International Journal of Design & Nature and Ecodynamics
Vol. 19, No. 2, April, 2024, pp. 489-496
Journal homepage: http://iieta.org/journals/ijdne

Modification of the Geotechnical Properties of Loess Using Eggshell Waste (El'Mghair Region)

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https://doi.org/10.18280/ijdne.190214

Received: 8 January 2024
Revised: 17 March 2024
Accepted: 26 March 2024
Available online: 25 April 2024

Keywords:
loess soil, collapse potential, soil stabilization, eggshell content, chemistry of the loess, sustainable materials

ABSTRACT

Soil stabilization with eggshell waste is an important aspect of sustainable engineering and environmental management. It offers a cost-effective and environmentally friendly solution for improving the physical and mechanical properties of soils. This study investigates the transformative impact of eggshell as a soil treatment agent on loess soil (EM). Various tests, including Proctor, collapse potential, Atterberg limits, shear strength, and chemistry of the loess were conducted to assess the changes in soil properties with different eggshell content (0, 2, 4, 6, 8 and 10%). The results reveal that eggshell significantly affects soil compaction, stability, plasticity, and shear strength. Notably, the addition of eggshell, especially at 10% content, shows promise in enhancing soil properties, making it a potential candidate for soil stabilization and moisture management applications. However, the complex relationship between eggshell content and soil behavior underscores the need for further research to unlock its full engineering potential and optimize its application in treating loess soil. Overall, soil stabilization with eggshell waste provides a sustainable alternative to traditional stabilizers, contributing to the goal of environmentally friendly and cost-effective solutions in civil engineering.

1. INTRODUCTION

In Algeria, where loess soils are prevalent specially in southern, managing the challenges associated with their high collapse potential is essential for sustainable construction and infrastructure development. This becomes even more critical given the growing concerns surrounding waste management in the country [1, 2]. Rapid urbanization and industrial growth have led to an increase in waste generation, prompting the need for innovative approaches to recycling and repurposing waste materials. One such approach under investigation is the use of eggshell waste, a byproduct of the food industry rich in calcium carbonate [3]. It has demonstrated promise in improving the properties of loess soils while also addressing Algeria's evolving waste management landscape. This article embarks on an investigation into the impact of eggshell waste on the collapse potential and suction characteristics of loess soils in Algeria, aiming to provide sustainable and locally available soil stabilization solutions in alignment with the country's waste management goals.

The study seeks to elucidate the feasibility and effectiveness of utilizing eggshell waste as a sustainable and locally available soil stabilizer specifically for loess soils, as studies have shown effective results by using it in the treatment of clay soil, this research aims to explore its potential for enhancing the engineering properties of loess soils [4, 5]. Through a rigorous laboratory study, encompassing soil testing, characterization, and analysis, we aim to provide valuable insights into the potential applications of eggshell waste in mitigating the geotechnical challenges posed by loess soils in Algeria [6]. Algeria's diverse geological and climatic conditions have long necessitated innovative solutions to address the distinct challenges associated with loess soils. In this context, various soil stabilization techniques have been explored, including stabilization with lime [7, 8], cement [9-12], slag [13, 14], chemical additives [15-18], as well as geosynthetics [19-21]. These methods have been employed to varying degrees of success, but the utilization of waste materials like eggshell waste represents a sustainable and potentially cost-effective alternative. More, the eggshell additive to soil stabilization performs best under specific environmental conditions. The studies indicate that eggshell powder can effectively substitute lime in soil stabilization, making the process more cost-effective and environmentally friendly [22].

This research is part of an ongoing effort to improve construction practices, mitigate soil-related issues, and promote environmentally responsible engineering solutions within Algeria. The outcomes of this study may offer practical strategies to enhance the performance and longevity of construction projects dealing with loess soils. Additionally, we will explore how eggshell waste compares to other stabilization techniques commonly used in the region.

In conclusion, the investigation outlined in this article underscores the significance of harnessing locally available waste materials, such as eggshell waste, to ameliorate the engineering properties of loess soils in Algeria. By examining the impact of eggshell waste and comparing it to established stabilization methods, we aim to provide valuable guidance for engineers and researchers working in geotechnical engineering and construction. Ultimately, our goal is to advance sustainable and effective solutions for the unique challenges posed by loess soils in this region.

2. MATERIALS

2.1 Loess soil EM

The El'Mghair region, located in the southern reaches of Algeria within the Oued Righ region, serves as the focal point of our research. Situated between the prominent cities of Biskra and Oued Souf in Figure 1, this region is renowned for its unique geological and environmental characteristics. The soil material selected for our study was carefully collected from this locale. El'Mghair's geographical location in the arid landscapes of southern Algeria imparts distinct challenges to construction and infrastructure development. The soil in this region, primarily consisting of loess deposits, exhibits particular susceptibility to collapse and cracking upon desiccation.

Figure 1. Location of the site

Given these challenges, the investigation into the effect of eggshell waste as a potential soil stabilizer in the El'Mghair region holds significant relevance. Our study seeks to address these geotechnical concerns by assessing the physical, chemical, and mechanical properties of (EM) loess Table 1, the grain-size analysis was achieved by dry sieving after washing according to French standard test and by sedimentary show in Figure 2 of the local loess and determining how the incorporation of eggshell waste may offer sustainable solutions for construction and engineering endeavors in this unique environmental context.

Table 1. Geotechnical characteristics of loess soil

Characteristics	Standards	EM
Natural water content w_{nat} (%)		15.1
Natural void ratio e		0.893
Specific gravity G_S	NF P94-50 (1995)	2.69
Unit weight solid γ_s (kN/m^3)	[23]	26.9
Natural dry unit weight γ_d (kN/m^3)		14.21
Degree of saturation S_r (%)		45.49
Sand (%)	NF P94-056 (1996)	32
Silt (%)	NF P94-057 (1992)	56
Clay (%)	[24, 25]	12
Coefficient of uniformity Cu		35.3
Liquid limit LL	NF P94-051 (1993)	31
Plastic limit PL	[26]	19
Plasticity index IP (%)		12
Maximum dry density (g/cm^3) γ_d	NF P94-093 (2014)	15.86
Optimal water content w_{opt}	[27]	17.77
Cohesion C (kPa)	NF P94-071 (1994)	90
Friction angle φ (°)	[28]	14

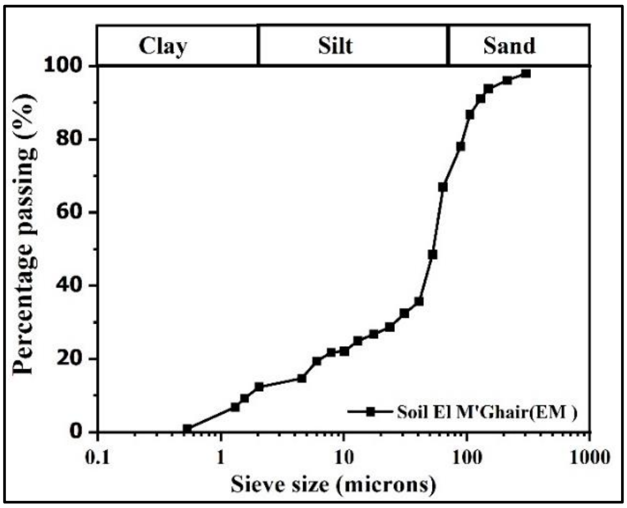

Figure 2. Grain-size distribution curves of loess soil

The combined analysis of various expressions and classifications consistently points to a compelling conclusion: the soil under study exhibits characteristics that align with the classification of loess soil. Multiple criteria utilized by different authors and researchers all converge to indicate a propensity for soil collapse, and behavior typical of loess soils.

These indicators include values suggestive of susceptibility to collapse, alongside specific parameters such as high compressibility and low density. Furthermore, the observations of minimal settlement upon variations in density further reinforce this classification. Altogether, these findings collectively support the assertion that the soil studied (EM) falls within the category of loess soil in Table 2, underlining its unique geotechnical attributes and behavior consistent with loess materials observed in similar regions [29, 30].

This information underscores the soil's tendency to experience settlement-related issues, indicating the importance of our research in addressing and mitigating such geotechnical challenges [1, 31, 32].

Table 2. Different expressions and classifications of loess soils

Auteur	Expression	Remarks	EM Loess
[33]	$\frac{w_L}{\left(\frac{\gamma_w}{\gamma_d} - \frac{1}{G_s}\right)}$	<1.0 collapse occur	0.934
[34]	$\alpha = \frac{(e_0 - e_L)}{(1 + e_0)}$	α<-0.3 prone to swelling α>-0.1 and $S_0 < 60\%$ susceptible to collapse	0.031
[35]	$K_d = \frac{w_L - w_0}{I_p}$	$K_d < 0$ highly collapsing soil $K_d < 0.5$ non collapsing soil $K_d < 0.5$ *swelling soil*	1.325
[36]	$K_L = \frac{\left(\frac{w_0}{S_0} - w_p\right)}{I_p}$	For $S_0 < 60\%$ $K_L > 0.85$ collapsing soil	1.183
[37]	$\gamma_{0d} < 1.28\ g/cm^3$ $\gamma_{0d} > 1.44\ g/cm^3$	Settlement be large, settlement will be small	1.421<1.28
[38]	$\delta = K(n_0 - 40)(30 - w_0)$	K=0.02 for loess sand K=0.03 for sand loess K=0.05 for typical loess K=0.08 for claley loess K=0.09 for loess like clay	5.344
[39]	$C_u \leq 4\%$ $4\% < C_u < 12\%$ $C_u \geq 12\%$	Safe from collapse Transition interval (collapse may occur) Soil is collapsible	35.3>12
[40]	$I_p < 20$, $15 < w_L < 35$	Collapse is susceptible	12<20, 15<31<35

2.2 Eggshell powder

Table 3 presents the chemical characteristics of the eggshell Waste utilized in this study. Additionally, Figure 3 offers a visual depiction of the eggshell Waste powder, allowing for a clearer understanding of its physical properties.

Figure 3. Waste eggshell and powder

Table 3. Chemical composition of the eggshell

Elements	Percent
CaO	94.78
Al_2O_3	0.005
SO_3	1.094
K_2O	0.096
MgO	0.983
MnO	0.004
Na_2O	2.514
P_2O_5	0.205
SiO_2	0.318

Eggshells primarily consist of calcium carbonate ($CaCO_3$). In fact, calcium carbonate makes up approximately 94% of the dry weight of an eggshell.

The remaining 6% includes various other compounds Table 3, but the predominant component is calcium carbonate, which gives eggshells their characteristic hardness and makes them a potential candidate for soil stabilization applications.

3. METHODS

Table 4 presents the different proportions of eggshell Waste incorporated to address the collapsible soil under investigation. The Atterberg limits according to the French standard [26] were measured on the soil fraction lower than 400µm, extracted by wet sieving from untreated soils. In order to measure the consistency limits on the soil-eggshell waste mixtures, the natural soil fraction was air-dried and mixed with different quantities of anhydrous eggshell powder in order to reach 2 to 10% eggshell addition such as during the soil treatment.

Table 4. Different mixtures used for the experimental program

Materials	Designation	Eggshell Waste Content
Eggshell waste	EM	EM + 0% Eggshell
	EM_{2E}	EM + 2% Eggshell
	EM_{4E}	EM + 4% Eggshell
	EM_{6E}	EM + 6% Eggshell
	EM_{8E}	EM + 8% Eggshell
	EM_{10E}	EM + 10% Eggshell

After excavating the soil, a standard Proctor test [27] was conducted to determine the Proctor optimum density (γ_{opt}) and optimum water content (w_{opt}) for both the raw soils and soil-eggshell mixtures at (2, 4, 6, 8, and 10%) eggshell content. The parameters from the Proctor tests (as indicated in the table) were used to prepare specimens for direct shear testing, compressibility testing.

Initially, a specified quantity of finely ground soil particles, following drying at 105°C for 24 hours, was meticulously blended with varying eggshell contents (2, 4, 6, 8, and 10%) in a dry state for 10 minutes using a paddle mixer to ensure adequate homogeneity. Subsequently, distilled water was added to the mixture to attain the w_{opt} value determined from the Proctor tests conducted on each eggshell-soil blend. The moistened eggshell-soil mixtures were mechanically mixed for 5 minutes (until the disappearance of any visible eggshell powder in the mix) before undergoing static compaction at 50 kPa with a constant deformation rate of 1 mm/min within a cylindrical mold. The specimens achieved the maximum dry density (γ_d) permitted by the compaction apparatus.

This process ensured consistent and reproducible conditions for testing and allowed for the investigation of the engineering properties of soil-eggshell mixtures across different eggshell content percentages.

Two groups of specimens were created: the initial group was designated for the compressibility test and had dimensions measuring 70mm in diameter and 20mm in height, while the second group was designated for the direct shear test and had dimensions measuring 60mm in diameter and 21mm in height Figure 4.

Figure 4. Schematic diagram of experimental program

4. RESULTS AND DISCUSSION

4.1 The effect of eggshell waste treatment on compaction

The results indicate that when 10% eggshell is added to the loess soil, it experiences an increase in water content to 19.8% and a higher maximum dry density of 17.9 kN/m³ compared to the untreated soil with 17.7% water content and 15.9 kN/m³ maximum dry density. The observation that the percentage of eggshell added to the soil leads to an increase in the optimum water content (w_{opt}) aligns with the general behavior of soil-stabilizer systems. When a stabilizer like eggshell is introduced, it often modifies the soil's particle interactions and, in some cases, increases the water-holding capacity of the mixture. This results in a higher w_{opt}, indicating that the soil-eggshell mixture requires more water for optimal compaction Figure 5.

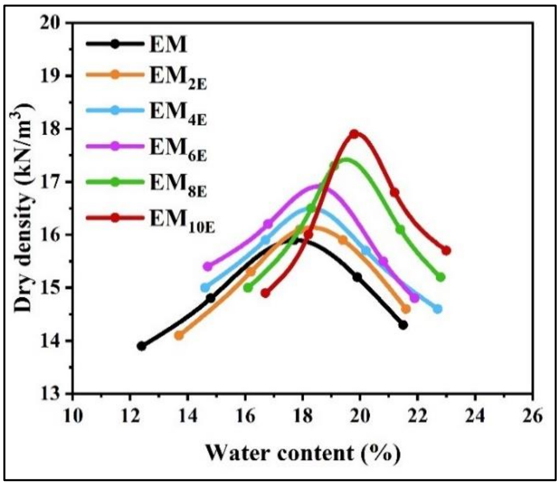

Figure 5. Effect of eggshell powder on Proctor parameters of soil

Notably, we mention that the increase in w_{opt} is more pronounced with smaller percentages of eggshell. This is a crucial observation as it suggests that even a relatively small amount of eggshell has a notable influence on the soil's water retention capacity. This information can be particularly valuable for engineering applications where precise control over water content is essential.

The increase in maximum dry density (γ_d) with the addition of eggshell is also a significant finding. It suggests that eggshell acts as an effective soil stabilizer, improving compaction characteristics. A higher γ_d indicates that the soil-eggshell mixture achieves greater particle packing and density, which can enhance its load-bearing capacity and reduce settlement potential.

4.2 The effect of eggshell waste treatment on collapse potential

The soil (EM) examined in this study exhibits a susceptibility to settlement, the collapse potential CP of the untreated sample EM is 9.4%. In the classification proposed by Jennings and Knight [41], the EM soil may trouble.

The collapsibility test results indicate a substantial reduction in collapsibility when 10% eggshell is introduced to the loess soil. In the untreated soil EM, the collapsibility is relatively high at 9.4%. However, with the addition of 10% eggshell, the collapsibility dramatically decreases to 0.6% Figure 6.

A decrease in collapse potential with an increasing percentage of eggshell is a positive finding. It suggests that eggshell is effectively stabilizing the soil. This can be attributed to the properties of eggshell, particularly its high calcium carbonate content. Calcium carbonate can enhance the soil's cohesion and reduce its susceptibility to collapse and settlement.

The increase in the optimum water content (w_{opt}) with eggshell addition also plays a role. It suggests that the soil-eggshell mixture requires more water for optimal compaction. This improved water retention can further contribute to soil stability by preventing excessive drying, which is a common cause of collapse in certain soils.

It's interesting to note that the effect of eggshell on collapse potential is more pronounced with smaller percentages. This implies that even a relatively small amount of eggshell can have a substantial impact on improving soil stability. This can be advantageous in practical applications, as it allows for cost-effective and sustainable soil improvement.

The results suggest that eggshell has the potential to be a valuable soil stabilizer, especially in areas where soil collapse is a concern. It could be applied to construction sites, foundations, or infrastructure projects to mitigate settlement risks and enhance the performance of the soil.

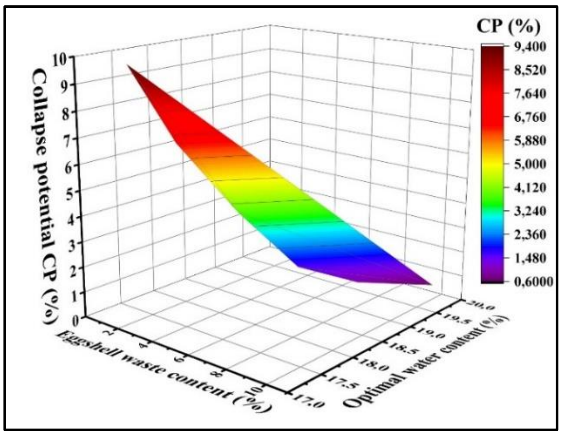

Figure 6. Effect of eggshell powder on collapse potential of soil

4.3 The effect of eggshell waste treatment on Atterberg limits

In untreated condition, the soil exhibits a liquid limit of 31% and a plastic limit of 19%, giving rise to a plasticity index of 12%. However, upon the introduction of 10% eggshell, distinct alterations emerge. The liquid limit decreases to 27%, while the plastic limit increases to 25% Figure 7.

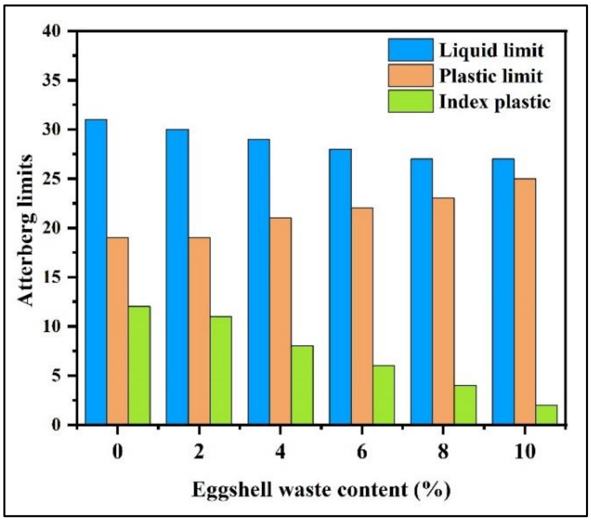

Figure 7. Effect of eggshell powder on Atterberg's limit of soil

The general trend we have observed, where the liquid limit decreases as the egg shell percentage increases making the soil less plastic with the decrease in the plasticity index. The most notable aspect of our results is the particular behavior observed at an eggshell content of 10%. The increase in the plastic limit suggests that the soil becomes more cohesive and less likely to collapse at lower moisture levels. In loess, the addition of eggshell powder can help reduce their plasticity, i.e., their tendency to deform under pressure, by acting as a bonding agent, eggshell powder may help stabilize particles and improve soil plasticity.

4.4 The effect of eggshell waste treatment on direct shear

The gradual increase in cohesion (C) and friction angle (φ) with added eggshell content is a common response when stabilizing soils. This suggests that the eggshell addition is gradually altering the soil's mechanical properties, making it less prone to shear failure. The subsequent proportional increase in cohesion (C) and friction angle (φ) with increasing eggshell content indicates that higher concentrations of eggshell have a more pronounced reinforcing effect on the soil. This is favorable for engineering applications as it implies improved shear strength and load-bearing capacity. The observation that eggshell treatment enhances shear resistance aligns with common soil stabilization practices. Eggshell can play a role in improving the mechanical properties of soils, making them more suitable for construction and load-bearing purposes. The significant convergence of cohesion (C) and friction angle (φ) values for 8% and 10% of added eggshell content suggests that there may be an optimal range of eggshell content for maximizing shear strength. Beyond this range, additional eggshell content might have diminishing returns in terms of shear strength improvement Figures 8-9.

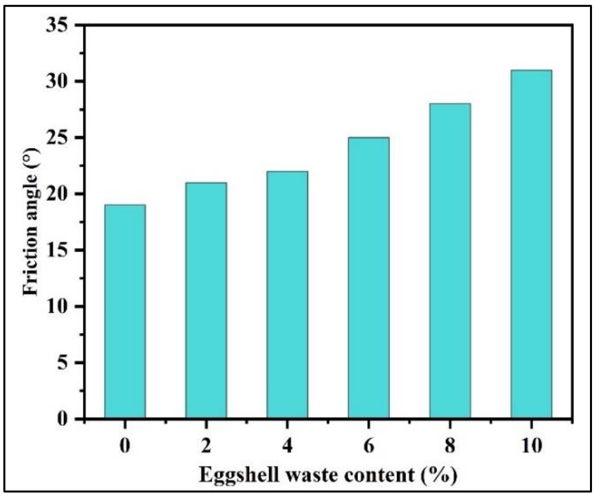

Figure 8. Effect of eggshell powder on friction angle

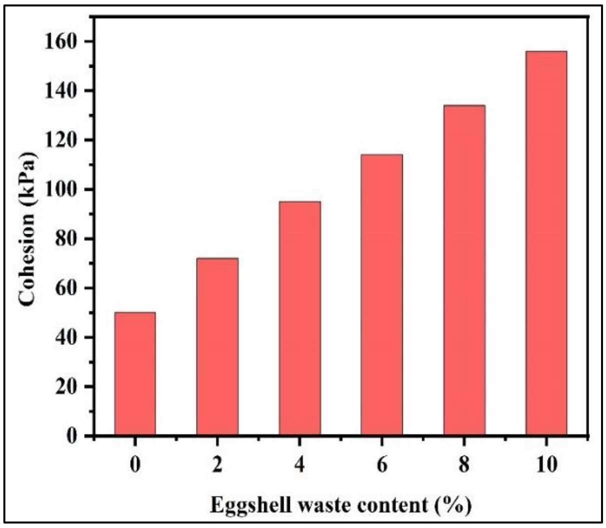

Figure 9. Effect of eggshell powder on cohesion

4.5 Chemistry of the loess before and after eggshell waste treatment

The chemical composition analysis of untreated loess soil and loess soil treated with 10% eggshell demonstrates significant alterations in the elemental content, which can have profound implications for the soil's engineering properties. With the addition of eggshell waste to loess soil, there is a substantial increase in calcium (Ca) content, primarily due to the presence of calcium carbonate ($CaCO_3$) in eggshell (Table 5). This increase in calcium initiates chemical reactions that produce calcium hydroxide ($Ca(OH)_2$), known for its cementitious properties and represented by the equation:

$$CaCO_3 + H_2O \rightarrow Ca(OH)_2 + CO_2 \quad (1)$$

This compound has the potential to improve soil stability and reduce collapsibility. Simultaneously, there is an increase in oxygen (O) content resulting from the breakdown of $CaCO_3$ during hydration reactions:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (2)$$

However, this addition leads to decreases in silicon (Si), aluminum (Al), iron (Fe), and carbon (C) content, indicating changes in mineral composition and a reduction in organic matter. Modest fluctuations in potassium (K), sodium (Na), magnesium (Mg), phosphorus (P), and sulfur (S) may influence the soil's capacity. Overall, these chemical changes highlight the eggshell treatment's potential to enhance the soil's engineering characteristics, particularly in terms of stability and strength, although further research and testing are essential to precisely evaluate its practical implications. The use of eggshell powder in soils can also have applications in the field of civil engineering, in improving the mechanical characteristics of the soil. Soil stabilization by eggshell powder can be mixed with soil to improve its stability and strength. Due to its high calcium composition, eggshell powder can act as a binder, helping to strengthen soil particles and reduce its susceptibility to erosion and deformation. Additionally, eggshell powder has the ability to absorb moisture, which can be beneficial for soils with high water content and can help reduce dew potential, thereby improving its stability and bearing capacity.

Table 5. Chemical composition of untreated loess and treated loess with 10% of eggshell

Elements	EM		EM_{10E}	
	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
Si	29.22	19.71	21.22	14.82
O	47.15	56.87	49.82	61.44
Al	11.04	7.99	9.04	6.57
Fe	3.29	1.12	1.91	0.67
Ca	1.32	0.62	11.88	8.40
K	1.27	0.62	0.96	0.48
Na	0.08	0.06	0.53	0.47
Mg	0.29	0.23	0.69	0.60
P	0.04	0.04	0.1	0.06
S	0.3	0.18	0.54	0.33
C	5.81	11.06	3.11	5.20

5. CONCLUSION

In conclusion, this study has demonstrated the promising potential of eggshell waste as a soil stabilizer for loess soils. The Proctor test results have shown that the addition of eggshell improves compaction properties by increasing the optimum water content and maximum dry density, indicating its effectiveness in enhancing soil density and reducing the risk of settlement.

Furthermore, the findings highlight that increasing the percentage of eggshell in the soil results in a significant reduction in collapse potential. This suggests that eggshell can effectively stabilize loess soils, enhancing their compaction, water retention, and overall stability. However, the unique behavior observed at 10% eggshell content warrants further investigation to understand its implications fully.

The influence of eggshell on soil plasticity is complex and varies with eggshell content. While there is a general trend of reduced plasticity with increasing eggshell content, the distinct behavior observed at 10% eggshell content raises questions about critical concentration levels. Further research is needed to unravel the mechanisms behind this phenomenon and its relevance in different engineering applications.

Moreover, the suction test results indicate a significant reduction in soil suction with the introduction of 10% eggshell. This finding suggests that eggshell treatment can substantially alter the soil's moisture retention characteristics, which could be beneficial in applications where reduced moisture retention is desired, such as soil stabilization or projects focused on improving drainage.

Overall, the addition of eggshell waste holds promises for enhancing the engineering properties of loess soils, particularly in Algeria's context. However, to fully harness its potential, additional research, including comprehensive geotechnical and mechanical testing, is essential to determine the optimal eggshell content range for specific engineering applications and to ensure long-term effectiveness. These findings open avenues for sustainable and effective solutions to address the challenges posed by loess soils in the region.

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NOMENCLATURE

EM	El'Mghair loess
E	eggshell waste
CP	collapse potential
LL	liquid limit
LP	plastic limit
IP	plasticity index
C	cohesion, kPa
Cu	coefficient of uniformity

Greek symbols

γ_s	unit weight solid, $kN.m^{-3}$
γ_d	natural dry unit weight, $kN.m^{-3}$
φ	friction angle, °