Effects of LC3 on the unconfined compressive strength of clay soils

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Soil improvement aims to reduce permeability, plasticity, shrinkage/swelling potential and to increase strength and stiffness. Portland cement (PC) is frequently used in the geotechnical field as a chemical soil improvement material. Given the energy consumed and excess CO_2 produced in PC production, it is vital to reduce cement consumption to increase economic and ecological sustainability. Recently, researchers have been investigating the use of alternative materials with lower CO_2 emission and production cost compared to PC in ground improvement applications. In this study, the effect of using limestone calcined clay cement (LC3) and nano-$CaCO_3$ on the unconfined compressive strength of soils was investigated in accordance with ASTM D1633 Method B. This study reveals for the first time the synergistic effect of the LC3 system containing nanomaterials on the unconfined compressive strength of high-plasticity soils as an alternative to traditional Portland cement-based binders. First, a high plasticity clay soil (CH) sample was prepared by mixing 90% kaolin and 10% bentonite. Mixture containing 15% of PC was considered as a control mixture. Then LC3 (containing 53% PC, 2% gypsum, 30% metakaolin and 15% limestone powder) was formed as a second treated mixture. And, as a third mixture, 5% nano-$CaCO_3$ was substituted for 15% limestone powder in the second mixture. Unconfined compressive strength (UCS), Axial strain at failure, (ε_f), Undrained shear strength (c_u), Modulus of elasticity (E_{50}), Toughness values were measured after 1 and 7 days of curing. Compared to the soil specimens improved with PC, the 7-day UCS values of the LC3 and LC3 with nano-$CaCO_3$ mixtures are only 26.4% and 33.8% lower, respectively. Additionally, the highest E_{50} value was measured in the mixture containing LC3 at the end of the 1-day curing period. LC3 reduces CO_2 emissions by up to 40% compared to PC and the low cost provided by the global abundance of the clay and limestone in its content. It is thought that LC3 is a sustainable alternative in soil improvement studies.

1 Introduction

The strength and durability of the soil supporting structures such as buildings, bridges, roads, and pavements are of high importance. In this context, if the soil where the structures are to be built is unsuitable, it must be improved. When soil improvement processes, which fall within the field of geotechnical engineering, are carried out appropriately, potential damage to the structures are prevented. Thus, by ensuring that structures continue to serve for longer periods, economic sustainability is benefited.

Another issue where sustainability can be contributed to during soil improvement is performing these improvements by reducing the amount of Portland cement used. Portland cement is the most commonly used material in the improvement works of expansive soils [1]. This objective stems from the high use of raw materials, energy consumption, and CO_2 emissions in the production of Portland cement. Cement manufacturing is directly responsible for approximately 5% of artificial CO_2 emissions, with 0.8–1.1 tons of CO_2 released against each ton of cement production [2]. With the increase in population and industrialization, cement production continues to increase even further every year.

Researchers are developing more ecological and economical cements instead of Portland cement. At this point, the most important steps taken are the use of different types of natural pozzolans or the indirect procurement of pozzolans. Today, LC3, which can show properties close to Portland cement thanks to the chemical reactions of calcined clay and limestone, is a popular research topic in this regard. LC3 has attracted attention as it causes 30-40% less CO_2 emissions compared to Portland cement [3]. Another field that has increasingly become a centre of interest today is nanomaterials. Despite the small amounts used, nanomaterials can provide superior properties to materials. These superior properties can be listed as increasing the load-bearing capacity and providing flexibility [4].

In this study, the effect of LC3 and the nanomaterial on the early-age unconfined compressive strength of the soil was investigated. LC3 cement was obtained by using 53% PC, 2% gypsum, 30% metakaolin, and 15% limestone powder. While nano-$CaCO_3$ was used alone in similar studies conducted by researchers [5,6,7], in this study, it was used within the content of LC3 cement. Improving mixtures were prepared by using nano-$CaCO_3$ at a rate of 5% of the limestone powder used in the aforementioned cement mixture. The improving mixture was added to the soil at a rate of 15% of the soil sample. The early-age strength of LC3 is low, and high-plasticity clays have a high binder requirement. Therefore, a 15% ratio was used so that the effects of the improving mixtures could be interpreted more clearly. This study simulates the shallow soil stabilization of clayey soils.

Following the improvement, the efficiency of the treatment can be measured by performing unconfined compressive strength tests after the samples were cured for 1 and 7 days.

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2 Materials and methods

2.1 Materials

In this study, a soil sample was obtained by using 90% kaolin and 10% bentonite. According to the Unified Soil Classification System (USCS), this soil was classified as high plasticity clay (CH) [8]. CEM I 42.5 R cement, gypsum, metakaolin, limestone powder (calcite) ($CaCO_3$), and nano calcite (nano-$CaCO_3$) were used to prepare the improving mixtures.

2.2 Preparation of Mixture

The mixture ratios to be obtained by substituting the untreated soil sample with 15% of the improving mixtures were calculated and are listed in Table 1. PC-15%, LC3-15%, and LC3-NC-15% powder mixtures were obtained by mixing the materials in the ratios given in the table. During the mixture preparation phase, the dry powder materials were first mixed by hand using plastic gloves for 2 minutes to ensure initial uniformity. Subsequently, water was added at the previously determined Optimum Moisture Content (OMC), and the mixture was hand-kneaded for 4 minutes. In order to disintegrate any formed agglomerates, the soil was gently crushed with a mallet and then kept in sealed plastic covers for 5 minutes for moisture equilibration. Finally, the mixture was kneaded for an additional 2 minutes to achieve a homogeneous state.

2.3 Methods

The unconfined compressive strength was determined as per ASTM D1633 Method B [9]. UCS specimens were prepared at the Maximum Dry Density (MDD), and the mixture was placed in 3 equal layers into a mold with a diameter of 38 mm and a height of 76 mm, where each layer was compacted at the specified energy level (20 blows). The UCS test was conducted with a computer-controlled testing machine after curing the samples for 1 and 7 days. In order to prevent moisture loss, the specimens were airtightly sealed in plastic films immediately after preparation and maintained in this state until the testing stage. All experimental procedures and curing processes were conducted under controlled laboratory conditions at a laboratory temperature of 22±2°C. A 1%/min strain rate (0.76 mm/min) was performed on all stabilized and untreated samples.

3 Experimental result and evaluation

Failure images belonging to the UCS test conducted after curing the specimens for 1 and 7 days are shown in Figure 1 and Figure 2, respectively. Axial stress-axial strain graphs for all specimens are given in Figure 3. In Table 2, strength, deformation and toughness parameters of soil mixtures stabilized with different additives are presented. These parameters are obtained by taking the average of the repeated tests.

With the addition of the improving mixtures to the unstabilized soil, the UCS values of all mixtures increased. Compared to the unstabilized soil, the UCS values of PC-15%, LC3-15%, and LC3-NC-15% mixtures increased by 552.7%, 320.0%, and 212.7%, respectively, after 1 day of curing.

It was determined that the increase rates of the UCS values for PC-15%, LC3-15%, and LC3-NC-15% mixtures with the increase in curing time (from 1 day to 7 days) were 57.4%, 80.1%, and 117.4%, respectively. This situation stems from the fact that the hydration rate and early-age strength of LC3 are lower compared to PC but increase over time [10]. In a similar study, it was stated that the UCS values of specimens improved with LC3 increased more with the increase in curing period from 3 days to 28 days compared to specimens improved with Portland cement [3]. The strength increase of LC3 is attributed to the Calcium Aluminium Silicate Hydrate (CASH) and higher amount of ettringite in addition to the C-S-H and CH hydration products of PC. The development of the soil pore structure is associated with the formation of cementitious gels such as ettringite and CSH/CASH gel, which tend to fill pores and create a denser structure [3]. Furthermore, unlike Portland cement, in LC3, the calcium carbonate ($CaCO_3$) from limestone and the aluminate (A) from metakaolin combine to form carboaluminates, which lead to the formation of more stable AFt (ettringite phases) that ensure the filling of voids [11].

The increase rate of UCS values with the increase in curing time is highest for the LC3-NC-15% mixture. It has been stated that the strength increase provided by the addition of nano-$CaCO_3$ results from the nucleation and nano-filler functions [12].

The decrease in the axial strain value at failure (ε_f) observed with the addition of improving mixtures to the specimens indicates that the material exhibits a more brittle behavior. However, in the LC3-15% (7-day) mixture, the opposite was observed, and ductility was found to be maintained. The lowest ε_f value was observed in the LC3-15% mixture at the end of the 1-day curing period, while it was recorded in the PC-15% mixture at the end of the 7-day curing period.

The increase in the modulus of elasticity (E_{50}) observed with the addition of improving mixtures to the specimens reveals that the additives make the soil matrix more rigid and the resistance to elastic deformation increases. The highest E_{50} value was obtained in the LC3-15% mixture at the end of the 1-day curing period and, in the PC-15% mixture at the end of the 7-day curing period. The increase in the toughness value observed with the addition of improving mixtures to the specimens shows that the energy dissipation capacity of the material under dynamic loads or crack propagation increases. The highest toughness value was reached in the PC-15% mixture at the end of the 1-day curing period and 7-day curing period. Although the LC3-15% mixture exhibits a lower UCS compared to PC-15% at an early age (1 day), its provision of higher E_{50} values can be attributed to the fine grain structure of LC3 providing early physical rigidity by filling soil voids.

Table 1. Mixtures prepared within the scope of the study.

Mixture	Kaolin	Bentonite	Portland Cement	Gypsum	Metakaolin	Limestone ($CaCO_3$)	Nano $CaCO_3$
Untreated soil	90%	10%					
PC-15%	76.5%	8.5%	15%	-	-	-	-
LC3-15%	76.5%	8.5%	7.95%	0.3%	45%	2.25%	-
LC3-NC-15%	76.5%	8.5%	7.95%	0.3%	45%	2.1375%	0.1125%

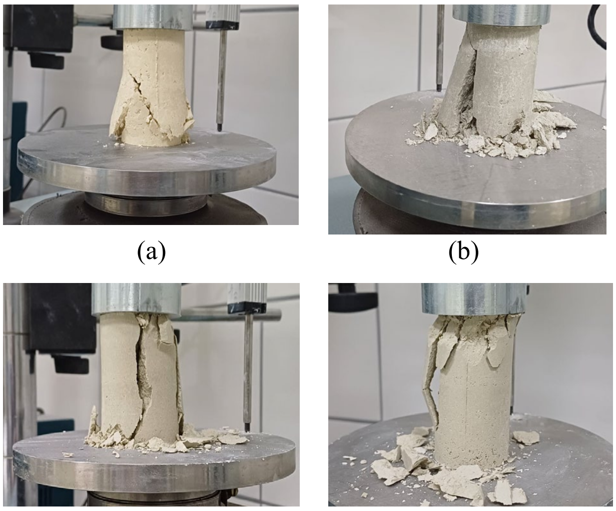

Figure 1. Failure patterns of the specimens after 1 day of curing in the UCS test: (a) Unstabilized Soil-1-day, (b) PC-15%-1 day,(c) LC3-15%-1 day, (d) LC3-NC-15%-1 day.

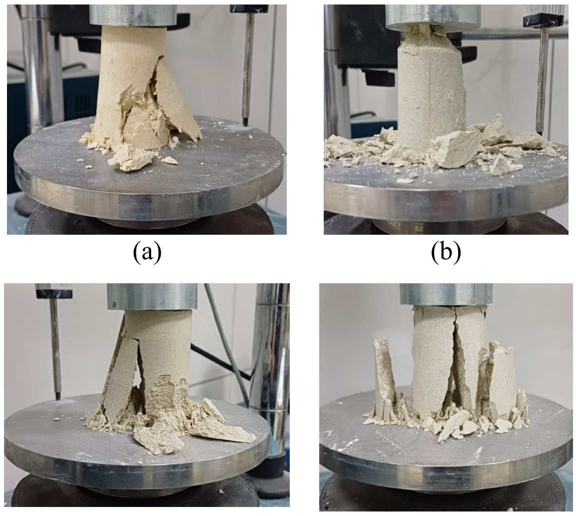

Figure 2. Failure patterns of the specimens after 7 days of curing in the UCS test: (a) Unstabilized Soil-7-day, (b) PC-15%-7-day, (c) LC3-15%-7-day, (d) LC3-NC-15%-7 day.

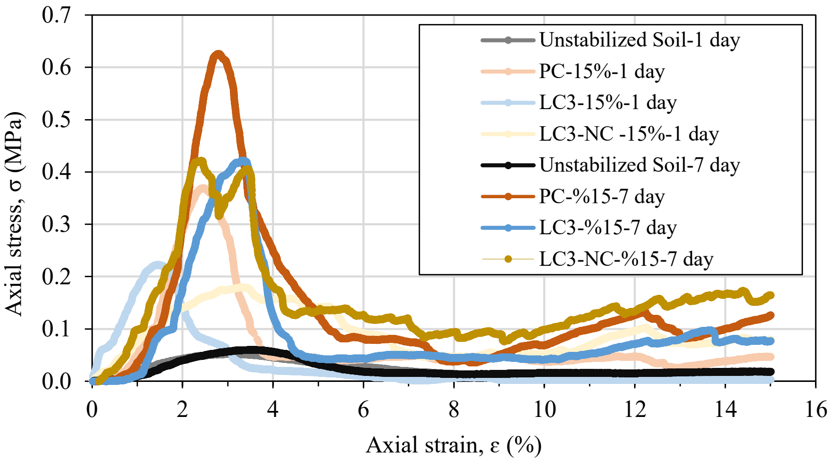

Figure 3. Axial stress-axial strain graphs of the specimens after 1 and 7 days of curing.

Table 2. Strength, deformation and toughness parameters of soil mixtures stabilized with different additives.

Curing duration	Mixture	UCS (MPa)	Axial strain at failure, ε_f (%)	Undrained shear strength, c_u (MPa)	Modulus of elasticity, E_{50} (MPa)	Toughness (mJ/mm^3)
1 day	Unstabilized Soil	0.055	2.793	0.028	0.022	2.72×10^{-4}
	PC-15%	0.359	2.229	0.180	0.123	6.89×10^{-4}
	LC3-15%	0.231	1.524	0.116	0.244	3.78×10^{-4}
	LC3-NC-15%	0.172	2.370	0.086	0.108	5.52×10^{-4}
7 day	Unstabilized Soil	0.057	3.490	0.028	0.017	2.78×10^{-4}
	PC-15%	0.565	2.530	0.282	0.174	11.6×10^{-4}
	LC3-15%	0.416	3.839	0.208	0.089	9.97×10^{-4}
	LC3-NC-15%	0.374	2.968	0.187	0.078	7.52×10^{-4}

4 Conclusion

Within the scope of this study, the UCS, Axial strain at failure, Modulus of elasticity and toughness of CH-class soil improved with Portland cement, LC3, and LC3 containing nano-$CaCO_3$ were compared. The findings obtained are listed below:

- The highest UCS value of the treated soil is obtained with Portland cement. However, soil improvement with LC3 also provided a high rate of potential.
- The mixture whose UCS values increased the most with the curing period from 1 day to 7 days was the mixture containing nano-$CaCO_3$. It is predicted that the effectiveness of the nanomaterial will be greater after 28 and 90 days of curing.
- The lowest axial strain at failure value (ε_f) and the highest E_{50} value were measured in the LC3-15% mixture at the end of the 1-day curing period, while the same trend observed in the PC-15% mixture when the curing period increased to 7 days.

Results show that soil stabilization with LC3 carries the potential to reduce Portland cement consumption and, accordingly, carbon emissions. Due to its low carbon emissions, LC3 cement offers a viable and efficient alternative to Portland cement for the more sustainable and environmentally friendly improvement of expansive soils.

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