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Laboratory evaluation on the effectiveness of polypropylene fibers on the strength behavior of CKD-stabilized Soil

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ABSTRACT

Improving the engineering properties of soils by chemical stabilization and using reinforcement material are means of complying with geotechnical design criteria. Nowadays, the use of chemical materials such as Portland cement and lime has been criticized despite the acceptable effect due to environmental pollution caused by their production as well as the contamination caused by these materials in the soil. One of the materials used to replace cement and lime is cement kiln dust (CKD), which has been used as filler in asphalt concrete, sewage sludge stabilization, and improving the physical and mechanical properties of soils in recent years. An experimental study was performed to evaluate strength behavior and microstructural characteristics of CKD-soil admixture reinforced by polypropylene fibers. The effect of content and length of fibers on mixture properties was investigated. The results indicated that CKD increases the strength of the soil, but its behavior is fragile. The use of fiber in combination with CKD, in addition to increasing the strength, makes the sample more ductile. The test results showed that the optimum content of polypropylene fibers is 0.5%. The failure pattern of fiber-reinforced specimens differed from that of fiberless specimens due to the bridge effect. The results of the UCS test agreed well with the results from the SEM analysis.

1. Introduction

The presence of soils with low bearing capacity is the main cause of damage to engineering structures such as foundations, roads, and embankments. Common methods of improvement of these soils include compaction, vibroflotation, precompression, stabilization by admixture, and jet grouting, as well as the use of stone columns and reinforcement. Portland cement and lime are widely used as chemical admixtures in ground improvement projects due to the occurrence of various chemical reactions such as cation exchange, flocculation/ agglomeration, and pozzolanic reaction (Al-Rawas et al., 2005; Mahedi et al., 2020). The use of these admixtures has been criticized despite the acceptable effect due to environmental pollution caused by their production as well as the contamination caused by these materials in the soil. The Portland 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 the cement industry (Ghavami et al., 2021). To this end, the researchers have been interested in utilizing waste materials and industrial by-products as cement replacement

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(Salahudeen et al. 2014; Ghavami et al., 2019; Arrieta Baldovino et al., 2020). In a cement production plant, dust is produced due to abrasion, crushing, handling, and cooking materials on the kiln and move within it. The use of dust, removing from cement kiln exhaust gas by air pollution control devices, in soil stabilization has been investigated in previous studies (Miller and Azad, 2000; Peethamparan et al., 2008; Salahudeen et al. 2014; Cui et al., 2018). The presence of free-lime (CaO), the high alkali content, and the large fineness of cement kiln dust (CKD) make it a potential candidate to improve the engineering properties of different soils. Besides, Ghavami et al. (2021) reported that by stabilization of soil with 15% CKD instead of 9% Portland cement, the needed energy to soil treatment and the equivalent CO_2 emission reduces considerably. Soil stabilized with chemical additives cause exhibits extremely brittle behavior (Tang et al., 2007; Ghavami et al., 2018). The elastic modulus of these soil stabilized has a similar trend to strength development (Wang et al., 2013; Ghavami and Rajabi, 2021). Incorporating polypropylene fiber inclusions within the soil can change the brittle behavior to a more ductile one, and make it exhibit strain-hardening characteristics (Tang et al., 2007; Zhao et al., 2020). Various assessments on geotechnical properties of soils mixed with polypropylene fiber and chemical additives such as Portland cement, lime, and fly ash have been carried out by other researchers (Cai et al., 2006; Muntohar et al., 2013; Kumar and Gupta, 2016; Sharma, 2018).

This study has been performed to determine the effect of polypropylene fiber on the strength behavior of clayey soil stabilized by CKD. A series of unconfined compressive strength (UCS) tests were conducted on CKD-treated soil samples with different percentages of fiber. The changes in the soil structure and the behavior of interfaces between fiber surface and soil were observed using a scanning electron microscope (SEM).

2. Materials and Methods

2.1. Experimental Program

The soil used in this study was obtained from a forest road located approximately 7 km east of Nowshahr, Mazandaran province, North of Iran (Fig. 1). Preliminary characterization tests were performed according to standard procedures of the American Society for Testing and Materials (ASTM) to assess the basic engineering properties of the soil. The results obtained from the tests on the soil are summarized in Table 1. The soil is classified as clay with high plasticity (CH) based on the Unified Soil Classification System (USCS). Table 2 gives the chemical composition of the soil that was analyzed using X-ray fluorescence (XRF) spectrometer. Cement kiln dust used in this research is a by-product from the Mazandaran cement factory in Iran. Percentages of the main chemical composition of the CKD are reported in Table 2. It has been suggested that for effective stabilization reactions to take place, the hydration modulus (ratio of the amount of CaO to the total amount of SiO_2, Al_2O_3, and Fe_2O_3) must be at least 1.7 (Kamon and Nontananandh, 1991). The values of components in Table 2 indicate that CKD could be used as a soil stabilizer. Polypropylene fibers used as reinforcement were provided by Vand Chemie Company. Photographs of the fibers and their characteristics are presented in Fig. 2 and Table 3, respectively.

2.2. Mixture Proportions

It has been inferred that 15% CKD by dry weight of the soil is a practical upper limit for cost-effective stabilization (Miller and Azad, 2000; Ghavami et al., 2021). According to some pertinent studies on soils stabilized by cementitious materials and fibers (Golchinfar and Abbasi, 2014; Patel and Singh, 2017), three different percentages of polypropylene fiber content (i.e. 0.25%, 0.5%, and 1% by dry weight of the soil), were chosen in this investigation. The effect of fiber length was investigated by increasing its length from 6 mm to 12 mm. The details of all the mixture proportions are listed in Table 4.

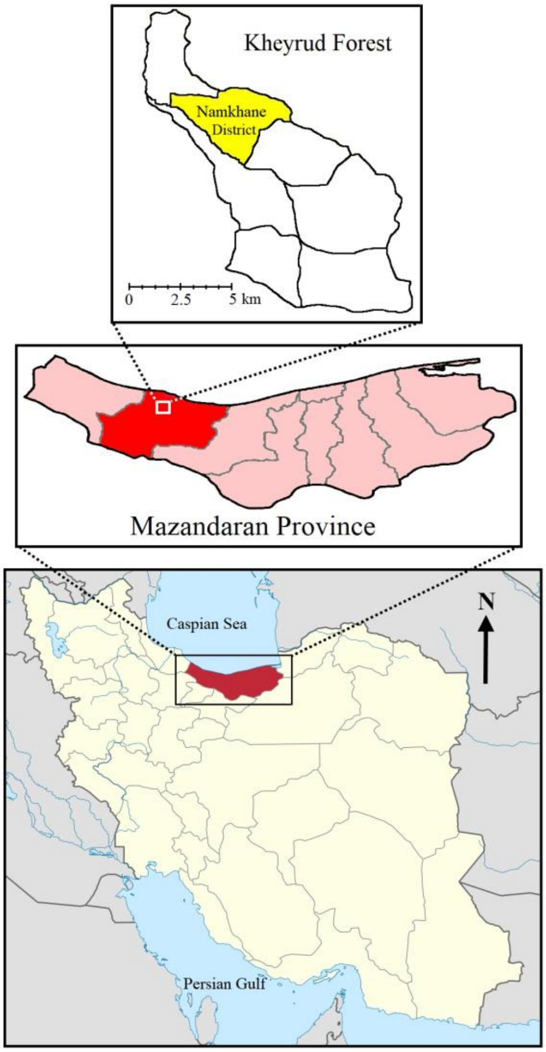

Figure 1. Location of the site and the soil specimen was obtained

Figure 2. Polypropylene fibers in different lengths

Table 1. Geotechnical properties of the soil

Properties	Value
Liquid limit (LL), %	58.1
Plastic limit (PL), %	25.9
Plasticity index (PI), %	32.2
Coarse-grained content (Diameter > 0.075 mm), %	15
Fine-grained content (Diameter < 0.075 mm), %	85
Specific gravity	2.74
Optimum moisture content (OMC), %	25.2
Maximum dry density (MDD), kN/m^3	14
Unconfined compressive strength (UCS), kPa	56
Soil classification (USCS)	CH

Table 2. Chemical constituents of the soil and cement kiln dust

Compound	Soil	Cement kiln dust
SiO_2	66.5	13.4
Al_2O_3	12.4	3.8
Fe_2O_3	6.05	2.9
CaO	0.64	45.8
MgO	1.74	1.1
SO_3	0.02	11.8
K_2O	3.25	3.81
Na_2O	1.12	0.69
Other	1.83	0.3
Loss on ignition	6.45	16.4

Table 3. Properties of polypropylene fiber

Properties	Value
Unit weight, g/cm^3	0.9
Average diameter, µm	20
Length, mm	6 and 12
Tensile strength, MPa	350
Melting point, ˚C	160

Table 4. The mixture proportion detailed

Sample	CKD content, %	Fiber content (Length = 6 mm), %	Fiber content (Length = 12 mm), %
S	0	0	0
15C	15	0	0
15C25P6	15	0.25	0
15C50P6	15	0.5	0
15C100P6	15	1	0
15C50P12	15	0	0.5

2.3. Methodology

The unconfined compressive strength test was conducted according to ASTM D 2166 with a loading rate of 1% per minute. The specimens were compacted into a cylindrical mold of size 38-mm diameter and 76-mm height and then were cured in plastic bags for periods of 7 and 28 days at a temperature of 23±2°C. After the UCS test, the SEM analysis was performed on three specimens including the untreated soil, 15% CKD and 15% CKD-0.5% fiber to further investigate the changes in the microstructure of the stabilized clay.

3. Results and Discussions

Stress–strain curves obtained from unconfined compressive strength tests at a curing time of 7 and 28 days are given in Figs. 3 and 4, respectively. It can be observed that CKD led to an increase in the strength of the soil, which is reported widely in previous studies (Miller and Azad, 2000; Peethamparan et al., 2008; Cui et al., 2018). The UCS for 15C were 265 and 607 kPa for curing days of

7 and 28, respectively. The CKD tends to produce relatively high pH levels in the presence of water (Peethamparan et al., 2008). 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). The developments of C-S-H and C-A-H gels intensity tend to increase with curing time. Based on the results of the UCS test, it can be concluded that CKD can potentially be used as a cementitious material in the improvement of high plasticity clays.

Stress–strain curves of soil-CKD-fiber mixtures indicate that the strength improves with fiber content up to 0.5% fiber content and thereafter decreases at 1% fiber content. The UCS for specimens with 0.25, 0.5, and 1% fiber after 7 days curing period were 353, 388, and 357 kPa (Table 5). The increase in the strength of the reinforced soil is due to the fibers act as small bonding elements at the interfaces, which is called the "bridge" effect (Fig. 5). When more than 0.5% polypropylene fiber is added to CKD-stabilized soil, the strength is reduced because of the segregation of soil particles caused by the additional fibers. The results reveal that the strength of soil-CKD-fiber mixtures, like that of CKD-stabilized one, increases with curing time. It can also be seen that fiber-reinforced specimens exhibit more ductile behavior. The inclusion of fibers within the CKD-stabilized soil reduces the brittleness of the response and increases the strain corresponding to the maximum stress, as illustrated in Figs. 3 and 4. The strain corresponding to the maximum stress for reinforced specimens with the fiber of length 6 mm ranges from 3.9% to 4.6% and 3.3% to 3.9% at 7 and 28 days, respectively. When the specimen is under load, the bridge effect of polypropylene fiber can efficiently prevent the further development of tension cracks and specimen deformation.

To investigate the effect of fiber length, the fiber length was doubled in the optimal amount of fibers (0.5%) and the UCS test was performed. The results showed that by increasing the length of the fibers to 12 mm, the maximum stress and the corresponding strain increase (Figs. 3 and 4), which is to be expected. The bridge effect is higher for 12 mm fibers than 6 mm fibers. Figs. 3 and 4 also depict that the initial stiffness of the fiber-reinforced specimens appears not to be affected by the fiber content and the fiber length. Three specimens including S, 15C, and 15C50P6 were subjected to SEM analysis (Figs. 6-8). According to the results obtained by SEM analysis, it can be deduced that the natural 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. The comparison of the SEM images indicates that adding CKD or CKD-fiber to the soil causes a significant change in the microstructure of the soil matrix. 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. It is seen from Fig. 8 that the distributed fibers interlock soil particles and cementitious products and help the soil particles form a unitary coherent matrix and limit the displacement. Therefore, the reinforcement of the CKD-stabilized specimen not only enhances the strength of the specimen but also is highly effective in its plastic behavior.

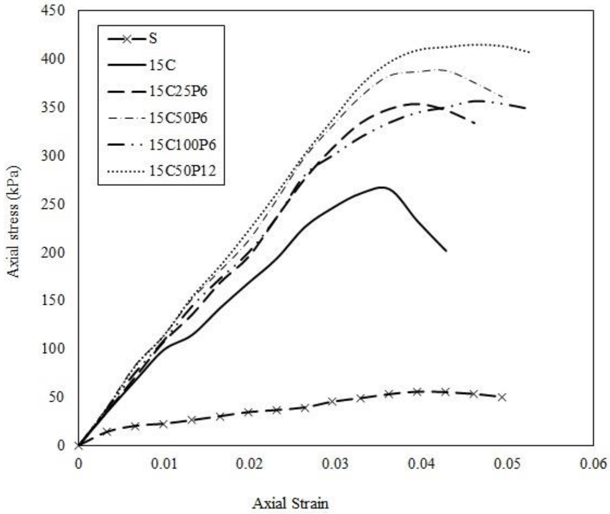

Figure 3. The stress–strain curves from UCS test on specimens after 7 days curing

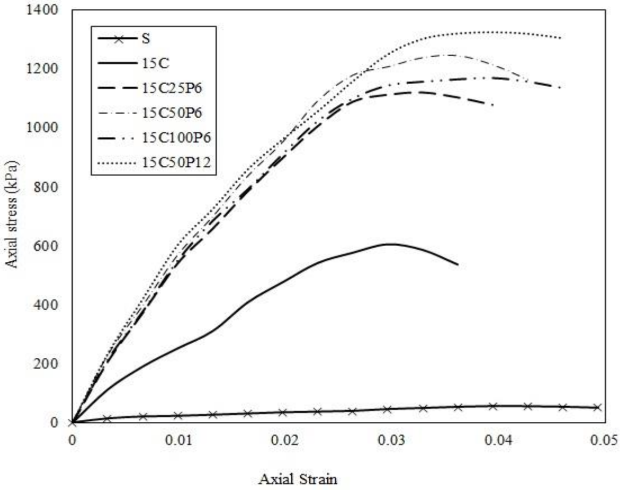

Figure 4. The stress–strain curves from UCS test on specimens after 28 days curing

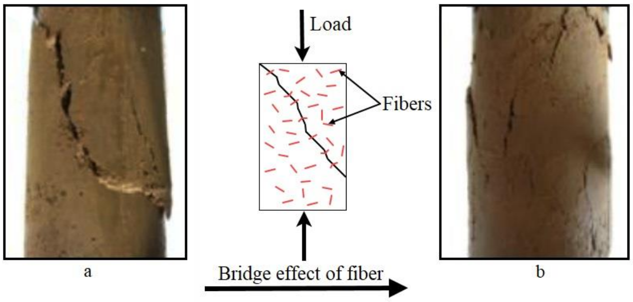

Figure 5. Bridge effect of fiber reinforcement: a) Soil+15%CKD (15C), b) Soil+15%CKD+0.5% Fiber (15C50P6)

Table 5. The unconfined compressive strength of specimens

Sample	Strength (kPa) after curing period (days)	
	7 days	28 days
S	56	56
15C	265	607
15C25P6	353	1120
15C50P6	388	1247
15C100P6	357	1170
15C50P12	415	1325

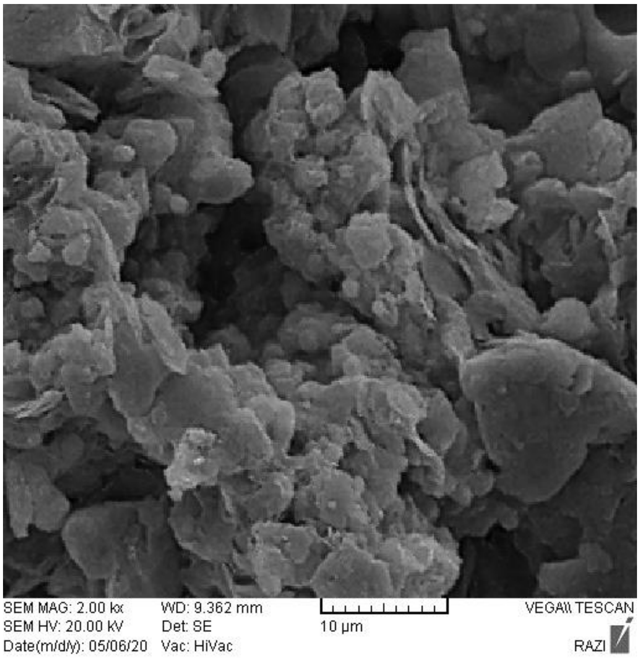

Figure 6. Scanning electron micrograph of untreated soil

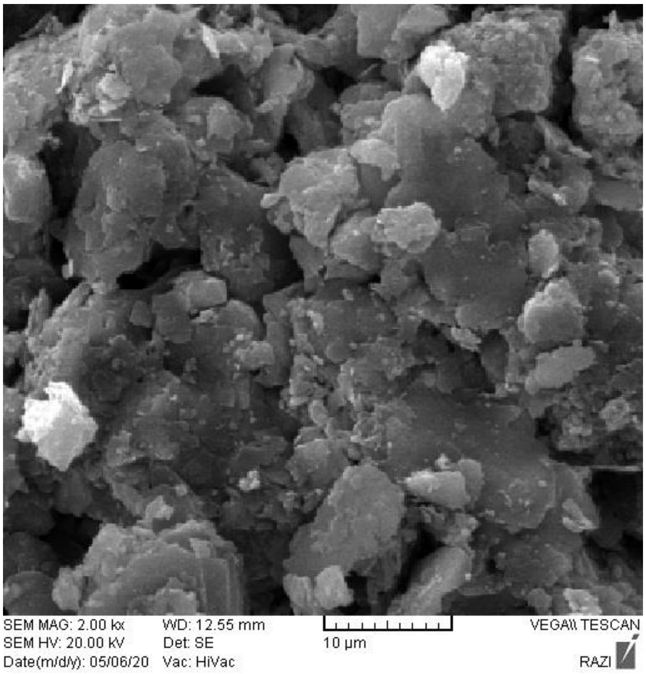

Figure 7. Scanning electron micrograph of CKD-stabilized soil (15C)

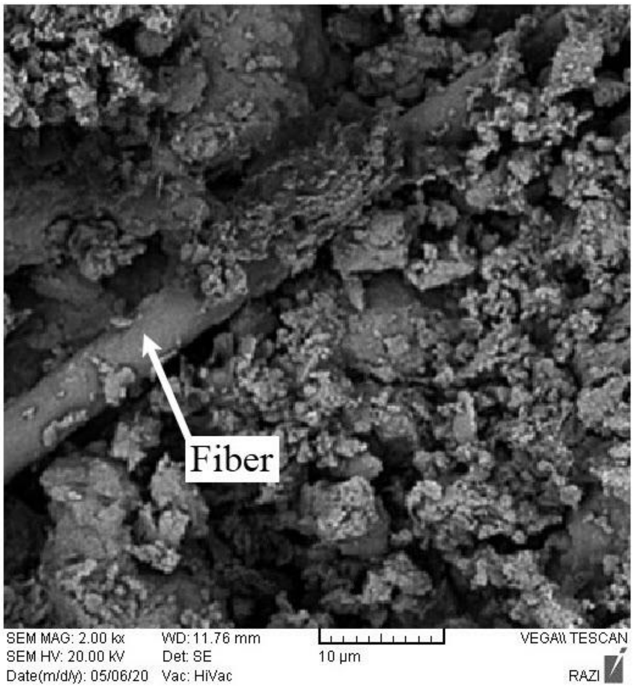

Figure 8. Scanning electron micrograph of fiber-reinforced soil (15C50P6)

4. Conclusion

In this study, the effect of polypropylene fibers on the strength properties of high-plasticity clay stabilized with cement kiln dust (CKD) as an industrial waste material was investigated. Based on the results obtained from unconfined compressive strength (UCS) tests, the significant increase in soil strength by the addition of CKD demonstrates the high potential of CKD for substituting traditional soil stabilizers such as Portland cement and lime. The scanning electron microscope of specimens indicated that the formation of cementitious products, i.e., calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), played an important role in the soil strength improvement. As the curing period increases, more C-S-H and C-A-H gels are produced, which leads to a denser and stiffer soil structure and clay structure and increased strength, so, that the 28-day strength of CKD-stabilized soil is more than twice the 7-day strength.

The inclusion of polypropylene fibers within CKD-stabilized soil caused an increase in the unconfined compressive strength and the corresponding axial strain. The UCS of fiber-reinforced specimens first increased and then decreased as the fiber content increased. The results showed that the optimum quantity of polypropylene fibers is 0.5%. This fiber content increased the strength of cement-stabilized soil to 388 and 1247 kPa after 7 and 28 days of curing, respectively. The failure pattern of fiber-reinforced specimens differed from that of fiberless specimens due to the bridge effect. The results of the UCS test agreed well with the results obtained from the SEM analysis.

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