

Influence of eggshell powder on the unconfined compressive strength and compressibility behavior of clay soil

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Abstract

In this study, the influence of eggshell powder on soil strength and compressibility behavior was investigated using unconfined compressive strength and oedometer tests. Soil specimens were prepared with different eggshell powder contents and tested after 7 and 28 days of curing. Eggshell powder produced a significant difference in soil behavior based on dosage. At appropriate contents, eggshell powder improved strength and decreased compressibility through filling voids, packing particles more effectively, and transferring stress within the soil matrix. However, excessive eggshell powder content led to lower strength due to disturbance of the soil skeleton and reduction in interparticle friction. At 10% eggshell powder, the maximum dry density increased from 1.656 to 1.683 g/cm³ while the optimum moisture content from 18% to 16%. The 7-day compressive strength increased about 28.4%, and compressibility decreased by approximately 7% as the final void ratio decreased from 0.45 to 0.42. Overall, eggshell powder acted mainly as a microstructural modifier rather than a strong cementing agent, and its effectiveness depended on the optimum content. The study confirms that eggshell powder is a promising sustainable physical soil modifier additive for improving selected soil engineering properties of clay soil.

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1. Introduction

Clayey soils are at risk of structural instability due to significant volume changes and resultant differential settlement [1]. In recent years, escalating environmental concerns have driven the use of waste-derived materials as a sustainable alternative to conventional construction materials. Geotechnical researchers and engineers alike have focused extensively on integrating these waste products into soil stabilization processes to enhance physical and mechanical soil properties. Beyond enhancing selected physical and mechanical soil properties, this approach may provide a dual advantage by reducing the environmental burden associated with waste disposal and by offering a potentially low-cost alternative to conventional manufactured stabilizers [2]. Other studies have also explored sustainable and alternative treatment approaches for improving the strength, durability, and geotechnical behavior of problematic soils. [3–5]. Among these materials, eggshell powder (ESP) has emerged as a promising option due to its chemical similarity to lime and its high calcium-based content. Eggshells are commonly classified as food or agricultural waste, yet they are rich in calcium carbonate (CaCO₃) [6], typically in the range of about 94% [7], which gives

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them significant potential for improving soil properties such as cohesion, plasticity, swelling behavior, and shear strength [1, 8]. The use of eggshell powder (ESP) and other sustainable stabilizing materials to improve engineering properties of clayey soil has been studied in several works. Diana et al. first studied this in 2017, which focused on the use of ESP to stabilize Kuttanad clay (a weak subgrade clay soil). Results showed that 12% ESP added significantly improved soil strength and reduced swelling behavior. Also, the stabilized soil possessed engineering properties similar to those obtainable with 4% lime stabilization, indicating that ESP may be considered a more viable, low-cost, environmentally friendly stabilizer for subgrade applications [9].

Adnan et al. (2024) also investigated ESP as a partial use replacement to lime for soil stabilization. The effect of different percentages of ESP (0.5% to 2%) on soil behavior were explored. The experiment found that the overall engineering aspects were better when the treated soil was compared with the untreated soil. Using ESP, the researchers estimated that the amount of lime could be replaced with ESP to increase soil compactness and strength while providing greater protection against environmental challenges and construction costs of traditional stabilizers [10].

More recently, a new study, Investigating Stabilization of Expansive Soils Using Eggshell Powder as an Eco-Friendly Additive, has also been conducted to study the stability of expansive clay soils using ESP contents ranging from 2.5% to 10%. It was found that shrinkage behavior reduced substantially and maximum dry density increased as the ESP content increased. The optimum ESP percentage was found to be approximately 7.5%, showing significant improvement in stabilizing the soil and making it suitable for engineering applications. The advances were ascribed to cementitious compounds produced from the reactions between the calcium compounds in the eggshell powder and silica in the clay soil [11].

The selection of eggshell powder in this study is justified by its availability, low cost, calcium-rich composition, and lower environmental burden compared with conventional stabilizers such as cement and lime. Although cement and lime are widely used and effective soil stabilizers, their production is associated with raw-material extraction, high-temperature processing, energy consumption, and CO₂ emissions [12]. Cement production alone has been reported to contribute approximately 7–8% of global CO₂ emissions, which has encouraged the search for low-carbon and waste-derived alternatives in geotechnical engineering [13]. In this context, eggshell powder is an abundant food and poultry waste generated from domestic, restaurant, hatchery, and poultry sources, and its reuse can reduce disposal problems while providing a locally available calcium-based additive [14]. Previous studies have shown that ESP can improve selected engineering properties of clayey soils, including compaction behavior, plasticity, UCS, and swelling response, although the optimum content varies depending on soil type, particle size, curing condition, and whether ESP is used alone or with other binders [12, 13]. Unlike calcined eggshell ash or eggshell-derived lime, untreated ESP does not require thermal conversion, thereby avoiding additional energy demand and calcination-related emissions. In comparison with conventional lime and cement, untreated ESP requires no high-temperature calcination, which reduces the thermal energy demand and process-related CO₂ emissions. However, a quantitative life-cycle or carbon-footprint assessment was not possible in this study. Therefore, ESP was selected in this study as a sustainable and low-cost soil modifier to evaluate whether untreated eggshell waste can improve the engineering behavior of clay soil without prior thermal treatment.

Although several studies have investigated eggshell-based materials in soil stabilization, the novelty of the present work lies in the direct use of untreated eggshell powder as a standalone soil modifier for CL clay without calcination, chemical activation, or combination with conventional binders. Previous studies commonly examined ESP as a partial replacement for lime, or used eggshell ash, eggshell-derived lime, or ESP in combination with lime, cement, quarry dust, plastic waste, or other additives [1, 7, 9–10]. In addition, many available studies focused mainly on expansive soils, subgrade improvement, swelling reduction, CBR, or strength enhancement [9, 11, 17]. Therefore, the present study contributes by evaluating untreated ESP alone at different contents and by linking its effects on compaction behavior, unconfined compressive strength, one-dimensional compressibility, and SEM-based microstructural features. This integrated approach

allows the role of untreated ESP to be interpreted not only in terms of strength change, but also in terms of particle packing, void filling, interparticle contact, and compressibility reduction.

Accordingly, this study aims to investigate the influence of untreated ESP contents of 0, 5, 10, 15, and 20% on the compaction characteristics, unconfined compressive strength, one-dimensional compressibility behavior, and microstructure of CL clay, and to identify the optimum ESP content for improving the soil response.

2. Materials

2.1 Clayey Soil

The clay soil was collected from an agricultural area in Babylon Governorate, Iraq. The physical and engineering properties of the natural soil were determined through standard laboratory tests as shown in Table 1. The soil is classified as CL-Lean clay based on the Unified Soil Classification System (USCS). The grain-size distribution for clayey soil (shown in Fig.1) was obtained by combining sieve analysis for the coarser fraction with hydrometer analysis according to ASTM D7928 for the fine-grained fraction.

Table 1. Physical properties of the soil

Property	Unit	Value	Standard
Specific gravity G_s	-	2.71	ASTM D854
Classification (USCS)	-	CL-Lean clay	ASTM D2487
Sand	%	7	-
Silt & Clay	%	93	-
Liquid limit	%	31	ASTM D4318
Plastic limit	%	21	ASTM D4318

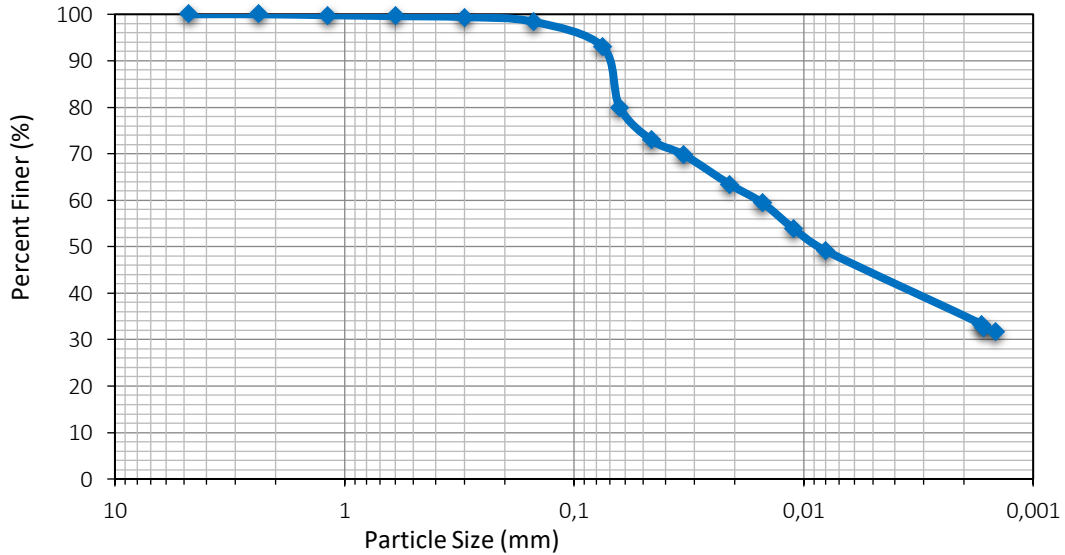


Fig. 1. The grain size distribution for clayey soil

2.2 Eggshell Powder (ESP)

The eggshell samples were obtained from a local poultry hatchery project. Figure 2 shows the eggshell preparation process. The collected shells underwent a rigorous cleaning process, followed by air-drying at ambient temperature. Subsequently, the inner membrane was removed and the dried shells were pulverized using a mechanical grinder to achieve the desired consistency. To control the particle size of the additive, the ground eggshell powder was sieved through a No. 40 sieve with an opening size of 425 μm , and only the passing fraction was used in preparing the soil-ESP mixtures. The grain-size distribution of eggshell powder is shown in Fig.3.



Fig. 2. The eggshell preparation

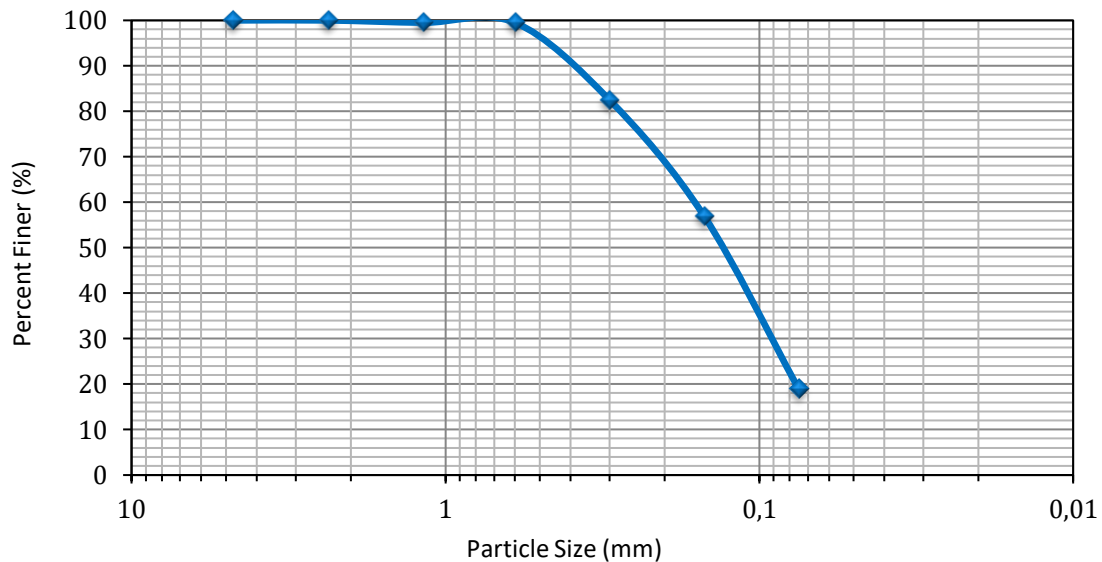


Fig. 3. The grain size distribution of eggshell powder

3. Methodology

After determining the basic properties of clayey soil, the soil was treated with varying percentages of eggshell powder (0, 5, 10, 15, 20) % by dry weight of soil. The ESP contents were selected based on the dosage ranges reported in previous eggshell-based soil stabilization studies [9, 11, 12]. The selected range was designed to include the untreated reference soil, low-to-moderate ESP contents comparable to previous studies, and higher contents to examine whether excessive untreated ESP could further improve the soil response or disturb the clay matrix. Therefore, these percentages were used to evaluate the dosage-dependent behavior of CL clay and to identify the most effective ESP content among the tested mixtures.



Fig. 4. UCS samples preparing and testing process

Standard Proctor tests were first conducted for untreated and ESP-treated mixtures in accordance with ASTM D698 to determine the maximum dry density (MDD) corresponding to the optimum moisture content (OMC). Based on these results the unconfined compressive strength UCS test specimens were prepared at their respective compaction condition. UCS tests were conducted

according to ASTM D2166/D2166M. The cylindrical specimens had a diameter of 38 mm and a height of 76 mm. For each ESP ratio, six samples were prepared: three at a curing time of 7 days and three at a curing period of 28 days as shown in Fig. 4. The specimens were then tested under axial compression, and the corresponding stress–strain curves were obtained. The specimens were loaded at a constant displacement rate of 1.27 mm/min, corresponding to an axial strain rate of approximately 1.67%/min, until failure.

4. Results and Discussions

4.1 Compaction Characteristics

At moderate ESP content, the partial void filling and better particle arrangement promote the density of soil structure during compaction, and help to account for this improvement. Above this level, however, MDD decreased slightly to approximately 1.68 g/cm³ at 15% ESP and to almost 1.66 g/cm³ at 20% ESP, indicating reductions of approximately 0.2% and 1.4% respectively compared to the maximum value at 10% ESP. The excessive ESP reduced compaction efficiency by disturbing the continuity of the clay matrix. It barely changed at 5% ESP, but decreased from around 18.0% for the untreated soil to about 16.2% at 10% ESP i.e., a decrease of about 10%. This reduction indicates that, with an ESP content in the moderate range, increased gradation and densification in packing can also reduce the quantity of water during the compaction phase of good lubrication effect. At higher ESP contents, additional water was needed to enhance particle lubrication, workability, and rearrangement during compaction. Furthermore, different irregular structure and surface texture of ESP particles could explain the increased water requirement when contents were high. In general, compaction results indicated that a 10% ESP dosage was the optimum content due to its maximum dry density and minimum optimum moisture content; however, with higher dosages the compaction efficiency will decrease while the water requirement will increase. The variations in maximum dry density and optimum moisture content with ESP content are shown in Fig. 5.

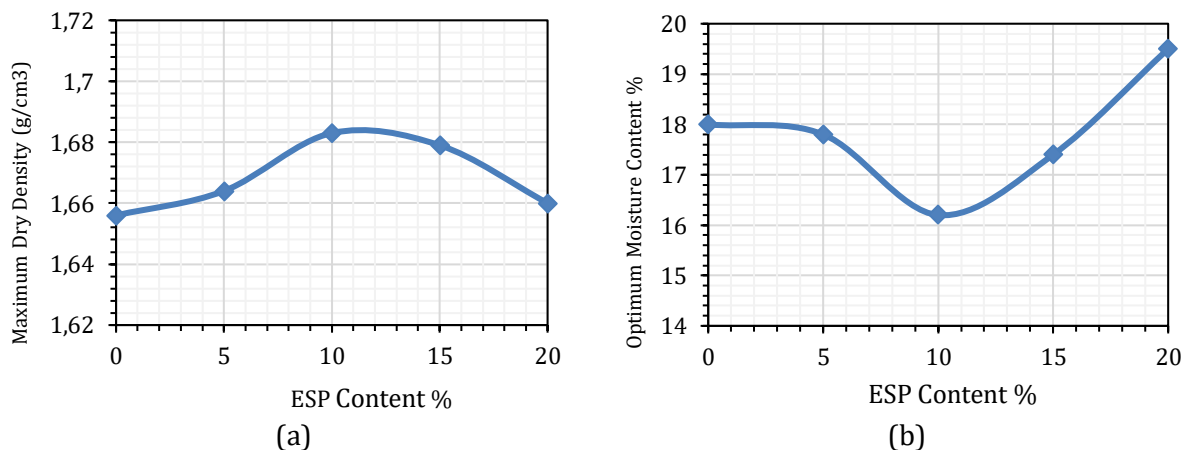


Fig. 5. (a) Maximum dry density with % ESP; (b) Optimum Moisture content with % ESP

The compaction behavior indicates that the role of untreated ESP is mainly physical rather than strongly cementitious. At low to moderate contents, ESP particles can occupy part of the inter-aggregate voids and improve the packing arrangement of the clay matrix. This explains the increase in MDD up to 10% ESP and the corresponding reduction in OMC.

The reduction in water demand at this dosage suggests that a denser and more efficient particle arrangement was achieved during compaction. Previous studies on eggshell-based soil additives also reported that improvement is strongly dependent on additive content and that optimum performance occurs only within a specific dosage range [13, 15]. At higher ESP contents, particularly 15% and 20%, the excess powder likely disturbed the continuity of the fine clay matrix and increased the heterogeneity of the compacted structure. Therefore, more water was required to lubricate the particles and improve workability, while the dry density decreased because the mixture became less efficiently packed.

4.2 Unconfined Compressive Strength (UCS)

Table 2 summarizes the mean UCS values and standard deviations of the replicate specimens at each ESP content and curing period. Fig. 6 shows an example stress-strain curve. Among all the ESP-treated mixtures, the 10% ESP mixture had the highest mean UCS, while the standard deviation values indicate the variability among the replicate specimens.

Table 2. Mean UCS values and standard deviation for different ESP contents and curing periods.

ESP (%)	7 days Mean $\pm$ SD (kPa)	28 days Mean $\pm$ SD (kPa)
5	99.15 $\pm$ 38.82	137.20 $\pm$ 5.23
10	275.00 $\pm$ 51.48	156.10 $\pm$ 5.37
15	152.85 $\pm$ 9.40	150.20 $\pm$ 14.85
20	133.10 $\pm$ 13.86	114.65 $\pm$ 2.05

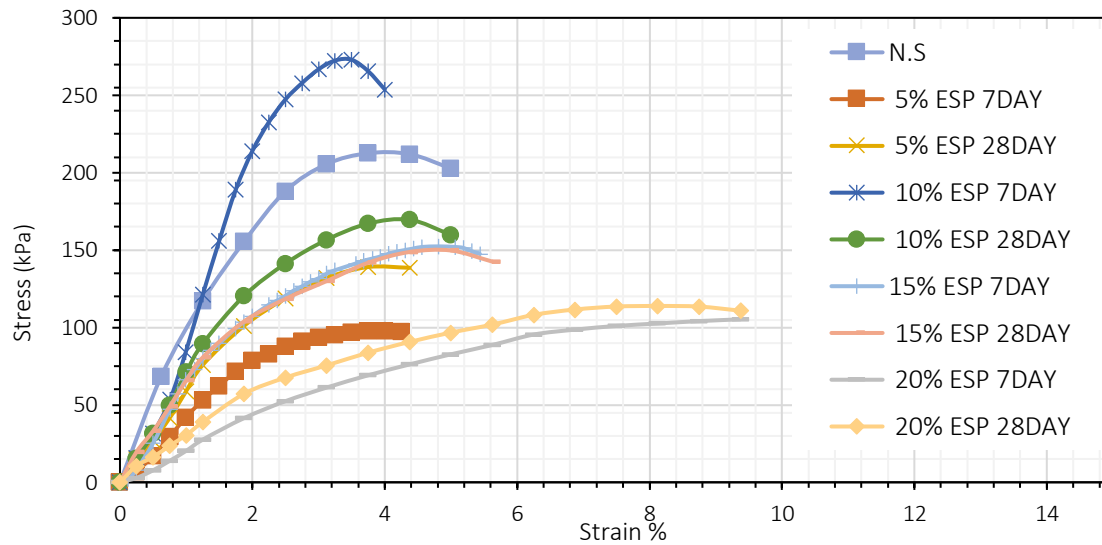


Fig. 6. Stress-strain results for treated and untreated clay soil with ESP

The results show that the mechanical response was strongly affected by both ESP content and curing period. The untreated clay soil reached a peak stress of 212.56 kPa and was used as the reference condition. Among the treated specimens, the 10% ESP mixture at 7 days showed the highest peak stress of 272.93 kPa, representing an increase of about 28.4% compared with the untreated soil. This improvement suggests that, at this dosage, ESP contributed to better particle packing, partial filling of interparticle voids, and improved contact between clay aggregates, which enhanced stress transfer during axial loading. However, this improvement was not sustained with longer curing time or higher ESP contents.

At 10% ESP, the peak stress was reduced from 272.93 kPa at 7 days to 169.57 kPa at 28 days. The decrease in UCS at 28 days could be due to moisture redistribution and shrinkage-induced micro cracking during curing, as well as specimen variability. Since these were not directly monitored, they are likely explanations rather than confirmed mechanisms. Since the ESP was untreated and not thermally activated in this study, its effect is considered mainly a physical modification of the soil fabric. However, limited chemical interactions cannot be confirmed or excluded because chemical and mineralogical analyses were not performed. At 5% ESP, the strength was lower than that of the untreated soil, suggesting that the dosage was insufficient to form an effective load-transfer structure. At 15% and 20% ESP, the reduction in strength may be attributed to excessive powder content, increased heterogeneity, disturbance of the clay matrix, and the formation of weak contact zones. Similar dosage-dependent behavior has been reported in previous ESP-based stabilization studies, where improvement occurred only within an optimum range and excessive additive content did not necessarily lead to further strength gain [12, 14, 16].

Overall, the UCS results indicate that 10% ESP was the most effective content among the tested mixtures for short-term strength enhancement, while higher contents reduced the mechanical efficiency of the soil-ESP matrix. Therefore, untreated ESP should be considered a physical soil modifier with limited dosage-dependent strength improvement rather than a conventional cementing stabilizer similar to lime or cement.

4.2.1 Undrained Cohesion

The undrained cohesion (C_u) was estimated from the unconfined compressive strength results as half of the peak UCS value, and its variation with ESP content is shown in Fig. 7. The results show that the effect of ESP on C_u was dosage-dependent and not linear. C_u was reduced sharply at 5% ESP and then increased and reached the maximum value at 10% ESP in 7 days. This could be explained by better particle packing and partial void filling, and better interparticle contact in the soil-ESP matrix. However, further increases in ESP content to 15% and 20% led to a reduction in C_u , which implies that ESP disturbed the continuity of the clay matrix and caused weak contact zones.

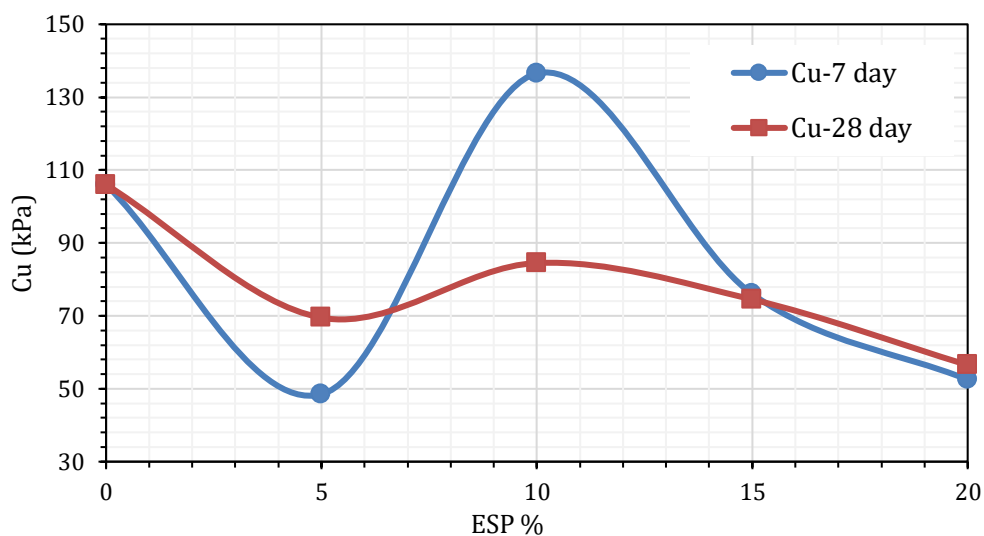


Fig. 7. Variation of C_u with ESP content

For the 28-day curing period, the difference in C_u was less pronounced. The lowest value was found at 5% ESP, and the highest value was also found at 10% ESP; the difference decreased slowly as ESP content was increased. Overall, 10% ESP was found to be the most effective content among the mixtures tested. However, the curing effect was not uniform across the mixtures, and untreated ESP was more of a physical soil additive than a cementitious stabilizer.

4.3 Consolidation Test

Figure 8 indicates that the addition of eggshell powder (ESP) significantly altered the one-dimensional compression behavior of the clay soil, and that the response was strongly dependent on ESP content. On the main loading branch, the void ratio decreased with increasing vertical pressure for all mixtures, which is consistent with progressive collapse of the clay fabric under confined compression. However, the rate and magnitude of this decrease varied with dosage. The untreated soil (N.S) showed a void ratio of about 0.64 at the lower stress level and decreased to nearly 0.45 at the highest applied pressure. With 5% ESP, the final void ratio was slightly lower, around 0.44–0.45, corresponding to a marginal reduction of about 1–2% relative to the untreated soil, indicating only a limited improvement in compressibility. The loading path for the oedometer was from 50 to 800 kPa and the unloading path was from 800 to 50 kPa. For this study, we focused on the comparison of void ratio between the untreated and ESP-treated soils.

The most favorable response was obtained at 10% ESP, where the final void ratio decreased to approximately 0.42, representing a reduction of nearly 7% compared with the natural soil and about 4–6% compared with the 5% and 15% mixtures. This suggests that 10% ESP produced the

densest structure under loading and therefore the greatest resistance to volumetric compression. At 15% ESP, the final void ratio remained around 0.43–0.44, corresponding to a reduction of about 2–4% relative to the untreated specimen, which indicates that the beneficial effect was still present but weaker than at 10% ESP. In contrast, the 20% ESP mixture had the least favorable results with a final void ratio of approximately 0.47, which is 3–4% greater than that of the untreated soil and 11–12% greater than the 10% mixture. This shows that the excessive ESP content does not decrease the compressibility of the soil but rather increases it. Mechanically, this improvement could be explained by better particle arrangement, partial filling of inter-aggregate voids and a denser fabric (i.e. that hindered deformation under load), as observed at moderate contents (10% ESP in particular).

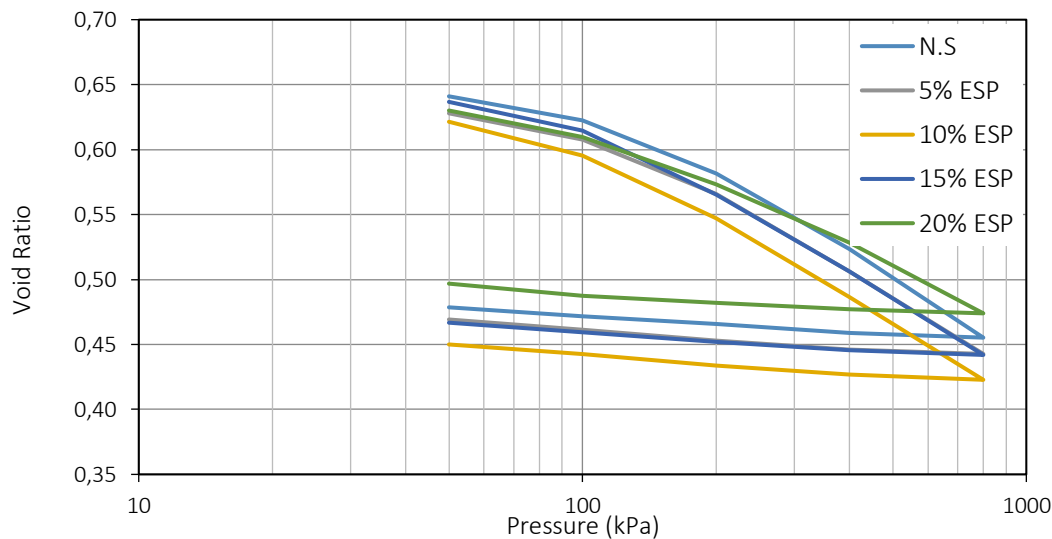


Fig. 8. Loading-unloading void ratio response at different ESP contents

However, with higher ESP content, the presence of particles was presumed to disturb the fine clay matrix continuity, decrease the structural uniformity, and result in weaker contact zones and thus lower stress transfer and the larger void ratio left in the soil during compression. In general, 10% ESP produced the lowest void-ratio response and the densest soil structure and higher ESP contents had less favorable overall deformation behavior. The compressibility behavior obtained confirms eggshell powder is largely a microstructural modifier and not a cementing agent for the whole process, in that its effectiveness is related to volume filling to maintain the granular skeleton.

The consolidation results are consistent with the compaction and UCS observations. The lower final void ratio at 10% ESP suggests that this content produced a denser and more stable soil fabric under one-dimensional loading. This improvement can be explained by partial filling of inter-aggregate pores and rearrangement of clay particles into a more compact structure. As a result, the treated soil at the optimum ESP content showed greater resistance to volume reduction under vertical stress. However, the higher void ratio observed at 20% ESP indicates that excessive powder content did not further improve compressibility.

Instead, it likely increased fabric disturbance and reduced the efficiency of particle packing, leaving a more open and compressible structure. This interpretation agrees with previous studies indicating that eggshell-based additives are effective only up to an optimum content, beyond which additional powder may not provide further improvement because the soil structure becomes less uniform and the available void-filling or bonding contribution becomes limited [13, 15, 16]. The SEM observations support this interpretation: the 10% ESP mixture showed a denser and more homogeneous matrix with fewer visible pores, while the 5% and 15% mixtures showed less efficient particle arrangement and weaker interparticle contact. Therefore, the combined macro-scale and microstructural results indicate that the optimum ESP content is controlled by the balance between void filling and soil-fabric disturbance.

The compression index (C_c) is between 0.165 and 0.210 and the swell index (C_s) is between 0.019 and 0.023 for the studied mixtures. The values are relatively small in comparison with the

compressibility indices of the mixtures and the main comparison in this study was based on the measured void-ratio response.

4.4 SEM Analysis

The microstructure of the clay soil after being treated with eggshell powder was studied using SEM. Image comparison of particle arrangement, pore distribution, and the degree of interparticle bonding could provide microstructural evidence for the observed changes in compressibility and strength behavior. SEM images in Fig. 9 showed that with 5% ESP, little improvement in the microstructure was obtained, because the soil matrix presented noticeable pores and loosely packed clay aggregates. The microstructure was denser and more homogeneous at 10% ESP, with fewer voids and improved particle arrangement, indicating that the soil fabric modification was more beneficial. However, in the 15% ESP images, excessive agglomeration and less uniformity were observed, indicating that the increase in ESP content disturbed the continuity of the clay matrix and created weaker interparticle contact zones. Hence, the SEM observations showed that the best microstructural improvement occurred when the ESP was 10%, while 15% seemed to be excessive. The physical modification mechanism proposed is partial void filling by ESP particles, better particle packing and better interparticle contact at moderate ESP contents. ESP disrupts the continuity of the clay matrix, resulting in a less uniform structure and reduced mechanical performance.

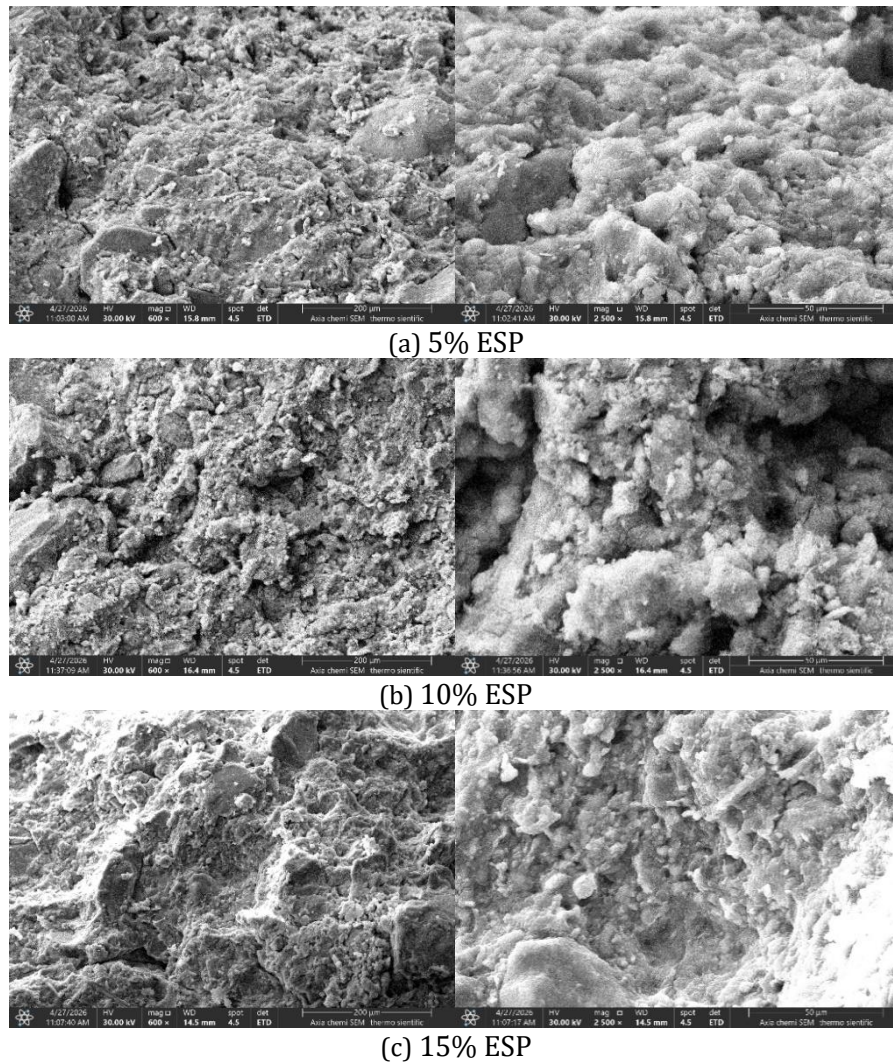


Fig. 9. SEM for clayey soil with ESP after 28 days

SEM observations indicate a predominantly physical modification mechanism, yet without XRD, XRF, or FTIR analysis it is not clear whether any specific reaction product is formed. Although this work focused on the untreated ESP, thermal activation through calcination can convert CaCO_3 -rich

eggshell into more reactive CaO (quicklime) which can improve its chemical stabilization potential. However, this requires additional energy and is a different treatment route from the low-processing ESP studied here [20].

5. Conclusions

- Under the investigated conditions, untreated ESP behaved predominantly as a physical and microstructural soil modifier. However, limited chemical interactions cannot be confirmed or excluded because chemical and mineralogical analyses were not performed.
- The overall response of the tested soil indicates that 10% ESP was the most appropriate content among the mixtures because it provided the best combination of densification, structural continuity, and resistance to volumetric deformation. The maximum dry density increased from 1.656 to 1.683 g/cm³, the optimum moisture content decreased from 18% to 16.2%, and the final void ratio decreased from about 0.45 to 0.42. The 10% ESP mixture also showed the highest short-term UCS response among the treated mixtures.
- The improvement at moderate ESP content was mainly due to the partial void filling, better particle packing, and better interparticle contact. The higher ESP contents in comparison, especially 20%, reduced the efficiency of the soil-ESP matrix due to the excessive powder intrusion and damage to the clay structure. The consolidation results also showed a few differences in calculated compression and swell indices among the tested mixtures, and the main improvement was seen in void ratio response.
- SEM observations confirmed the macro-scale results by showing a denser and more homogeneous microstructure at 10% ESP, with fewer pores and improved particle arrangement compared to the 5% and 15% mixtures. These results support the interpretation that untreated ESP predominantly modifies soil fabric under these conditions, although only limited chemical contributions can be excluded without chemical and mineralogical analysis.
- The present results are limited to CL clay and the maximum curing period is 28 days. Future investigations should consider longer curing periods, other soil types, finer ESP fractions, XRD/XRF/FTIR and pH monitoring, durability and leaching tests, use of small amounts of reactive binders and life cycle assessment to further assess long-term engineering and environmental performance.

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