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Original Article

Evaluation of the Influence of the Addition of Lime, Cement and Calcium Chloride on the Allowable Capacity of Housing Foundations: Cost and Feasibility Analysis

Solis Alex Valero Hinostroza[1], Deysi Katherin Leon Cardenas[1], Yemily Daniela Meza Ninalaya[1], Marko Antonio Lengua Fernandez[1,*]

[1]*Department of Civil Engineering, Continental University, Huancayo, Perú.*

[*]*Corresponding Author : mlengua@continental.edu.pe*

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Abstract - *Amidst the global surge in urbanization, the construction industry faces a critical crossroads: how to transform weak, clayey soils into reliable foundations for sustainable housing-without resorting to expensive or environmentally harmful methods. As climate extremes and population density intensify, innovative ground improvement technologies have become an urgent priority for developing nations. This research pioneers the use of calcium chloride as a high-performance, low-cost additive for clayey soil stabilization, challenging the dominance of traditional lime and cement solutions. Through a comprehensive experimental program-including granulometry, Atterberg limits, Proctor compaction, California Bearing Ratio (CBR), direct shear, and bearing capacity tests-various dosages of lime (3–12%), cement (5–20%), and calcium chloride (2-8%) were evaluated. Cost and feasibility analyses were also performed to ensure real-world applicability. The findings are striking: 6% calcium chloride not only delivered a dramatic leap in bearing capacity (116% increase, from 1.13 to 2.44 kg/cm²), but also achieved a remarkable 912% surge in unconfined compressive strength. Even more compelling, construction costs plummeted-concrete expenses dropped by 72% and steel by 75% compared to untreated soils. These results reveal a game-changing path for resource-limited regions, where traditional stabilization is often unaffordable. By demonstrating both superior mechanical performance and major cost savings, this study positions calcium chloride as a catalyst for a new era in geotechnical engineering-where resilient, affordable infrastructure can be achieved on even the poorest soils.*

Keywords *- Soil stabilization, Calcium chloride, Lime and Cement.*

1. Introduction

In recent decades, soil stabilization has become an essential field in civil engineering, driven by the need to guarantee safe, stable, and durable infrastructure in the face of adverse geotechnical conditions, which represent one of the main challenges for urban and transport development. The global soil stabilization market is projected to reach a value of USD 42,898.32 million by 2032, with a compound annual growth rate of 5.1 % between 2024 and 2032 [1], reflecting both the magnitude of the problem and the growing relevance of technological solutions. Nevertheless, it is estimated that approximately 44 % of projects carried out in critical soils experience significant delays and cost overruns as a result of the limited load-bearing capacity of the soil [2]. This situation demonstrates that the problem is not limited to mechanical strength alone but directly affects both the economic viability and the structural safety of construction projects. In this context, the situation is particularly critical in Latin America, which accounts for around 8 % of the revenues of the global soil stabilization market [3], and where a strategic opportunity exists to implement innovative solutions adapted to its complex geotechnical reality. In the case of Peru, a large portion of the territory exhibits limitations related to allowable bearing capacity, compromising the safety of buildings and road infrastructure [4].

The problem intensifies in rapidly growing urban areas, where demographic pressure demands immediate solutions. In Lima and Callao, for example, the Japan-Peru Center for CISMID identified districts such as San Juan de Lurigancho, Chorrillos, and Villa El Salvador built on sandy or poorly compacted soils [5], a condition that significantly increases seismic vulnerability. In Villa El Salvador, approximately 88 % of dwellings are at risk in the event of a major earthquake [6, 7]. Similarly, in Huancayo, heterogeneous soils have been identified: while some sectors are well consolidated, others, such as La Ribera, Palián, Torre Torre, and Pucará, consist of silty-clayey soils whose allowable capacity barely reaches 0.85 kg/cm², below the international standard of 1.0 kg/cm² [8]. This condition compromises both structural safety and the durability of civil works, making it essential to focus on stabilization approaches that increase the soil's load-bearing capacity to standardized limits.

Given this scenario, chemical stabilization using binders has established itself as one of the most efficient strategies to strengthen the bearing capacity and mechanical properties of weak soils [1, 2]. Among the most commonly used materials are cement and lime, due to their cementing properties and wide availability in the construction industry [9]. In the Peruvian context, cement production reached 1.06 million tons in 2024, while lime consumption, a key input for the manufacture of cement and other stabilizers, reached 30 million tons annually, highlighting its growing importance in soil improvement projects [10, 11].

2. Materials and Methods

In Iran, scholars from the Department of Civil Engineering analyzed the stabilization of clayey soils by incorporating ordinary Portland cement as a chemical binder. The mixtures, prepared with 5%, 10% and 15% cement by dry weight, were tested through unconfined compressive strength and bearing capacity analyses. The untreated soil exhibited a capacity of only 2 MPa, whereas the stabilized samples reached up to 12 MPa with 15% cement. The improvement was attributed to the pozzolanic reaction between calcium hydroxide, released during cement hydration, and the active silica and alumina in the clay minerals, producing cementitious gels such as Calcium Silicate Hydrate (C–S–H) and Calcium Aluminate Hydrate (C–A–H). These compounds progressively filled the soil pores and created inter-particle bonds, thereby reducing compressibility, increasing stiffness and markedly enhancing shear resistance. This evidence reconfirms the efficiency of Portland cement in strengthening clayey subgrades and foundation soils under heavy loading conditions [12].

In India, researchers at the National Institute of Technology examined the use of Cement Kiln Dust (CKD) as a sustainable additive for clay stabilization. CKD, rich in lime, free CaO and other pozzolanic oxides, was added in dosages of 5%–20%. Mechanical tests revealed that at 20% CKD, the bearing capacity rose by approximately 12%, and the California Bearing Ratio (CBR) increased significantly. The mechanism involved the hydration of free lime and its reaction with the soil's clay minerals, producing cementitious bonds that reduced plasticity and swelling while improving density. Furthermore, CKD lowered permeability and shrinkage, improving volumetric stability of the subgrade. These results not only confirmed the technical feasibility of CKD but also underlined its environmental importance, since it reuses a large-volume industrial residue from cement plants [13, 14].

In China, the Institute of Geotechnical Engineering of the School of Transportation investigated cement/slag-based mixtures for stabilizing soft clays. Cement contents of up to 50% were tested, curing samples for 28 days. The stabilized clays reached compressive strengths exceeding 1.0 MPa, while untreated soils barely resisted 100–150 kPa. This increase was associated with the formation of secondary cementitious compounds due to the interaction between slag and calcium hydroxide from cement hydration, which accelerated long-term strength gain. The study demonstrated that cementitious binders increased strength and improved durability under wetting–drying cycles, which is critical in road foundations and embankments subjected to fluctuating environmental conditions [15].

In Tirunelveli, India, lime stabilization of clayey soils was systematically analyzed with additions from 1% to 10%. Unconfined compressive strength increased from 7 MPa in natural soil to 12 MPa with 10% lime. The reaction mechanism involved cation exchange between Ca^{2+} ions from lime and Na^{+} or K^{+} ions adsorbed in the clay mineral lattice, reducing double-layer thickness and decreasing soil plasticity. Additionally, long-term pozzolanic reactions generated C–S–H gels, which further enhanced strength. The treated soils exhibited reduced swelling potential, lower liquid limit and improved workability, confirming lime's suitability for pavements and embankments [16, 17].

In Nigeria, lateritic soils were treated with calcium chloride ($CaCl_2$) in proportions of 0%–8%. Mechanical testing showed significant gains in UCS and CBR, with 4% $CaCl_2$ producing UCS values of 298.1, 356.3 and 391.7 kN/m² after 7, 14 and 28 days of curing, respectively. The unsaturated CBR rose to 8.02%. The improvement was due to Ca^{2+} ions accelerating cementation processes and reducing soil suction variability, while chloride ions promoted salt crystallization within the pore spaces, increasing particle interlocking. This chemical stabilization improved strength, stiffness and reduced collapsibility in lateritic soils commonly used as subgrades [18, 19].

In India, studies evaluated expansive soils treated with alkophin (a mineral additive with silica and alumina phases) and calcium chloride. Proportions of 3%–9% alkophin and 0.25%–1% $CaCl_2$ were tested. Results showed that the plasticity index and swelling potential decreased, while UCS and dry unit weight increased. The optimum combination was 6% alkophin and 1% $CaCl_2$, producing stable soil matrices with reduced permeability and higher resistance to shrink–swell cycles. This synergy confirmed that blended additives can control expansion by both reducing double-layer thickness and creating cementitious bonds [20].

In the United Kingdom, a literature review demonstrated the potential of Calcium Carbide Residue (CCR), an industrial by-product rich in calcium hydroxide, for soil stabilization. CCR-treated soils showed enhanced compressive and shear strength, reduced swelling pressure and improved compressibility. In addition, CCR immobilized heavy metals and other contaminants through chemical precipitation and ion exchange, which added environmental benefits. This makes CCR not only a mechanical stabilizer but also a remediation material for polluted soils, reinforcing its sustainable use in geotechnical engineering [21].

In Malaysia, stabilization of highly organic soils with Magnesium Chloride ($MgCl_2$) was carried out. The natural soil had very poor mechanical characteristics (UCS of 13 kPa, liquid limit of 128.25%, and organic matter content above 50%). When 6% $MgCl_2$ was incorporated, UCS rose to 96 kPa after 28 days, nearly seven times higher. Microscopic analysis by FESEM and EDAX revealed reduced porosity and formation of Magnesium Silicate Hydrate (M–S–H), which acted as a binder between soil particles. However, dosages higher than 9% reduced strength because of inter-particle repulsion and excessive salt crystallization. The results confirmed $MgCl_2$'s dual role as a chemical stabilizer and microstructural modifier [22].

In Iran, complementary research on bentonite and yellow marl stabilized with $MgCl_2$ (3%–12%) at different curing temperatures (5°C, 25°C, 35°C) demonstrated that UCS increased with curing at 25°C, but higher curing temperatures led to lower strengths due to incomplete ion exchange. Direct shear tests showed strength reduction under saturation, although cohesion improved initially. XRD, SEM, FTIR, and EDAX analyses confirmed the presence of Magnesium Silicate Hydrate (MSH) and Magnesium Aluminate Hydrate (MAH), which enhanced bonding by filling pores and forming flocculated structures. Thus, $MgCl_2$ was shown to be sensitive to curing temperature but effective in promoting microstructural reorganization [23].

In Spain, sulfate-bearing soils from the Ebro Valley were treated with PC-8, a magnesium-rich binder. At 4%–8% dosage, expansive clays improved from 0.5–1.0 MPa to 2–5 MPa in UCS, while recycled aggregates contaminated with 5% sulfates reached 11–13 MPa when PC-8 was combined with GGBS. Long-term swelling tests confirmed that PC-8 significantly reduced sulfate expansion, outperforming lime-based stabilization. This is attributed to the binding capacity of magnesium-based compounds, which react with sulfates to form stable, non-expansive products [24].

In Malaysia, marine clay from the West Coast Expressway project was stabilized with $MgCl_2$. Samples treated with 6% $MgCl_2$ peaked at 137 kPa UCS at seven days, compared with untreated samples of about 60–70 kPa. However, strength decreased over longer curing due to secondary reactions that induced repulsive forces between clay particles. This highlights the importance of monitoring long-term stability when using salt-based stabilizers [25].

In India, lime additions of up to 25% in soils with plasticity indices between 10 and 30 significantly reduced plasticity and increased bearing capacity, validating lime as a reliable additive for pavement subgrades. Strength gains were mainly due to cation exchange and pozzolanic reactions producing long-lasting cementitious bonds [26].

In Turkey, phosphogypsum (PG) combined with lime was tested for expansive clays. At 30% PG and 4% lime, UCS reached 1.82 MPa with a CBR of 92.2%, exceeding pavement subbase design standards. At 20% PG and 6% lime, UCS rose to 3.76 MPa, nearly 16 times the natural soil's strength. The treatment also reduced the liquid limit, plasticity index and free swelling. These improvements confirmed that PG–lime combinations can provide strong, non-expansive subbases while recycling industrial residues [27].

In Australia, mixtures of expansive clay with Tire-Derived Aggregates (TDA) and lime were tested. UCS values rose from 126.7 kPa in untreated soils to more than 452.2 kPa at 10% TDA and 6% lime, while swelling potential dropped from 7.5% to 0.5%. The use of TDA not only improved geotechnical properties but also contributed to environmental sustainability by reusing waste tyres [28, 29].

In Turkey, expansive soils treated with lime (5%), fly ash (20%) and gypsum (5%) under four months of curing showed substantial reductions in swelling. Free swelling dropped from 90.1% to 0.2% with lime in surface mixing, and to 43.3% with column applications. Fly ash and gypsum also improved swelling resistance but were less effective than lime. The study concluded that surface mixing is optimal for shallow stabilization, while column methods are more effective for deep stabilization of expansive subgrades [30].

Most previous studies have concentrated on improving the geomechanical behavior of soils, emphasizing parameters such as compressive resistance, CBR, and complementary indicators, including reduced plasticity or increased maximum dry density. Although these factors are relevant, comparatively less attention has been devoted to the evaluation of allowable bearing capacity, which represents a practical and decisive criterion in foundation engineering.

This gap is significant, since the structural safety and economic feasibility of civil works depend not only on the intrinsic enhancement of soil properties but also on the actual ability of the ground to transfer loads through foundations without compromising stability. Therefore, it is necessary to promote integrated approaches that connect soil property improvement with its direct implications for the bearing capacity of shallow foundations. In this context, the present research aims to analyze the effect of lime, cement, and calcium chloride additions on the allowable bearing capacity of residential foundations, incorporating in parallel a cost–benefit and feasibility assessment aimed at defining practical and sustainable design criteria for civil infrastructure.

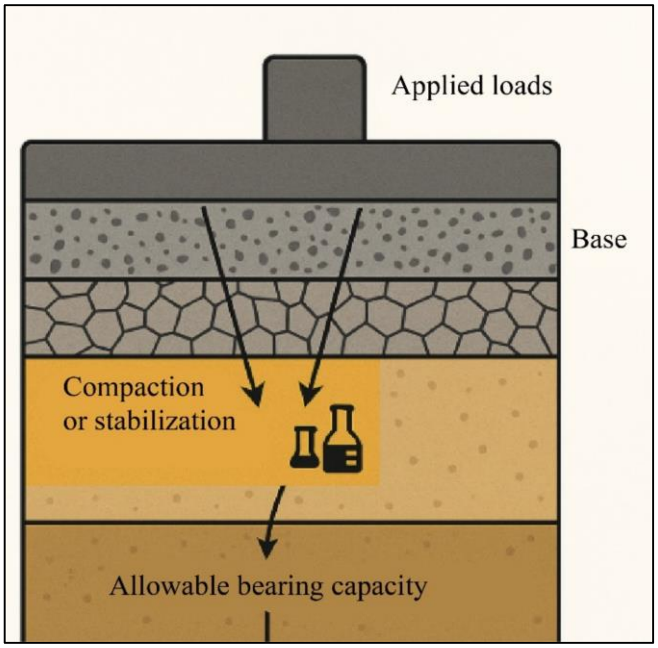


Fig. 1 Pavement layers and their influence on the bearing capacity of the soil

3. Materials and Methods

3.1. Soil

Soil is understood as a natural medium formed by a combination of mineral particles and organic matter, with voids that may be partially or fully occupied by air and water in different proportions [31]. Its mechanical performance is governed by parameters such as gradation, plasticity, cohesion, permeability, and compaction, making it a key component in civil engineering projects. The bearing capacity and stability of soils directly condition the design efficiency and service performance of structures [32].

3.2. Soil Stabilization

Soil stabilization refers to the enhancement of its physical, chemical, and mechanical properties in order to achieve greater strength and long-term durability under external loads and environmental variations. This improvement can be carried out through methods such as mechanical compaction, chemical treatments, or the incorporation of stabilizing agents like cement, lime, polymers, industrial by-products, or other additives [33].

3.3. Subgrade

The subgrade corresponds to the natural soil layer that functions as the foundation for pavements, transmitting and distributing applied loads to the underlying ground [34]. Its stability, often increased through compaction or stabilization, must guarantee sufficient bearing capacity to avoid premature deformations or structural failure [35].

Figure 1 shows that stabilizing and compacting the subgrade increases pavement capacity, reduces settlement, and extends road service life.

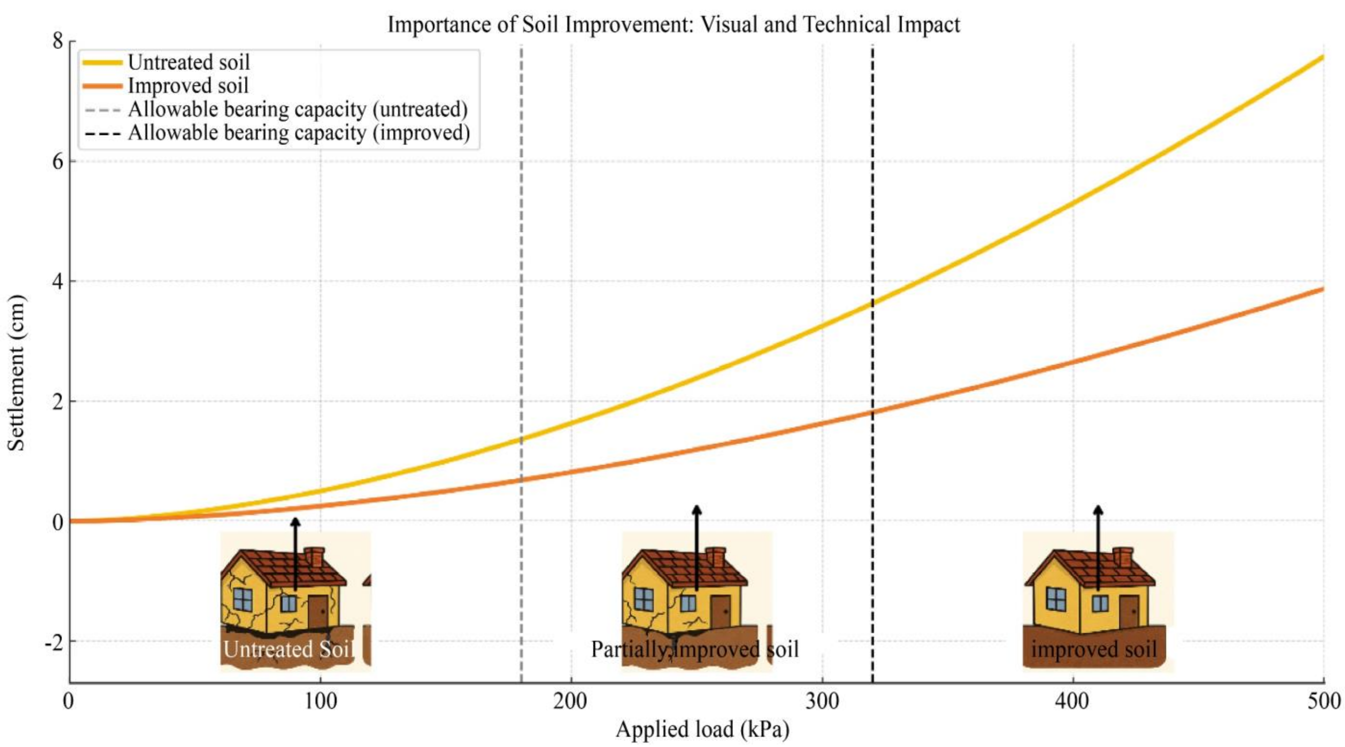


Fig. 2 Importance of soil improvement: visual and technical impact

3.4. Allowable Capacity

The allowable soil capacity is defined as the load that can be safely carried without causing excessive settlement or structural failure [36]. It is expressed in units of pressure (kPa or kg/cm²) and is fundamental for the design of foundations in buildings. The value is controlled by variables such as soil classification, compaction, water content, and the presence of cohesive or coarse-grained particles [37]. Figure 2 integrates the load-settlement response of the soil with the structural performance of a building subjected to different levels of improvement. It is observed that, for an unimproved soil, the curve presents a steep slope, indicating significant settlements under moderate loads and, consequently, the appearance of structural cracks. As the soil is improved, the slope of the curve decreases and the allowable capacity (intersection with the normative settlement limits) increases, allowing it to support higher loads with lower deformations.

Visually, this is represented by progressively more stable and crack-free dwellings, showing that soil intervention - through stabilization or compaction techniques - not only increases the allowable capacity, but also mitigates the occurrence of differential settlement, preserving the integrity of the foundation and superstructure. Thus, the figure reinforces the importance of adequate soil treatment to ensure the safety and durability of buildings.

Fig. 3 Cement

3.5. Cement

Cement is widely used in the manufacture of concrete and mortar, and when mixed with water, it produces a paste that hardens through hydration. Its performance can be further enhanced with the addition of supplementary materials such as fly ash or blast furnace slag, which also provide sustainability benefits and improve its behavior under different conditions [39].

The cement used in the project, shown in Figure 3, corresponds to Portland cement type I and Table 1 details its main physical and chemical properties, highlighting that its 7% air content significantly improves the workability of the mixture. With a density of 3.13 g/cm³, it reflects a considerable mass, while its compressive strength of 449 kg/cm² at 28 days highlights its relevance for structural performance. In addition, the levels of magnesium oxide (2.9%) and sulfur oxide (2.8%) are crucial to avoid unwanted expansive reactions, ensuring the material's long-term stability.

Table 1. Physical and chemical properties of cement

Cement	Value
Air content (%)	7
Density g/cm^3	3.13
Compressive strength at 28 days kg/cm2	449
MgO (%)	2.9
SO3 (%)	2.8

3.6. Lime

Lime is an alkaline material produced through the calcination of limestone at elevated temperatures. It is available principally in two variants: calcium oxide and calcium hydroxide [40]. This material is frequently applied in geotechnical practice to improve clayey soils by lowering plasticity and increasing load-bearing strength. Lime improves the cohesion, shear strength, and durability of soils and is less expensive and more environmentally friendly than other stabilizers. It is produced from limestone and can be combined with other materials such as fly ash to optimize its properties [41].

Figure 4 shows the lime used, while Table 2 presents the chemical properties of lime carbonate, highlighting its 98% calcium carbonate content, which qualifies it as a high-purity material, ideal for applications requiring chemical stability. Among its secondary components, manganese oxide (0.55%) can influence the coloration and catalytic properties of the material; silica (0.27%) and alumina (0.50%) affect its reactivity and mechanical strength; iron trioxide (0. 09%) contributes to coloration and structural resistance; titanium dioxide (0.03%), appreciated in industrial processes, improves resistance to degradation; and sulfur trioxide (0.25%), which in high concentrations, could modify the reactivity of the material.

Table 2. Chemical properties of lime carbonate

Lime	(%)
Calcium Carbonate	98.00
Manganese Oxide	0.55
Silica	0.27
Alumina	0.50
Iron Trioxide	0.09
Titanium Dioxide	0.03
Sulfur Trioxide	0.25

Fig. 4 Lime

3.7. Calcium Chloride

Calcium chloride is a compound formed by calcium and chlorine, present in minerals such as sinjarite and antarcticite. It appears as a crystalline material of whitish aspect, with high solubility in water. It shows hygroscopic behaviour and liberates heat when undergoing dissolution. It is obtained from natural sources such as brine and seawater.

In the food industry, it is used as an additive (E509) to improve the firmness of fruits and vegetables, in cheese making and as a stabilizing agent in beverages. It is also used in dust and ice control on roads, and as an accelerant in construction [42].

Figure 5 shows the calcium chloride used, and Table 3 presents the chemical and physical properties of calcium carbonate, where the density of calcium carbonate is 2.15 g/cm³, indicating that it is a relatively light material. Its melting point is 772 °C, which makes it resistant to high temperatures and suitable for applications in thermally demanding environments.

In addition, its chemical composition includes 36.1% calcium (Ca) and 63.9% chlorine (Cl), elements that give it desiccant properties.

Table 3. Properties of calcium carbonate

Physical Properties	
Density	2.15 g/cm^3
Melting point	772 °C
Hygroscopicity	25%
Chemical properties	
Calcium (Ca) content	36.1%
Chlorine (Cl) content	63.9%

Fig. 5 Calcium chloride

3.8. Measurement Indicators

3.8.1. Soil

Once the soil has been extracted and placed in the laboratory, the process of quartering begins, as shown in Figure 6, in order to start the subsequent tests properly. This process is crucial to ensure that the sample is representative of the original soil and that the tests reflect the real conditions of the material. In this way, the accuracy and validity of the results obtained in subsequent tests are guaranteed.

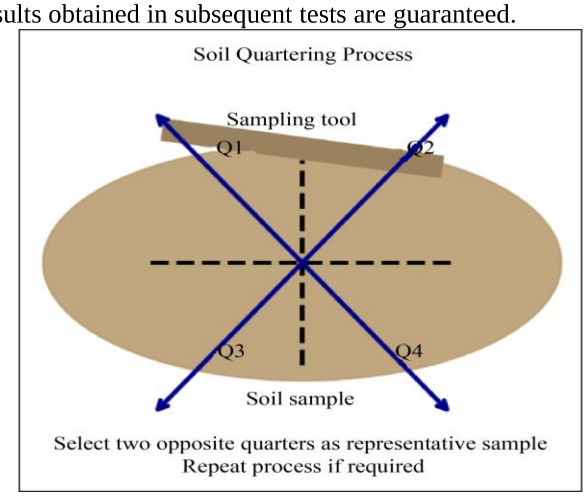


Fig. 6 Soil sample

3.8.2. Granulometry

Granulometry is the analysis of the particle size distribution in a granular material, fundamental to characterize its composition, optimize the formulation of mixtures and ensure quality in construction and engineering applications [43]. The particle size analysis was carried out in accordance with the MTC E 107 standard [44]. According to this standard, the soil sample must be completely dried; in this case, an oven was used at a temperature of 110 °C until reaching constant weight, ensuring the total elimination of moisture. Subsequently, the sample was subjected to a sieving process in which the sieves varied in size from 5" to number 200, moving in a circular motion to keep the material in constant movement over the meshes. This procedure, as shown in Figure 7, ensures an effective separation of the particles and allows a correct classification of the soil.

Fig. 7 Granulometry

3.8.3. Atterberg Limits

The determination of the Atterberg limits was carried out in order to characterize the soil plasticity, following the procedures established in standards MTC E-110 and MTC E-111, for the determination of LL. A 100 g soil sample previously sieved through the No. 40 mesh was tested using the Casagrande apparatus according to the standardized method, obtaining a value of 40%. LP was determined by rolling threads of approximately 3 mm in diameter until they fractured into segments close to 6 mm in length, yielding a value of 22%. Based on these results, the plasticity index (IP) was calculated using the relation IP = LL – LP, resulting in a value of 18%, which is a direct indicator of the plastic behavior of the analyzed material.

3.8.4. Soil Classification

Soil classification is fundamental to understanding soil properties and behavior. In this work, the soil was classified as CL (low plasticity clay), as shown in Figure 8. This indicates that the soil has moderate compactability and some sensitivity to moisture variation, which may influence its behavior under different environmental conditions.

Symbol	Description (USCS Classification)
GW	Well-graded gravels, gravel-sand mixtures, little or no fines
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
GM	Silty gravels, gravel-sand-silt mixtures
GC	Clayey gravels, gravel-sand-clay mixtures
SW	Well-graded sands, gravelly sands, little or no fines
SP	Poorly graded sands, gravelly sands, little or no fines
SM	Silty sands, sand-silt mixtures
SC	Clayey sands, sand-clay mixtures
ML	Inorganic silts, elastic silts, very low plasticity
CL	Inorganic clays, low to medium plasticity
OL	Organic silts and organic clays, low plasticity
MH	Inorganic silts, high plasticity
CH	Inorganic clays, high plasticity
OH	Organic clays, high plasticity

Fig. 8 Soil classification symbols

3.8.5. CBR

Modified Proctor

For the compaction analysis, the soil samples were modified with lime (3–12%), cement (5–20%), and calcium chloride (2–8%) under different moisture conditions. Each blend was introduced into the Proctor mold and densified through incremental layering, after which cylindrical specimens were extracted, as shown in Figure 9. The specimens were then weighed, and a portion was partially oven-dried to determine dry unit weight and water content. By repeating this procedure with the different additive dosages, the compaction curves were obtained, from which the maximum dry density and the optimum moisture ratio corresponding to each mixture were established.

Fig. 9 Modified proctor

Figure 10 presents the compaction curve of the natural soil without additives, where the maximum dry density of approximately 2.16 g/cm³ is achieved at an optimum water content of around 7.8%. This point reflects the most favorable balance between water and compaction, allowing the soil to reach its peak dry density according to the Proctor test. When the moisture level exceeds this optimum, the dry density decreases due to the disruptive effect of excess water in the compaction process.

CBR

The CBR test was conducted following the MTC E-132 standard [44], maintaining the normative conditions of compaction at optimum moisture, soaking until full saturation, and load application up to 2.5 mm and 5.0 mm penetrations. The contribution of this research lies in the incorporation of lime, cement, and calcium chloride into the soil before compaction, in order to evaluate their direct influence on the bearing capacity compared to untreated soil. The experimental sequence and testing setup are presented in Figure 11 (a-g), which illustrates the process from mixing with water and additives to compaction, soaking, and load application in the equipment.

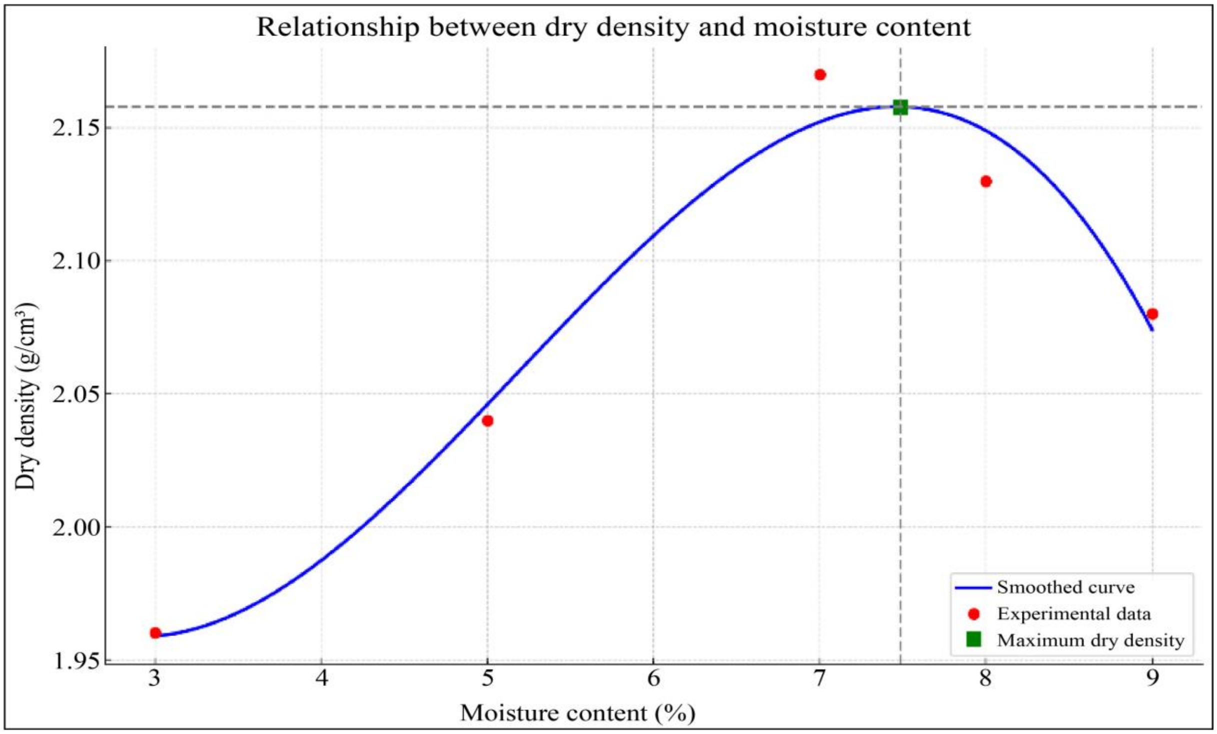


Fig. 10 Maximum dry density vs. Moisture content

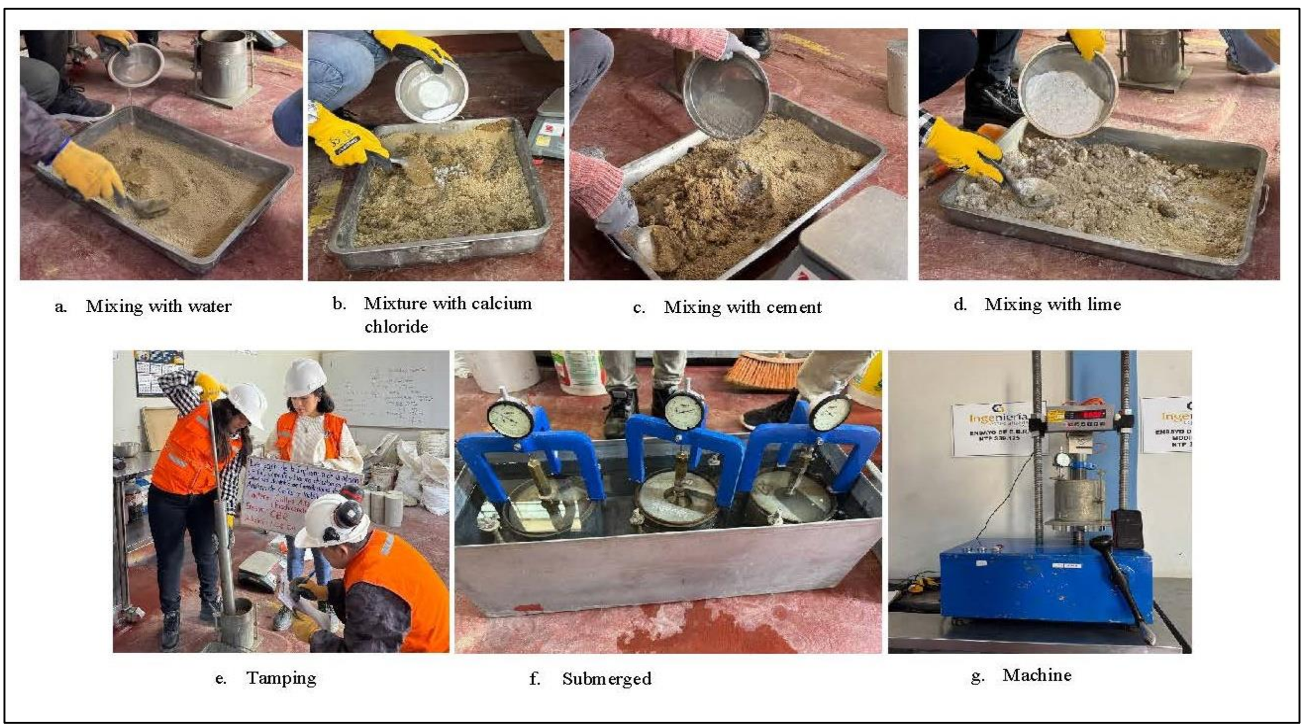


Fig. 11 CBR

Direct Cuy

The analysis followed the MTC E-123 standard [44] using specimens prepared with soil passing the No. 4 sieve and tested under consolidated drained conditions at a controlled displacement of 0.5 mm per minute. Figure 12 documents the specimen preparation, shear box assembly, and loading setup. The study focused on how the incorporation of lime, cement, and calcium chloride at programmed dosages modifies the shear response of the soil, quantified by the parameters c′ and φ′.

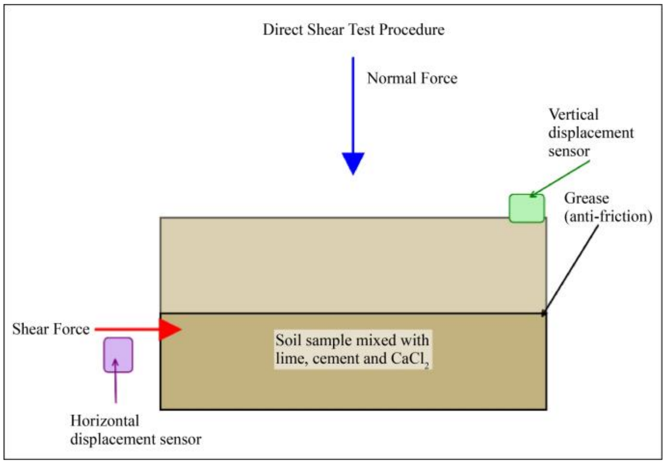


Fig. 12 Direct cut

Unconfined Compressive Strength

The test was performed under two control modes: deformation control and load control. In the first case, axial strain was applied at a constant rate ranging from 0.5% to 2% per minute, while both load and deformation readings were taken every 30 seconds until specimen failure or until reaching 20% strain. Under load control, the applied stress was adjusted to achieve a progressive axial deformation, with continuous monitoring of load-displacement behavior. This methodology enabled the assessment of how the incorporation of lime, cement, and calcium chloride modified the unconfined compressive strength of the soil in comparison with the untreated condition, as illustrated in Figure 13.

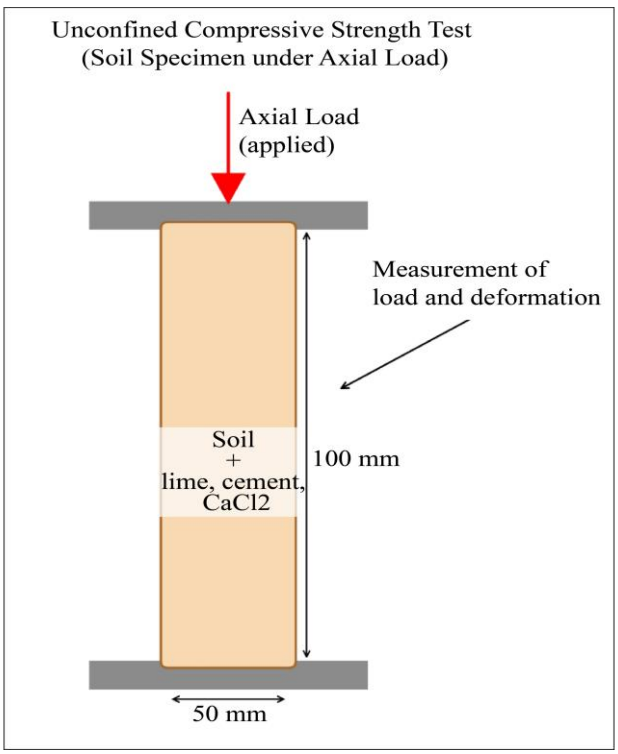


Fig. 13 Unconfined compressive strength

4. Results and Discussion

This section presents the outcomes of adding various proportions of lime, cement, and calcium chloride to soil mixtures, with emphasis on evaluating their influence on the material's behavior.

4.1. CBR

4.1.1. CBR 95% and 100% without Addition

Figure 14 shows the soil without additives (0%), which reached a CBR of 2.98% at 95% compaction and 4.35% at 100%. These values reflect a very low strength and are insufficient for housing foundations. The poor performance is explained by the absence of cementing agents binding the particles, resulting in a weak skeleton and high deformability. This condition coincides with that described for untreated clayey soils, where plasticity and low dry density limit the support capacity [47].

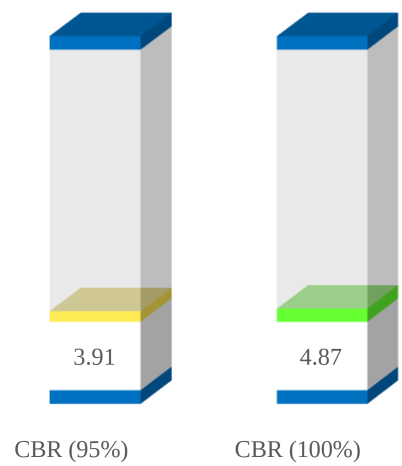


Fig. 1 CBR

4.1.2. CBR 95% with Lime, Cement and Calcium Chloride

Figure 15 shows the response of soils treated with lime, cement, and calcium chloride compacted to 95%. For lime addition, the CBR rose from 2.98% in the untreated sample to 3.91% with 3%, to 4.87% with 6%, and reached 7.95% at 9%.

When the lime content was further increased to 12%, the strength dropped to 6.03%. This trend is attributed to the hydration of lime, which produces $Ca(OH)_2$. The presence of this compound elevates the alkalinity of the medium, accelerating the breakdown of siliceous and aluminous phases in clay minerals and enabling the subsequent formation of cementitious gels (C-S-H and C-A-H), which increase cohesion, while cation exchange replaces monovalent cations with Ca^{2+}, reducing the diffuse double layer and promoting particle flocculation. Nevertheless, when the dosage exceeds the optimum value, the accumulation of free lime produces an overly rigid soil with shrinkage microcracking, which explains the observed drop. In this regard, Salehi et al. [47, 48] also found that lime can increase CBR and compressive strength by 1.37 and 1.24 times, respectively, but that excessive doses reduce its effectiveness.

Cement, on the other hand, showed a more pronounced improvement: the CBR increased to 5.21% with 5%, 8.91% with 10%, and reached 16.87% with 15% addition. However, when the dosage was increased to 20%, the value dropped to 14.25%. The increase is explained by the fact that cement, upon hydration, forms products such as Calcium Silicate Hydrates (CSH) that densify the soil matrix, fill pores, and reduce compressibility while encapsulating clay particles and reducing their plasticity.

However, an excess of cement generates an overly rigid and brittle structure, with loss of ductility and capacity to dissipate stresses. Consequently, resistance to dynamic loads decreases. This result is consistent with the findings of Bandara et al. [49], who, when stabilizing road soils, reported a 97% increase in CBR and up to a 275% increase in dry density with 3.5% cement, but warned that higher contents may reduce treatment efficiency due to over-rigidity.

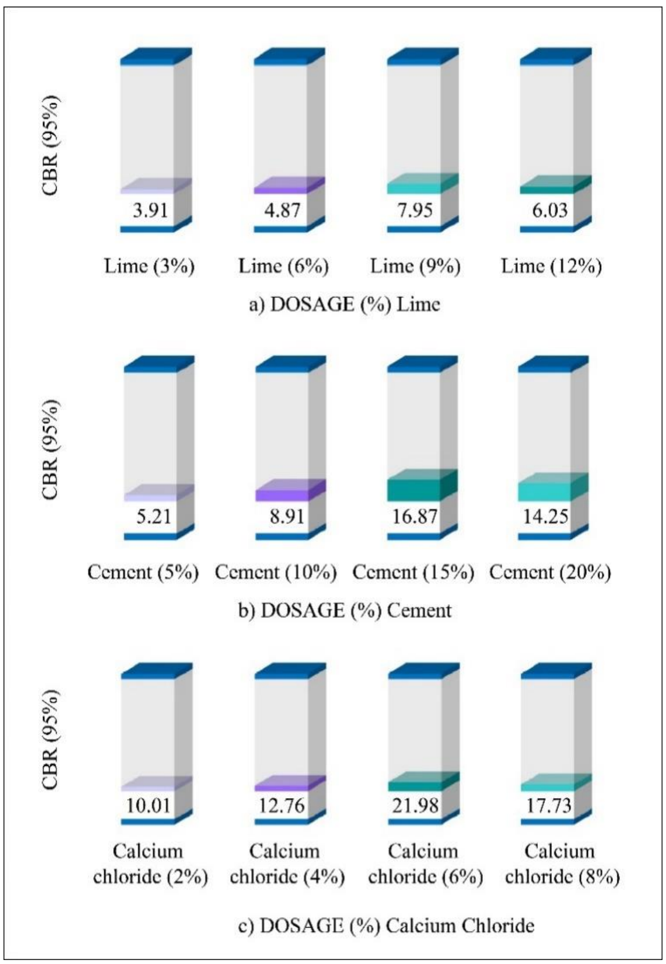


Fig. 2 CBR 95%

Finally, calcium chloride was the additive with the greatest impact: the CBR increased to 10.01% with 2%, 12.76% with 4%, and reached a maximum of 21.98% with 6%. However, with an 8% dosage, the value decreased to 17.73%. The increase is due to the fact that $CaCl_2$ provides Ca^{2+} ions that replace weak cations in the exchange complex, reducing the diffuse double layer and promoting the flocculation of fine particles, which increases cohesion and reduces plasticity. Moreover, this compound accelerates hydration processes that consolidate the structure in the short term. However, higher doses lead to salt crystallization and electrostatic repulsion, reducing internal cohesion. This behavior is consistent with the findings of researchers in Nigeria [18, 19], who reported increases in Compressive Strength (UCS) up to 391.7 kN/m^2 at 28 days of curing and an unsaturated CBR of 8.02% with 4% $CaCl_2$, but observed reductions when the optimum dosage was exceeded.

In conclusion, the results show that all three additives follow the same pattern: significant increases up to an optimum value, followed by a decrease when the appropriate dosage is exceeded. While lime acts by reducing plasticity and promoting pozzolanic reactions, cement densifies the structure through hydration, and calcium chloride improves flocculation and increases ionic cohesion. In excess, all produce negative effects: over-rigidity in lime and cement, and loss of cohesion due to ionic dispersion in the case of calcium chloride.

4.1.3. 100% CBR with Lime, Cement and Calcium Chloride

Figure 16 presents the behavior of soils treated with lime, cement, and calcium chloride at full compaction. When lime was incorporated, the CBR of the untreated soil (3.91%) rose progressively, reaching 5.19% with 3%, 7.34% with 6%, and peaking at 11.07% with 9%. At 12%, however, the strength declined to 10.65%.

This tendency is attributed to the increase in alkalinity produced by lime hydration, which promotes the breakdown of clay minerals and stimulates the generation of reaction products such as C-S-H and C-A-H, enhancing the internal soil framework. The exchange of Ca^{2+} with lighter cations also diminishes the diffuse double layer, favoring flocculation and strengthening particle bonding. Once the optimum lime dosage is exceeded, surplus material remains unreacted, leading to accumulation within the soil matrix and a subsequent decrease in strength.

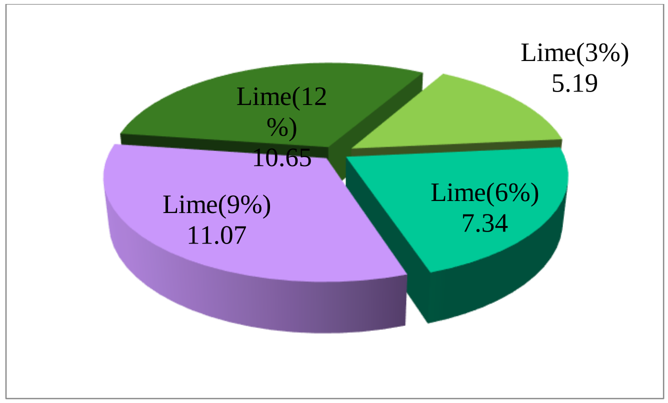
Similarly, Salehi et al. [47, 48] reported that adding lime improved CBR and UCS by factors of 1.37 and 1.24, respectively, with diminished effectiveness at higher dosages. Although their work primarily addressed UCS, the mechanisms they described align with those used to interpret the rise and subsequent decline observed in the CBR results of this study, reinforcing that both parameters consistently capture lime-induced changes in soil behavior. In the case of cement, the CBR increased to 7.87% with 5%, 10.19% with 10%, and reached a maximum of 18.87% with 15%, before decreasing to 16.73% with 20%. This behavior is due to the hydration of cement compounds (C_3S and C_2S), which generate cementitious products capable of filling voids and densifying the soil matrix, thereby reducing its compressibility and encapsulating clay particles. However, once the optimal threshold is exceeded, the soil–cement matrix becomes rigid and brittle, losing ductility and the ability to absorb deformations.

Consistent with these findings, Bandara et al. [49] reported that stabilizing soils for road construction with cement increased CBR by up to 97% and maximum dry density by 275% with only 3.5% addition. However, higher dosages reduced effectiveness due to excessive stiffness, confirming that both UCS and CBR follow the same pattern of improvement followed by a loss of efficiency. The results of this study, focused on CBR, expand this conclusion and show that the trend also applies to parameters directly related to soil bearing capacity.

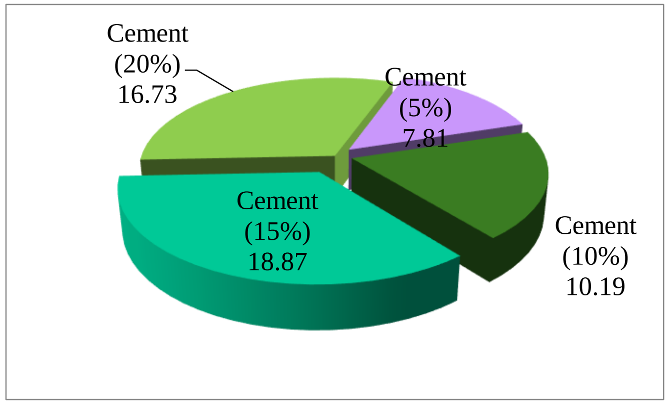
Finally, calcium chloride was the additive with the greatest effect: the CBR rose to 13.45% with 2%, 15.13% with 4%, and reached a maximum of 28.33% with 6%, before decreasing to 24.87% with 8%. The increase is attributed to the replacement of weak cations with Ca^{2+}, which reduces the diffuse double layer and promotes particle flocculation, thereby increasing cohesion. Moreover, $CaCl_2$ accelerates hydration processes that consolidate the soil in the short term. However, when the concentration exceeds the optimal level, salts induce crystallization and electrostatic repulsion between particles, which reduces strength.

In line with these results, studies in Nigeria [18, 19] showed that the addition of 4% $CaCl_2$ progressively increased UCS up to 391.7 kN/m² after 28 days of curing, and the unsaturated CBR reached 8.02%. However, beyond this dosage, effectiveness declined. Although their focus was mainly on UCS, the parabolic pattern described by those authors fully matches the CBR results of the present study, confirming that the mechanisms of improvement and deterioration manifest consistently across different mechanical parameters.

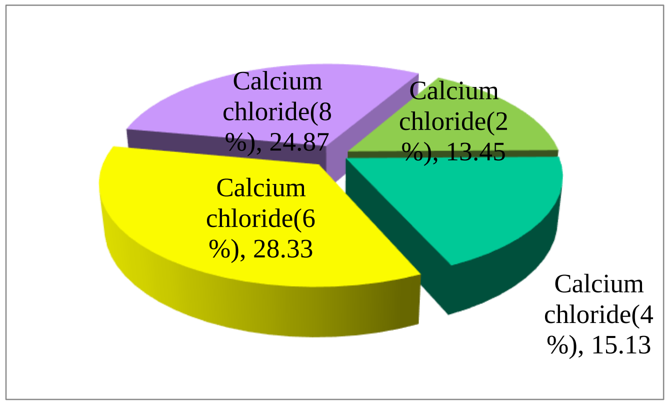
In conclusion, the CBR results at 100% compaction validate the same pattern observed at 95%: progressive increases up to an optimal value, followed by a decrease when the appropriate dosage is exceeded. Previous studies, which were mostly focused on UCS, reinforce this trend and confirm that flocculation, cation exchange, and the formation of cementitious products are consistently reflected in both CBR and UCS. Therefore, although the parameters differ in nature, the observed behavior is convergent and demonstrates the robustness of the stabilization mechanisms with lime, cement, and calcium chloride.



(a) CBR (100%) with Lime



(b) CBR (100%) with Cement



(c) CBR (100%) with calcium chloride

Fig. 3 CBR 100%

4.2. Allowable Capacity

Figure 17 illustrates the bearing capacity values obtained for soil stabilized with lime and calcium chloride, considering the proportions that achieved the highest CBR performance. The untreated reference soil registered an admissible capacity of 1.13 kg/cm². When 6% lime was incorporated, the capacity rose to 1.75 kg/cm², evidencing a clear gain in resistance. The application of 4% calcium chloride yielded 2.10 kg/cm², marking a more pronounced improvement over the natural soil. With 9% lime, the result was 2.11 kg/cm², only marginally higher than the 6% dosage but still superior to the untreated condition. The best outcome was observed with 6% calcium chloride, reaching 2.44 kg/cm², which demonstrates the strong effect of this additive in reinforcing soil strength. These findings confirm the effectiveness of both stabilizers, although calcium chloride produced the greatest enhancement in admissible capacity.

These results are indirectly supported by the literature, although most previous studies have focused on the (UCS) and CBR, without directly reporting on bearing capacity values. In India [16, 17], for example, it was observed that with 10% lime, the strength reached 12 MPa compared to 7 MPa in natural soils, demonstrating the effectiveness of this additive in improving cohesion and material stiffness. Similarly, Nigeria [18, 19] reported that with 4% $CaCl_2$, the UCS increased to 391.7 kN/m² after a 28-day curing period, while the unsaturated CBR increased to 8.02%. In contrast, the untreated soil showed values of 207.8 kN/m² and 4.01%, confirming the substantial improvement in load-bearing capacity achieved with this compound. The beneficial role of lime is associated with its pozzolanic interaction with soil silicates and aluminates, leading to the formation of binding phases such as C-S-H and C-A-H, while in the case of $CaCl_2$ the improvement is explained by the action of calcium ions, which induce flocculation and reduce the plasticity index, consolidating particles and increasing their bearing capacity [16-20]. Taken together, it can be stated that both additives effectively contribute to optimizing the mechanical properties of soils, which supports the results obtained in this study and reinforces their applicability in foundation and infrastructure projects.

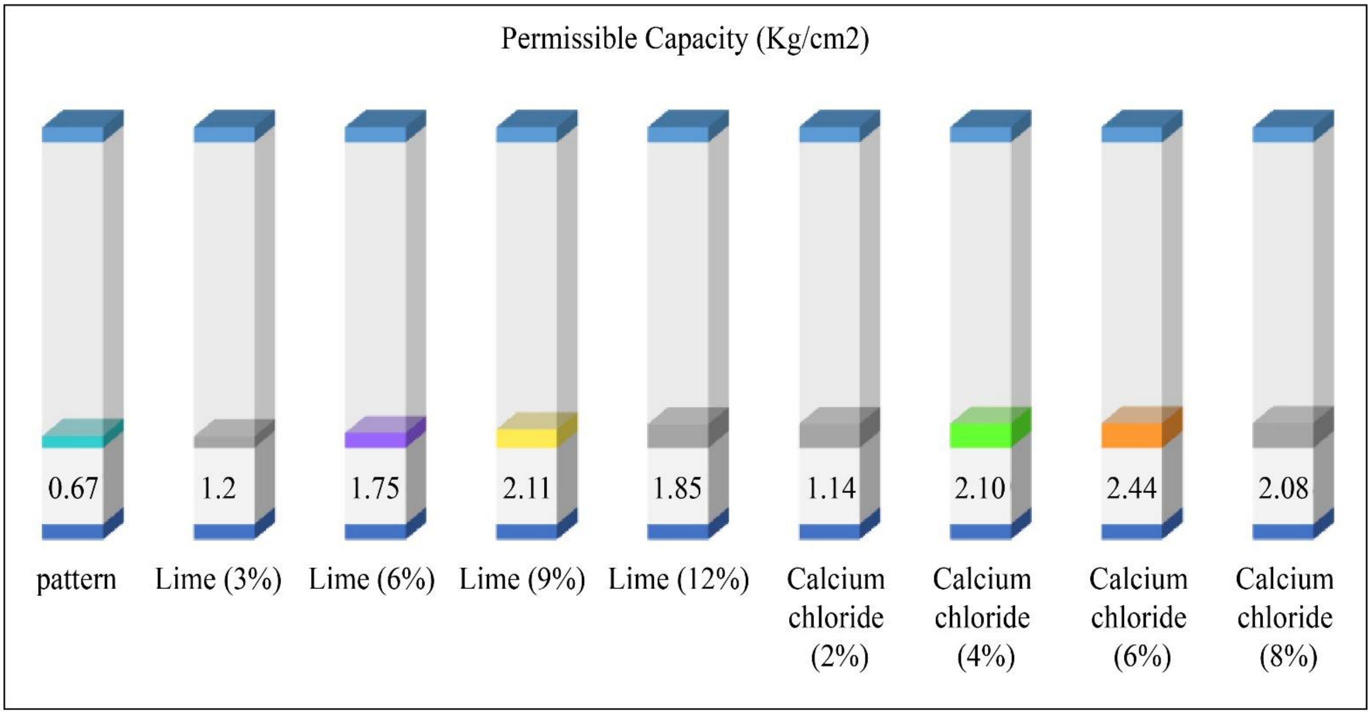


Fig. 4 Admissible capacity

4.3. Compressive Strength (qu)

It should be emphasized that applying a conventional allowable bearing capacity check to cement-stabilized soils is inappropriate, since that criterion is more suitable for untreated or lightly treated deposits and does not capture the compressive response governing cemented mixtures [50].

In practice, the use of cement increases stiffness, and the compressive strength becomes the most reliable metric for assessing the performance of cement-treated soils in geotechnical studies [44, 51]. Even so, excessive cement may induce a rigid and brittle fabric, lowering ductility and the ability to dissipate energy under dynamic actions.

Figure 18 presents the outcomes obtained for the different cement contents analyzed. The untreated soil registered a compressive strength of 10.34 kg/cm², while the incorporation of 10% cement increased the value to 87.19 kg/cm², and 15% cement produced a maximum of 104.67 kg/cm². A similar trend has been observed in stabilization studies carried out by Razali and Shukor et al. [52, 53]. The improvement in resistance is linked to the hydration and pozzolanic activity of Portland cement, which generates binding phases such as C-S-H and C-A-H. These reaction products densify the soil matrix by reducing porosity and plasticity while improving particle-to-particle contact, thus producing a more compact and mechanically robust skeleton [12-15].

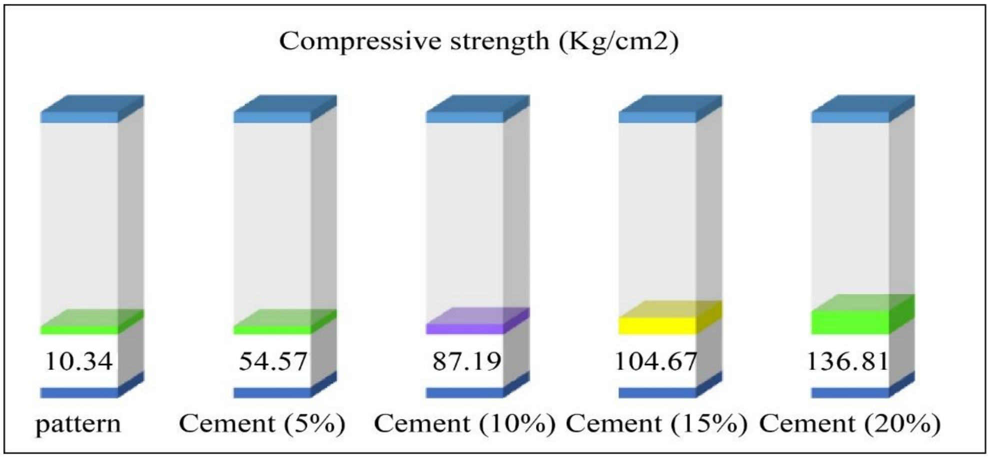


Fig. 5 Admissible capacity

4.4. Feasibility

4.4.1. Seismic Parameters

According to standard E030 [54], all parameters will be established according to its guidelines:

- Study zone: The zone is located in the Huancayo plane, which, according to that standard, is classified within seismic zone 3, as shown in Figure 19. Consequently, the corresponding zone factor will be Z = 0.35 [54].
- Soil factor: The soil factor has been determined as S3 = 1.20 [54], according to the characteristics of the soil in the study area.
- Use factor: This factor is assigned according to the type of construction planned. In this case, given that the zone is intended for buildings such as housing, offices and hotels, the use factor will be U = 1 [54]. This value reflects the specific characteristics of the types of buildings planned to be constructed in the zone.
- Reduction coefficient (R): The value of this coefficient is 8 [54], since this is a reinforced concrete structure with portal frames.

With these parameters defined, the inelastic spectral analysis of pseudo-accelerations was performed using equation 1.

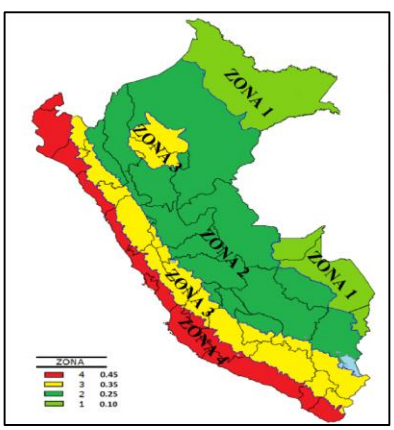


Fig. 19 Seismic zones

$$S_a = \frac{Z.U.C.S}{R}.g \quad (1)$$

With these parameters defined, the inelastic spectral analysis of pseudo-accelerations was performed using equation 1.

Where:
Z: Seismic zone coefficient
U: Importance coefficient
C: Ground amplification coefficient
S: Subsoil coefficient
R: Seismic force reduction coefficient
g: Gravity

4.4.2. Housing Structuring

The floor plan dimensions of the house were 12 x 12 meters, a common characteristic in the houses of Huancayo-Palian. The structural system is composed of portal frames, with a total of 5 stories, as shown in Figure 20, designed according to the stiffness and strength requirements established by the seismic-resistant design standard (E030) [54]. For this purpose, 50 x 50 cm columns and 25 x 40 cm beams were used throughout the building.

In addition, the solid slabs were dimensioned with a thickness of 15 cm, which ensures the stability of the structure. Regarding the compressive capacity of the concrete, a value of 210 kg/cm² was adopted for the columns, beams, slabs, and footings. This level of resistance ensures both the reliability and durability of the structure, particularly against seismic forces and other load demands.

After modeling the house in ETABS, the forces at the base of a central column were extracted, the results of which are presented in Table 4, where the loads acting on the footing are detailed, including the dead load (63.98 tons), the live load (15.01 tons) and the moments generated in both directions due to seismic and gravity forces.

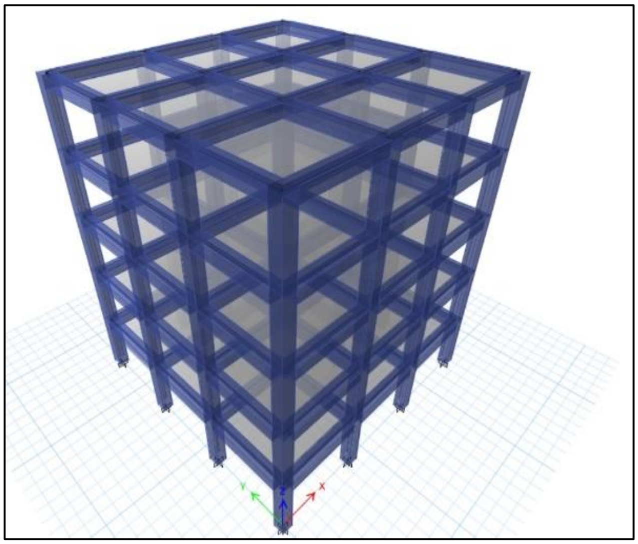


Fig. 20 ETABS model of a typical house

The design of the footing was then carried out using the capacities obtained, as shown in Figure 20. For this purpose, the design was evaluated considering each allowable capacity, ensuring that the foundation system complied with the established structural and safety requirements.

Tabla 4. Loads acting on the footing

Gravity loads			
PM (Dead load)		63.98 Ton	
Pv (Live load)		15.01 Ton	
Longitudinal direction		**Transversal direction**	
Mmx (Dead load moment)	0.0212 Ton.m	**Mmy (Dead load moment)**	0.0212 Ton.m
Mvx (Moment live load)	0.0079 Ton.m	**Mvy (Moment live load)**	0.0079 Ton.m
Msx (Seismic moment)	9.09 Ton.m	**Msy (Seismic moment)**	9.09 Ton.m
Psx (Axial load)	6.17 Ton	**Psy (Axial load)**	6.17 Ton

Therefore, Figure 21 shows the detailed plan of the dimensions of the footings evaluated. In item a, corresponding to the standard footing (without any additions), the dimensions are 3.80 m × 3.80 m. In item b, with the addition of 6% lime, the dimensions are 2.30 m × 2.30 m; in item c, with 9% lime, they are reduced to 2.20 m × 2.20 m.

In item d, with the addition of 4% calcium chloride, the dimensions are 2.10 m × 2.10 m; and finally, in item e, with 6% calcium chloride, the dimensions reach 2.00 m × 2.00 m. It should be noted that all footings have ¾" rebar reinforcement, arranged with a uniform spacing of 0.275 meters.

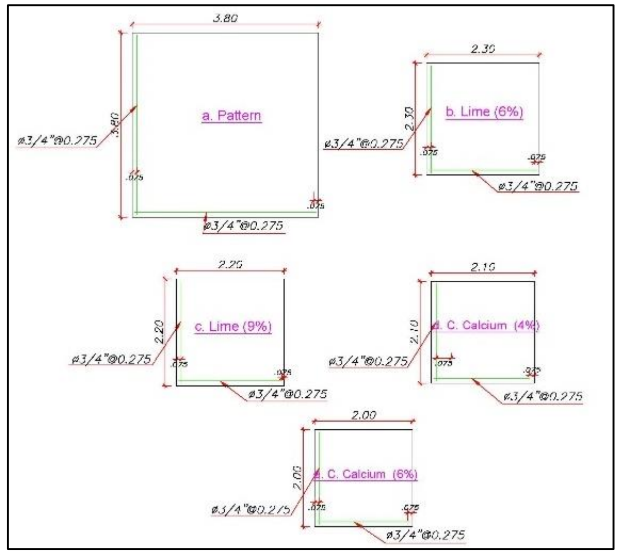


Fig. 21 Detail in plan of the footings

Figure 22 shows the elevation detail of the footings, applicable to all the cases mentioned in Figure 20, since the geometry and distribution of the reinforcement remain constant. The foundation rests on compacted natural soil, with a concrete slab and a screed to ensure stability and leveling. The reinforcement consists of steel bars Ø 3/4"@0.275 m in both directions, optimizing structural resistance, while the central column is anchored to the footing to ensure adequate load transfer.

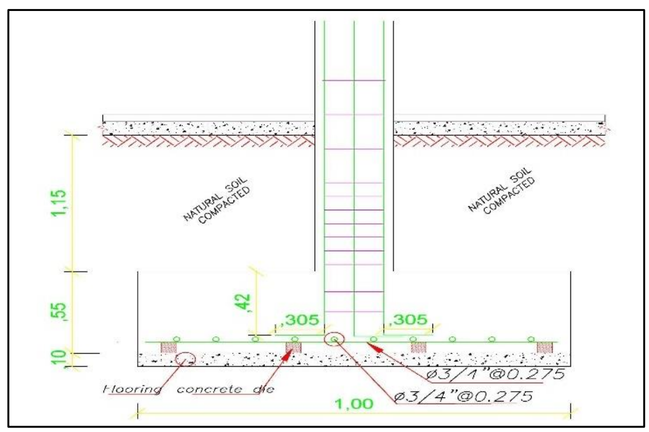


Fig. 22 Detail in elevation of the brake shoes

4.4.3. Foundation Cost Analysis

According to Figures 21 and 22, the cost analysis was performed, and the concrete and steel metering corresponding to each footing was considered. Once the metrics were obtained, the Unit Price Analysis (UPA) was prepared, including the costs of labor, materials and hand tools. This made it possible to determine the unit cost of both concrete and steel for each alternative evaluated. Subsequently, the total cost was calculated by multiplying the metric by the respective APU.

Figure 23 shows the results for the concrete, showing that the standard footing, without any addition of lime or calcium chloride, had a cost of S/4,181.05. With the addition of 6% lime, the cost was reduced to S/1,531.71; with 9% lime, it was S/1,401.41. On the other hand, with the addition of calcium chloride at 4%, the cost was S/ 1,276.90, and with 6% of this additive, the cost was S/1,158.19. With the addition of 6% calcium chloride, the latter presented the lowest total cost in concrete, standing out as the most economical option. This result is especially impressive, since it shows how a simple modification in the mix can significantly optimize construction costs.

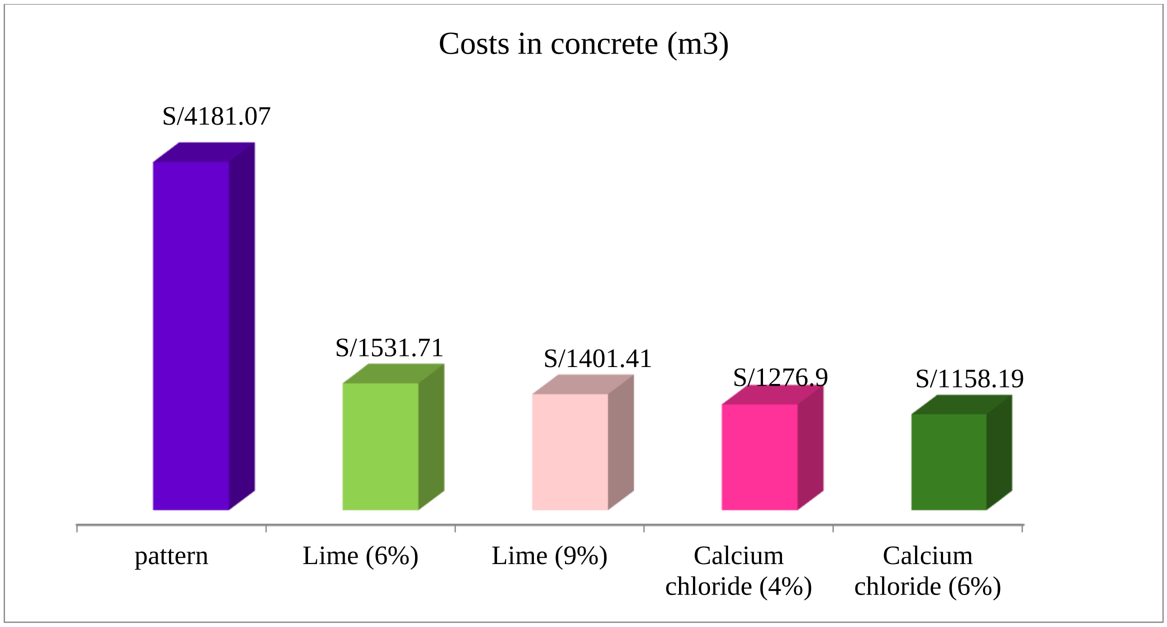


Fig. 23 Costs of concrete footings

Regarding steel, as shown in Figure 24, the cost for the footing without addition was S/ 2,081.83. With 6% lime, it was reduced to S/ 757.64; with 9% lime, it was S/ 692.61. With the addition of calcium chloride at 4%, the cost was S/ 630.49, and with 6% of this additive, the final cost was S/ 571.07. Again, adding calcium chloride at 6% proved to be the most efficient, as it achieved the lowest cost in steel. This finding reinforces the technical and economic feasibility of using this additive in foundation projects, representing a remarkable improvement compared to conventional footing.

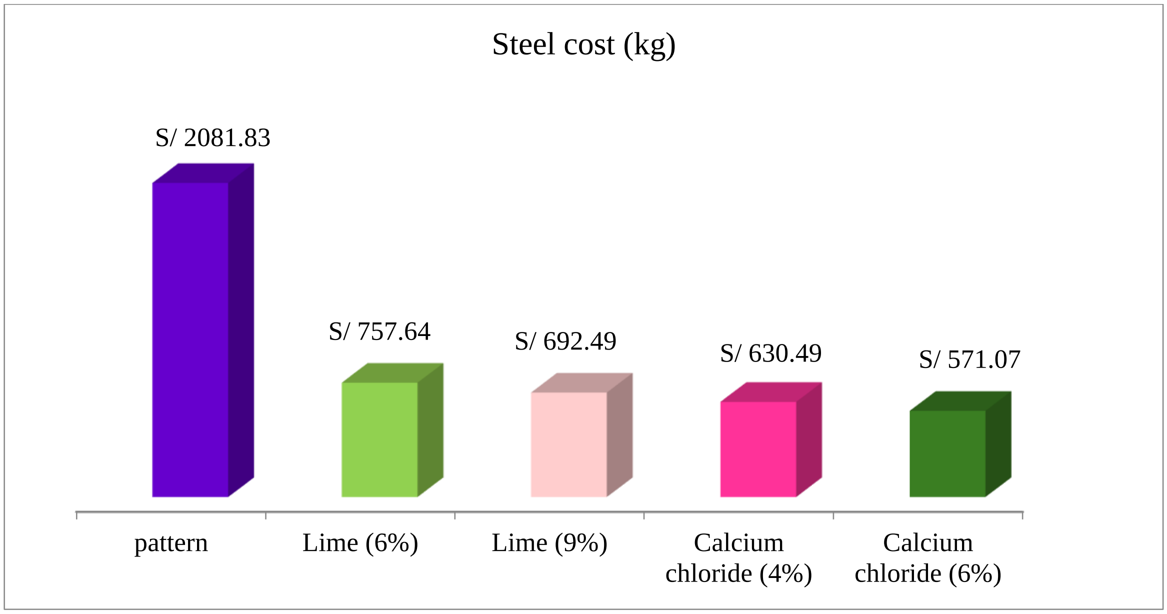


Fig. 24 Footing steel costs

In contrast, most previous research has focused on the mechanical stabilization parameters (CBR or UCS), without explicitly considering their effect on foundation costs. For example, studies in India [16, 17] and Nigeria [18, 19] reported significant increases in UCS and CBR with lime and $CaCl_2$, but did not analyze their economic impact. Therefore, it is essential to complement the technical evaluation with a cost analysis, as this approach allows for a more accurate determination of the real feasibility of these additives in foundation projects. In this way, it is ensured that the proposed solutions not only meet structural requirements but are also sustainable and economically competitive in current construction scenarios.

5. Conclusion

The outcomes of the CBR tests at 95% and 100% compaction indicate a notable enhancement in soil resistance when lime, cement, and calcium chloride are incorporated. The most favorable values were obtained with 9% lime, 15% cement, and 6% calcium chloride. Specifically, lime achieved 7.95% at 95% and 11.07% at 100% compaction; cement reached 16.87% at 95% and 18.87% at 100%; while calcium chloride provided the highest performance, with 21.98% at 95% and 28.33% at 100%. These findings confirm that optimizing the dosage of these additives substantially increases the bearing capacity and compressive resistance of the soil, which enhances its suitability for foundations and pavement works. Nevertheless, excessive dosages should be avoided, as they may cause the soil to become overly rigid and lose part of its flexibility.

The admissible capacity evaluation confirmed that both lime and calcium chloride enhance soil strength, although the effect of calcium chloride is more pronounced. The untreated soil recorded a capacity of 1.13 kg/cm². With 6% lime, this value increased to 1.75 kg/cm², while the application of 6% calcium chloride produced the highest capacity, reaching 2.44 kg/cm². This represents a substantial improvement over the natural soil. The findings suggest that calcium chloride provides a stronger contribution to soil stabilization than lime, making it a more effective alternative for foundations and pavement applications. Overall, calcium chloride stands out as the most efficient additive for maximizing bearing capacity, delivering clear gains compared with the reference soil.

The analysis of compressive strength in soils treated with cement revealed that the untreated sample had a resistance of 10.34 kg/cm². With the addition of 10% cement, the strength increased to 87.19 kg/cm², and at 15% dosage, it further rose to 104.67 kg/cm². These outcomes demonstrate a marked enhancement in compressive strength, confirming the efficiency of cement as a stabilizing agent. This behavior is expected, as cement functions as a binder that augments soil stiffness and its ability to resist compressive loads. Consequently, cement-stabilized soils are highly suitable for applications such as pavement bases or structural foundations where both high load-bearing capacity and durability are essential. In comparison with conventional foundation soils, which do not achieve the same degree of reinforcement without additives, cement-treated soils exhibit significantly greater consolidation, indicating that cement plays a crucial role in soil stabilization.

The cost analysis performed for the foundation shows that the standard footing, without additives, has a total cost of S/4,181.05 in concrete and S/2,081.83 in steel. By incorporating calcium chloride at 6%, the total cost of the footing is significantly reduced to S/1,158.19 in concrete and S/571.07 in steel, which represents a significant decrease compared to the standard footing. This finding is key, since the addition of calcium chloride not only reduces material costs, but also optimizes the economic efficiency of the foundation project. Furthermore, using this admixture can improve the durability of concrete, especially in adverse climatic conditions or environments where faster setting times are required, highlighting the importance of considering alternatives that are more economical and can also contribute to sustainability and better long-term structural performance.

Limitations of the study include variability in soil properties because, although extensive testing was performed on soil mixtures with different additives, the natural variability of soil in different locations could influence the results, limiting generalization to other geographic contexts. In addition, the tests were conducted under controlled laboratory conditions, which do not fully simulate real environmental conditions, such as humidity and thermal fluctuations, that could affect the behavior of additive-stabilized soils. The short-term mechanical properties of the soil were also evaluated, but the long-term effects of the additives (lime, cement, calcium chloride) on the durability of the stabilized soil, especially under repeated loading cycles and extreme climatic conditions, were not considered. The study did not address in depth the interaction between the additives and how they might behave synergistically or interfere with soil properties, which could generate unforeseen effects. Finally, the limited soil sample size used in the study does not reflect the full variability of soils in other regions or under different geotechnical conditions, and the dosages of the additives evaluated were also limited, which did not cover the full range of possibilities.

Future research should emphasize the evaluation of the durability and long-term response of soils stabilized with these additives, considering how variables like exposure time, variations in moisture, and environmental conditions influence their properties and load-bearing capacity over extended periods. It would also be relevant to explore combinations of lime, cement and calcium chloride with other alternative stabilizers, such as industrial wastes or organic materials, to improve sustainability and reduce soil stabilization costs. In addition, studies could be conducted on the interactions between the different additives to identify combinations that generate synergistic or negative effects on soil properties, thus optimizing treatments and reducing costs. Additional research could focus on soils with extreme properties (very wet or arid) to evaluate the effectiveness of the additives in adverse conditions, which would allow expanding the application of these treatments to diverse geotechnical conditions. It would also be important to carry out field tests to verify the results obtained in the laboratory under real construction conditions, observing the interaction between the stabilized soils and the built structures, as well as their behavior under seismic events and dynamic loads. In addition, the environmental impact of the additives, particularly calcium chloride, should be investigated to ensure that their use does not cause negative effects on the environment or public health in the long term. Finally, given the seismic classification of the study area, future research could focus on the ability of stabilized soils to resist seismic movements, evaluating their behavior under extreme seismic conditions to ensure structural safety.

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