

# Factors Influencing Lime Stabilization of Clayey Soils: A Comprehensive Analysis

## Factores que Influyen en la Estabilización con Cal de Suelos Arcillosos: Un Análisis Integral

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**ABSTRACT:** The electrochemical reactivity of clays bestows them with distinct mechanical and chemical attributes. This responsiveness renders them acutely sensitive to mineralogical composition, such that even marginal proportions of clay minerals can provoke substantial shifts in soil properties and mechanical behaviors. This inherent complexity presents a pivotal challenge in prognosticating the efficacy of lime stabilization for both clays and clayey soils. Additionally, the enhancement of post-lime treatment strength hinges on various intrinsic variables of clay properties (e.g., particle size distribution, organic content) and treatment conditions (e.g., lime dosage, temperature, curing durations pre- and post-compaction, moisture content, etc.). The present study seeks to elucidate pivotal treatment factors that optimize the potential for achieving maximal gains while minimizing associated costs within lime-based treatment methodologies. Through rigorous evaluation of outcomes derived from tests conducted on clayey soils sourced from diverse Canadian locations, coupled with the assimilation of insights from antecedent research endeavors, this study provides pragmatic guidelines for effective lime treatment strategies.

**KEYWORDS:** clayey soils, lime, mechanical properties, treatment optimization.

### 1 LIME STABILIZATION IN CLAYEY SOILS: A COMPREHENSIVE REVIEW

Clayey soils, ubiquitous in various geotechnical applications, pose challenges due to their intricate nature (Reeves *et al.*, 2006, Nelson & Miller, 1997), particularly in cold regions like Canada (Graham & Au, 1985, Leroueil *et al.*, 1991). Lime stabilization emerges as a promising technique, leveraging the chemical reactions between lime and clay minerals to enhance soil properties (Bell, 1996). This study delves into the pivotal factors influencing the effectiveness of lime stabilization, drawing insights from tests conducted on clayey soils across diverse Canadian locations.

The mineralogical composition of clays plays a crucial role in determining their responsiveness to lime stabilization. Even minor variations in clay mineral proportions can lead to substantial alterations in soil properties and mechanical behaviors (Bell, 1996). Particle size distribution, chemical and organic matter further contribute to the overall complexity, influencing the effectiveness of lime treatment.

The transformation of lime-treated clayey soils at the macro-scale stems from molecular-level reactions (Cherian & Arnepalli, 2015). With sufficient moisture, lime induces cation exchange and pozzolanic reactions, pivotal for soil modification and stabilization. Initially,  $\text{Ca}^{2+}$  ions from lime interact with metallic ions on clay particles' surfaces, bolstering inter-particle attraction and reducing the diffuse hydrous double layer (DDL) thickness, thereby promoting flocculation. This process enhances soil workability and short-term strength by diminishing plasticity and swelling tendencies. Subsequently, in an alkaline environment ( $\text{pH} \geq 12.4$ ) created by hydrated lime, silica and some alumina within the clay mineral lattice, particularly at particle edges, dissolve. This process forms cementitious compounds like calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) through pozzolanic

reactions, involving the interaction between free  $\text{Ca}^{2+}$  ions from lime and dissolved  $\text{Si}^{4+}$  and  $\text{Al}^{3+}$  ions from the soil. This strengthens the clay, improving its properties, especially strength, and resistance to environmental factors like water variations and freeze-thaw cycles (Hilt & Davidson, 1960, Bell, 1996, Eades & Grim, 1960, Khattab *et al.*, 2007, Diamond & Kinter, 1966, Eisazadeh & Eisazadeh, 2015, Rogers *et al.*, 1996, Rogers *et al.*, 1997, Cabane, 2004). Particularly in hot-dry climates, lime can undergo carbonation, reacting with carbon dioxide, which hinders cementitious product formation and weakens material strength. However, this effect can be mitigated through proper curing conditions (Rogers *et al.*, 1996, Rogers *et al.*, 1997).

Pozzolanic reactions persist with sufficient reactive clay minerals, free calcium ions, and moisture, ceasing when dissolved silica-alumina and free calcium ions are depleted. Subsequently, excess free lime in the mix precipitates in aggregate voids, causing a loss of inter-particle friction (Cherian & Arnepalli, 2015).

Lime dosage and pozzolanic activation efficiency rely on factors such as desired improvement extent, environmental conditions, lime and soil types, and clay fraction (CF). The combination and proportion of minerals, defined by properties like cation exchange capacity (CEC), specific surface area (SSA), and Si/Al molar ratio, are crucial determinants (Barman & Dash, 2022, Cherian & Arnepalli, 2015, Shvarzman *et al.*, 2002).

Clayey soils possess distinct characteristics shaped by their clay mineral composition, influenced by geological processes such as chemical weathering, hydrothermal alteration, and sedimentation. These hydrous aluminosilicates, influenced by weathering, parent material, and environmental conditions, determine essential properties like charge density, CEC, plasticity, cohesion, pH, and reactivity (Strawn *et al.*, 2015, Sposito, 2008, Murray, 2006). Lime interactions with minerals such as montmorillonite, illite, and kaolinite elicit diverse soil responses, affecting both short-term and

long-term processes. The mineralogical variations in clayey soils lead to different reactions when interacting with lime, depending on their initial properties.

While all clay minerals react with lime, distinctions in exchangeable cations and the formation of unique cementitious compounds contribute to complexity. Montmorillonite, compared to illite or kaolinite, promptly responds to lime, inducing immediate changes such as reduced plasticity and increased flocculation-induced water content. This rapid response is closely tied to the significant reduction in the diffuse double layer (DDL) thickness, primarily attributed to montmorillonite's silica/alumina structure characterized by higher CEC and Si/Al molar ratio (Bell, 1996, Bell, 1993, Barman & Dash, 2022). Additionally, montmorillonite clays exhibit faster responses to lime stabilization, resulting in earlier strength gains compared to kaolinitic clays (Bell, 1996).

Soils rich in clay and organic matter exhibit heightened CEC that retain cations in the pore solution (Strawn *et al.*, 2015, Cherian & Arnepalli, 2015). The CEC value mirrors the dominance of expansive clay minerals; for instance, montmorillonite boasts a CEC of 80–150 meq./100 g, while illite ranges from 15 to 40 meq./100 g. In contrast, heavily weathered/oxidised soils like kaolinite exhibit low CEC (1–15 meq./100 g). Thus, this parameter is positively correlated with specific surface area (SSA). This SSA profoundly influences soil sorption capacity, particularly with calcium cations or hydrated lime, crucial in the reactive nature of soil-lime interactions, impacting lime stabilization (Cherian & Arnepalli, 2015). The heightened reactivity and sorption capacity, mainly within minerals, stem from abundant surface sites (Heister, 2016). A greater SSA offers more active lime interaction sites, affecting both sorption capacity and pozzolanic reactions. For example, montmorillonite, with a loosely packed structure, exhibits a substantial surface area of 800 m<sup>2</sup>/g (internal and external areas) (Mitchell & Soga, 2005), justifying rapid strength gain compared to kaolinite (more pozzolans) (Bell, 1996, Boardman *et al.*, 2001). Kaolinite's lower reactivity, attributed to a 10–20 m<sup>2</sup>/g SSA, results from well-packed silica and alumina (considering only external surface area) (Mitchell & Soga, 2005, Miranda-Trevino & Coles, 2003). High SSA clays need higher initial dosages to address charge deficiency before free lime engages in long-term pozzolanic reactions, while low SSA soils demand less dosage due to fewer exchangeable sites for lime fixation (Cherian & Arnepalli, 2015).

Given the inherent challenges in directly measuring CEC and SSA, various modeling techniques are employed to establish correlations between essential soil properties such as Atterberg limits, clay fraction (CF), and soil-water retention curve. Additionally, multivariate probabilistic approaches offer valuable insights (Sharma *et al.*, 2021).

CEC and SSA serve as pivotal chemico-mineralogical properties, reflecting the structural composition and morphological features of clayey soils. These properties substantially influence the soil's chemical reactivity with lime, encompassing factors like layer thickness and interlayer (Strawn *et al.*, 2015). When considering their impact on soil stabilization or improvement, CEC and SSA emerge as major governing factors during lime treatment. However, it's important to note that they do not act lonely; rather, they interact with a multitude of other parameters. For instance, the

nature of cation species, both substituted and non-substituted, plays a significant role in lime treatment.

Despite the importance of CEC and SSA, they do not provide a complete comprehensive understanding of soil reactivity with lime and the subsequent cementitious reactions responsible for soil strength gain. Factors such as density charge, including permanent charges due to isomorphous substitution in layered clay minerals or pH-dependent charges related to the Si/Al ratio and hydrogen bonding (Sposito, 2008), as well as zeta potential (ZP), reflecting charge distribution at the solid-liquid interface (Sparks, 1998), and soil acidity, referring to the portion of the soil's total CEC occupied by acid cations, primarily H<sup>+</sup> and Al<sup>3+</sup>, and percentage base saturation (PBS), referring to the fraction of exchangeable base cations in total CEC (Cherian & Arnepalli, 2015), all contribute significantly to the soil-lime interaction process (Cherian & Arnepalli, 2015). These elements highlight the multi-dimensional nature of soil stabilization and improvement, emphasizing the complexity of the interaction process.

Nevertheless, a rapid reactivity in soils, exemplified by montmorillonite, may not necessarily correlate with ultimate strength gain. After further aging, montmorillonite's additional strength is not as high as that achieved by kaolinitic clays (Bell, 1996). Among the main clay minerals, kaolinite exhibits superior mechanical properties, followed by illite and smectites (Cabane, 2004). This underscores the importance of distinguishing between mechanical enhancement and structural alteration, highlighting the pivotal role of soil chemico-mineralogical composition in determining clay strength. Key mineral parameters - origin, structural compositions, and morphological properties (layer thickness, composition, ionic content, stacking order, and degree of order) - collectively influence clay behavior during lime treatment (Cherian & Arnepalli, 2015). Beyond the quantity of pozzolanic components, the nature of reactions, such as lime's silica-focused attack in montmorillonite forming calcium silicate hydrate (CSH) and alumina-focused reaction in kaolinite forming calcium aluminate hydrate (CAH), plays a pivotal role (Eisazadeh & Eisazadeh, 2015, Bell, 1996). Thus, the quantity of lime should primarily be related to the clay mineral content of the soil, considering the clay fraction and the proportion of different minerals.

Pozzolanic reactions initiate at the chemical binding threshold known as "lime fixation point (LFP)" or "initial consumption of lime (ICL)", often linked to the soil's affinity. At this stage, additional lime ceases to significantly alter the plastic limit. This threshold aligns with soil-lime-water solution pH of 12.4, crucial for initiating pozzolanic reactions in an alkaline environment with high solubility of silicon and aluminum ions (Bell, 1996). This pH value, represent lime saturation of the pore water (Ciancio *et al.*, 2014). The methodology for determining the LFP is standardized, taking into account inherent limitations of the test, such as scenarios where achieving this threshold value may not be attainable (ASTM, 1999).

Various correlations and methodologies have been developed, allowing the estimation of the lime fixation point (LFP) based on specific soil characteristics such as the clay-size fraction (Hilt & Davidson, 1960), liquid limit and plasticity index (Nelson & Miller, 1997). Based on extensive research projects conducted on clayey soils, the lime fixation point (LFP) is typically found to be in the

range of 1-3%. Beyond this threshold, lime becomes available to enhance the soil's strength through pozzolanic reactions (Bell, 1996). For effective stabilization, some authors propose a lime dosage of 1% by weight for every 10% of the clay-size fraction in the soil. Importantly, it is consistently observed that the optimum lime dosage is maintained below 8% (Ingles & Metcalf, 1972, Basma & Tuncer, 1991). Additionally, a linear relationship between LFP and the proportion of clay has been proposed, expressed as  $LFP = \text{Clay fraction (\%)} / 35 + 1.25$  (Hilt & Davidson, 1960).

pH, when correlated with inputs like mineralogy and chemical composition, becomes a potential indicator of soil property shifts, even with minor fluctuations. Its variation mainly relies on the liquid–solid ratio and ion concentration in the soil pore fluid. Assessing pH changes with lime reveals alterations in the physicochemical environment, driven by instantaneous equilibrium among various medium components (Pansu, 2006). This evaluation offers insight into the effectiveness of lime soil treatment and aids in determining the optimal lime dosage. Moreover, the lime fixation point (LFP) corresponds to the point where further addition of lime does not bring further changes in the plastic limit (Bell, 1996). Thus, when combined with pH, this parameter not only enhances the precision of LFP determination but also helps in estimating the required lime for stabilization.

For clayey soil, the required lime dosage depends on the clay fraction and mineralogy. However, ensuring sufficient improvement in resistance involves meeting minimum requirements. Research shows that lime treatment is less effective on coarse soil grains, leading to a decrease in small strain shear modulus with larger grain sizes (Tang *et al.*, 2011). This implies that silt and sand proportions also influence resistance development. Fine-grained soils recommended for lime stabilization must meet specific criteria: clay content above 20 percent, sum of silt and clay fractions preferably exceeding 35 percent, and plasticity index exceeding 10 (Broms, 1991, Cabane, 2004), or a passing of 75µm and plasticity index exceeding respectively 25% and 10% (McNally, 2017, Little Dallas, 2000). However, according to others, lime treatment is adequate for a clay content over 40% or a plasticity index over 10 (Cabane, 2004). Additionally, the technical guide report GTS (Technique, 2000, LCPC-SETRA, 2000) recommends lime treatment only for a plasticity index greater than 20. Thus, insufficient clay content necessitates additional additives like pozzolans, sources of silica and alumina such as fly ash and ground blast furnace slag, combined with lime, or the use of lime kiln dust (LKD) (Broms, 1991, MANUAL, 2004).

Lime is not recommended for stabilizing sulfate-rich soils due to the risk of ettringite-based sulfate-induced heave damages (Cherian & Arnepalli, 2015). Moreover, certain substances present in soil, both natural (organic matter, sulfide compounds like gypsum and pyrite, etc.) and anthropogenic (fertilizers containing nitrates, phosphates, sulfur, etc.), can adversely affect soil-lime reactions (ASTM, 1999). For instance, organic matter can disrupt clay flocculation and inhibit the pozzolanic reaction, thus reducing soil strength by increasing the soil's cation exchange capacity and limiting silicate dissolution (LCPC-SETRA, 2000, Rey *et al.*, 2000, Harvey *et al.*, 2010, Tremblay *et al.*, 2002). Sulfates also pose a significant challenge to soil lime stabilization, disrupting

pozzolanic reactions and fostering the growth of minerals like ettringite and thaumasite, which increase soil swelling and impede resistance development (Gaily, 2012, Cabane, 2004, Rajasekaran & Narasimha Rao, 2005). Critical factors influencing their formation include clay type and content, alumina, silica input, and the dissolution kinetics of sulfur-bearing minerals. Even low concentrations (<1%) of sulfates can cause disruptions (Rajasekaran & Narasimha Rao, 2005, Cabane, 2004, Le Borgne, 2010). A potential solution to mitigate these issues involves a retreatment approach, applying lime twice: first to induce ettringite formation and then to stabilize the soil (Cabane, 2004). Other components, such as nitrogen compounds like ammonium nitrate (fertilizer), chlorides and others, have also been discussed by several authors as detrimental in influencing the stabilization process (Cabane, 2004, Le Borgne, 2010, Cuisinier, Le Borgne, *et al.*, 2011).

Defining treatment conditions for clayey soil stabilization is crucial post-characterization. This includes selecting the appropriate lime type, dosage, moisture content, compaction energy, pre-compaction time, and total curing time. Temperature control may also be essential to align with treatment objectives.

Key lime characteristics for soil treatment include CaO content (available or combined), grind fineness, and reactivity. Quicklime (CaO) and hydrated lime (Ca(OH)<sub>2</sub>) are commonly used for soil stabilization, each with distinct advantages. Quicklime's smaller crystal size, higher reactivity, and faster hydration process result in reduced water content, accelerated pozzolanic reactions, lower plasticity, and higher strength compared to hydrated lime (Barman & Dash, 2022).

In lime soil stabilization, water content is crucial for achieving optimal strength. While maximizing density is important, prioritizing favorable conditions for strength development is essential when selecting the moisture content, considering a given lime dosage. Water facilitates the pozzolanic reaction, but excess moisture can delay strength development (Locat *et al.*, 1990, Cabane, 2004). Thus, achieving a balance in water content is vital.

The addition of lime to clayey soil significantly alters its compaction behavior, typically resulting in a flattened compaction curve. Initially, lime induces a reduction in maximum density (MD), especially noticeable in expansive clays, while simultaneously increasing the optimum moisture content (OMC). This is attributed to the formation of a flocculated structure, facilitated by cation exchange processes, and an immediate formation of cementitious compounds that tend to bind the soil grains (Bell, 1996, Vitale *et al.*, 2017). This trend continues until a certain lime dosage, typically around 3% (Hussain & Dash, 2015), beyond which MD begins to increase, and OMC decreases at a slower rate. This change can be attributed to the concentration of Ca<sup>2+</sup> ions near clay surfaces, causing free water molecules to diffuse and counteract attractive forces, facilitating easier compaction (Barman & Dash, 2022). Some researchers noted maximum flocculation at 4% lime content, resulting in a structure resistant to compaction efforts (Salehi & Sivakugan, 2009, Barman & Dash, 2022). Research on lime-treated clay typically reveals a single-peak compaction curve, but some soils may exhibit two or one-and-a-half peaks, particularly those with high liquid limits exceeding 70% or substantial sand content with liquid limits below 30% (Lee & Suedkamp, 1972). Notably, the lime dosage offering

minimum MD does not necessarily correspond to maximum resistance; studies suggest decreases in resistance beyond the optimum lime addition for maximum unconfined compressive strength, mainly due to reduced dry density (Bell, 1996).

Water content doesn't just affect compaction behavior but also soil strength in lime-stabilized soils. The long-term enhancement of shear strength and soil stability is mainly tied to the pozzolanic reaction process, influenced by the diffusion of calcium cations in the presence of interstitial water (Diamond *et al.*, 1963). However, the impact of water content on soil strength varies among studies. Some suggest higher strength with water content above optimum due to improved lime diffusion and a more uniform curing environment (Sabry & Parcher, 1979, Guo *et al.*, 2007, Mateos & Davidson, 1963), while others propose better strength on the drier side of optimum (Ramesh & Sivapullaiah, 2011). Additionally, the physical model of shear strength development over time indicates that water content promotes the formation of cementation products, strengthening the soil, although at a slower rate with higher water content (Locat *et al.*, 1990). Ultimately, the lime dosage and the duration of the pozzolanic reaction determine the final strength, which tends to be similar regardless of water content (Locat *et al.*, 1990, Tang *et al.*, 2011).

Effective compaction is pivotal for enhancing the strength of treated soils, with higher compaction energy generally correlating with improved compressive strength. However, it's imperative to carefully manage factors such as the timing of compaction, even amid potential technical and logistical challenges encountered onsite (Di Sante *et al.*, 2015).

Research indicates that compacting lime-treated soil immediately after application is crucial to preserve formed cementitious compounds (Osinubi, 1998). Delaying compaction, especially within the critical first 12 hours, leads to a decrease in soil density, exacerbated by higher temperatures. This delay detrimentally affects the development of cementation compounds at particle contact and between clay flocs, resulting in increased soil porosity. Consequently, the cementitious products formed during this period tend to bind the soil grains, creating clods that act as individual grains and ultimately hinder compatibility. The reduction in maximum density (MD) is accompanied by an increase in the optimum moisture content (OMC) (Osinubi, 1998). Importantly, this delay significantly reduces unconfined compressive strength both in the short and long term, due to decreased density (Mitchell & Hooper, 1961, Ali & Mohamed, 2017, Di Sante *et al.*, 2015, Bell, 1996).

Pozzolanic reactions progress slowly, necessitating extended curing periods of months or even years for desired strength in treated clayey soils. Continuous lime presence and a pH above 10 are crucial for ongoing cementitious compound formation (Little, 1998). However, sufficient silica or alumina presence is necessary to sustain these reactions (Bell 1996). While low lime amounts lead to initial strength increases, reaching peak strength demands higher lime levels and ample time. Rapid strength gains are typically observed within the first 7 days (Bell, 1996), or up to 28 days, especially with high lime content (Jha & Sivapullaiah, 2015, Zhang *et al.*, 2020), followed by a slower increase thereafter. These periods signify the most active stages of cementitious reactions (Bell, 1996).

Curing temperature significantly affects strength development.

Higher temperatures expedite curing, yielding stronger results, while temperatures below 4°C hinder reaction rates (Bell, 1996, Zhang *et al.*, 2020). For example, Al-Mukhtar *et al.* (2014) noted a substantial increase in both pozzolanic reaction rate and compression strength when the temperature rose from 20°C to 50°C. The importance of curing temperature is highlighted by various researchers (Boardman *et al.*, 2001, Bell, 1996, Rao & Shivananda, 2005, Ali & Mohamed, 2017). Despite severe environmental conditions or load damage, the strength gain process persists through autogenous healing (Little, 1998).

It's important to note that achieving a uniform distribution of lime, moisture content, compaction effort, and other discussed parameters throughout the soil-lime mixture is crucial during the treatment phase to prevent significant variations in strength.

Treatment conditions extend beyond soil compatibility and resistance. Lime treatment alters the diffuse hydrous double layer (DDL), impacting plastic limit and plasticity index until reaching the lime fixation point (LFP) (Bell, 1996, Hilt & Davidson, 1960, Mitchell & Hooper, 1961). Increasing lime dosage, reduces swelling and swell pressure of expansive soil (Al-Rawas *et al.*, 2005), while also affecting consolidation behavior by modifying compression and recompression indices (Salehi & Sivakugan, 2009). Moreover, increasing lime content, typically up to LFP enhances soil hydraulic conductivity by altering microstructure and increasing inter-aggregate pore size. However, the effect of curing time on hydraulic conductivity depends on the development of the cementitious matrix through pozzolanic processes. Generally, longer curing times lead to a decrease in inter-aggregate pores and subsequent hydraulic conductivity reduction (Nalbantoglu & Tuncer, 2001, Tran *et al.*, 2014, Cuisinier, Auriol, *et al.*, 2011).

Furthermore, extended curing times can increase liquid limit and shrinkage limit (Afès & Didier, 2000, Hussain & Dash, 2015), while significantly reducing swelling potential (Afès & Didier, 2000) and increasing preconsolidation pressure (Rajasekaran & Rao, 2002).

Compaction delay disrupts initial cementitious bonding between clay particles, impacting swelling tendency and strength gain. Higher temperatures within the first 12 hours partially mitigate this effect. Additionally, compaction delay affects hydraulic conductivity, initially increasing it but gradually declining over time due to ongoing cementation. Despite temperature's ability to enhance conductivity, it cannot fully counteract the detrimental effects of compaction delay, resulting in decreased conductivity after submersion (Ali & Mohamed, 2017).

Lime treatment alone may not suffice; combining hydraulic binders may be necessary depending on factors like clay type, environmental conditions, and cost. Geotechnical studies, outlined in the GTS technical guide report (LCPC-SETRA, 2000, Technique, 2000), establish criteria for assessing soil suitability for lime treatment such as minimal swelling (<5% Volumetric Swelling), an immersion CBR (ICBR) above 20, ICBR to immediate bearing index (IBI) ratio exceeding 1, and simple compression resistance exceeding 2.5 MPa for frost resistance (LCPC-SETRA, 2000, Cabane, 2004). However, these specifications may vary based on specific conditions, such as environmental conditions and application requirements.

In summary, predicting the behavior of clayey soils with lime treatment is challenging due to their diverse composition.

Measurable properties such as pH, plasticity, particle size, and density can guide treatment formulation, particularly for stabilization purposes. This article aims to provide insights into key parameters affecting lime treatment success, focusing on the formulation phase. Laboratory experiments will demonstrate the impact of these parameters, enhancing our understanding and the effectiveness of soil stabilization.

## 2 MATERIALS AND METHODS

### 2.1 Testing Materials—Soils and Lime

For valorization purposes, two industrial lime residues (lime by-products), designated as C24 and C34, were utilized in treating two fine-grained soils, S1 and S2, extracted from distinct locations within Quebec, Canada. S1, obtained from Saint-Marc-sur-Richelieu, is classified as high plasticity inorganic clay, while S2, from Marbleton, is classified as slightly plastic silty clay according to USCS classification. Soil 1 was used without sieving, while 85% of S2 was used after passing through a 2.5 mm sieve for optimal treatment. Mineralogical characterization focused on particles passing 400µm. Granulometry curves of S1 and S2, along with a summary of soil characteristics (e.g., Atterberg Limits, Granulometry, Relative Density, Optimum Compaction, Unconfined Compressive Strength, and Soil pH), are presented in Figure 1 and Table 1.

Figure 2 to figure 5, and Table 2 depict the XRD (X-ray Diffraction) analysis of Soil 1 (S1) and Soil 2 (S2), as well as the lime residues C24 and C34. The mineralogy of both soils indicates that neither S1 nor S2 predominantly contain clay minerals and can be classified as Lean Clay Soils. S1 is characterized by dominant Albite, significant Quartz and Microcline, and minor Calcite, Clinocllore-1M1lb, and Ferro-ferru-fluoro-leakeite, while S2 predominantly comprises Quartz, with significant Albite and Muscovite, and minor Clinocllore-1M1lb, Fe+2-bearing minerals, and Calcite Syn. The XRD analysis of lime residues C24 and C34 revealed their derivation from quick lime and slaked lime, respectively. C24 is dominated by Lime, with significant Calcite, Anhydrite, and Calcium Ruthenium Oxide Hydrate, while C34 exhibits dominant Portlandite and Calcite syn, significant Thiohydantoin, and minor Calcium Silicon Carbonate Sulfate Hydrate and Calcium Aluminum Iron Sulfate Hydrate.

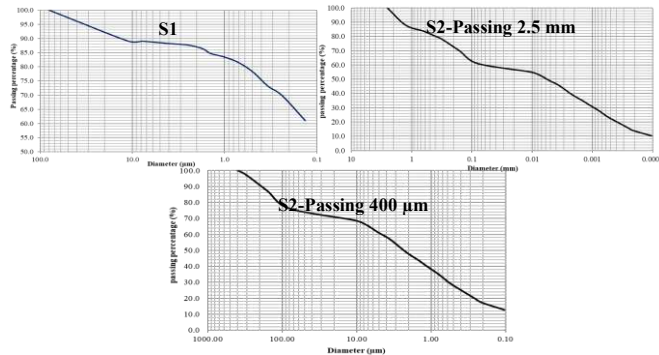


Figure 1. Granulometric curves of Soil 1 (S1) & Soil 2 (S2).

Table 1. Summary of studied soil characteristics (S1 & S2).

Atterberg Limits (ASTM D4318)							
	Natural Water Content (Ws)	Liquid Limit (L <sub>1</sub> )	Plastic Limit (P <sub>1</sub> )	Shrinkage Limit (S <sub>1</sub> )	Plasticity Index (PI)	Liquidity Index (LI)	Consistency Index (CI)
S1	59.6 %	69.0 %	24.2 %	11.4 %	45.0 %	79.0 %	21.0 %
S2	14.8 %	21.4 %	15.7 %	14.8 %	5.7 %	-16.0 %	116.0 %
USCS classification			Granulometry (Clay, silt, Sand) ASTM D422 - ASTM D7928				
S1	CIH high plasticity inorganic clay			(87.0 %, 13.0 %, - 0%)			
S2	CL-ML- Silty Clay, Sand and Clayey Silt, Slightly Plastic			(32.0 %, 20.0 %, 39.5%)			
		Passing 2.5 mm		(38.0 %, 22.0 %, 40.0%)			
		Passing 400 µm		(48.0 %, 28.0 %, 24.0%)			
Clay Activity		Relative Density - ASTM D854		Optimum Compaction - ASTM D698			
(Dry mass Density, Water Content, Saturation Degree)							
S1	51.7%	2.775	(1424.7 Kg/m <sup>3</sup> , 31.2%, 91.3%)				
S2	17.3%	2.812	(2030.0 Kg/m <sup>3</sup> , 11.2%, 81.8%)				
Unconfined Compressive Strength (UCS) (ASTM D2166)							
State			UCS (Kpa)				
Intact Soil			185.4				
Maximum Density (Reshuffled & Compacted)			115.4				
Maximum Density (Reshuffled & Compacted)			200				
pH (25°)							
S1	8.7						
S2	8.6						

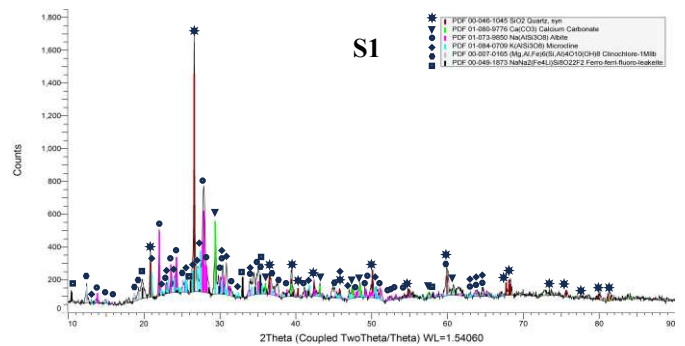


Figure 2. XRD analysis of Soil 1 (S1).

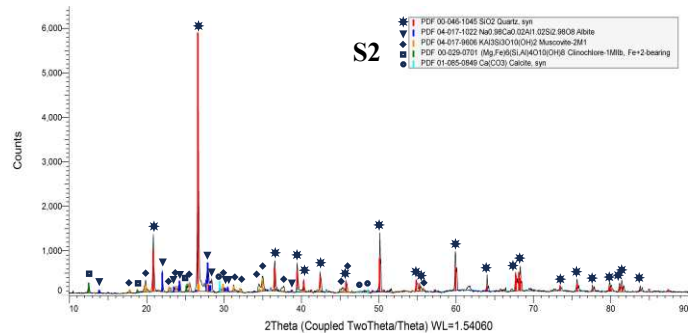


Figure 3. XRD analysis of passing 400µm of Soil 2 (S2).

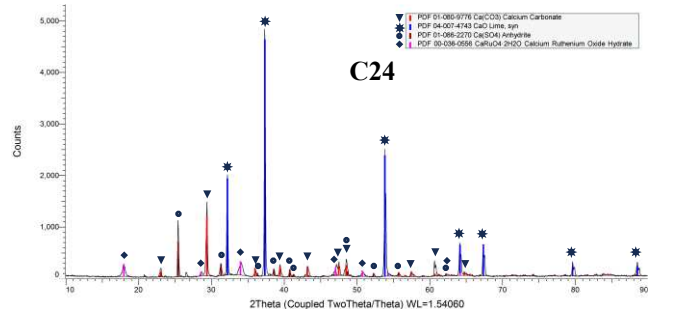


Figure 4. XRD analysis of C24 Lime.

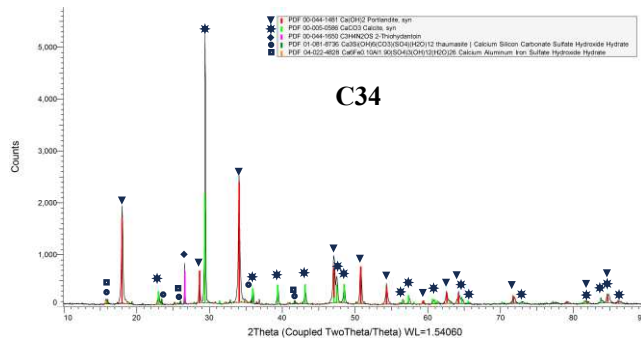


Figure 5. XRD analysis of C34 Lime.

Table 2. Semi-quantitative estimation of minerals in the studied soils and the limes used, based on XRD analysis.

X-ray Diffraction (XRD)						
S1	Quartz, syn	Calcite	Albite	Microcline	Clinochlore-1MI1b	Ferro-ferri-fluoro-leakeite
	19.5%	7.4%	38.8%	21.6%	6.4%	6.3%
S2-P400µm	Quartz, syn	Calcite, syn	Albite	Muscovite-2MI	Clinochlore-1MI1b, Fe+2-bearing	
	44.8%	2.1%	25.5%	21.6%	6.1%	
C24-P150µm	Lime, syn	Calcite	Anhydrite	Calcium Ruthenium Oxide Hydrate		
	49.6%	18.7%	18.4%	13.3%		
C34-P630µm	Portlandite, syn	Calcite, syn	Thiohydantoin	Calcium Silicon Carbonate Sulfate Hydroxide Hydrate	Calcium Aluminum Iron Sulfate Hydroxide Hydrate	
	29.4%	38.8%	23.3%	5.6%	2.9%	

## 2.2 Experimental program

In the experiment, soils S1 and S2 underwent treatment with lime dosages (C24 and C34) and various initial water contents (W). After treatment, the lime-treated soils were cured briefly before compaction, typically between 2 and 4 hours (except for some samples), in a sealed environment at 25°C. Compaction was conducted according to the ASTM D698 Standard, employing either a normal compaction energy (NE) of 600 KJ/m<sup>3</sup> or a modified compaction energy (ME) of 2 700 KJ/m<sup>3</sup> for select samples to assess energy impact. The primary focus was on monitoring soil compaction variations, particularly optimum moisture content (OMC) and maximum dry density ( $\rho_{dmax}$ ), relative to soil-lime dosage (C) and time before compaction (tbc) settings.

Following similar treatment conditions, samples were prepared and subjected to a longer curing duration after compaction (tac) in a sealed environment at 25°C before testing their unconfined compression strength (ASTM D2166 Standard), denoted as UCS. The main objective was to measure the Maximum Unconfined Compression Resistances (UCS<sub>max</sub>) of treated soils and corresponding initial moisture content (W) for a given lime dosage, time before compaction, and time after compaction.

The method proposed by Eades and Grim (1966) for determining the optimal dosage value is sensitive to lime quality, soil impurities, and components such as sulfates, phosphates, and organics (ASTM, 1999), alongside factors like temperature and the glass electrode characteristics of the pH-meter instrument

(Greenland & Hayes, 1981). Hence, the study also assesses the significance of plastic limit (PL) in enhancing the accuracy of optimum dosage ( $C_{opt}$ ) determination. This entails adjusting the interpretation of pH-C curves to deduce the correct  $C_{opt}$ . To achieve this, the standard test method ASTM D6276-19 was used to estimate the soil-lime proportion requirement for soil stabilization, relying on soil pH assessment with lime dosage. Maintaining a controlled temperature between 24 and 25°C in the preparation and measurement environment minimized temperature effects on obtained values. The pH progression of the soil-lime mixture was monitored using two pH meters, with their characteristics outlined in Table 3. Plastic limits were examined in different treated samples with varied dosages, initially moistured to their natural liquid limits. PL tests were conducted after a consistent 2-hour cure in a sealed environment at 25°C, followed by air drying under ambient conditions.

It is important to note that dosages for treatment were based on the dry weight of the soil fraction studied (2.5 mm sieve for soil 2, total passing for soil 1). This discrepancy should be considered when comparing the dosage effect between soil 1 and soil 2. For instance, transitioning to dosages based on the fine fraction of passing 75µm requires correction factors of 10/6 for soil 2, as 75µm represent 60% of the total soil. No correction is necessary for soil 1 since it already passes through the 75µm sieve. Therefore, C and C<sub>75µm</sub> represent dosages calculated based on the dry weight of the soil fraction studied and the fraction of 75 µm respectively.

Furthermore, it's important to acknowledge that the results presented regarding optimum compaction serve as a fundamental basis for addressing other aspects studied in this article. The compaction behavior has been thoroughly investigated in a previous study using the same soils and lime residues (Babanas & Courcelles, 2023).

Table 3. Characteristics of pH-meters.

Name	PHN	PHO
Description	refillable flat surface pH electrode	-
Operating conditions:	0 to 50°C (32 to 122°F) / < 80% RH	Measuring range: pH 0 - 14 Temperature Range: 0 °C - 80 °C
Range and Accuracy:	0.00 to 14.00 / ± 0.01pH typical	Connector : BNC Type of junction : Polyester Shaft Material : POM
Specifications	Temp. Compensation : Automatic from 0 to 90°C (32 to 194°F) Ingress Protection (IP) : IP57 (Partial dust protection, temporary water immersion)	Sensor Type : Combined electrode Reference System : Ag/AgCl Reference electrolyte : Gel Membrane glass : U Membrane resistance (25°C) : < 250 MΩ Ingress Protection (IP): IP67 (Complete dust protection, temporary water immersion)

## 3 RESULTS AND ANALYSIS

### 3.1 Optimum Compaction

Lime treatment significantly reduces the density of lean clay soils S1 and S2 within the dosage range of 2% to 7%. Maximum densities and the corresponding optimum moisture content (OMC) display a near-linear decrease and increase, respectively, particularly with short time before compaction (tbc) ranging from 2 to 4 hours. This trend is particularly evident in soil 2, treated with C24 and C34, which have average tbc durations of 2.7 to 2.8 hours and a standard deviation of 0.42 hours. Similarly, soil 1 treated with C34 has an average tbc of 2.6 hours, with a standard deviation of

0.29 hours (Figure 6, 7).

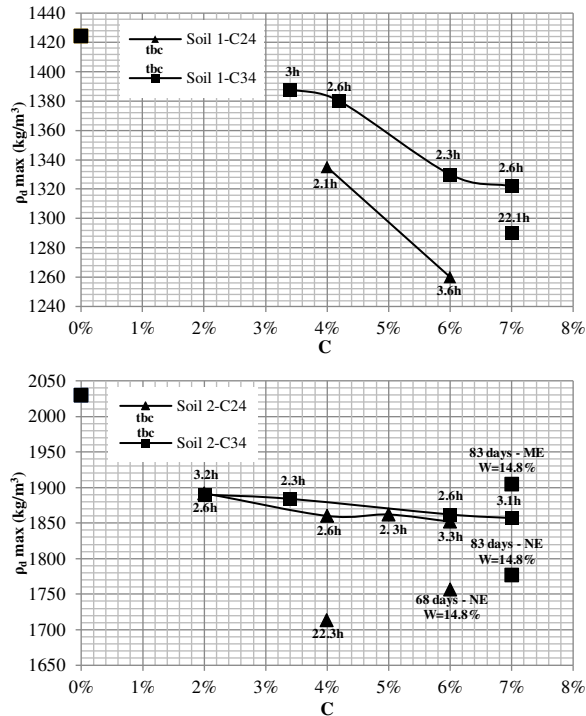


Figure 6. Evolution of maximum dry density ( $\rho_{d \max}$ ) with dosage (C) and time before compaction (tbc) for S1 and S2 treated with C24 and C34 (Babanas & Courcelles, 2023).

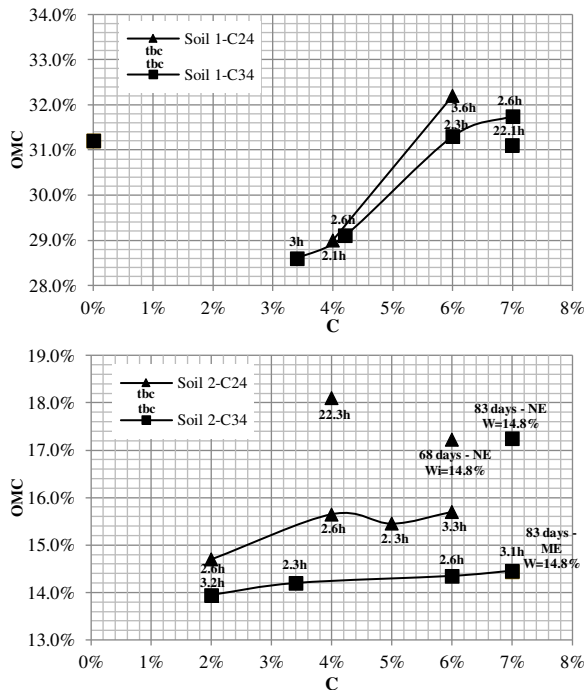


Figure 7. Evolution of Optimum Moisture Content (OMC) with dosage (C) and time before compaction (tbc) for S1 and S2 treated with C24 and C34 (Babanas & Courcelles, 2023).

The rate of decrease and increase of  $\rho_{d \max}$  and OMC are influenced by lime quality, nature and proportions of soil's mineralogy, and tbc. For example, with short tbc durations, Soil 1 treated with C24 and C34 experienced decrease rates of 37.5 kg/m<sup>3</sup> and 20.2 kg/m<sup>3</sup> per percent of C, while Soil 2 treated with C24 and C34 experienced decrease rates of 96.6 kg/m<sup>3</sup> and 69.8 kg/m<sup>3</sup> per percent of C. Specifically for soil 2, the rate decrease of  $\rho_{d \max}$  is 57.9 kg/m<sup>3</sup> and 41.9 kg/m<sup>3</sup> per percent of C<sub>80µm</sub> for treatment with C24 and C34. Transitioning from C24 to C34 treatment accelerates the decrease rate by double for soil 1 and 1.4 times for soil 2. Conversely, switching from soil 1 to soil 2, the decrease rate is 1.5 times for C24 and doubles for C34 treatment. Soil 2's higher reactivity, attributed to its mineralogy with over twice the quartz content compared to soil 1, suggests C24 lime's superiority. Bell (1996) demonstrated that lime enhances resistance in fine quartz, achieving a UCS of 1.25 MPa in 1 day with 4% lime, compared to over 28 days for kaolinite and longer for Montmorillonite. This reactivity drives rapid cementitious compound formation, affecting density and resistance. Differences between C24 and C34 stem from varying CaO and Ca(OH)<sub>2</sub> levels, as well as sulfuric mineral components like thiohydantoin and calcium silicon carbonate sulfate hydroxide, impacting reactivity and stabilization.

Increasing the tbc, especially nearing 24 hours, reduces density, notably in soil 2. Transitioning from 2.6 to 22.2 hours decreased density by 30 kg/m<sup>3</sup> (S1, C34) and 140 kg/m<sup>3</sup> (S2, C24) with similar lime dosages (7% and 6.7% of C<sub>80µm</sub>). This effect is more pronounced with higher lime doses and limes rich in available CaO or Ca(OH)<sub>2</sub>. Similarly, this tbc transition also increased OMC, by 0.6% (S1) and 2.4% (S2). This delay effect aligns with findings from Osinubi (1998). The physico-chemical reason is the formation of cementitious compounds, which bind soil grains and create clods, ultimately hindering compatibility, influenced by mineralogy, dosage, and moisture. For instance, consider soil 2 treated initially with 6% C24 lime and natural moisture content (14.8%), left for 68 days before density and OMC assessment. Comparing to 4% dosage and a 22-hour tbc, we expected decreased density and increased OMC. However, we observed a reversible behavior due to insufficient initial moisture, resulting in weaker clod development.

Regarding the energy effect, treating soil 2 with 7% of C34 lime and natural moisture content resulted in a higher density and lesser OMC over a tbc of 83 days. The energy impact could be partially amplified due to weaker clods formed because of inadequate initial moisture content.

Notable variations in OMC relative to the natural OMC (NOMC) are observed, depending on soil type, lime type, dosage, and tbc. OMC values either exceed or fall below NOMC, with consistent exceeding in S2 for all dosages. For S1, optimal compaction occurs below 5% and 6% for C24 and C34, respectively. This threshold shifts with increasing tbc, as demonstrated by S1 treated with 7% C34, where a tbc of 22 hours nearly aligns OMC with NOMC, contrasting with an OMC associated with 6% C34 and a tbc of 2.3 hours.

### 3.2 Optimum Resistance

In our study, we aimed to optimize initial moisture content (W) for maximum unconfined compressive strength (UCS<sub>max</sub>) with a fixed lime dosage (C), time before compaction (tbc), and time after

compaction (tac) (Figures 8, 9). Supporting the 28-day slow strength development hypothesis, Soil 2 consistently showed higher resistance, with an average tbc of 2.6 hours, confirming its superior reactivity. C24 lime maximized strength, consistent with earlier findings. Plotting UCS<sub>max</sub> against lime dosages revealed optimal levels (C<sub>opt</sub>), with variations between soils and a shift from C24 to C34 lime. Soil 2 achieved a UCS<sub>max</sub> of 2.05 MPa with 2% of C24, with an average tbc of 2.5 hours and tac of 72.7 days (Standard deviation: 0.17 hours and 1.5 days). Soil 2 attained a UCS<sub>max</sub> of 1.12 MPa with 3.4% of C34, with an average tbc of 2.7 hours and tac of 58.7 days (Standard deviation: 0.45 hours and 0.6 days). Soil 1 achieved a UCS<sub>max</sub> of 0.48 MPa with 6% of C34, with an average tbc of 2.6 hours and tac of 58 days (Standard deviation: 0.35 hours and 1.7 days).

Compared to moisture content leading to maximum densities (OMC), UCS<sub>max</sub> values may vary, particularly due to lime type and tbc. Soil 1 treated with C24 showed UCS<sub>max</sub> with W higher than OMC (1% and 0.8% for dosages of 4% and 6%, respectively), with an average tbc of 2.7 hours. In contrast, for soil 1 treated with C34, UCS<sub>max</sub> occurred with W lower than OMC (0.6%, 1%, and 3.2% for dosages of 3.4%, 4.2%, and 6%, respectively), with an average tbc of 2.6 hours. Soil 2 treated with C24 exhibited W almost equivalent to OMC (with a maximum gap of 0.1%) for dosages ranging from 2% to 6%, with an average tbc of 2.7 hours. Similarly, for soil 2 treated with C34, UCS<sub>max</sub> occurred with W lower than OMC (2.3%, 1.4%, and 1.2% for dosages of 2%, 3.4%, and 6%, respectively), with an average tbc of 2.7 hours.

Delaying tbc had a detrimental effect, notably seen in soil 2 treated with 4% of C24 lime, resulting in decreased UCS<sub>max</sub> and increased associated W.

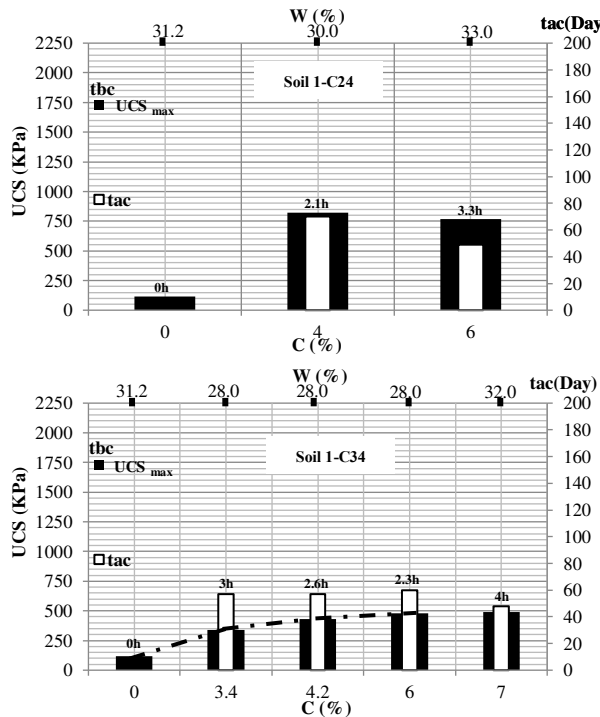


Figure 8. Maximum UCS (UCS<sub>max</sub>) of treated S1 and corresponding initial moisture content (W) for a given lime residue (C24 or C34), dosage (C), time before compaction (tbc), and time after compaction (tac).

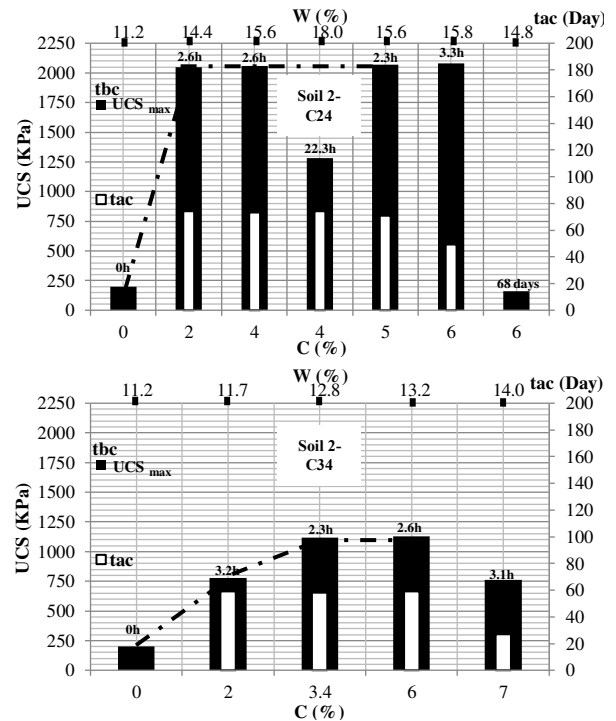


Figure 9. Maximum UCS (UCS<sub>max</sub>) of treated S2 and corresponding initial moisture content (W) for a given lime residue (C24 or C34), dosage (C), time before compaction (tbc), and time after compaction (tac).

### 3.3 Optimal Treatment Dosage (C<sub>opt</sub>)

Despite maintaining a controlled temperature (around 25°C), disruptions in measured pH were evident, both during the transition from a pH of 'PHO' to 'PHN' (pH-meter instruments) and in repeated measurements with the same instrument (Figure 10, 11). Pinpointing the exact cause of these disruptions is challenging. However, analyzing the plastic limit (PL) evolution with lime dosage (Figure 12) offered a solution, aiding in the identification of the optimal dosage previously determined based on UCS evolution with lime dosage.

C<sub>opt</sub> corresponds to the lime dosage at which PL stabilizes (e.g., 3.8% and 6% for Soil 1 and Soil 2, respectively, treated with C34) or the peak representing the maximum PL (e.g., 4.2% and 2.2% for Soil 1 and Soil 2, respectively, treated with C24). Projecting these C<sub>opt</sub> values onto the pH-C curve adjusts the interpretation method for determining C<sub>opt</sub>, identifying the dosage yielding a pH of 12.4 (e.g., Soil 1 and 2 treated with C24) or the dosage at which the pH begins to stabilize (or the first pH marking pick), particularly in cases where achieving a pH of 12.4 is not feasible (e.g., Soil 1 and 2 treated with C34).



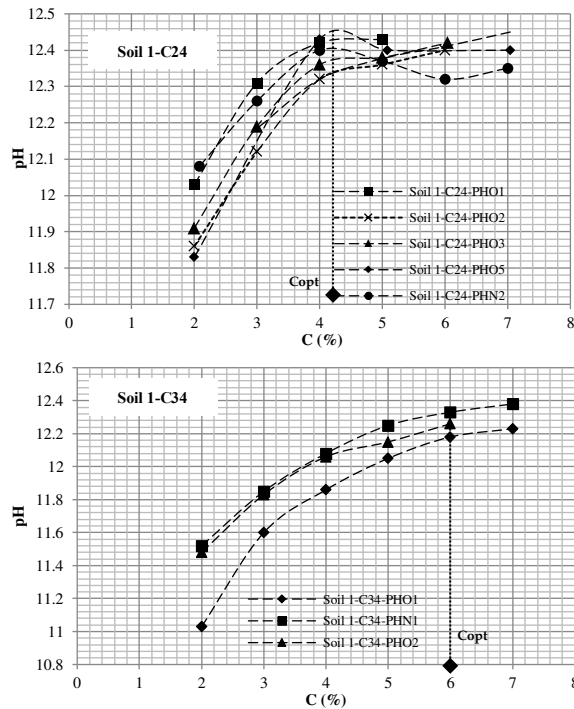


Figure 10. pH evolution of S1 with C24 & C34 dosages, and optimal dosages (Copt) based on LP and UCS<sub>max</sub> analysis with C24 & C34 limes.

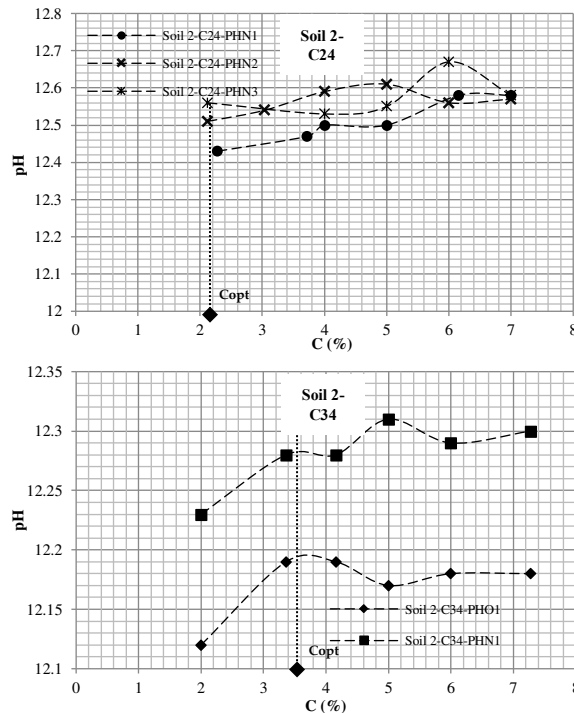


Figure 11. pH evolution of S2 with C24 & C34 dosages, and optimal dosages (Copt) based on LP and UCS<sub>max</sub> analysis with C24 & C34 limes.

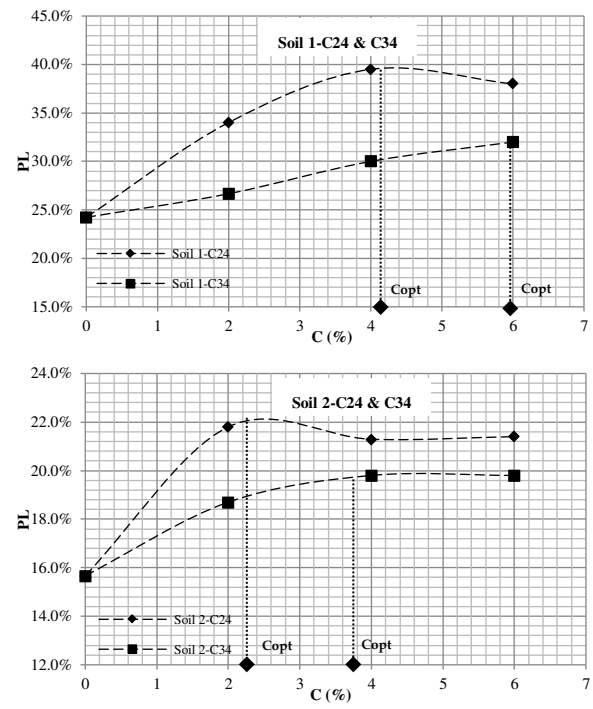


Figure 12. LP evolution of S1 & S2 with C24 & C34 dosages, and optimal dosages (Copt).

#### 4 CONCLUSIONS

In our study on clayey soil stabilization with lime, we focused on optimizing compaction and resistance in lean clay soils S1 and S2 using lime residues C24 and C34. Lime treatment significantly reduced soil density within a 2% to 7% dosage range, with a near-linear decrease in maximum densities and an increase in optimum moisture content (OMC), especially with short time before compaction (tbc) of 2 to 4 hours. The rate of density decrease was influenced by lime quality, soil mineralogy, and tbc. S2, with a high proportion of fine quartz, exhibited a higher rate of reduction. Both soils showed higher reactivity with C24 than C34, primarily due to the available CaO in C24. Experiments showed that a tbc under 3 hours optimizes compaction for balanced strength development. Delayed compaction, nearing 24 hours with higher lime doses, reduces density, raises OMC, and weakens strength. Insufficient moisture increases density, lowers OMC, affecting clod hardness. OMC may not always exceed the natural OMC (NOMC), varying with soil type, mineralogy, lime type, dosage, and tbc. Similarly, the moisture content leading to maximum strength development may not surpass OMC and is influenced by lime type and tbc. Finlay, for precise dosage formulation, we recommend a combined approach involving the study of plastic limit evolution and pH evolution with lime dosage, enhancing accuracy in determining the optimum lime dosage (Copt). Additionally, we propose a new interpretation technique: identifying the lime dosage at which the pH stabilizes or reaches the first pH inflection point. This method offers improved accuracy, especially when achieving a pH of 12.4 is not feasible.

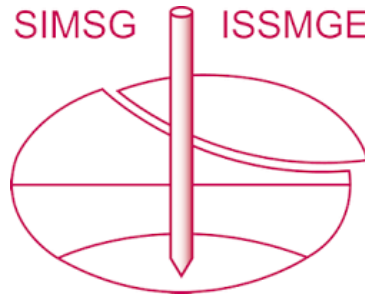
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