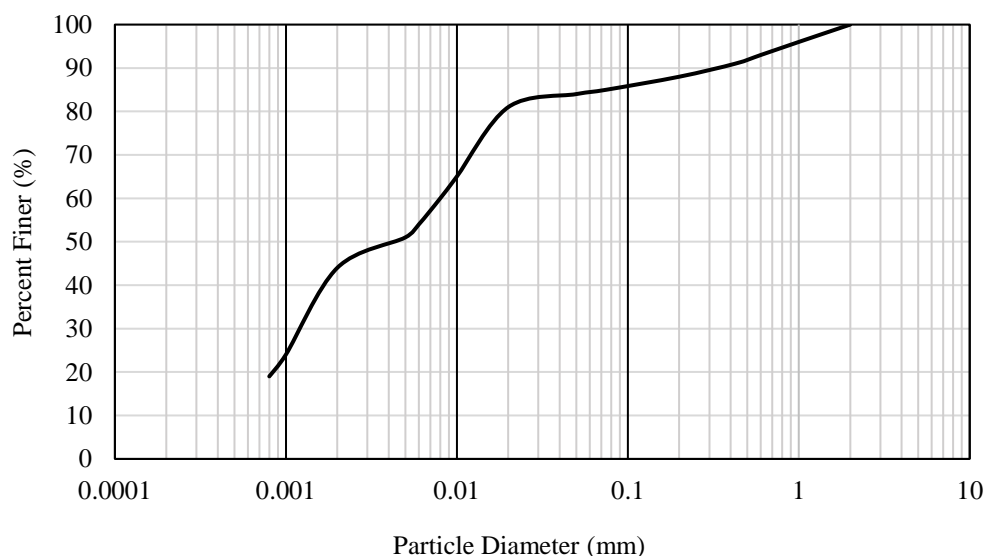


Figure 2. The grain size distribution of the soil

Table 1. Geotechnical properties of the soil

properties	Standard	Value
Liquid limit (LL), %	ASTM D4318	58.1
Plastic limit (PL), %	ASTM D4318	25.9
Plasticity index (PI), %	ASTM D4318	32.2
Unified soil classification system (USCS)	ASTM D2487	CH
Specific gravity	ASTM D854	2.74
Maximum dry density (MDD), kN/m ³	ASTM D698	14
Optimum moisture content (%), %	ASTM D698	25.2
Unconfined compressive strength (UCS), kPa	ASTM D2166	56

The CKD was provided by the Mazandaran cement factory in Iran. The chemical constituents of CKD are given in [Table 2](#). In this research, fly ash (FA) obtained from Farafozoun company (in Iran) was utilized, that its chemical composition is shown in [Table 2](#). Because the

SiO₂+Al₂O₃+Fe₂O₃ content is above 70% and sulfur trioxide (SO₃) content is less than 5%, this fly ash can be categorized into class F according to ASTM C618. The specific gravity of the CKD and the FA was 2.69 and 2.1, respectively.

Table 2. Chemical constituents of cement kiln dust and fly ash

Compound	Cement kiln dust	Fly ash
SiO ₂	13.4	53.5
Al ₂ O ₃	3.8	27.3
Fe ₂ O ₃	2.9	7.2
CaO	45.8	5.5
MgO	1.1	2.1
SO ₃	11.8	0.9
K ₂ O	3.81	1
Na ₂ O	0.69	0.4
TiO ₂	0.3	0.5
Loss on ignition	16.4	1.6

It has been inferred that 15% CKD by dry weight of the soil is a practical upper limit for cost-effective stabilization [13, 16, 18, 19]. Accordingly, in this study, 15% CKD was selected, and a partial replacement of the CKD with 10, 20,

and 30% FA by dry weight was applied to produce various mixtures. A total of five combinations based on soil with single and mixed modes of stabilizers, as shown in [Table 3](#), were studied.

Table 3. Mixture proportion

Sample	CKD content (by dry weight of the soil), %	Replacement of CKD by FA (by dry weight), %
S	0	0
S15C	15	0
S15C10F	15	10
S15C20F	15	20
S15C30F	15	30

To fabricate the treated soils, the premeasured amounts of CKD and FA 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 the proctor compaction test were prepared through the ASTM D698. Cylindrical samples were having a diameter of 38 mm and height of 76 mm, used in the unconfined compressive strength (UCS) tests, were prepared at their corresponding optimum moisture content and maximum dry density by static compaction. 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. The UCS test was performed on the specimens according to ASTM D2166. In order to investigate the changes in the microstructure of the stabilized soil, the specimen treated by CKD, as well as specimen treated by CKD-FA, was evaluated by scanning electron microscope (SEM). The samples were carefully trimmed into a small cube with dimensions of ~1 cm from the central part of the specimens made for the UCS test. Before the SEM images were taken, gold-coating pretreatment was implemented.

3. RESULTS AND DISCUSSION

3.1. COMPACTION CHARACTERISTICS

Standard Proctor compaction tests were carried out to determine the optimum moisture content (OMC) and maximum dry density (MDD) of all mixtures. The compaction curves of mixtures with different percentages of additives are shown in [Figure 3](#). As can be seen, the

addition of CKD resulted in a decrease (about 6%) in the MDD and a slight increase in the OMC of the soil. This trend is in agreement with previous studies [\[13, 19, 20\]](#), which may be explained by the flocculation and cementation of soil particles due to the addition of CKD.

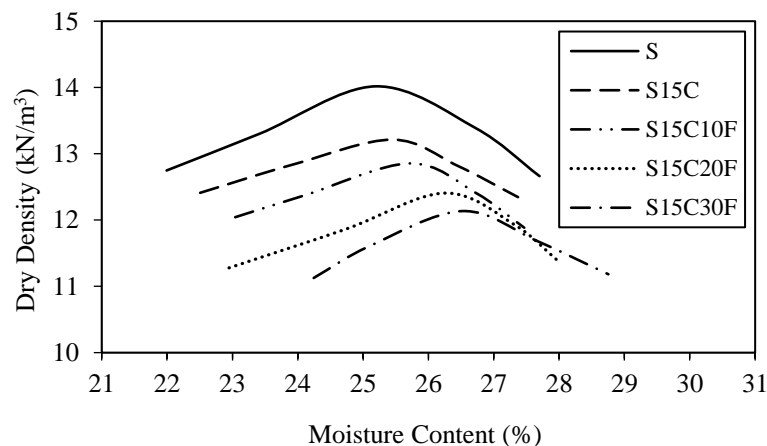


Figure 3. Variation in compaction characteristics of untreated soil and treated soil

While the MDD value of the CKD-treated soil was 13.2 kN/m³, the same value decreased to 12.9, 12.4, and 12.2 kN/m³ when the CKD was partially replaced with 10, 20, and 30% fly ash, respectively. In addition, a 30% replacement of CKD by FA causes the OMC to increase from 25.4 to 26.6%, compared with the CKD-treated soil. The decrease in the MDD values may be regarded as an immediate formation of cemented products with the presence of fly ash, which may reduce compatibility [\[21,](#)

[22\]](#). The increase in the OMC is due to the additional water held by the flocculent soil structure resulting from the cementitious reaction. The specific gravity of fly ash used in the study is too low compared to specific gravity values of the CKD. Therefore, the specific gravity of the mixture decreases together with the increase in the percentage of FA replacement, and this situation causes the decrease in the MDD value.

3.2. UNCONFINED COMPRESSIVE STRENGTH (UCS)

The UCS test is a widely used laboratory test for stabilized soils. [Figure 4](#) and [Figure 5](#) depict the effect of additives on stress-strain curves of treated soil obtained from the UCS test at curing time of 7 days and 28 days, respectively. It can be observed that CKD led to an increase in the strength of the soil, which is reported widely in previous studies [\[13, 16, 19\]](#). The CKD tends to produce relatively high pH levels in the presence of water [\[14\]](#). This high pH causes silica and alumina to be dissolved out of the

structure of the soil and to combine with the calcium in the CKD to produce calcium silicate hydrate (C-S-H) or calcium aluminate hydrate (C-A-H). As shown in [Figure 4](#) and [Figure 5](#), higher contents of FA resulted in higher strength. The UCS of the samples with a partial replacement of the CKD by 10, 20, and 30% FA was 300.8, 327.6, and 350.6 kPa at 7 days, respectively. It can be seen that the strength of the mixture with partial replacement of the CKD by 30% FA was 32% higher than soil stabilized

with 15% CKD only at 7 days of curing. This increase in strength, in addition to the formation of secondary cementitious materials due to the reaction between silica and alumina from the fly ash and the clay minerals with the calcium hydroxide released from CKD, can also be attributed to the filling ability property of fly ash, which helps to bind soil particles and cementitious products. The

results reveal that the strength of the stabilized soil for all of the mixtures increases with curing time, which was expected. Because the process of hydration and the formation of cementitious products is time-dependent, over time, more hydration products (C-S-H and C-A-H gels) are produced resulted in an increase in the strength.

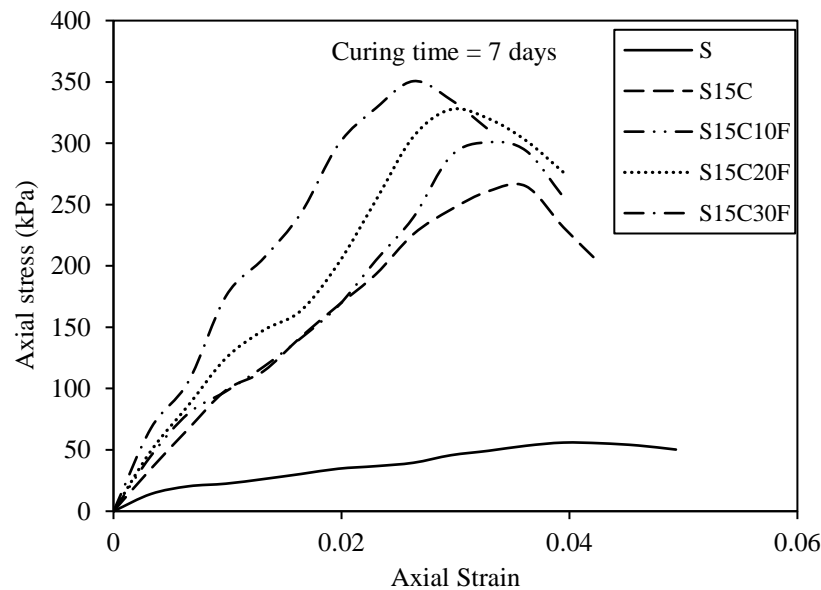


Figure 4. Effect of the additives on unconfined compressive strength at 7 days of curing

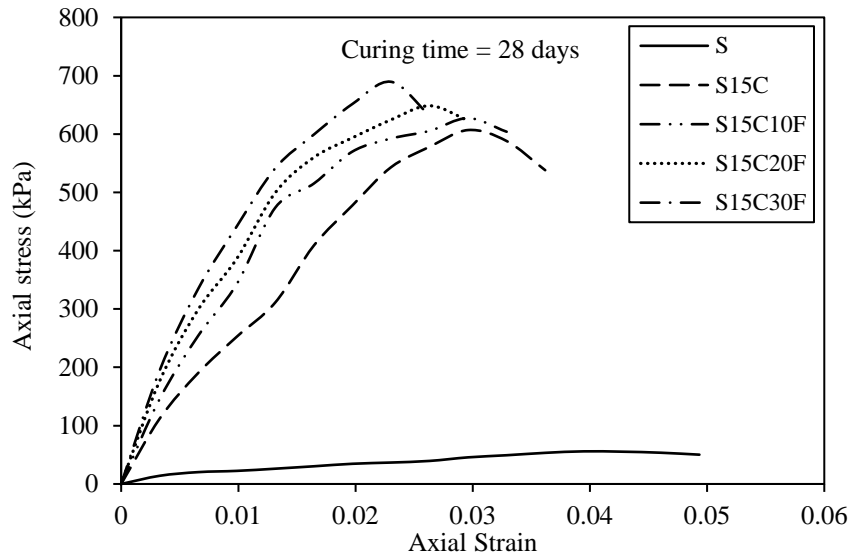


Figure 5. Effect of the additives on unconfined compressive strength at 28 days of curing

The mechanical behavior of the treated soil had a brittle behavior compared with non-treated soil due to the formation of cementitious compounds. In [Figure 4](#) and [Figure 5](#), it can be seen that the stress–strain curves of the stabilized soils relative to the raw soil have a trend to move upward, and the failure strain has a trend to move towards the origin. The strain at peak strength is considered as failure strain, which is an important indicator for evaluating the deformation characteristics of geotechnical materials. The failure strain of raw soil is 3.95%. A decrease in failure strain is observed for CKD-stabilized

soil compared to non-treated soil. This trend is consistent with previous studies [\[16, 19\]](#). For S15C30F, it is reduced to 2.63% and 2.3% after 7 and 28 days of curing, respectively. The decrease in failure strain could be due to the breakage of rigid bonding between soil particles and stabilization agent. The soil deformation modulus is an essential parameter for the analysis of soil behavior. A common method to determine the soil elastic modulus is using the tangent modulus of the stress–strain curve obtained from unconfined compression tests. As an alternative method to find this parameter, a secant modulus

that is determined for 50% of peak axial stress (E50) can be utilized. The effect of additives on the modulus of elasticity (E50) is indicated in [Figure 6](#). The short-term modulus of the mixtures at 7 days increased but had a greater modulus at 28 days. It has a similar trend to

strength development. The modulus of elasticity (E50) varies mainly between 8 and 52 MPa is about 30–75 times greater than UCS. This result agrees in general with the previous studies on soil stabilization with cementitious materials [\[23, 24\]](#).

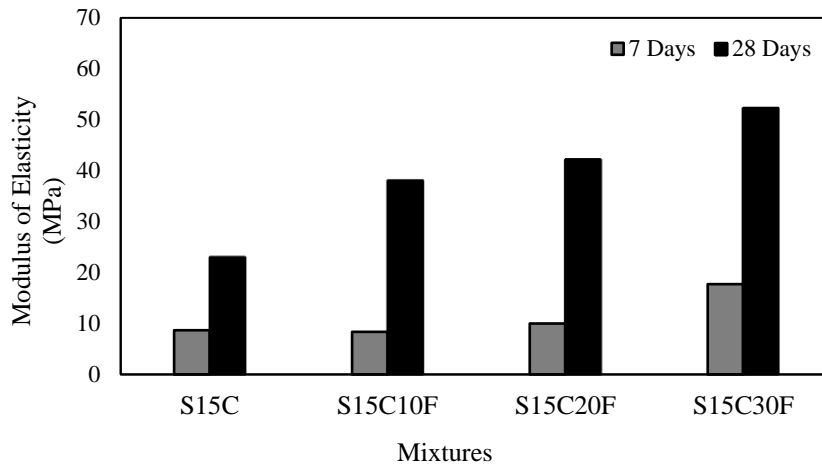


Figure 6. Effect of the additives on modulus of elasticity of the soil

3.3. SEM ANALYSIS

Three specimens (S, S15C, and S15C30F) were subjected to SEM analysis ([Figure 7](#)). It is clearly seen from [Figure 7\(a\)](#) that the untreated clayey soil consisted of particle packs, where the pores are visible. These pores can be attributed to the aggregation of clay particles in the presence of water, which leads to large voids in the untreated soil. [Figures 7\(b\) and 7\(c\)](#) show significant changes in the microstructure of the soil matrix when mixed with either CKD or CKD-FA after 28 days. According to the SEM images, the specimens that contain CKD are denser and more homogeneous than the CKD-

free specimen because the hydration reaction products coat the clay particles and fill the voids partially between the particles. This finding is in line with the outcomes reported by Peethamparan et al. (2008) and Ghavami et al. (2021) [\[14, 25\]](#). Moreover, the FA particles, which are clearly shown among clay-CKD clusters ([Figure 7\(c\)](#)), reduce the volume of pores resulting in overall denser. It can also be seen that the formed secondary C–S–H gel covers the surface of FA particles. The filling effect of fly ash and its pozzolanic reaction has also been observed by Wang et al. (2013) [\[24\]](#).

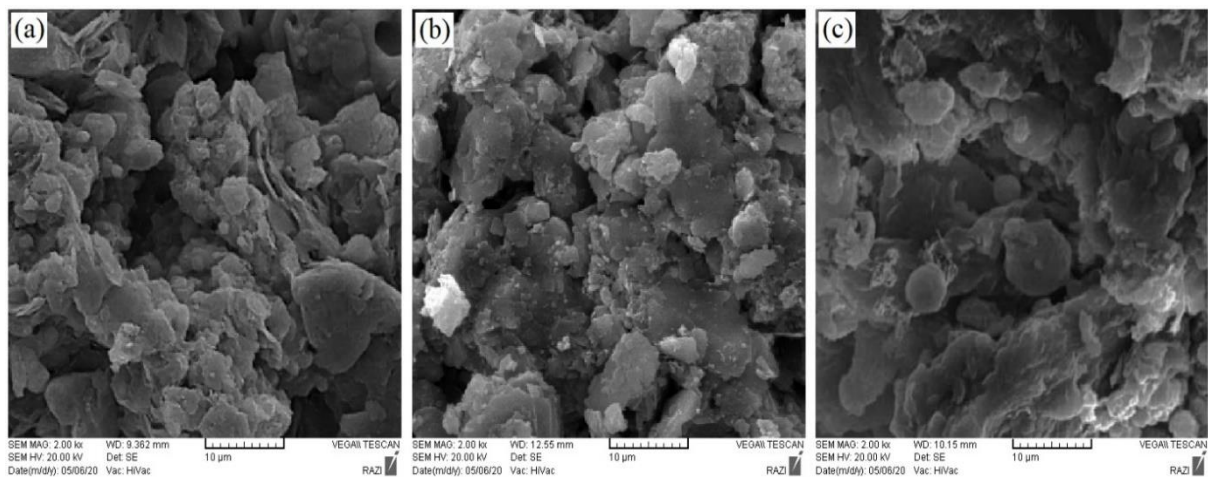


Figure 7. Scanning electron micrograph of specimens: (a) Untreated soil, (b) S15C, (c) S15C30F

4. CONCLUSION

This study investigates compaction and strength characteristics of the high-plasticity clay obtained from a forest road in North of Iran when it was stabilized with cement kiln dust (CKD), where the CKD was partially replaced with fly ash (FA). The addition of 15% CKD resulted in a decrease in the maximum dry density (MDD)

and a slight increase in the optimum moisture content (OMC) of the soil. When the CKD is partially replaced with FA, the OMC increases, and the MDD decreases compared with the CKD-only mixture. The CKD treatment improved the unconfined compressive strength of the high-plasticity clay from 56 kPa to 265 and 606.9

kPa after 7 and 28 days, respectively. After partially replacing the CKD with FA, it is observed that the strength increased with an increase in the FA content. The strength of the mixture with partial replacement of the CKD by 30% FA was 32% higher than soil stabilized with 15% CKD only at 7 days of curing. The results revealed that the strength of the stabilized soil increases with curing time. Because the process of hydration and the formation of cementitious products is time-dependent, over time, more hydration products (C-S-H and C-A-H gels) are produced resulted in an increase in the strength. The results of the

UCS test agreed well with the results from the SEM analysis. The SEM images showed significant changes in the microstructure of the soil matrix when mixed with either CKD or CKD-FA. The specimens with additives were denser and more homogeneous than untreated specimens because the cementitious products coat the clay particles and fill the pores partially between the particles. The results of this study show the use of cement kiln dust and fly ash as industrial wastes may provide sustainable geotechnical construction.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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