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Influence of by-product material and calcined pozzolan on some geotechnical characteristics of cement treated fine-grained soil: Comparative study

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Abstract: Stabilizing unstable soil is a significant challenge in civil engineering, especially in regions with soft clay. This study examines the compaction and strength properties of stabilized soils incorporating calcined kaolin clay (CKC), Portland cement (PC), and marble dust powder (MDP). Two binder systems were developed: PC-CKC and PC-MDP, and their performance was evaluated through compaction, Atterberg limits, and unconfined compressive strength (UCS) tests. Soil treatments involved adding 3% PC with varying percentages (3%, 6%, and 9%) of CKC or MDP, based on previous studies identifying 3% PC as optimal. UCS specimens were cured for 3, 7, and 28 days to assess strength development. The results showed that both CKC and MDP enhanced the geotechnical properties of cement-stabilized soils. However, CKC outperformed MDP in reducing the plasticity index and increasing UCS values. These findings highlight the potential of calcined kaolin clay as a sustainable additive for soil stabilization, offering a long-term solution for recycling industrial by-products and improving the performance and durability of infrastructure projects.

Keywords: *Atterberg limits, Calcined pozzolanic and waste materials, Soil Stabilization, Unconfined Compressive Strength.*

1. Introduction

The southern area of Iraq is plagued by problematic soil, especially soft clay. The use of regions with difficult soil and water conditions, frequently containing weak soil occurrences, for construction is becoming more popular as civil engineering develops quickly. However, executing construction projects on soft soils, which exhibit high compressibility, instability, low bearing capacity, differential settlement, and slip failure, presents significant challenges and limitations [1]. In most cases, strengthening the feeble subsoil is necessary to provide a proper foundation for different kinds of constructions [2, 3].

Nowadays, there is a growing global trend toward using waste materials in soil stabilization or strengthening procedures. The significant generation of trash and pozzolanic materials with not only create environmental risks but also problems with deposition, is the main driver for this change-out. Using these materials in building projects has the potential to greatly reduce these difficulties. For example, soil stabilization is a method that uses chemical changes to improve or maintain soil stability, which improves the soil's engineering qualities [4-6]. Stabilization methods are effective for dealing with variety of subgrade materials, from granular materials to expensive clay. Because of its adaptability, it is possible to set design guidelines and choose the correct amounts of chemical additions and admixtures to achieve the required engineering performance. The process of correcting soft soil's undesirable characteristics is known as soil stabilization. This can be accomplishes mechanically by implementing physical modifications by introducing stabilizer [7, 8]. In order to improve the soil's overall performance, this process can also be utilized to increase engineering attributes including strength, permeability, and durability.

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Today's soil reinforcement techniques should follow the circular economy's tents, emphasizing energy-efficient solutions that minimizing greenhouse gas emissions and make use of waste and recycled resources [9]. There are several recommendations for ecologically responsible soil stabilization; the most common and well discussed is to use waste products as additions to poor subsoil. Using waste materials as additives has several benefits, such as lowering costs by removing the need for extra resources and assisting in the mitigation of waste disposal problems, which are frequently expensive and difficult. Additionally, adding the right amount of waste material can increase the soil's maximum density and shear strength while reducing compressibility.

Cement production process have many negative effects including natural resources high consumption, release of environmentally polluting materials in large proportions, and relatively high production costs. Increased production of cement with the industrialization has contributed in the increment of CO_2 being released to the atmosphere. Cement production is responsible for approximately (7%) of the world's carbon dioxide (CO_2) emissions [10]. Globally, the cement industry is projected to grow by (5%) annually. In light of this, researchers have focused on developing new binder materials that utilize replacements or reducers to cement usage. These materials, known as calcined pozzolanic and waste materials, undergo a pozzolanic reaction, enabling them to self-harden by reacting with cement and producing cementitious gels. However, certain by-product materials, such as marble dust powder (MDP), contain free lime (CaO) contents.

In this study, the main calcined pozzolan used was calcined kaolin clay (CKC) in different combinations. CKC is a cementitious material that conforms to Committee [11] Class N pozzolan specifications. Calcined kaolin ($Al_2Si_2O_7$) is a pozzolanic substance that undergoes thermal activation via burning kaolinite clay at temperatures between (700 and 800) degrees Celsius [12, 13]. CKC is a pozzolanic material that has a higher surface area compared with Portland cement and belongs to the class N pozzolan. It is characterized by its high reactivity and comprises approximately (50–55) % SiO_2 and (40–45) % Al_2O_3. A secondary calcium silicate hydrate (C-S-H) gel is created when it reacts chemically with calcium hydroxide. Through the improvement of its pore structure, this gel helps to increase the concrete's strength and durability.

Marbles are natural stones that are generated when limestone and dolomite are recrystallized at high temperatures and pressures [14, 15]. Marble plants generate two different kinds of waste: slurry and powdered marble waste, as byproducts of their cutting and polishing processes. However, due to the lack of efficient valorization procedures in the ornamental stone industry, these waste kinds pose threats to the environment since they are either disposed of in landfills or stored in warehouses for possible future use in alternative applications [16-19]. Marble dust powder (MDP), a residual material generated during the cutting, shaping, and polishing of marble, has shown promise as a beneficial additive in concrete mixtures. The main focus of this research is the effects of stabilizing unstable soil by using cement in combination with new binary blended mixtures of (CKC) or (MDP). The efficacy of the mixture in boosting durability, decreasing flexibility, and strengthening soil will be evaluated. Figure 1 representing flowchart a summary of the study.

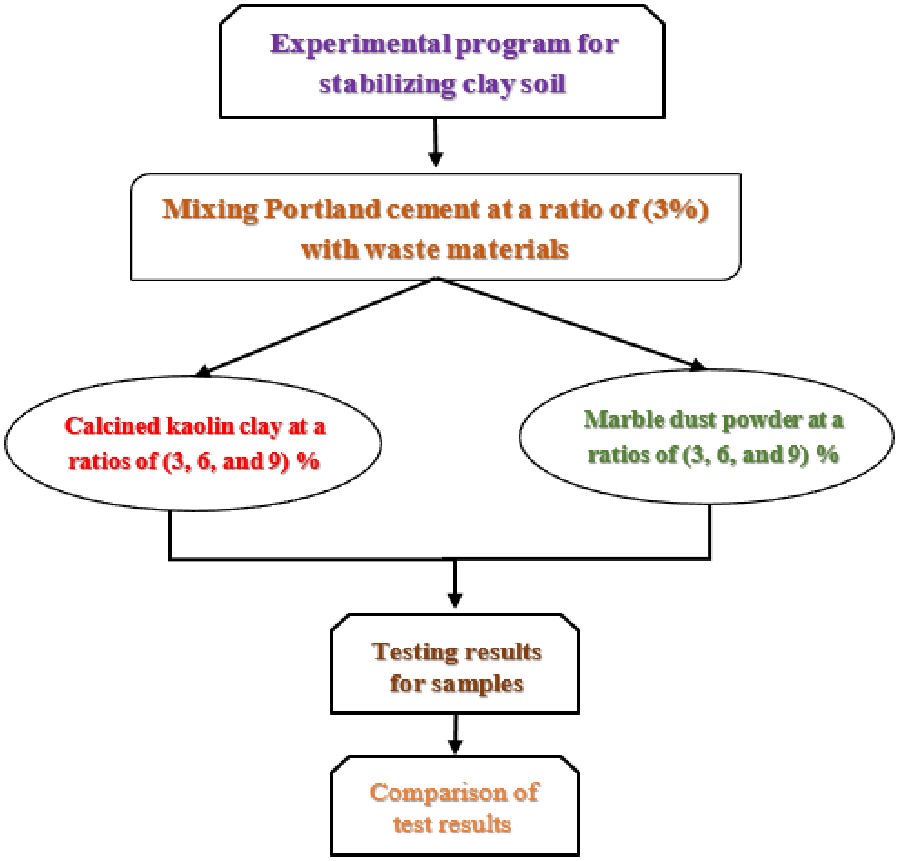

Figure 1.
A research process flowchart.

2. Materials & Methods

This study's primary materials of investigation include soil, Portland cement (PC), calcined kaolin clay (CKC), and marble dust powder (MDP). This section gives a summary of these materials' characteristics.

2.1. Treated Soil

In the Al-Muthanna Governorate in southern Iraq, samples of the tested soil were taken from a particular location in As Saiyid Alib (31 32 10.3 N 45 17 30.7 E), which is roughly (280) km south of Baghdad and near to Al-Samawah City. Using disturbed sampling techniques, the data was collected from borrow pits at a depth of (1.0) m. Table 1 displays the properties of the soil under study. This table lists the parameters used in the current experiment, such as classification, index characteristics, and soil grain size fractions. Shimadzu's EDX-720 Energy Dispersive X-Ray Fluorescence Analyzer was used to analyze X-ray fluorescence spectrometry (XRF) data in order to quantify the oxide concentrations.

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Table 1.
The soils' chemical and physical characteristics.

Characteristic	Standard	Value and description
0rganic content (%)	ASTM D 2974	1.31
Specific Gravity	ASTM D 854	2.75
pH	ASTM D 4972	3.96
Clay fraction (%)	ASTM D 422	35.1
Silt fraction (%)	ASTM D 422	32.3
Sand fraction (%)	ASTM D 422	32.6
Liquid limit index (%)	ASTM D4318	46
Plasticity index (%)	ASTM D4318	22
Linear shrinkage (%)	ASTM D4943	8.10
Unified soil classification (USCS)	ASTM D 2488	CH
Optimum water content (%)	ASTM D 698	15.60
Maximum dry unit weight (kN/m^3)	ASTM D 698	1.71
Unconfined Compression Stress (kPa)	ASTM D 2166	68
Chemical composition		
SiO_2 (%)		56.12
Al_2O_3 (%)		22.34
Fe_2O_3 (%)		8.14
MgO (%)		1.69
CaO (%)		0.10
TiO_2 (%)		1.92
Na_2O (%)		0.41
K_2O (%)		3.56

2.2. Calcined Kaolin Clay

The kaolin clays employed in this research were sourced from the western regions of Iraq. These clays underwent a calcination process at (800°C) for two hours, with at a pace of (5°C) each minute, resulting in the conversion to a pozzolan material named calcined kaolin clay (CKC). Following calcination, the CKC was gradually cooled to room temperature over a period of 24 hours. Subsequently, the CKC was ground using the air blast technique to achieve a finer, more reactive material. Table 2 lists the calcined clay's (CKC) chemical properties. Additionally, the physical properties including specific gravity, fineness (m^2/kg), and median particle size (μm) are recorded as (2.59, 1640, and 14.3), respectively.

2.3. Marble Dust Powder

One by-product of the production of marble masonry is waste marble dust powder (MDP). MDP was gathered, in this study, as a sludge from masonry plants located in the Middle Euphrates area of Iraq, Al-Hillah city. It was the waste of marble shaping and sawing. Chemical and physical characterizations were carried out on the MDP waste to assess its usage possibility in the production of concrete or mortar. The chemical constituents of the waste marble dust powder (MDP) were determined and tabulated in Table 2.

2.4. Cement

According to ASTM C150/C150-07 [20] Portland cement type I (PC) was used for all the concrete mixes. The cement's chemical and physical properties are displayed in Tables 2 and 3.

Table 2.
The chemical composition of MDP, PC, and CKC.

Chemical composition %	PC	CKC	MDP
CaO	62.79	0.84	82.1
SiO_2	20.58	54.7	1.47
Al_2O_3	5.60	37.4	0.84
Fe_2O_3	3.28	1.72	0.34
MgO	1.94	0.42	0.40
K_2O	0.59	0.54	0.08
Na_2O	0.29	0.37	1.17
SO_3	2.35	0.13	0.68
P_2O_5	--	0.29	0.28
TiO_2	-	0.68	-
LOI	1.94	2.91	2.83

Table 3.
Physical properties of PC, CKC and MDP.

Property	PC	CKC	MDP
Fineness [m^2/kg]	338	1640	569
Specific gravity	3.14	2.59	2.68
Median particle size [μm]	16.8	14.3	24.8
Color	Grey	Off-White	Light grey

2.5. Sample Preparation and Curing Conditions

The procedure employed in this study involved dividing the samples by two sections: the first comprised the natural soil, while the second incorporated additives such as CKC, MDP, and PC as admixtures. These admixtures were blended with the subgrade soil to facilitate stabilization, alongside fly ash and cement mixes. Six varying proportions of CKC, and MDP were (0, 3, 6, and 9) % of total specimen weight. While, the proportions of PC selected was (3%) by the dry weight of the natural soil with different binders used to stabilize the soil. Following the initial characterization of the natural soil, it underwent sieving through a (5) mm sieve and subsequent air-drying at approximately (105°C). The soil was then mixed with CKC, MDP, and PC. Ensuring uniform distribution required meticulous preparation and adequate time. Subsequently, the Proctor compaction test found the maximum dry density along the course of the study. Maximum Dry Density (MDD) of the blends, following the guidelines outlined in BS 1377-4 [21]. During the mixing process, the natural soil-PC, natural soil-PC-CKC, and natural soil-PC-MDP blends were meticulously mixed until a uniform coloration was achieved. The various mixtures used in this work are presented in Table 4. The unconfined compressive strength test was conducted in accordance with the standards [22] for all soil types: untreated compacted soil and stabilized soil. As seen in Figure 2, an automated unconfined compressive strength-testing machine was used to produce UCS measurements. Specimens with a diameter of (38) mm and a height of (76) mm were created by the use of a fixed volume mold in the compaction process.

The mixture of soil and additives were dry mixed first, an amount of water calculated according to the Optimum Moisture Content (OMC) of each corresponding mixture then added to make paste in which be inserted inside the mold and compressed using hydraulic jack as viewed in Figure 3. Compaction test findings for each percentage of CKC, MDP, and PC were used to determine the particular densities and moisture contents, which were then used to produce the specimens. After the compaction process, the samples were removed from the mold, weighed, and then wrapped in cling film. Then, in order to speed up the drying process, they were stored at room temperature (20 ± 2°C) in sealed plastic bags. Each of the four groups of specimens was assigned a distinct curing length (0, 7, 14, and 28 days). Two specimens were carefully produced for each percentage of CKC and MDP for each of these designated curing periods in order to guarantee the accuracy of the findings. Tests were carried out using [23] protocols once all specimens had been prepared.

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Table 4.
Mix proportion composition.

Mix description	PC (%)	CKC (%)	MDP (%)
Natural Soil (NS)	0	0	0
Soil + Cement (SC)	3	0	0
SC-3 CKC	3	3	0
SC-6 CKC	3	6	0
SC-9 CKC	3	9	0
SC-3 MDP	3	0	3
SC-6 MDP	3	0	6
SC-9 MDP	3	0	9

Figure 2.
Unconfined compressive strength testing.

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Figure 3.
UCS sample preparation.

3. Results and Discussion

3.1. Atterberg limits

The Atterberg limits test results are listed in Table 5. Figure 4 shows the impact of various binary blends that contain CKC or MDP added to soil-PC mixtures on the index of plasticity (I.P.), plastic limit (P.L.), and liquid limit (L.L.). The L.L. test findings demonstrated that the value of L.L. of cement-stabilized soil increased as the percentages of CKC and MDP increased. Nonetheless, CKC had a greater impact than MDP; as shown in Table 5, CKC percentages led to increases in L.L. that were greater than MDP's. The results for the plastic limit showed the same pattern. Overall, adding CKC or MDP decreased the treated soil's index of plasticity (I.P.). However, as Figure 4 illustrates, the results indicated that the lowest I.P. value was achieved when CKC was added at a rate of 9%. The cement-soil plasticity was enhanced by both components, hence mitigating the impact of variations in water content. According to Jafer et al., cement-stabilized soil treated with two distinct fly ashes exhibited similar behavior [24, 25].

Table 5.
Atterberg Limits Test Results.

Mix description	Atterberg Limits		
	Liquid Limit (L.L. %)	**Plastic Limit (P.L. %)**	**Plasticity Index (P.I. %)**
Natural Soil (NS)	46	24	22
Soil + Cement (SC)	48	25	22
SC-3CK	50	29	21
SC-6CK	52	33	19
SC-9CK	54	36	18
SC-3 MP	49	27	22
SC-6 MP	50	29	21
SC-9 MP	52	32	20

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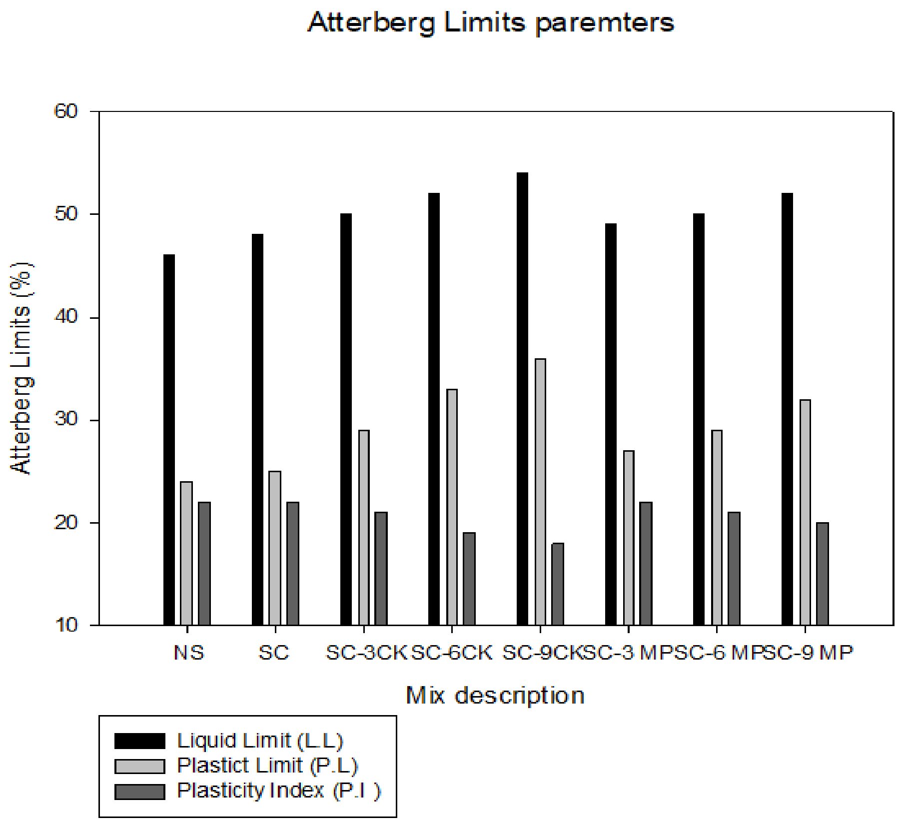


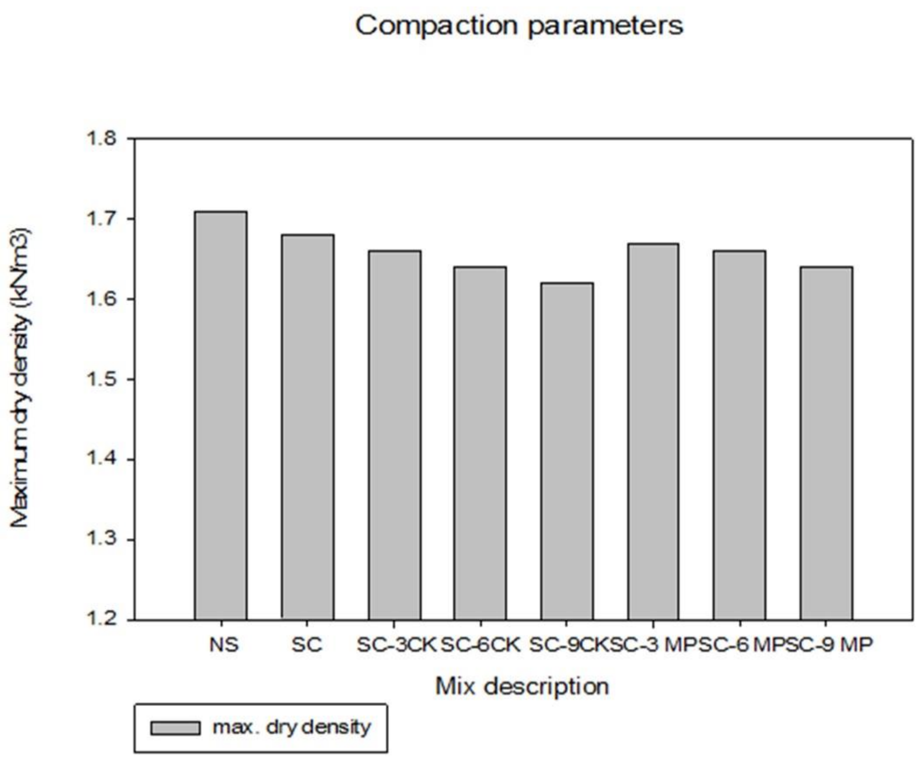
Figure 4.
Effect of using CKC and MDP on the index of plasticity.

3.2. Compaction Test

The results of standard proctor test of soil samples handled using various binary blends containing cement with various percentages of CKC or MDP are listed in Table 6. When comparing the values of maximum dry density MDD of the soil samples handled with different blend, it was found that all additive used caused a reduction in MDD in reference to the untreated soils (see Figure 5-a). On the other hands, the value of optimum moisture content (OMC) increased significantly with the use of additive materials as shown in Figure 5-b. This may be due to the increase in water demand after incorporating the additive materials that have CaO in their chemical content [26, 27]. When comparing the performances of CKC and MDP and their effect on MDD and OMC of the cement-stabilized soil, it was obvious that CKC decreased MDD and increased OMC in values higher than those for MDP. Referring to the chemical composition of both CKC and MDP, it can be recognized that CKC has higher CaO content than MDP that makes it has a higher water demand. This in turn led to increase the OMC and reflected on the decreased values of MDD.

Table 6.
Standard Proctor test results.

Mix description	Compaction parameters	
	Maximum dry density (kN/m³)	Optimum water content (%)
Natural Soil (NS)	1.71	15.6
Soil + Cement (SC)	1.68	16.2
SC-3 CK	1.66	16.8
SC-6 CK	1.64	17.1
SC-9 CK	1.62	17.4
SC-3 MP	1.67	15.9
SC-6 MP	1.66	16.4
SC-9 MP	1.64	16.9



(a) MDD of the soil treated with various binders.

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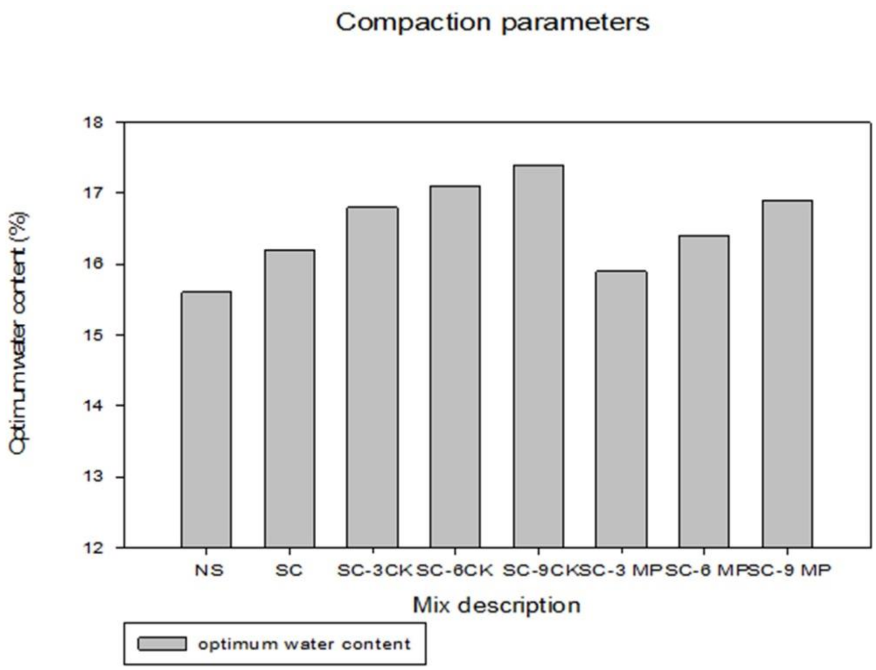

(b) OMC of the soil treated using various binders.

Figure 5.
Results of Compaction test.

3.3. Unconfined compressive test (UCS)

The results of UCS test of the soil specimens various binders and curing times used to the material are articulated in Table 7 as well as presented in Figure 6. From these table and figure, it is clear that the soil strength was enhanced significantly after using OPC alone at the first stage. Further strength developments were then obtained after the incorporating CKC and MDP. UCS recorded increased values with the increased contents of both CKC and MDP until reached (6%). After that, there was a slight reduction in UCS at (9%) of MDP while UCS continued in rise even at (9%). This could be due to the absence of CaO required for further pozzolanic reaction in case of MDP that is available in enough content in case of CKC shown in Table 2.

In terms of comparative performance, CKC exhibited a superior performance to that of MDP in term of the improving of soil-PC strength particularly at (6%) dosage. At the aforementioned percentage, after 28 days of curing UCS became 1156 kPa and 912 kPa for CKC and MDP, respectively, in comparison to (860) kPa for the only PC-treated soil, as seen in Figure 6. Results of UCS test showed that at the age of 28 days, a noticeable increase in UCS was obtained from (1040 to 1156) kPa after the increase on CKC content from (3 to 6) %, however, UCS barley improved after CKC became (9%); recorded (1178) kPa. This is indicating that the best CKC percentage to improve UCS can be twice that of OPC used. This scenario has not happened in case of using MDP in which considerable reduction in UCS values from (912 to 858) kPa with the increased MDP content from (6 to 9) % at the same mentioned age 28 days. The obtained UCS test findings are consistent with those reported by Jafer, et al. [25]; Zainab, et al. [28] and Jafer, et al. [29].

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Table 7.
Unconfined compressive strength results.

Mix description	Unconfined Compressive Strength (UCS) kPa		
	Curing time \ days		
	3	7	28
Natural Soil (NS)	68	68	68
Soil + Cement (SC)	332	690	860
SC-3CK	436	764	1040
SC-6CK	573	855	1156
SC-9CK	566	865	1178
SC-3 MP	389	718	890
SC-6 MP	406	736	912
SC-9 MP	318	664	858

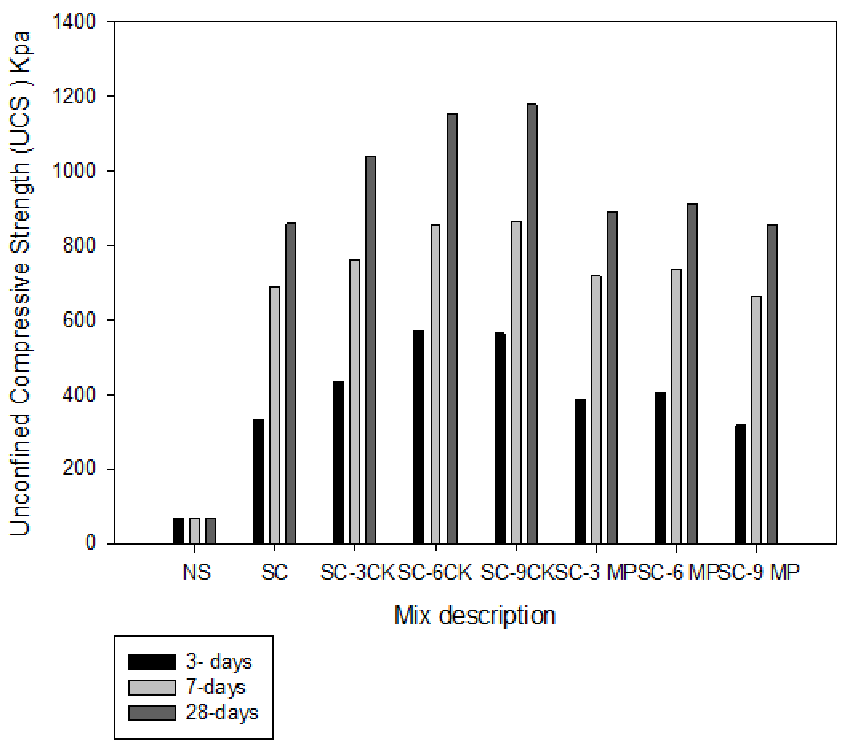

Figure 6.
UCS for different curing periods and different binders.

4. Conclusions

This article is devoted to investigate the performance of two different materials (CKC and MDP) as additive to cement-stabilized soil in terms of the improving of the soil geotechnical properties such as unconfined compressive strength, Atterberg limits, and compaction characteristics. Based on the obtained and presented results in previous section, the conclusion can be as follows:

1. MDD of the stabilized OMC rose whereas soil declined with the use of both CKC and MDP along with PC. However, the results revealed that compaction parameters were highly affected by CKC rather than the MDP.
2. The use of both CKC and MDP led to increases in both L.L. and P.L. of the stabilized soil, still, P.L. increased more than L.L. did, resulting in a reduction in I.P. for all binders. Moreover, CKC had

the best effect on Atterberg limits in which lowest value of I.P. (18) was obtained by using (9%) CKC compared with (22) for the soil with no treatment.

3. The UCS findings showed a considerable development in soil strength particularly in case of using CKC. UCS was improved by (17) times referring to UCS value of untreated soil following a 28-day healing period. Despite of that the application of MDP with PC increased UCS noticeably; the CKC exhibited much better strength improvement than MDP throughout all curing periods.
4. Finally, the results of this research work indicated that both CKC and MDP can be comfortably used in addition to PC to improve and enhance several geotechnical properties of fine-grained soil.
5. The use of CKC and MDP can be consider as an advantage in term of soil improvement as well as in the fixation of negative environmental impact of these materials.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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