# Effects of LC3 on the compaction and consistency properties of clay soils

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**Abstract.** In the geotechnical field, ordinary Portland cement (PC) is frequently used as a chemical soil stabilization material. Considering the energy spent in the production of PC and the excess $CO_2$ produced, it is vital to reduce cement consumption to increase sustainability. Researchers are investigating the use of alternative materials with lower $CO_2$ emissions and production costs compared to PC. One of the alternative materials is limestone calcined clay cement (LC3). This cement type contains 53% PC, 2% gypsum, 15% limestone powder ($CaCO_3$), and 30% metakaolin. The novelty of this research lies in the comparative evaluation of standard LC3 and LC3 modified with Nano-$CaCO_3$ to enhance the geotechnical properties of clayey soils. In this study, besides PC mixtures, different LC3 mixtures were obtained by replacing $CaCO_3$ with Nano-$CaCO_3$. These stabilizer mixtures were mixed with the clay soil sample at 5%, 10%, and 15% ratios. In order to investigate the soil stabilization effects, untreated soil and these 9 mixtures were subjected to Proctor tests after determining the Atterberg limits. Compared to the unstabilized soil, the maximum dry density (MDD) values increased by 4.24% with the addition of 15% PC. Similarly, the MDD values increased 2.32% with 15% LC3 mixture. Furthermore, 2.31% increment was observed with the addition of 15% LC3 containing Nano-$CaCO_3$ (LC3-NC). Moreover, the Atterberg test results indicate that, increasing the dosage of stabilizer decreased the liquid limit (LL) and plastic index (PI) values of the soil and increased the plastic limits (PL) for all mixtures.

## 1 Introduction

Currently, the most common method used to improve the bearing capacity of weak soils is chemical soil stabilization using cement. However, using the cement results in high $CO_2$ emissions, significant raw material consumption and intensive energy use. In this context, new binder materials are attracting increasing attention in environmental research to reduce cement use [1]. Recent research in this area focuses on limestone calcined clay cement (LC3), which is obtained by substituting calcined clay and limestone powder for a portion of the cement clinker [2–4]. Unlike Portland cement, LC3 cement produces carboaluminates as a result of reactions between calcined clay and limestone during hydration. LC3 cement has a lower early-age strength compared to ordinary Portland cement (PC), but this difference is getting closer in later-age strengths. Therefore, LC3 has the potential to be widely used as a greener soil stabilizer due to its ability to reduce greenhouse gas emissions by approximately 20-23% [2]. Furthermore, clay and limestone, which are the main components making up to 45% of LC3, are geographically widespread. Given that, the cost of clay is significantly lower in many regions, particularly in Africa, using LC3 instead of PC can reduce soil stabilization costs [5]. The number of studies on the application of LC3 in soil stabilization is insufficient, and more experimental research is needed in this area.

Overall, the application of LC3 in stabilizing clayey soils not only adds a new dimension to the field but also helps reduce carbon footprints by offering a sustainable and environmentally friendly alternative to traditional techniques. Estimates show that using LC3 instead of PC for the stabilized sub-base of a 1 km two-lane road can save approximately 350 GJ of thermal energy, 12,594 kWh of electrical energy, and 27,420 kg of $CO_2$ emissions [6]. Increased use of soil-based materials such as kaolin and calcite can further reduce energy consumption and $CO_2$ emissions [7]. In this study, LC3 and LC3 with nano-$CaCO_3$ were considered to investigate the effects on the consistency and compaction properties of the clayey soil. Nanomaterials significantly improve the strength properties of cementitious systems, even with small amounts used in the mixture. It has been reported that replacing 3% of cement with nano-$CaCO_3$ can increase early age strength of soil [8]. In another study focusing on the stabilization of clay subsoils was stated that the optimum dosage of nano-$CaCO_3$ is 1% [9]. It has been shown that nano-$CaCO_3$ has superior performance in soil improvement [8, 9]. These superior properties can be listed as increasing the load-bearing capacity and providing flexibility [10]. Furthermore, the addition of nano-$CaCO_3$ provides a strength increase through nucleation and nano-filler functions [11].

In this study, the Atterberg limits of high plasticity clay treated with PC, LC3 and LC3 containing nano-

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$CaCO_3$ (LC3-NC) were compared. High-plasticity clays have a high LC3 binder requirement. Therefore, 5%, 10%, and 15% ratios were used so that the effects of the improving mixtures could be interpreted more clearly. These ratios were determined by reviewing previous studies.

In a study conducted by Ashraf et al. [12], soil was stabilized with cement dosages ranging from 0% to 10%. The results indicated that after 28 days of curing, the strength increase was significantly pronounced up to an 8% utilization rate, beyond which the rate of strength gain slowed down. Durability tests also confirmed this dosage as optimal. Similarly, in an experimental study by Rehman et al. [13] on the stabilization of clayey soils, a 4% cement content was determined as the optimal ratio, as it provided the highest dry density and strength. In the present study, binder dosages of 5% and 10% were selected to align with these optimum ratios reported in the literature. Additionally, a higher dosage of 15% was incorporated to comparatively evaluate the effects of an elevated stabilizer content on the experimental outcomes. For example, researchers have conducted studies using fly ash in proportions of 10%-18% [14,15]. Note that this study simulates the shallow soil stabilization of clayey soils. Additionally, Proctor tests were carried out to determine the optimum moisture content (wopt) and maximum dry density (MDD) for each mixture.

Unlike previous studies in the literature, this research integrates nano-$CaCO_3$ into LC3 cement for use in soil stabilization. The aim of this study is to investigate the physical and chemical effects of PC, LC3, and nano $CaCO_3$-substituted LC3 stabilizing mixtures on the liquid limit, plastic limit, plasticity index, optimum moisture content, and maximum dry density properties of high plasticity clay (CH). The objective of this study contributes to advancing sustainability efforts within the field of geotechnical engineering.

## 2 Materials and methods

High plasticity clay (CH) soil sample was created according to the Unified Soil Classification System (USCS) by using 90% kaolin and 10% bentonite. 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. The amounts of materials used in the mixtures prepared within the scope of this study are presented in Table 1. Also, the specific gravity values of the materials are given in Table 1. The proportions of the materials in LC3 cement were selected based on the optimal proportions determined in the studies by Gonthier et al. [16].

During the mixture preparation phase, the dry powder materials were first dry blended manually for 2 minutes to ensure initial distribution. Firstly, the liquid limit and plastic limit values were determined by starting with a small amount of water and it increased incrementally. After adding water, the mixture was allowed to rest for 5 minutes to ensure homogenous water distribution within the clay, followed by re-mixing manually to achieve full homogeneity.

For the Proctor test, water was added at approximately the previously determined plastic limit amount, and the mixture was manually kneaded for 5 minutes. Experiments were performed by preparing a distinct mixture for each water content level.

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

| Materials (Specific gravity) | Untreated soil | PC-15% | LC3- 15% | LC3-NC-15% |
|---|---|---|---|---|
| Kaolin (2.65) | 90% | 76.5% | 76.5% | 76.5% |
| Bentonite (2.70) | 10% | 8.5% | 8.5% | 8.5% |
| PC (3.13) | - | 15% | 7.95% | 7.95% |
| Gypsum (2.40) | - | - | 0.3% | 0.3% |
| Metakaolin (2.56) | - | - | 45% | 45% |
| Limestone (2.93) | - | - | 2.25% | 2.1375% |
| Nano-$CaCO_3$ (2.93) | - | - | - | 0.1125% |

Atterberg limits were determined as per ASTM Standard D4318 [17]. This technique supports the Atterberg limits experiments using the Casagrande device, which measured the liquid limit by counting the number of blows needed to seal the groove created in the soil sample. The plastic limit was established by rolling soil samples into threads of approximately 3 mm in diameter until they commenced to crumble, adhering to the conventional approach. The plasticity index, which gives an indication of the soil's plasticity properties, is defined as the difference between the liquid limit and the plastic limit. The Proctor experiments were conducted as per ASTM Standard D698 and D558 [18,19]. A Proctor mold with a diameter of 105 mm and a height of 115 mm was used. A 2.5 kg rammer was dropped freely 25 times on each of the 3 layers to compact the soil sample at different moisture contents. All experimental procedures were conducted under controlled laboratory conditions at a laboratory temperature of 22±2°C.

## 3 Experimental results and evaluation

### 3.1 Experimental results

The first columns of Fig. 1 present the liquid limit, plastic limit and plastic index of uncured high plastic clay soil, respectively. Although the extent of change varied depending on the type of stabilizing mixture used, the addition of stabilizing mixtures to unstabilized

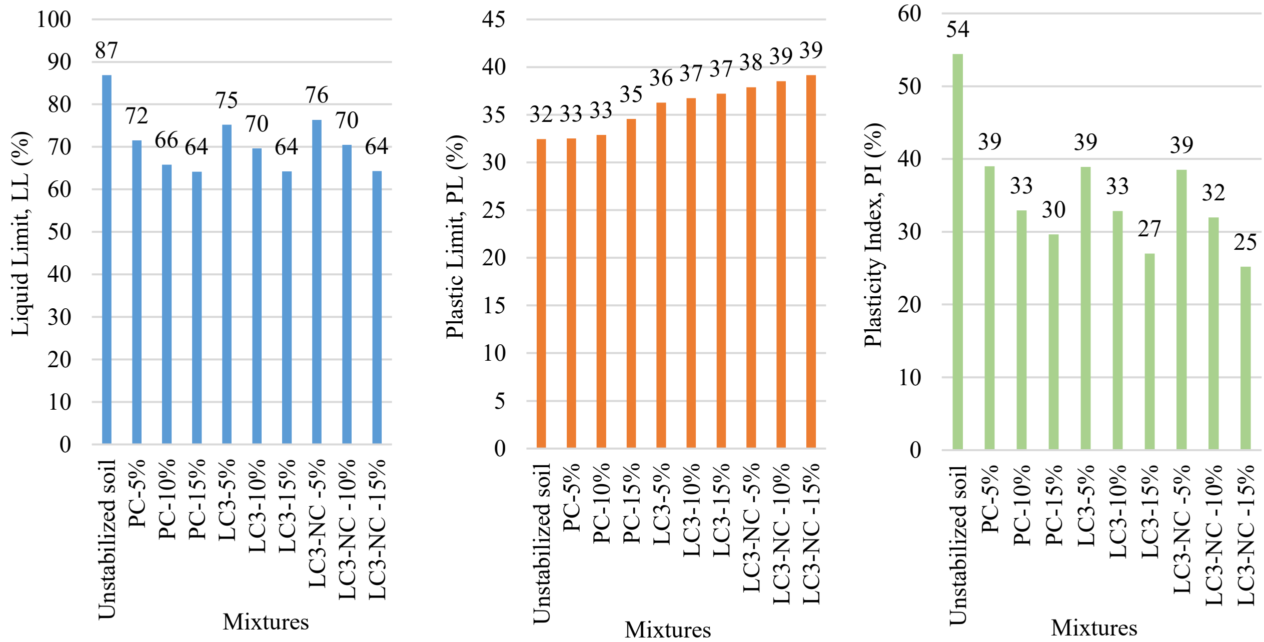


**Fig. 1.** (a) Liquid limit, (b) plastic limit, and (c) plasticity index values of mixtures.

soil caused a decrease in the liquid limit and plasticity index, and an increase in the plastic limit. Increasing the dosage of additives decreased the liquid limit (LL) and plastic index (PI) values of the soil and increased the plastic limits (PL). Thus, it was determined that all conditioner mixtures used transformed the untreated soil into a less swelling, more stable material. The mixture with the lowest plasticity index was found to be LC3-NC -15%. Except for the PC-5% blend, all improved soils transitioned from CH to MH classification (Fig. 2).

Figs. 3, 4, 5, and 6 show the proctor test results with the zero air voids curves of mixtures. Figs. 7 and 8 compare the results of the Proctor compaction test, showing the maximum dry density and optimum moisture content for each sample. From the figures, it is seen that with the addition of stabilizing mixtures to the unstabilized soil, maximum dry density values increased slightly.

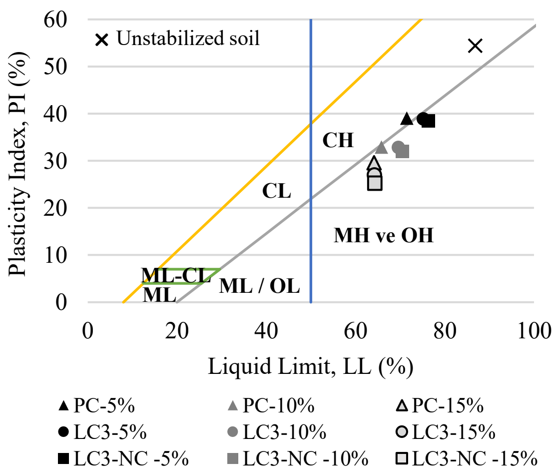


**Fig. 2.** Distribution of the study soils on the Casagrande Plasticity Chart.

### 3.2 Discussion

The change in these values is hypothesized to be primarily associated with the physical effects of cement particles than to their chemical effects, since the tests were carried out before the onset of hydration to isolate the effect of physical interactions between soil and added PC [20]. However, chemical effects such as accelerated ion exchange (cation exchange) might also play role. When cement is added to the soil, cation exchange (Ca2+) is expected to initiate in the first few seconds with the onset of hydration. Cement particles use the water in the soil for the reaction, which may lead to a decrease LL generally decreases as the free water decreases. Due to agglomeration (clumping of particles), the soil could become brittle earlier, potentially increasing PL. Therefore, PI value drops rapidly, and the soil tends to behave less clayey [21].

LC3 containing metakaolin and calcite appears to create a more complex effect compared to PC. Metakaolin is a very fine and pozzolanic material [22]. Due to its high surface area, it exhibits a tendency for higher initial water absorption than PC, therefore the amount of LL reduction tends to be lower compared to PC. Since calcite may provide a microfiller effect, LC3 potentially fills the voids more than PC. The plasticity index decreases somewhat more controllably compared to PC samples.

The 0.75% Nano-CaCO3 in the mixture is suggested to induce a nucleation effect. The liquid limit depends on the amount of free water between the particles. The relatively minor decrease in LL compared to other mixtures could be explained by the high surface area of nanomaterials, which potentially enables them to trap a significant amount of free water [23]. Since the plastic limit value is higher compared to other mixtures, the lowest PI values were observed in the mixture

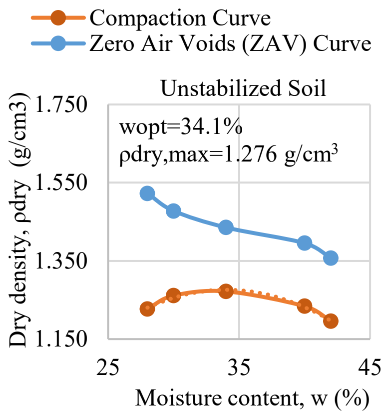


**Fig. 3.** Compaction and zero air voids curves of unstabilized soil.

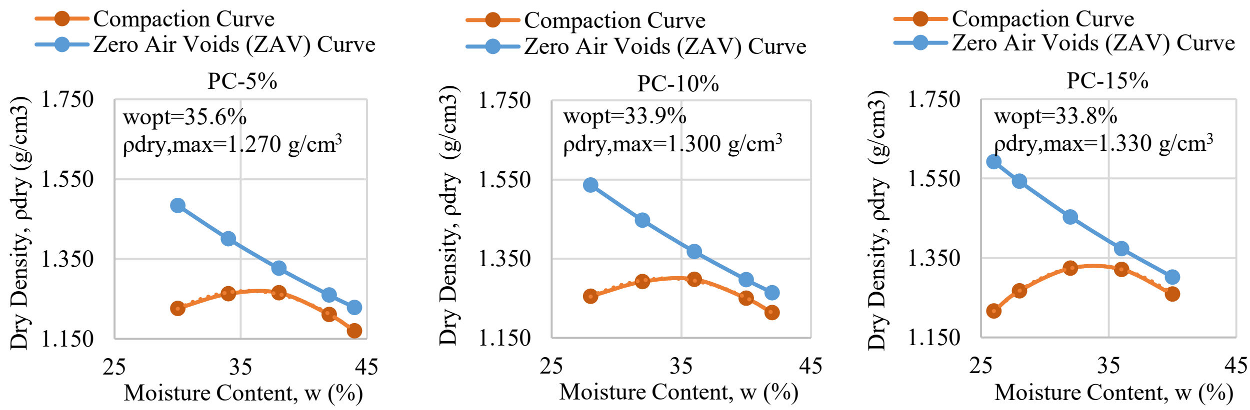


**Fig. 4.** Compaction and zero air voids curves of mixtures (a) PC-5%, (b) PC-10%, (c) PC-15%.

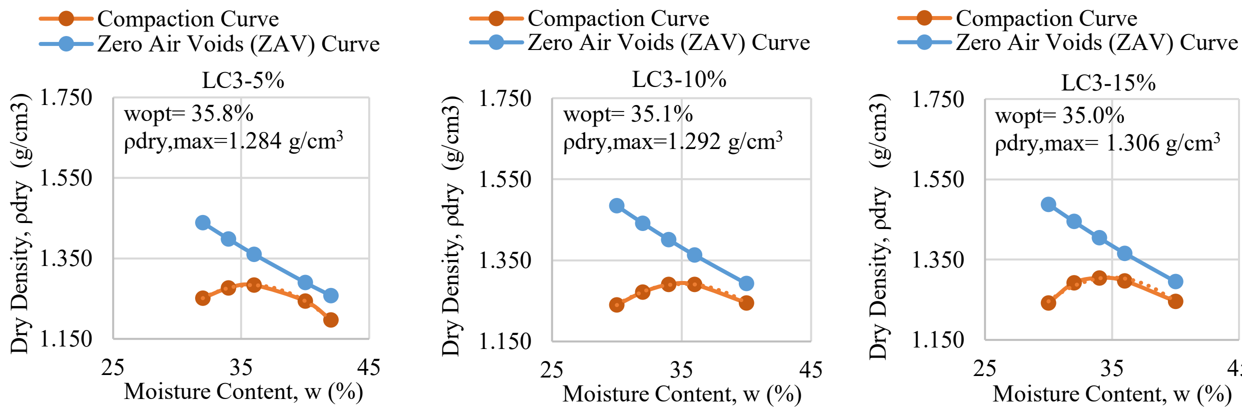


**Fig. 5.** Compaction and zero air voids curves of mixtures (a) LC3-5%, (b) LC3-10%, (c) LC3-15%.

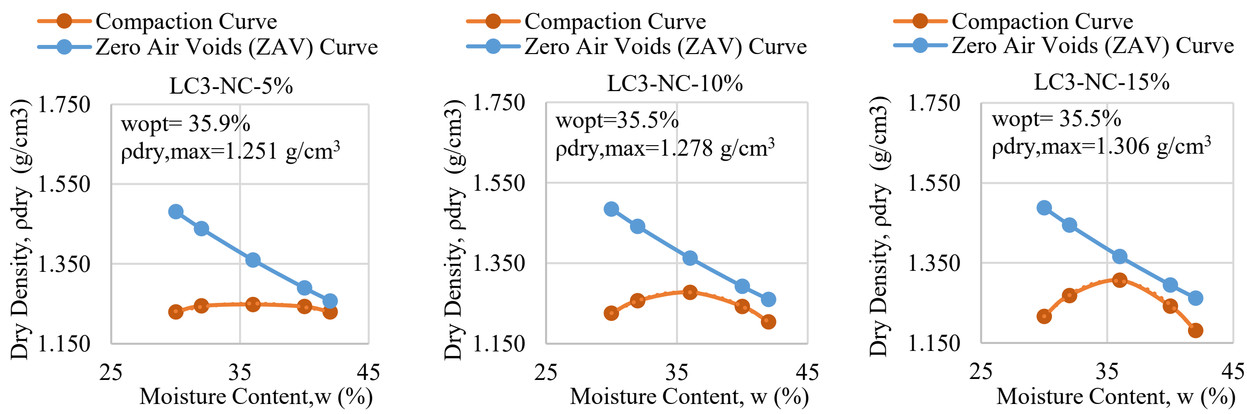


**Fig. 6.** Compaction and zero air voids curves of mixtures (a) LC3-NC-5%, (b) LC3-NC-10%, (c) LC3-NC-15%.

containing nano-CaCO3. Nanoparticles with high water retention capacity may cause the soil to behave "solid" earlier. Nano-CaCO3 is anticipated to increase the Ca2+ ion concentration in the environment [24], which could theoretically accelerate flocculation in clay soil compared to cement. In other words, the soil might coagulate faster with the help of nanoparticles, even if the C-S-H gel has not yet formed.

Kaolin and bentonite clay have inherently low compaction and hydrophilic capacity. The added stabilizing materials with higher specific gravity likely result in higher maximum dry density [25]. Moreover, PC mixtures potentially filled interparticle voids compared to other mixtures. In a study conducted by Marangu et al. [26], LC3 and PC stabilizing mixtures were mixed separately into the soil at ratios of 1%, 1.5%, and 2% (based on the dry weight of the soil). The researchers reported that when different cement dosages were added, the maximum dry unit weight of the soil increased, while the optimum moisture content decreased.

In the mixtures containing nano-calcite, a lower MDD value was observed compared to mixtures containing PC and LC3. Optimum moisture content values have varied. It has been observed that the stabilizing mixture containing nano-calcite leads to an increase in water demand. This could be attributed to the excellent water retention properties of nanomaterials. This behavior appears to be consistent with the well-known water retention properties of nanomaterials reported in literature [27].

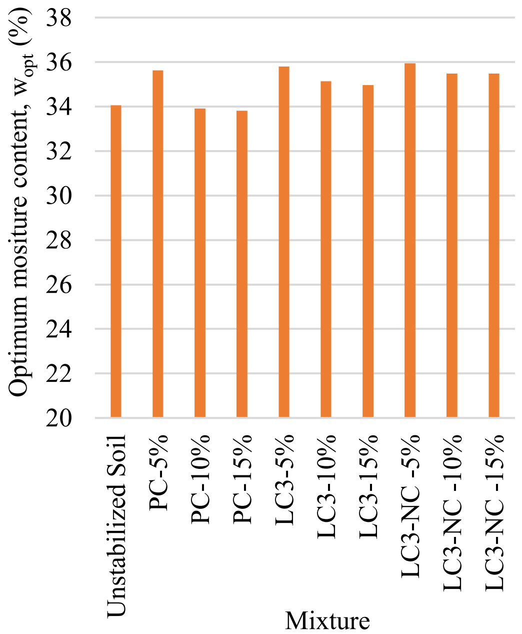


**Fig. 7.** Comparison of optimum moisture content values of mixtures.

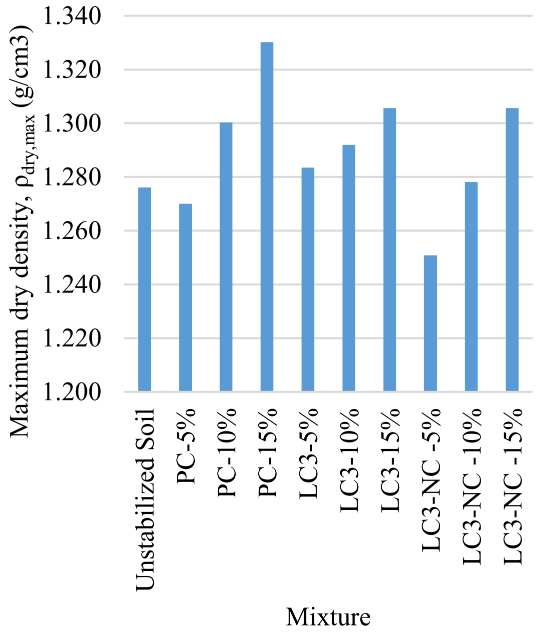


**Fig. 8.** Comparison of maximum dry density values of mixtures.

## 4 Conclusion

Within the scope of this study, the properties of high plastic clay were improved by using PC, LC3, and nano-$CaCO_3$-replaced LC3 cement. These mixtures were used for soil stabilization by replacing 5%, 10%, and 15% of the unstabilized soil (90% kaolin and 10% bentonite clay). The changes in liquid limit, plastic limit, and plasticity index were investigated using Atterberg test and optimum moisture content, maximum dry density values were obtained by Proctor test. The following results were obtained:

- The addition of stabilizing mixtures to unstabilized soil decreased the liquid limit and plasticity index for all cases. Therefore, soil classification changes from CH to MH.
- With the addition of stabilizing mixtures to unstabilized soil, maximum dry density values increased slightly for both cases. Although, the maximum dry density values of mixtures with 15% LC3 and LC3-NC combinations are just 1.8% lower compared to PC.

50% less clinker is used in the manufacturing of LC3, and the metakaolin and $CaCO_3$, are easier to find locally. Lower manufacturing costs, energy use, and $CO_2$ emissions are all directly impacted by this decrease in clinker content. LC3 shows promising preliminary potential as a suitable alternative for soil stabilization, as it enables higher efficiency with reduced cement content in the stabilization of weak soils.

This study was limited to Atterberg limits and Proctor tests. Future research should focus on the mechanical tests be performed after 7, 28, and 90 days of curing of the stabilizing mixtures. This will allow for the examination of not only the physical effects of the stabilizing mixtures but also their chemical effects during the hydration process.

All data, models, and code generated or used during the study appear in the submitted article.
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