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Materiales

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Physicochemical interpretation of the stabilization mechanisms of clayey soils using recycled brick powder: A physicochemical, mechanical, and geotechnical assessment

Interpretación físico química de los mecanismos de estabilización de suelos arcillosos mediante polvo de ladrillo reciclado: una evaluación fisicoquímica, mecánica y geotécnica

J. Sangabriel-Lomelí[1], P. J. López-González[1*], O. Moreno-Vázquez[1], N. Sánchez-Zarate[2], J.Z. Escobar-Galván[3]

[1] Department of Civil Engineering, Tecnológico Nacional de México / ITS de Misantla, Km 1.8 Carretera a Loma del Cojolite, Misantla 93821, Veracruz, Mexico.

[2] Department of Environmental Engineering, Tecnológico Nacional de México/ ITS de Misantla, Km 1.8 Carretera a Loma del Cojolite, Misantla 93821, Veracruz (México).

[3] Department of Business Management Engineering, Tecnológico Nacional de México/ ITS de Misantla, Km 1.8 Carretera a Loma del Cojolite, Misantla 93821, Veracruz (México).

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Abstract

Clayey soils exhibit high plasticity, volumetric instability, and low load-bearing capacity, which limit their use in infrastructure applications. This study evaluates the potential of recycled brick powder as a sustainable stabilizing additive and proposes a chemical interpretation of the mechanisms responsible for the observed geotechnical and mechanical improvements. Laboratory testing included Atterberg limits, modified Proctor compaction, and compressive strength at 7, 14, and 28 days, combined with a theoretical physicochemical analysis based on cation exchange, flocculation–agglomeration, and pozzolanic reactions. Although instrumental microstructural techniques (XRD, SEM–EDS) were not applied, compositional ranges reported in the literature for ceramic residues—rich in SiO_2, Al_2O_3, and Fe_2O_3—were used to interpret reaction pathways. Results show that brick powder reduces soil plasticity, increases dry density, and enhances compressive strength over time, with the 7% mixture exhibiting the highest performance. The gradual strength gain observed at 14 and 28 days provides indirect evidence of secondary gel formation (C–S–H and C–A–H), consistent with pozzolanic processes commonly reported for aluminosilicate–calcium systems. These findings demonstrate that recycled brick powder represents a technically viable, low-cost, and environmentally beneficial stabilizer for clayey soils. The study opens avenues for further research using advanced chemical and microstructural characterization.

Keywords: Soil stabilization, recycled brick powder, compressive strength, pozzolanic reactions, physicochemical mechanisms.

Resumen

Los suelos arcillosos presentan alta plasticidad, inestabilidad volumétrica y baja capacidad de soporte, lo que limita su uso en obras de infraestructura. Este estudio evalúa el potencial del polvo de ladrillo reciclado como aditivo estabilizante sostenible y propone una interpretación química de los mecanismos responsables de las mejoras geotécnicas y mecánicas observadas. Los ensayos incluyeron límites de Atterberg, compactación tipo Proctor modificado y resistencia a compresión a 7, 14 y 28 días, complementados con un análisis fisicoquímico teórico basado en intercambio catiónico, floculación–aglomeración y reacciones puzolánicas. Aunque no se aplicaron técnicas instrumentales de microestructura (XRD, SEM–EDS), se emplearon rangos de composición química reportados en la literatura para residuos cerámicos —ricos en SiO_2, Al_2O_3 y Fe_2O_3— con el fin de interpretar las vías de reacción.Los resultados muestran que el polvo de ladrillo reduce la plasticidad del suelo, incrementa la densidad seca y mejora la resistencia a compresión con el tiempo, destacando la mezcla al 7% como la de mayor rendimiento. El aumento progresivo de la resistencia a 14 y 28 días proporciona evidencia indirecta de la formación de geles cementantes secundarios (C–S–H y C–A–H), coherente con procesos puzolánicos típicos de sistemas aluminosilicato–calcio. Estos hallazgos demuestran que el polvo de ladrillo reciclado es un estabilizante técnica y ambientalmente viable para suelos arcillosos. El estudio abre oportunidades para investigaciones futuras mediante técnicas avanzadas de caracterización química y microestructural.

Palabras clave: Estabilización de suelos, polvo de ladrillo reciclado, resistencia a compresión, reacciones puzolánicas; mecanismos fisicoquímicos.

* *Corresponding author. E-mail*: jlopezg@itsm.edu.mx ;
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1 Introduction

Civil engineering currently faces the urgent challenge of integrating sustainable practices in soil improvement, particularly in regions where clayey subgrades exhibit low bearing capacity, high plasticity, and poor durability under environmental stressors (Shirazi *et al*., 2020; Onyelowe *et al*., 2023; Al-Arafat *et al*., 2024). These problematic soils undermine the long-term performance and safety of road infrastructure, necessitating effective stabilization techniques to enhance geotechnical properties (Archibong *et al*., 2020; Zada *et al*., 2023; Jia *et al*., 2023). Chemical stabilization has emerged as a widely adopted method to improve soil strength, reduce plasticity, and optimize compaction behavior, thereby increasing the load-bearing capacity and resilience of subgrades (Mahedi *et al*., 2020; Archibong *et al*., 2020).

Traditionally, stabilizing agents such as lime and Portland cement have been the most commonly used due to their proven effectiveness (Zhao et al., 2023; Li *et al*., 2024). However, their widespread use raises significant environmental concerns, as their production processes require high energy consumption and result in substantial greenhouse gas emissions (Mohammed *et al*., 2023; Abdul-Wahab *et al*., 2021). These sustainability challenges have driven the exploration of alternative materials that meet technical requirements while minimizing the environmental footprint of civil construction projects.

In recent years, increasing attention has been focused on the reuse of industrial and agricultural by-products for soil stabilization (Jalal *et al*., 2020; Alqaisi *et al*., 2020). Waste materials such as fly ash, blast furnace slag, rice husk ash, and ceramic waste have demonstrated pozzolanic activity and potential as partial or full substitutes for conventional stabilizers in various geotechnical applications (Renjith *et al*., 2021; Gidebo *et al*., 2023). Among these, brick powder—a by-product generated from construction and demolition waste or defective ceramic manufacturing—has gained prominence due to its high content of amorphous silica (SiO_2) and alumina (Al_2O_3), which react beneficially with clay minerals to improve soil properties (Raj *et al*., 2024; Boukhatem *et al*., 2024).

In clay stabilization, physicochemical mechanisms play a central role in determining the effectiveness of alternative additives. The amorphous silica (SiO_2) and alumina (Al_2O_3) present in recycled brick powder have been shown to participate in pozzolanic reactions when combined with calcium-rich pore fluids, promoting the formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels that progressively cement soil particles. These reactions reduce the thickness of the diffuse double layer, enhance flocculation–agglomeration, and increase the internal bonding of the soil matrix, resulting in measurable improvements in plasticity, compaction behavior, and long-term strength. Understanding these mechanisms is crucial for interpreting the performance of brick powder as a stabilizer within different soil mineralogies.

Previous studies have reported significant improvements in the engineering behavior of soils stabilized with brick dust, including reductions in plasticity index, increases in maximum dry density, and enhanced compaction characteristics (Peláez *et al*., 2024; Ni *et al*., 2022). These enhancements not only improve the mechanical performance of subgrades but also support circular economy principles by valorizing ceramic waste that would otherwise be discarded in landfills.

Nonetheless, critical knowledge gaps remain regarding the highest performance within the tested rangeof brick powder required to achieve effective soil stabilization, especially under local geotechnical and environmental conditions. In regions such as Misantla, Veracruz (Mexico)—characterized by expansive clay soils and increasing infrastructure demands—there is a lack of site-specific research addressing the use of ceramic waste as a sustainable soil stabilizer. Without localized empirical data, the full potential of brick powder remains underutilized.

In this study, recycled brick powder is evaluated as an independent stabilizing additive rather than as a direct or partial replacement for Portland cement. Cement-stabilized and brick powder–stabilized mixtures were designed and analyzed separately in order to clearly distinguish their respective stabilization mechanisms, performance trends, and sustainability implications.

This study aims to address this gap by evaluating the geotechnical behavior of clay soils stabilized with 3%, 5%, and 7% brick powder (by dry weight). Laboratory tests—including Atterberg limits and Standard Proctor compaction—were conducted to assess changes in plasticity, optimum moisture content, and maximum dry density. The main objective is to identify the highest performance within the tested range that maximizes soil stability while promoting the use of sustainable materials in regional civil infrastructure.

Through this research, new insights are provided into the valorization of ceramic waste in road engineering, supporting regionally adapted stabilization strategies and reinforcing the importance of integrating circular economy principles in geotechnical solutions (Bardam *et al*., 2022; Shinde *et al*., 2024; Gravina da Rocha *et al*., 2021), especially in regions where problematic soils continue to challenge construction durability and resilience (Pu *et al*., 2021;

Piechowicz *et al*., 2024).

The integration of recycled materials such as ceramic waste into engineering applications aligns with current trends in chemical and environmental engineering. Recent studies published in the Revista Mexicana de Ingeniería Química have highlighted the importance of waste valorization, sustainable processing, and the development of environmentally friendly materials, particularly through the use of alternative cementitious systems, geopolymeric materials, and recycled industrial residues (Montañez *et al*., 2024; Tejeda *et al*., 2019; Torres *et al*., 2019). These approaches support the incorporation of aluminosilicate-rich waste into engineering applications, as explored in the present study through the use of recycled brick powder as a stabilizing agent.

2 Materials and methods

2.1 Soil

The clayey soil used in this research was collected from the community of Kilometer 9, located in the municipality of Misantla, Veracruz. This region experiences severe damage to its transportation infrastructure, primarily due to the low bearing capacity and high plasticity of local soils, which tend to deform under cyclic loading and seasonal moisture variations. For this reason, stabilization with brick powder was proposed as a strategy to enhance the soil's physical and mechanical performance while promoting the use of recycled materials.

The soil was extracted at a depth of 0.5 m to avoid organic matter and surface contamination. Samples were transported in sealed bags to the laboratory and prepared according to ASTM D4220 and ASTM D4221 standards (ASTM, 2020; ASTM, 2020). Prior to testing, the material was air-dried, manually disaggregated, and passed through a No. 4 sieve (4.75 mm) to ensure homogeneity.

This type of clayey soil is common in the central region of Veracruz and is characterized by a fine-grained, cohesive matrix with a tendency toward shrink–swell behavior. Its mineralogical characteristics—typically rich in aluminosilicates—make it responsive to chemical additives capable of altering its structure and improving its engineering behavior. These features justify its selection as a representative material for evaluating the effectiveness of brick powder as a stabilizing agent. Based on the particle size distribution and Atterberg limits obtained in this study, the soil was classified as CL (low-plasticity clay) according to the Unified Soil Classification System (USCS), confirming its fine-grained and cohesive nature.

2.2 Physical characterization of the soil

2.2.1 Particle size distribution

To determine the particle size distribution of the soil, a sieve analysis was conducted in accordance with ASTM D422 (ASTM, 2022). The materials were oven-dried prior to testing and manually sieved using a stack of standard sieves placed on a vibrating table.

2.2.2 Particle size distribution

The apparent relative density of the soil was determined following ASTM D854-14 (ASTM, 2014). The material was brought to a saturated surface-dry condition, and volumetric measurements were performed using a truncated cone and a Chapman flask.

2.3 Consistency limits

The liquid and plastic limits of the natural soil and stabilized mixtures were determined according to ASTM D4318-17 (ASTM, 2017), using the Casagrande cup for the liquid limit and the thread-rolling method for the plastic limit. The plasticity index was calculated as the difference between these two values. These parameters are essential for soil classification and for assessing residual plasticity after treatment with the additive.

2.4 Standard proctor

The Standard Proctor test was applied to determine the maximum dry density and optimum moisture content of each mixture, following ASTM D698-12 (ASTM, 2012). Both natural and stabilized soils were compacted in a cylindrical mold in three layers, applying 25 blows per layer using a 2.5 kg rammer dropped from a height of 30.5 cm.

2.5 Cement

The cement used was Portland composite cement type CPC 30R, characterized by high early strength, achieving the required compressive strength within 3 days, in accordance with the specifications of the Mexican standard.

2.6 Stabilizing additive: Brick powder

The additive used was red brick powder obtained from local ceramic industry waste. Brick fragments were ground using a hammer mill and sieved through a No. 100 mesh (150 μm), in accordance with ASTM E11 (ASTM, 2020), to ensure a fine and uniform particle size suitable for soil interaction. The powder was stored in sealed containers under dry conditions until it was incorporated into the mixtures.

Table 1. Chemical compound of brick dust (%).

CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	Author
23.8	41.6	13.24	11.25	1.116	2.31	(Rabiu & Mosaberpanah, 2025).
10.11	52.37	24.43	2.14	2.43	0	(Qin *et al.*, 2024).
9.81	57.67	14.91	5.02	1.86	3.2	(Rovnaník *et al.*, 2016).
6.7	53.3	16.6	7.4	1.1	0	(Chen, *et al* 2019).
5.56	61.05	17.04	6.92	0.88	2.49	(Lliso, *et al.*, 2025).
8.47	59.72	16.9	6.93	1.37	2.21	(Zhu *et al.*, 2025).
12.83	53.35	16.48	6.2	0.28	2.95	(Öze *et al.*, 2024).
0.63	41.47	39.05	12.73	1.59	2.81	(Tremiño *et al.*, 2021).

Table 2. Experimental design for plasticity and compaction tests.

Run	Nomenclature	% Portland Cement (by weight)	% Brick powder (by weight)
1	SN0	0	0
2	SL3	3	0
3	SB3	0	3
4	SL5	5	0
5	SB5	0	5
6	SL7	7	0
7	SB7	0	7

Note: (Experimental matrix used to evaluate the plasticity behavior and compaction properties of the stabilized mixtures).

The proportions used were 3%, 5%, and 7% by weight relative to the dry weight of the soil.

Recycled brick powder has been widely employed in international studies as a supplementary cementitious material or soil stabilizer in sustainable construction applications (see Table 1). Although advanced analytical characterization (such as XRF, XRD, or SEM-EDS) was not performed in this study, the chemical composition of ceramic brick waste is well documented in the literature. Recycled brick materials typically contain predominantly SiO_2 (55–70%), Al_2O_3 (10–25%), Fe_2O_3 (5–10%), and smaller quantities of CaO, MgO, and alkali oxides. These oxides are directly associated with the puzolanic reactivity and cementitious potential of ceramic residues when they are incorporated into clayey soils.

The high silica and alumina contents in brick powder are known to react with available calcium hydroxide ($Ca(OH)_2$) in alkaline environments—either naturally present in soils or provided through cement addition—to form secondary cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H). These reactions contribute to long-term strength gain, reduced plasticity, and improved structural stability. The variability observed in the chemical composition reported by previous authors (Table 1) helps justify the use of locally available ceramic residues in the context of Misantla, Veracruz, even without direct chemical testing of the material employed, as the ranges typically fall within expected pozzolanic thresholds.

This comparative analysis supports the rationale for incorporating brick powder as a sustainable stabilizing additive, aligning with both the geotechnical needs of the region and broader circular economy principles.

Although advanced instrumental techniques such as X-ray diffraction (XRD), X-ray fluorescence (XRF), or scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM–EDS) were not applied in this study, the physicochemical interpretation was supported by well-established chemical composition ranges of recycled brick powder reported in the literature. These studies consistently report high contents of SiO_2, Al_2O_3, and Fe_2O_3, which are directly associated with pozzolanic reactivity in soil–binder systems. This approach allows a theoretically grounded interpretation of stabilization mechanisms while explicitly recognizing the need for future research incorporating direct chemical and microstructural characterization.

2.7 *Experimental design*

Mixtures containing 3%, 5%, and 7% brick powder were prepared and compared to untreated natural soil. Each mix was labeled using a specific code. Table 2 presents the experimental design used for the consistency limit and compaction tests.

The selected brick powder contents (3%, 5%, and 7% by dry weight of soil) were chosen based on commonly reported dosage ranges in previous studies on soil stabilization using ceramic waste and supplementary cementitious materials. These percentages represent low, intermediate, and relatively high additive contents, allowing the identification of performance trends and the determination of an the highest performance within the tested range while maintaining practical feasibility, workability, and material efficiency.

3 Results

Figure 1 illustrates the variation in the liquid limit of soils stabilized with Portland cement and brick powder, compared to untreated soil. The results show that, overall, the addition of cement and brick powder reduces the liquid limit relative to the untreated soil, suggesting a decrease in soil plasticity and, consequently, a lower susceptibility to plastic deformation.

However, mixtures containing cement exhibit a lower liquid limit than those with brick powder, regardless of the percentage added. This indicates that cement has a more pronounced effect on reducing soil plasticity.

Nonetheless, brick powder also demonstrates a positive stabilizing effect, although the liquid limit remains slightly higher at each dosage compared to cement. This may indicate a higher plasticity than cement-stabilized soil yet still represents an improvement over untreated soil.

Regarding the plasticity index, the mixtures stabilized with cement exhibited a more pronounced reduction compared to those stabilized with brick powder. As shown in Figure 2, the plasticity index of the cement-stabilized mixtures ranged between 7.5% and 11%, while the mixtures with brick powder showed slightly higher values, ranging from 6.5% to 10.5%.

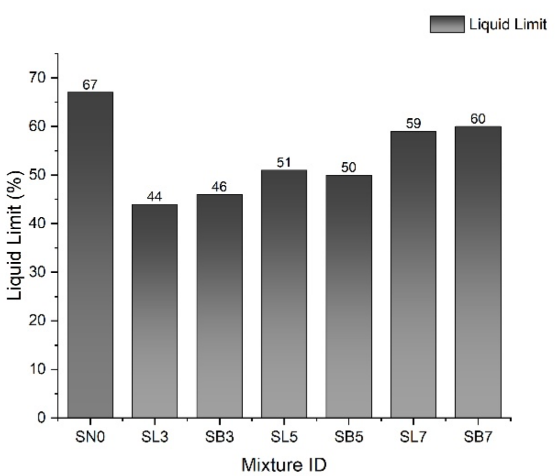

Figure 1. Liquid limit graph with different additive percentages.

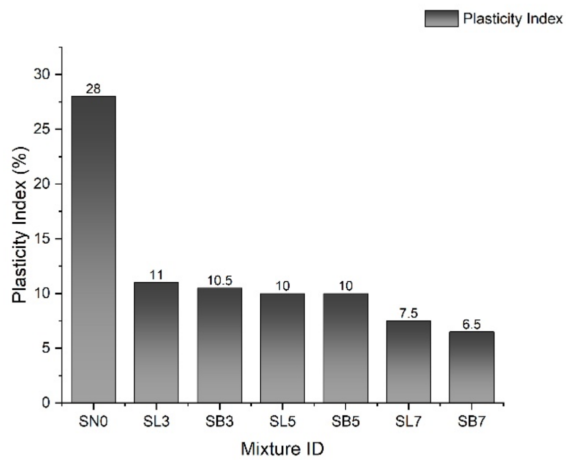

Figure 2. Plasticity index graph with different additive percentages.

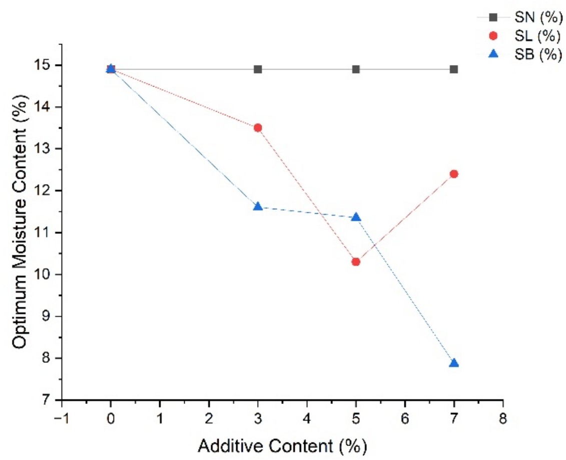

Figure 3. Optimum moisture content graph.

These results support the hypothesis that cement has a stronger effect on improving the soil's plastic behavior by significantly reducing its plasticity compared to brick powder. This reduction in the plasticity index is critical, as it indicates an enhanced ability of the soil to resist plastic deformation, which is desirable for the stability and load-bearing capacity of the stabilized soils.

Regarding optimum moisture content, mixtures with cement exhibited a higher water retention capacity, with values reaching up to 20% for the mixture containing 7% cement (SL7), as shown in Figure 3. In contrast, mixtures with brick powder showed lower optimum moisture values, ranging from 17.5% to 19.5%.

These results suggest that, in addition to improving plasticity, cement also significantly influences the amount of water required to achieve optimal soil compaction. Cement's ability to increase optimum moisture content may be associated with the formation of calcium gel, which enhances water retention in

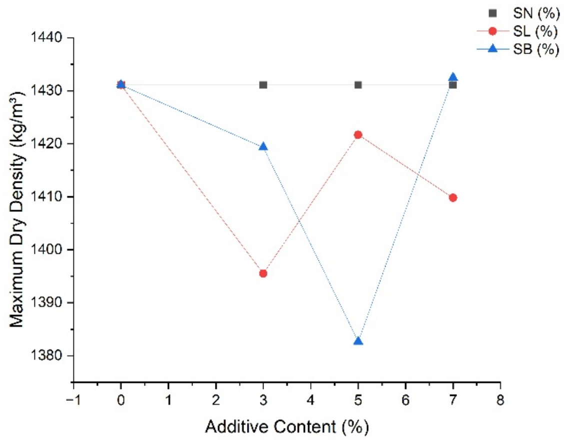

Figure 4. Dry unit weight graph.

the soil. This effect is important for achieving higher compaction density and improved long-term stability.

Finally, with regard to dry unit weight, mixtures stabilized with cement exhibited higher values, reaching up to 1530 kg/m^3, compared to brick powder-stabilized mixtures, which did not exceed 1510 kg/m^3, as shown in Figure 4.

This behavior suggests that cement promotes better soil stabilization, contributing to an increase in the density of the stabilized mixtures. A higher dry unit weight indicates greater soil compaction, which enhances the strength and stability of the material when used in construction, particularly in projects requiring a high degree of compaction.

Figure 5 shows the evolution of the compressive strength of soil samples stabilized with different proportions of Portland cement (series SL3, SL5, SL7) and brick powder (series SB3, SB5, SB7), compared with the untreated soil (SN0). Overall, a progressive increase in strength is observed as curing age increases (7, 14, and 28 days), confirming the typical development of cementitious and pozzolanic processes in soil–binder systems. The treatments incorporating Portland cement produce consistent strength gains from early ages; for instance, the SL7 series exhibits notable improvements over the control as early as day 7, attributable to the early hydration of the C_3S phase and the formation of dense C–S–H gels.

On the other hand, the mixtures stabilized with brick powder display an equally favorable behavior, particularly from 14 days onwards, with SB5 and SB7 standing out. This trend is consistent with the pozzolanic nature of the ceramic residue, whose reaction proceeds more slowly and depends on the availability of $Ca(OH)_2$. In the SB series, where no external cement was added, the availability of calcium is limited to naturally occurring trace amounts in the soil. Therefore, the observed strength gain is primarily attributed to particle rearrangement, flocculation–agglomeration, and microstructural densification, with only a minor contribution from

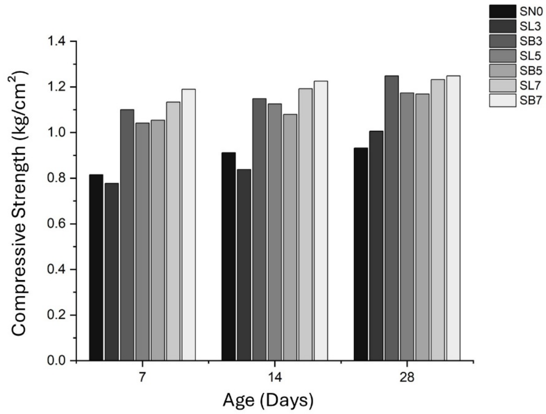

Figure 5. Compressive strength.

slow and limited pozzolanic interactions. At 28 days, the SB7 and SL7 mixtures reach the highest strength values within the dataset, suggesting that both the increased cementitious content and the higher proportion of ceramic material contribute to mechanical enhancement through the formation of secondary cementitious products (C–A–H and C–S–H).

In summary, the graphical comparison shows that both Portland cement and brick powder enhance the strength of the soil, although through different mechanisms. Portland cement provides an immediate improvement, whereas brick powder exhibits a more gradual yet equally effective response, reaching competitive strength values at 28 days. These findings support the potential of ceramic residue as a sustainable alternative for soil stabilization, reducing cement consumption and promoting the valorization of construction industry by-products.

4 Discussion

It is important to note that the proposed physicochemical interpretation is based on indirect evidence derived from the observed mechanical behavior and supported by well-established literature on ceramic residues. No direct chemical or mineralogical analyses (e.g., XRF or XRD) were performed on the specific materials used in this study. Therefore, the mechanisms discussed should be interpreted as a theoretically supported framework rather than experimentally confirmed at the microstructural level. This limitation represents an opportunity for future research to validate the proposed mechanisms through advanced characterization techniques.

These results are consistent with recent contributions reported in the Revista Mexicana de Ingeniería Química, where the use of industrial and construction residues has been associated with improvements in physicochemical performance and sustainability of engineering materials (Montañez *et al*., 2024; Tejeda *et al*., 2019; Torres *et al*., 2019). In particular, the incorporation of aluminosilicate-rich waste into cementitious and geopolymeric systems has been shown to enhance material properties through mechanisms such as pozzolanic reactions and structural densification, supporting the interpretation proposed in this study.

The results obtained in this study confirm that both cement and brick powder are effective additives for improving the plastic and compaction properties of soils. In particular, cement proved to be a more efficient stabilizer, achieving significant reduction in liquid limit and plasticity index compared to brick powder. This behavior is consistent with previous findings, such as those reported by Zhao *et al*. (2023), who observed that cement induces chemical stabilization reactions such as calcium gel formation—that improve soil structure and reduce susceptibility to deformation (Zhao *et al*., 2023). These reactions tend to enhance the mechanical properties of the soil, particularly in terms of compressive and shear strength, which translates into higher load-bearing capacity and improved resistance to cracking. Additionally, cement reduces soil plasticity, decreasing deformability and enhancing performance under load (Li *et al*., 2024).

Regarding brick powder, although it also shows positive effects on soil plasticity, it does not produce as marked a reduction in liquid limit and plasticity index as cement. This may be attributed to the chemical nature of brick powder, which, unlike cement, lacks the same capacity to induce pozzolanic reactions in the soil. Nonetheless, its effectiveness as a stabilizing agent is noteworthy. As reported by Raj *et al*. (2024), the use of recycled materials such as brick powder can be a viable and sustainable option for soil stabilization, due to its low cost and its ability to enhance soil plasticity without significantly compromising long-term performance (Raj *et al*., 2024). Despite its lower efficiency compared to cement, brick powder offers environmental and economic advantages, since it is a recycled material that contributes to waste reduction and minimizes environmental impact.

From an environmental standpoint, several recent studies have emphasized the importance of incorporating recycled materials into geotechnical engineering. According to Alqaisi *et al*. (2020), the use of alternative materials such as brick powder reduces the demand for natural resources and lowers the carbon footprint of construction, making it a sustainable and cost-effective alternative for soil stabilization Alqaisi *et al*., 2020). This approach is increasingly relevant within the framework of circular economy and sustainable waste management.

In terms of compaction properties, the results indicate that cement-stabilized mixtures achieved higher dry unit weights, reaching up to 1530 kg/m^3. This suggests that these mixtures not only exhibit better plasticity but also enhance the soil's compaction capacity and strength. This behavior aligns with the findings of Jia *et al*. (2020), who reported that cement increases the density of stabilized mixtures, improving their shear strength and structural stability (Jia *et al*., 2020). The increase in dry unit weight is associated with improved soil compaction, which enhances its load-bearing capacity and makes it more suitable for construction projects requiring high mechanical performance.

On the other hand, mixtures with brick powder also showed improved compaction properties, although their dry unit weight values were slightly lower than those of cement-stabilized mixtures, with a maximum of 1510 kg/m^3. This difference may be attributed to the physical nature of brick powder, which, lacking the strong reactivity of cement, results in less efficient compaction. However, this does not disqualify brick powder as a viable option. As noted by Ni *et al*. (2022), brick powder remains an effective additive for improving the mechanical properties and crack resistance of untreated soils (Ni *et al*., 2022).

In summary, the choice of stabilizing agent depends on the specific application and project requirements. If the primary objective is to enhance plasticity and mechanical strength, cement is the most effective option. However, brick powder represents an attractive alternative when seeking a more economical and sustainable approach.

From an environmental perspective, the use of recycled brick powder as a soil stabilizer helps reduce the environmental impact associated with the production of Portland cement, whose manufacturing process requires high temperatures (exceeding 1400 °C) and generates significant carbon dioxide emissions. By utilizing brick powder derived from pre-existing ceramic waste such as construction debris or defective pieces from the ceramic industry additional industrial processes are avoided, and the volume of material destined for landfills is reduced.

Economically, brick powder represents a low-cost alternative, as it can be locally sourced with minimal processing. This reduces expenses related to transportation, procurement of commercial inputs, and energy consumption, making it an especially attractive option for rural communities or regions with limited resources.

Moreover, its application promotes a circular economy within the construction sector by transforming waste into a valuable technical resource. This practice also supports the development of public policies aimed at incorporating recycled materials in road infrastructure projects, thereby fostering sustainability and efficiency in the industry.

Furthermore, the compressive strength results reinforce the conclusions obtained from plasticity and compaction behavior, providing a broader understanding of the mechanical performance of the stabilized soils. Mixtures treated with Portland cement (SL3, SL5, SL7) exhibited superior early-age strength due to the rapid hydration of cement and the immediate formation of C–S–H gels, which significantly improve the internal bonding and stiffness of the soil matrix. This explains the notable increases in strength observed at 7 and 14 days, particularly in high-cement mixtures.

In contrast, mixtures stabilized with brick powder (SB3, SB5, SB7) showed a more gradual yet consistent increase in compressive strength over time. While the ceramic residue is less reactive in early stages, its pozzolanic activity becomes more evident at later curing ages. The SB7 mixture, in particular, achieved the highest compressive strength among the brick-powder series at 28 days, approaching the performance of cement-stabilized samples. This behavior indicates that brick powder contributes to long-term strength development through the delayed formation of secondary cementitious compounds, such as C–S–H and C–A–H, which arise from the interaction between amorphous silica, alumina, and available calcium in the soil.

The progressive improvement observed with increasing brick powder content confirms the suitability of the selected dosage range. In particular, the superior performance of the 7% mixture indicates that this proportion provides an effective balance between mechanical enhancement and sustainable material use. Lower contents (3% and 5%) contribute to plasticity reduction and gradual strength gain, while higher contents enhance pozzolanic activity without compromising compaction behavior, supporting the selection of these dosages for practical geotechnical applications.

These findings highlight that, although cement remains the most efficient stabilizer for applications requiring immediate mechanical performance, brick powder provides a valuable sustainable alternative capable of delivering competitive strength at later ages. The combined improvements in plasticity, compaction, and compressive strength confirm the technical feasibility of incorporating ceramic waste into geotechnical applications, supporting both environmental and economic benefits. This reinforces the relevance of brick powder as a viable low-carbon stabilizer for road infrastructure projects.

The results suggest that brick powder alone does not behave as a fully reactive pozzolanic binder due to the limited availability of calcium in the system. Instead, its stabilizing effect is mainly governed by physical and physicochemical mechanisms, while true pozzolanic reactions are more significant in the presence of cement.

Conclusions

The effectiveness of recycled brick powder in stabilizing clayey soils was demonstrated by significant improvements in plasticity and compaction properties. The addition of brick powder at proportions of 3%, 5%, and 7% resulted in a progressive reduction of the plasticity index, indicating decreased deformability and an increased load-bearing capacity without excessive deformation.

The analysis suggests that a 7% brick powder mixture is the most suitable for stabilizing clay soils, achieving better performance by reducing the liquid limit and plasticity index, as well as increasing the maximum dry density. This dosage represents an optimal balance between technical enhancement and efficient additive use.

Although Portland cement exhibited superior mechanical improvement, the use of brick powder offers considerable economic and environmental advantages. Being a recycled and low-cost material, it represents a viable and sustainable alternative to reduce the environmental impact associated with conventional stabilizers.

Beyond the technical benefits observed, the application of recycled brick powder contributes to lowering the carbon footprint linked to soil stabilization by reducing reliance on highly emissive materials such as Portland cement. Its local availability, low cost, and residual origin make it an attractive option for road infrastructure projects in rural or resource-limited areas, promoting practices aligned with circular economy principles and sustainable construction.

In addition to the improvements observed in plasticity and compaction behavior, the compressive strength results provide further confirmation of the mechanical benefits associated with brick powder stabilization. Although cement-stabilized mixtures achieved the highest early-age strength due to rapid hydration reactions, soils treated with brick powder exhibited a steady and meaningful increase in compressive strength, particularly at 28 days. The 7% brick powder mixture demonstrated the best performance among the ceramic-based treatments, indicating that its pozzolanic activity contributes to long-term strength development through the gradual formation of secondary cementitious compounds. This outcome reinforces that brick powder not only improves the workability and compaction characteristics of clayey soils but also enhances their mechanical resistance over time, positioning it as a technically viable and environmentally responsible stabilizer for sustainable road infrastructure.

It should be noted that the present study did not include direct chemical or microstructural characterization techniques such as XRD, XRF, or SEM–EDS. Consequently, the interpretation of physicochemical stabilization mechanisms was based on compositional ranges and reaction pathways widely reported in the literature for recycled ceramic materials. Future research should incorporate advanced analytical techniques to directly verify the formation of cementitious phases and microstructural changes, thereby strengthening the understanding of brick powder–soil interactions.

Long-term studies on the mechanical behavior of soils stabilized with this additive are recommended, particularly under varying moisture, temperature, and cyclic loading conditions, to support its implementation in real-world projects.

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