Global NEST Journal, Vol 26, No X, pp 1-8

Pine cone ash stabilization of expansive soils

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Received: 09/09/2023, Accepted: 01/01/2024, Available online: 16/02/2024
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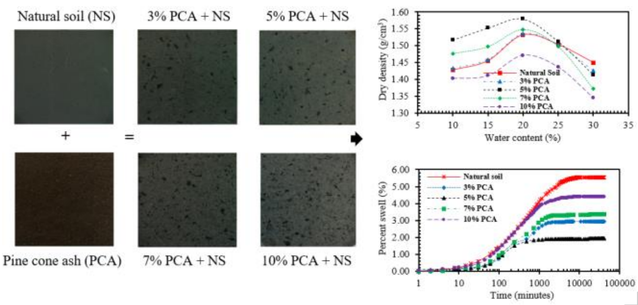
https://doi.org/10.30955/gnj.005378

Graphical abstract



Abstract

The use of appropriate waste materials to stabilize problematic soils, such as expansive soils that are responsible for geotechnical damage, is a common practice in geotechnical engineering. This study presents the use of pulverized ash from the combustion of pine cone (PC) waste as a stabilizing agent to improve the engineering properties of expansive soils. A series of laboratory tests were carried out to examine the effect of different percentages of pine cone ash (PCA) content (3%, 5%, 7%, and 10%) on the Atterberg limits, swelling potential (Sp), linear shrinkage, compressibility, and unconfined compressive strength (q_u) of naturally occurring swelling soils and the PC ash-treated soils. The results showed that PC ash contents of 5% and 7% contributed to a significant reduction in the swelling and shrinkage potential and an improvement in the coarsest texture, brittleness behavior, compaction properties, and compressive strength of the treated soils. Conversely, PC ash contents below 3% and above 7% showed minimal changes in the index and engineering properties of the PC ash-treated soils. In particular, the PC ash content of 5% resulted in optimal mitigation of the poor properties of the treated soils. The use of pine cone ash as a stabilizing agent represents a suitable and complementary subgrade soil material for expansive soils on which lightweight structures are built.

Keywords: compressive strength, expansive soils, pinecone ash, soil stabilization, swell potential, waste materials.

1. Introduction

Over the decades, numerous materials have been used to mitigate the poor properties of expansive soils that cause damage to various civil engineering structures due to their high-water adsorption capacity. Chemical additives such as cement, fly ash, lime, glass powder, gypsum, and fumed silica have been widely used for this remediation purpose (Abiodun and Nalbantoglu 2015; Mousavi 2017; Ta'negonbadi and Noorzad 2018; Barišić *et al*. 2019; Bumanis *et al*. 2020; Ikechukwu *et al*. 2021; Naveen *et al*. 2023; Niyomukiza *et al*. 2023; Otito 2023). In addition, low-cost agro-industrial wastes such as biomass, rice-corn husks, organic hulls, and quarry dust have been effectively used to mitigate the engineering properties of problematic soils (Yalley and Asiedu 2013, Jha and Sivapullaiah 2017; Onyelowe and Duc 2020; Thirukumaran *et al*. 2023). Other researchers used wastes such as coconut, leather, lime, and biomedical wastes; coffee husk, and mango seeds to improve the geotechnical properties of expansive soils (Jayasree *et al*. 2015; Atahu *et al*. 2019; Varaprasad *et al*. 2020; Galvín *et al*. 2021; Parihar and Gupta 2021; Singh and Gupta 2021; Tseganeh *et al*. 2021; Tamiru 2023).

It has been observed that the use of ash extracts or pulverized mass from the waste materials can alter the mineralogy and improve the index and engineering properties of a wide range of problematic soils (Sharma and Sivapullaiah 2017; Farah and Nalbantoglu 2019; Liang *et al*. 2020). Therefore, the use of readily available, low-cost waste materials offers significant economic potential for improving the engineering properties of expansive soils (Ramaji 2012; Maneli *et al*. 2016; Phetchuay *et al*. 2016; Yang *et al*. 2018; Aamir *et al*. 2019; Chen *et al*. 2021; Abdelkader *et al*. 2022; Yarbaşı *et al*. 2023).

However, comprehensive studies of various types of waste materials are essential to develop cost-effective techniques to mitigate the low strength and volume change properties of extensive soils (Ikeagwuani and Nwonu 2019; Soltani *et al*. 2020). The semi-arid climate of Northern Cyprus transforms saturated expansive soils in the wet season to unsaturated conditions during the prolonged dry season (Malekzadeh and Bilsel 2014; Öncü and Bilsel 2017).

The expansive behavior of these semi-arid soils creates serious problems when interacting with light engineering structures constructed on, in, or through them (Emeh and Igwe 2016; James and Pandian 2016; Cabrera *et al*. 2018). Changes in the volume and strength properties of expansive soils often result in damage to the foundation structures of lightly loaded structures such as buildings, highways, pavements, and underground utilities (Nelson and Miller 1997; Abbas *et al*. 2023). In addition, the periodic moisture fluctuations in the soil result in excessive heaving during the rainy season and shrinkage in the dry season, resulting in significant damage to light structures and increased annual repair costs (Nelson and Miller 1997; Abbas *et al*. 2023). Under these circumstances, the use of timely and cost-effective soil improvement techniques to stabilize the poor engineering properties of expansive soils is crucial, especially in lightweight structures. Although locally available, low-cost lime can be an attractive additive for reducing swelling, shrinkage, plasticity, and compressibility of expansive soils, as well as increasing shear strength (James and Pandian 2016; Abiodun and Nalbantoglu 2017; Öncü and Bilsel 2017), the presence of large amounts of soluble sulfates in expansive soils hinders the effective use of lime stabilization (Abiodun 2013; Celik and Nalbantoğlu 2013; Malekzadeh and Bilsel 2014). Some of the expansive soils in Cyprus contain highly soluble sulfates (Celik and Nalbantoglu 2013).

Therefore, this study focuses on the use of unique alternative, locally sourced and low-cost waste materials to stabilize the poor engineering properties of expansive soils. Specifically, this research investigates the use of PC ash obtained from pine cone (PC) waste to improve the volume change behavior and unconfined compressive strength properties of tropical expansive soils. Pine cones (PCs) are one of the most common agroforestry wastes in nature (Khalaf *et al*. 2023; Kovacsne *et al*. 2023), and they shed profusely from September to December, accumulating at the base of pine trees (Yang, *et al*. 2018; Stephen and Salaheldin 2020). Numerous studies have examined the biochemical, environmental, and nutritional benefits of pine cone (PC) materials (Balekoglu *et al*. 2020; Stephen and Salaheldin 2020). Previous research has demonstrated the potential of PC ash content as a source of humus for agricultural applications (Lan *et al*. 2021; Yadav *et al*. 2022; Wojewódzki *et al*. 2023). Furthermore, the utility of PC is well documented in various fields such as agrochemical, pharmaceutical and reinforcing fillers (Xu *et al*. 2012; Halil and Omer 2017; Sahin and Yalcin 2017).

However, there is a notable gap in published studies focusing on the use of PC ash to mitigate the poor engineering properties of expansive soils. To address this issue, the present study investigates the potential of ash extract from the collected PC waste materials as a cost-effective alternative for soil stabilization. The PC ash produced by the combustion of oven-dried PC waste at 250 °C is used to study its influence on the particle size distribution, Atterberg limits, linear shrinkage, swelling potential, compressibility properties and the unconfined compressive strength of PC-Ash treated soils to investigate different PC ash contents of 3%, 5%, 7% and 10% based on the dry weight of the unit.

2. Materials and methods

2.1. Expansive soil and pine cone

The expansive soil used in this study comes from the coastal region of the Mediterranean and was mined from a depth of 1.0 m. The natural soil exhibited high compressibility, high plasticity, and significant shrinkage and swelling potential. Table 1 contains the index properties of natural soil (NS) and pine cone ash (PCA).

Table 1. Physical and index properties of the natural soil and pine cone ash

Soil index properties	Quantities	
	Soil	PC ash
Clay size fraction, < 2 µm (%)[a]	61	24
Silt size fraction, 2–74 µm (%)[a]	36	76
Sand size fraction, > 74 µm (%)[a]	3	---
Specific gravity, Gs[b]	2.65	1.58
Maximum dry density, $\rho_{d(max)}$ (g/cm^3)[c]	1.53	---
Optimum moisture content, w_{opt} (%)[c]	21	---
Liquid limit, LL (%)[d]	59	---
Plastic limit, PL (%)[d]	30	---
Plasticity Index, PI (%)[d]	29	---
Linear shrinkage, Ll (%)[e]	21	---
USCS Classification[f]	CH (Unified Soil Classification System).	

[a] *According to ASTM (1998) D422*
[b] *According to ASTM (2006) D854*
[c] *According to ASTM (2007) D698*
[d] *According to ASTM (2000a) D4318*
[e] *According to BS 1377-2 (1990)*
[f] *According to ASTM (2000b) D2487-00*

PC waste was collected from the Eastern Mediterranean University campus during the summer season. The PC ash was obtained by burning PC waste in an oven at 250 °C for 48 hours. The granular mass of PC ash extract was then produced by pulverizing the oven-dried PC waste using a mechanical powder crusher machine (Malekzadeh and Bilsel 2014, Hidalgo *et al*. 2021). Notably, the PC ash extract contained a silt particle size fraction ranging from 2 µm to 74 µm, as shown in Figure 1.

Figure 1. The pine cone (PC) ash

2.2. Preparation of specimens

The treated soils with different PC ash contents were prepared with the optimal moisture content determined using the standard Proctor compaction test performed on the natural soil. To prevent moisture loss, the soil-ash admixtures were carefully stored in air-tight polyethylene bags and allowed to cure for 24 hours to ensure proper interaction between soil and PC ash. The addition of PC ash to the expansive soil included percentages of 3%, 5%, 7%, and 10% based on dry unit weight. Comprehensive evaluations of index (physical) properties, one-dimensional swelling, one-dimensional consolidation, and unconfined compression tests were conducted on the PC ash-treated soils and compared with those of the natural soil.

3. Experimental methods

This pilot study evaluated the effectiveness of PC ash in alleviating the poor properties of expansive soils. The index and engineering properties of the natural soil and PC ash-treated soils were determined and compared, showing significant improvements after treatment. To assess particle size distribution, compaction characteristics, plasticity, index, and linear shrinkage of the natural and PC ash-treated soils, experimental test methods were conducted in accordance with ASTM standards such as ASTM (1998) D422, ASTM (2007) D698, ASTM (2000a) D4318, and British standard, BS 1377-2 (1990). In addition, the swelling potential, compressibility properties, and unconfined compressive strength of these soils were examined using one-dimensional swelling, one-dimensional consolidation and unconfined compression tests conducted in accordance with ASTM standards ASTM (2008) D4546 and ASTM (2004) D2435 and ASTM (2004) D2166. The results show the potential of PC ash as an effective agent for improving the engineering properties of expansive soils.

4. Results and discussion

A series of laboratory tests were carried out to examine the effect of different PC ash content (3%, 5%, 7%, and 10%) on the Atterberg limits, swelling potential (Sp), linear shrinkage, compressibility properties, and unconfined compressive strength (q_u) of natural and the PC ash-treated soils.

4.1. Particle size distribution

Table 2 shows the particle size distribution of the natural soil and its response to different PC ash contents (3%, 5%, 7%, and 10%) in the PC ash-treated soils. The natural soil consists of 61% clay-sized particles and 36% silt-sized particles, while the PC ash consists of 24% clay-sized particles and 76% silt-sized particles.

Table 2. Particle sizes fraction of the natural and PC ash-treated soils

Properties	Natural soil	PC ash-treated soils			
		3% PC ash	5% PC ash	7% PC ash	10% PC ash
Clay (%)	61	51	43	40	37
Silt (%)	36	46	54	56	58
Sand (%)	3	3	3	4	5

The incorporation of PC ash into the treated soils resulted in reduced clay fines and an increase in silt particle size. These observations can be attributed to a pozzolanic reaction in the PC ash-treated soils, leading to the flocculation of clay particles and a shift towards a more granular soil texture and brittle behavior. Consequently, the PC ash-treated soils exhibited a friable, incohesive, and granular texture. At PC ash contents of 3%, 5%, 7%, and 10%, there was a significant reduction in clay fines by 16%, 30%, 35%, and 39%, respectively, accompanied by an increase in silt-sized particles 27%, 50%, 56%, and 61%, respectively. The significant reduction in fines of soils treated with various waste ash was reported by Noaman *et al.* (2022), Zagvozda *et al.* (2022), and Sai Pradeep and Mayakrishnan (2023).

4.2. Compaction characteristics

Figure 2 shows the compaction curves and illustrates the maximum dry density (MDD) and optimum water content (OMC) for both natural and PC ash-treated soils with different PC ash contents of 3%, 5%, 7%, and 10%. Table 1 shows the MDD and OMC values of the natural soil, which were found to be 1.53 g/cm^3 and 21%, respectively.

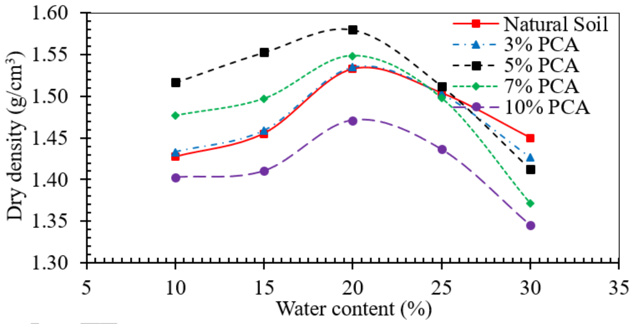


Figure 2. OMCs and MDDs of natural and PC ash-treated soils

The initial dry density values of PC ash-treated soils with 3% and 5% PC ash content were significantly higher, while the value at 7% PC ash content was slightly higher than the OMC. The PC ash-treated soil with 5% PC ash content had the highest MDD value, while the MDD value of the PC ash-treated soil with 3% PC ash content was equal to that of the natural soil. However, the MDD values for PC ash-treated soils with PC ash contents above 7% fell below the MDD value of the natural soil, indicating that increased moisture content according to the MDD values weakened the particle binding strength of the soils treated with PC ash. The highest MDD value and increased OMC values in the PC ash-treated soil with a PC ash content of 5% can be attributed to a very good bond between the natural soil and the PC ash particles, which filled the voids in the natural soil and resulted in an increase in the MDD values. In contrast, the PC ash-treated soil with a PC ash content of 10% had significantly lower initial and final MDD values than the MDD value of the natural soil, probably due to the higher percentage of the PC ash content with lower specific gravity. As mentioned earlier, the optimal PC ash content required to fill the pore voids between the particles is 5%. The percentage above this value does not contribute to the MDD value. Similar trends were observed in the studies reported by Nath *et al.* (2018), Ekinci and Aydin (2020), Sefene (2021), and Munirwan *et al.* (2023).

4.3. Atterberg limits

Figure 3 shows the comparison of plasticity index (PI) values between the natural soil and the PC ash-treated soils with different PC ash contents. Incorporation of pine cone ash (PCA) in proportions of 3%, 5%, 7%, and 10% into the treated soils resulted in a reduction in the plasticity index and a change in plasticity behavior. The PI values of the treated soils showed a significant decrease in PC ash contents of 5% and 7%.

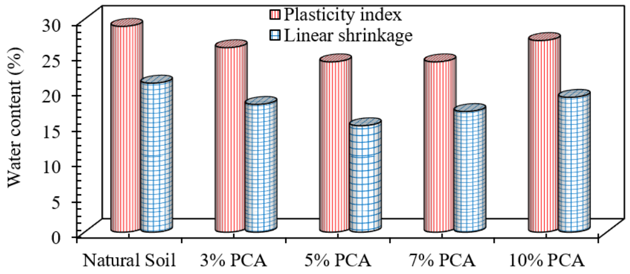


Figure 3. PI and LS values of natural and PC ash-treated soils

Notably, the treated soil with a PC ash content of 5% showed the most significant reduction in PI, as the PC ash promoted better flocculation and aggregation resulting in a decrease in fine and coarser texture. Conversely, the treated soils with PC ash contents below 5% or above 7% experienced the least reduction in their PI values. These specific PC ash contents did not result in changes in the PC ash-treated soils. The PI decreased by 17% in the treated soils with 5% and 7% PC ash contents, respectively, while the PI decreased by 11% and 9% in the treated soils with 3% and 10% PC ash contents, respectively. The results obtained from the plasticity index values are consistent with those obtained from the MDD and OMC values. Furthermore, similar trends in the use of other waste ash reduced the liquid limit, plastic limit, and plasticity index of natural clay soils in studies by Aparna (2022), Patel and Hetal (2022), Zagvozda *et al.* (2022), Nadia *et al.* (2023), and Tang *et al.* (2023).

4.4. Linear shrinkage

The linear shrinkage (LS) of the natural soil and PC ash-treated soils at different PC ash contents was evaluated and the test results obtained are shown in Figure 3. The results showed a reduction in LS of 14%, 29%, 19%, and 10% for PCA contents of 3%, 5%, 7%, and 10%, respectively. Notably, the soils treated with 5% and 7% PC ash content showed a significant reduction in LS values. Other recent studies (Melese 2022; Sai Predeep and Mayakrishnan 2023; Gomes and Holanda 2023) reported an identical significant reduction in linear shrinkage of the treated soils with different waste ash. The decrease in LS values observed in this study is consistent with the trends observed in the MDD and PI values of the PC ash-treated soils, indicating changes in soil properties as a result of PC ash treatment.

4.5. One-dimensional swell

Figure 4 shows the swelling potentials (SPs) as a function of the time-log and shows a comparison between the natural soil and the PC ash-treated soils with different PC ash percentages. Table 3 provides a summary of the SPs, primary swelling rates, and secondary swelling rates for both the natural and PC ash-treated soils. The high SP that the natural soil exhibits indicates its highly expansive nature.

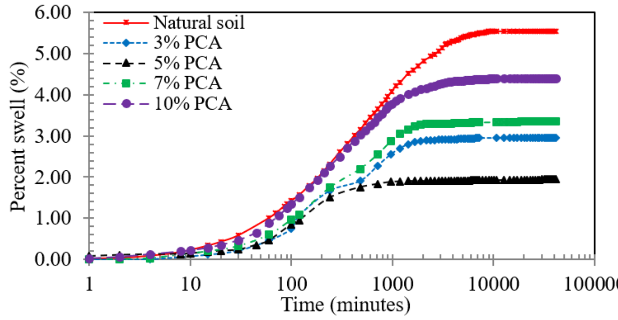


Figure 4. One-dimensional swelling potential curves of natural and PC ash-treated soils

Table 3. One-dimensional swell test results of natural and PC ash-treated soils

Properties	Natural soils	3%	5%	7%	10%
Swell potential, SP (%)	5.56	2.95	1.90	3.31	4.44
Primary swell slope ratio	0.24	0.12	0.07	0.14	0.20
Secondary swell slope ratio	0.06	0.01	0.007	0.01	0.02

In contrast, the PC ash-treated soils with PC ash contents of 3% and 7% showed almost similar significant reductions in their primary and secondary SPs. Specifically, the treated soil containing 5% PC ash demonstrated the most significant reduction in primary and secondary SPs, while the 10% PC ash-treated soil showed the least reduction compared to the other PC ash-treated soils. The most significant decrease in SPs occurred in soils treated with 5% PC ash. This observation in this study agrees with Mohamed *et al.* 2022 when different proportions of dry-weight proportions of rice husk powder were applied to treated soils and significantly reduced the swelling potential of the treated soils. The SP results of the treated soils in this present study were consistent with the results obtained for the maximum dry density (MDD), plasticity index (PI), and linear shrinkage (LI) of the PC ash-treated soils at different PC ash contents. The results obtained in this study are consistent with the study of Karthik *et al.* 2022 using fly ash in different proportions to stabilize expansive soils. The optimal effect was achieved at 20% fly ash, the specific gravity, MDD, and q_u were significantly increased and Sp and PI of the treated expansive soils were significantly reduced.

4.6. One-dimensional consolidation

One-dimensional consolidation tests using an oedometer were conducted to examine the compressibility characteristics of both the natural and PC ash-treated soils. Figure 5 shows the void ratio versus log pressure (*e*-log σ') curves, illustrating the behavior of the natural soil and treated soils with different PC ash additions. Table 4 provides a comprehensive summary of compression index (C_c), expansion index (C_r), preconsolidation pressure (σ_p), and swelling pressure (Sp) values for both natural and PC ash-treated soils. The incorporation of PC ash resulted in a reduction in the compressibility characteristics of the treated soils, mainly due to the reduction in the plasticity of the treated soils. The use of PC ash facilitated aggregation and cementation within the clay fines, which contributed to significant changes in plasticity and thus a reduction in the compressibility behavior of the treated soils. The drastic reduction in compressibility characteristics found in this study is consistent with the results reported in studies conducted by Sharo *et al.* (2022) and Salih *et al.* (2023). A notable trend was observed wherein a decrease in C_c, C_r, and Sp was accompanied by an increase in σ_p for PC ash additions of 3%, 5%, 7%, and 10%, respectively. As shown in Table 4, there was a significant reduction in Sp by 44%, 50%, 31%, and 24% and a reduction in C_c by 8%, 32%, 41%, and 32% for PC ash contents of 3%, 5%, 7%, and 10%, respectively. Furthermore, the C_r values of PC ash-treated soils decreased by 19%, 30%, 30%, and 50%, with PC ash additions of 3%, 5%, 7%, and 10%, respectively. The preconsolidation pressure (σ_p) was determined from the e versus log σ' curve using the conventional method of Casagrande (Casagrande, 1936; Ural and Küçüker 2021).

Table 4. Compressibility characteristics of natural and PC ash-treated soils

Properties	Natural soils	3%	5%	7%	10%
Compression index (C_c)	0.37	0.34	0.25	0.22	0.25
Expansion index (C_r)	0.11	0.089	0.077	0.077	0.055
Preconsolidation pressure, (σ_p) (kN/m^2)	60	80	95	85	65
Swell pressure, Sp (kN/m^2)	98	55	49	68	75

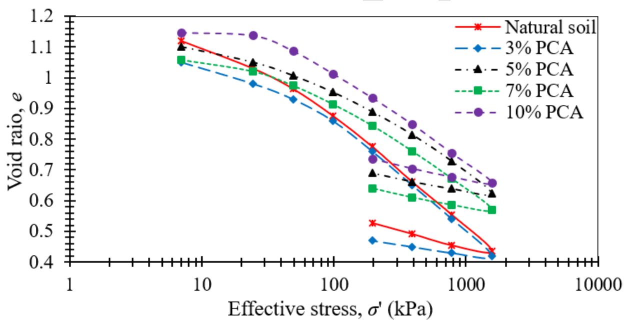


Figure 5. One-dimensional consolidation curves of natural and PC ash-treated soils.

Comparing the compression curves in Figure 5 with the values reported in Table 4 revealed an increase in σ_p values. Specifically, the σ_p of PC ash-treated soils increased by 33%, 58%, 42%, and 8% with the additions of 3%, 5%, 7%, and 10% PC ash, respectively. Among the different PC ash contents, the PC ash content of 5% resulted in the most significant reduction in the compressibility characteristics of the treated soils compared to the natural soil. These results were consistent with the results obtained for the swelling potential values of the PC ash-treated soils at different PC ash contents, as also shown in Figure 4 and Table 3.

4.7. Unconfined compression test

The unconfined compression test was conducted on both natural and PC ash-treated soils with PC ash contents of 3%, 5%, 7%, and 10%. The relationships between axial stress and the axial strain for these soils are shown in Figure 6. The natural soil had the lowest strains, ε values, and ductile behavior. Conversely, the PC ash-treated soils with 3% PC ash additives experienced failure at a lower strain value than the natural soil, indicating less ductile behavior. In contrast, the PC ash-treated soils with 5% and 7% PC ash contents showed failures at high strain values, suggesting brittle behavior. Notably, the PC ash-treated soils with PC ash content of 5% and 7% showed a significant increase in unconfined compressive stress, q_u values at failure, indicating high strength and stiffness behaviors.

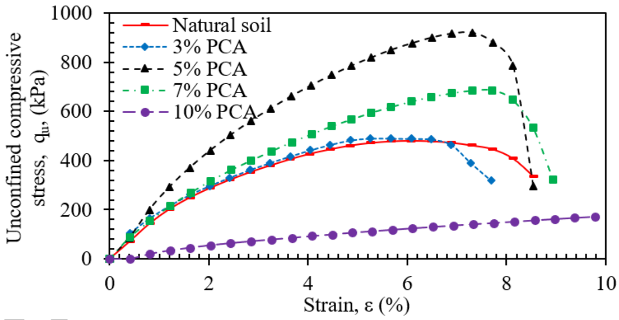


Figure 6. Axial stress versus axial strain curves of natural and PC ash-treated soils

On the other hand, the PC ash-treated soils with 3% and 10% PC ash additives produced unconfined compressive strength, q_u values lower than soils treated with 5% and 7% PC ash. At the same time, the unconfined compressive strength, q_u value of the soil treated with 10% PC ash was lower than the value obtained in the natural soil. Figure 6 also shows the relationship of unconfined compressive strength, q_u at different PC ash contents, and shows that PC ash content of 5% gives the highest compressive strength compared to other PC ash contents, which also increased 85% more than the value obtained in the untreated soil. The significant improvement in the unconfined compressive strength, q_u of the soils treated with PC ash is consistent with the results in the study by Hasan *et al.* 2016 with different proportions of bagasse ash and slaked lime. It was observed that the soil treated with 25% bagasse ash gave an optimal q_u result that was 3.2 times (around 80%) higher than the untreated sample. This improvement in the q_u value of PC ash-treated soils is promising and shows that PC ash can be effectively used to improve expansive soils with low compressive strength. This increase in strength shows that PC ash can be effectively used both to improve the swelling soil and to improve the swelling potential.

5. Conclusions

This study involved a comprehensive series of laboratory tests to investigate the potential and effects of pine cone ash as an admixture to improve the physical and engineering properties of expansive soils. The main conclusions from the analysis of the test results are as follows:

- The incorporation of PC ash significantly reduced the clay fines content in the treated soils at different PC ash contents, while simultaneously increasing the proportion of silt-sized particles, resulting in a more granular texture and brittle behavior.
- The compaction characteristics, indicated by maximum dry density (MDD) and optimum moisture content (OMC), were changed for specific percentages of PC ash content. The maximum MDD value was achieved in the treated soils with 5% PC ash content.
- The reduction in plasticity index (PI) and linear shrinkage (LS) of the treated soils were consistent with changes in particle size of the PC ash-treated soils. At PC ash contents of 5% and 7%, the PI decreased by 17%. Likewise, the PI was reduced by 11% and 9% at PC ash contents of 3% and 10%, respectively. Linear shrinkage (LS) decreased significantly at a PC ash content of 5% and showed the largest reduction. Subsequently, PC ash contents of 3% and 7% also led to significant LS reductions. Conversely, the lowest reduction in LS was observed at a PC ash content of 10%.
- One-dimensional swelling tests revealed significant swelling potential (SP) reductions of 47%, 66%, 41%, and 20% for PC ash contents of 3%, 5%, 7%, and 10%, respectively. At different PC ash contents, both primary and secondary SPs decreased significantly compared to the natural soil, further supporting the influence of PC ash on particle size changes.
- The results obtained from one-dimensional consolidation tests showed significant reductions in the compression index, expansion index, and swelling pressure of the PC ash-treated soils compared to the natural soil. In contrast, the test results showed a significant increase in the preconsolidation pressure values of the PC ash-treated soils compared to the natural soil. In particular, the incorporation of 5% PC ash content showed remarkable improvements in the compressibility characteristics of the PC ash-treated soil.
- The results of the unconfined compression test results showed that the addition of 3% PC ash gave an unconfined compressive strength, q_u similar to that of the natural soil, while a PC ash content of 7% increased the q_u by 29%. PC ash content of 10% resulted in a 75% reduction in q_u. Conversely, with the addition of 5% PC ash, a doubling of q_u was observed, indicating a remarkable improvement in unconfined compressive strength with more brittle behavior.
- These results explore the potential utility of PC ash as a beneficial admixture to mitigate the weak engineering properties of expansive soils. The results show that the use of PC ash is a promising alternative and additive for improving expansive soils and preventing environmental pollution.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data supporting the results of this study are available in the supporting information for this article.

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