Titre: Title:	Compaction behavior of clayey soils treated with lime by-products
Auteurs: Authors:	Hamza Babanas, & Benoit Courcelles
Date:	2023
Type:	Communication de conférence / Conference or Workshop Item
Référence: Citation:	Babanas, H., & Courcelles, B. (octobre 2023). Compaction behavior of clayey soils treated with lime by-products [Communication écrite]. GeoSaskatoon 2023, Saskatoon, SK, Canada (6 pages). https://publications.polymtl.ca/67116/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/67116/
Version:	Version soumise à l'éditeur / Submitted version Non révisé par les pairs / Unrefereed
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Nom de la conférence: Conference Name:	GeoSaskatoon 2023
Date et lieu: Date and Location:	2023-10-01 - 2023-10-04, Saskatoon, SK, Canada
Maison d'édition: Publisher:	
URL officiel: Official URL:	
Mention légale: Legal notice:	

Compaction Behavior of Clayey Soils Treated with Lime By-Products

BRIDGING INFRASTRUCTURE & RESOURCES
OCT 1–4
GeoSaskatoon 2023

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ABSTRACT

Understanding the intricate relationship between lime treatment, soil characteristics, compaction behavior, and curing time is crucial for achieving desired soil density and compaction properties. This study investigates the impact of lime by-product treatment on clayey soils and reveals that the combined influence of mineralogy, chemical components, and dosage determines the effectiveness of the cation exchange reaction, resulting in shifts in optimal compaction points along specific saturation curves. The time before compaction significantly affects soil density and lime treatment efficiency. Excessive delay in compaction compromises cementation, emphasizing the importance of optimal compaction time which is around two to three hours. The compaction curves offer insights into the required lime saturation level for effective cation exchange. These findings, along with other highlighted aspects in the article, have practical implications for soil stabilization and lime by-product treatment, providing guidance to engineers and researchers in optimizing lime application in clayey soil applications.

1 INTRODUCTION

Lime treatment is a technique that improves the physical properties of clayey soil, enhancing its strength, bearing capacity, and reducing its sensitivity to climatic changes such as water immersion and frost (Guney et al. 2007) (Khattab, Al-Mukhtar, and Fleureau 2007) (Tang, Vu, and Cui 2011). The addition of lime to hydrated clay soil induces immediate changes by promoting the flocculation and agglomeration of particles into aggregates (Herzog and Mitchell 1963). This alteration in texture occurs mainly due to the exchange of calcium ions (Ca^{2+}) with clay particles at the surface or interlayer level (Hilt and Davidson 1960) (Eades and Grim 1960) (Choquette, Berube, and Locat 1987) (Prusinski and Bhattacharja 1999) (Al-Mukhtar, Lasledj, and Alcover 2010).

The absorption of calcium by the clayey soils leads to a reduction in the thickness of the diffuse double layer, resulting in a modification of the density of electric charges of clay particles. This change causes the particles to be attracted to each other, forming weakly bonded flocs at the edges of the clay particles (Eades and Grim 1960) (Diamond, White, and Dolch 1963) (Prusinski and Bhattacharja 1999). Flocculation is also influenced by the modification of the cation exchange capacity (CEC) of soil minerals (Diamond and Kinter 1965) (Locat, Bérubé, and Choquette 1990).

Flocculation alters the clay structure, transitioning from a flat, parallel arrangement to a more random edge-to-face structure. This transformation leads to an increase in the internal friction angle, improvement in soil consistency, strength, and bearing capacity (Leroueil and Le Bihan 1996) (Bell 1996) [(Prusinski and Bhattacharja 1999). The flocculation reaction can continue in the long term, particularly under high basicity conditions, as calcium hydrates crystallize on the surfaces of soil particles (Hilt and Davidson 1960) (Diamond, White, and Dolch 1963) (Arabi and Wild 1986) (Choquette, Berube, and Locat 1987) (Locat, Bérubé, and Choquette 1990) (Bell 1996) (Rao and Rajasekaran 1996) (Vitale et al. 2017).

The extent of these modifications, whether short-term or long-term, is influenced by the lime dosage, the form of calcium in the lime used (available CaO or $Ca(OH)_2$), and the soil mineralogy that determines the cation exchange capacity (CEC) (Hilt and Davidson 1960) (Bell 1996) (Basma and Tuncer 1991). The CEC is known to be high for smectites, moderate for illites, and low for kaolinites. Furthermore, the initial treatment conditions (cure time before compaction, hydration, temperature) also play a role in modifying the bulk density of aggregates, soil density, and the strength of the soil associated with the formed aggregates (Locat, Bérubé, and Choquette 1990) (Osinubi 1998) (Rao and Shivananda 2005).

The originality of the work relies on the use of by-products derived from lime kiln production instead of pure lime. This article focuses on studying one aspect of the modifications brought by lime treatment, namely flocculation, and its influence on soil and lime characteristics, initial treatment conditions, and curing conditions (cure time before compaction). The investigation of flocculation is based on analyzing the evolution of compactness in treated soils and its dependence with respect to treatment conditions.

2 EXPERIMENTAL PROGRAM

The study examines two clayey soils collected from different locations in Quebec, Canada. Soil S1 is obtained from Saint-Marc-sur-Richelieu and is classified as high plasticity inorganic clay, while Soil S2 is obtained from Marbleton and is classified as slightly plastic silty clay. Table 1 provides a summary of the characteristics of these two soils.

The experiment involved treating two soils with different initial water contents (W_i) using varying lime dosages (C). The lime-treated soils were then cured for a specific time before compaction (tbc) in a sealed environment at 25°C. Subsequently, the soils were compacted using a normal compaction energy (NE) of 600 KJ/m^3, except for one dosage in soil 2, which received a modified compaction energy (ME) of 2700 KJ/m^3.

Table 1. Characteristics of tested soils

Characteristics (%)	S1	S2
Natural water content[1]	59.6	14.8
Liquid limit	69	21.4
Plastic limit	24.2	15.7
Shrinkage limit	11.4	14.8
Sand	0	40
Silt	13	22
Clay	87	38

The study aimed to investigate the influence of lime type, dosage, curing time, and compaction energy on the compaction behavior of the soils. The analysis focused on examining the compaction curves, specifically the maximum density (ρ_{dmax}) and optimum water content (W_{iopt}). The limes used in the study are two industrial lime residues known as C24 and C34, which are derived from lime kiln production. These lime residues have a lower calcium oxide (CaO) or calcium hydroxide ($Ca(OH)_2$) content compared to standard limes. The specific characteristics of these limes can be found in Table 2 and Table 3.

Table 2. Characteristics of C24 lime

Chemical Properties (%)	C24 (0 – 150 µm)
Calcium carbonate ($CaCO_3$)	33.1
Available calcium oxide (CaO)	48.5
Magnesium oxide (MgO)	0.8
Total Calcium (Ca)	52.1
Silica (SiO_2)	3.5
Ferric oxide (Fe_2O_3)	0.4
Alumina (Al_2O_3)	1.2
Total sulfur (S)	2.7
Total carbon (C)	4.3
Fire loss	15.4
Neutralizing power ($CaCO_3$ = 100)	121.5

Table 3. Characteristics of C34 lime

Chemical Properties (%)	C34 (0 – 630 µm)
Calcium (Ca)	33.6
Magnesium (Mg)	0.34
Available calcium hydroxide ($Ca(OH)_2$)	31.1
Soluble potassium oxide (K_2O)	0.07
Phosphoric Anhydride (P_2O_5)	0.01
Assimilable P_2O_5	0.01
Humidity (H_2O)	20.2
Neutralizing power ($CaCO_3$=100)	82.7
Neutralizing power (Carbonate fraction)	38.8
Efficacity (E)	87.4
Agricultural value index (AVI)	72.3

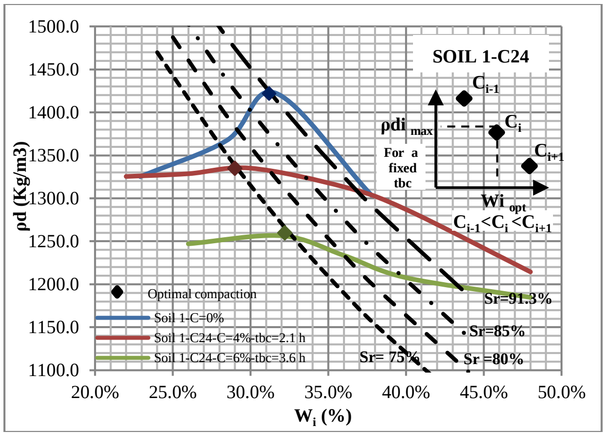
3 RESULTS

The compaction curves of the treated soils have demonstrated several significant results.

First, lime treatment reduces the density of clayey soils (Figures 1 and 2). Optimum points (W_{iopt}, ρ_{dmax}) representing maximum densities at optimal moisture content vary depending on soil type. Following treatment, these optimum points shift to a distinct saturation curve of the natural soil. Soils rich in clay fractions (e.g., Soil 1, Figure 1) experience shifts of optimal points towards higher saturation levels, while soils with moderate or low clay fractions (e.g., Soil 2, Figure 2) undergo shifts of optimal points towards lower saturation levels.

Second, the treatment flattens the Proctor curves, especially in soils with higher clay fractions (Soil 1). Using higher quality lime, such as C24, enhances this flattening effect (Figures 1 and 2).

Third, increasing lime dosage within curing times ≤ 3 hours shifts the optimum points along a specific saturation curve of the natural soil, resulting in lower peak density (ρ_{dmax}) and increased optimal moisture content (W_{iopt}). This shift is predicated on transitioning from a notable to higher dosage. Saturation levels (Sr), defining the shift curves, vary depending on soil type and lime used: 75% (Figure 1-C24), 80% (Figure 1 and 2-C34), and 85% (Figure 2-C24). The difference between the optimal saturation curves is significant with the most effective lime (C24). Positive differences occur with significant clay fractions, while negative differences occur when the clay fraction is small compared to other fractions (silt, sand).



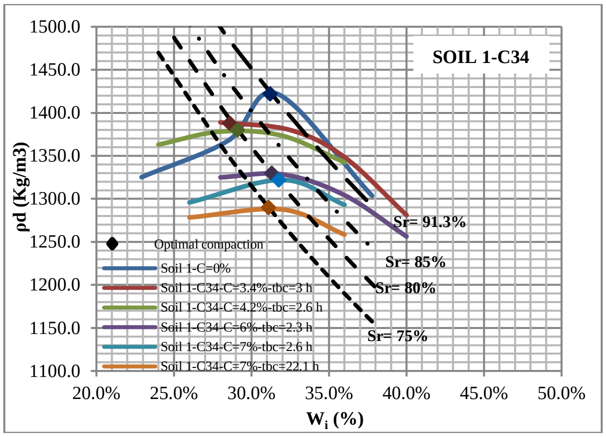


Figure 1. Compaction curves of S1 with C24 and C34 limes

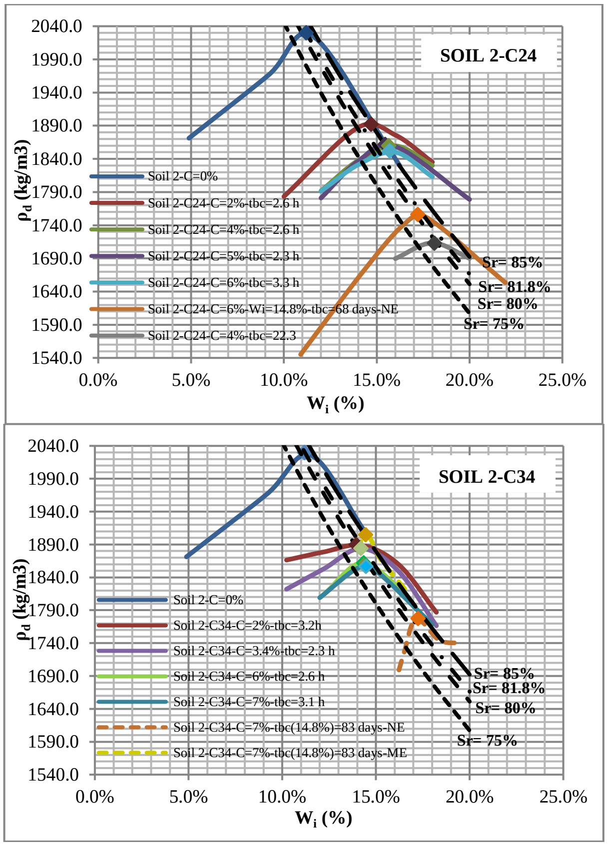


Figure 2. Compaction curves of S2 with C24 and C34 limes

Fourth, analyzing the slopes of maximal density (ρ_{dmax}) and optimal moisture content (W_{iopt}) in relation to lime dosage (Figures 3 and 4) highlights the impact of lime and soil type. Within a specific dosage range, the relationship is nearly linear, but beyond that range, the effect on reducing ρ_{dmax} or increasing W_{iopt} becomes less significant. For example, exceeding a 6% lime dosage for Soil 1 treated with C34 has a negligible effect on shifting the corresponding optimum point.

Fifth, increasing the curing time before compaction reduces the maximum density and shifts towards lower saturation curves. This effect is more pronounced when tbc exceeds 3 hours and approaches 24 hours. The magnitude of this change depends on the soil type, particularly the clay fraction, as well as the type and dosage of lime used. This observation applies to both soils (Figure 1-C34-7%, Figure 2-C24-4% & 6%).

Sixth, increasing the compaction energy leads to a progressive shift along the same compaction curve. Specifically, in Figure 2, when using C34 with a lime dosage of 7%, an increase in compaction energy results in the observed shift along the saturation curve.It is important to note that the saturation curves presented and discussed in this context specifically refer to the saturation curves of natural soils.

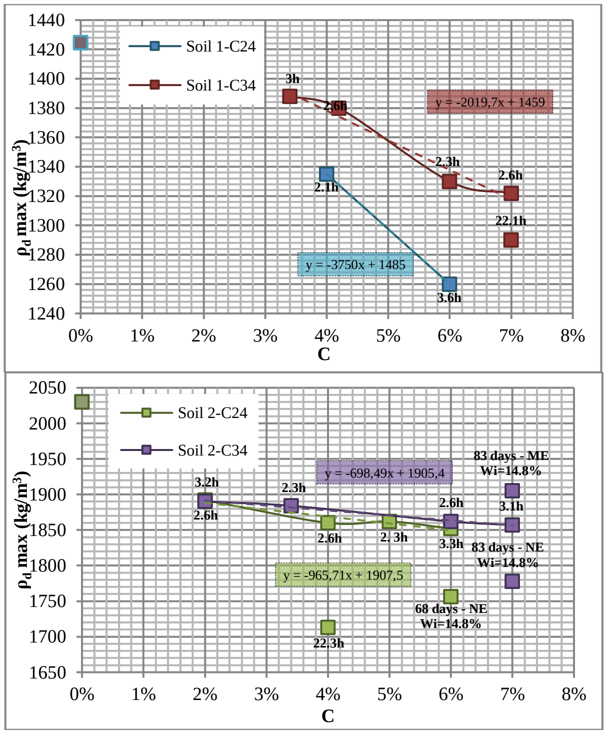
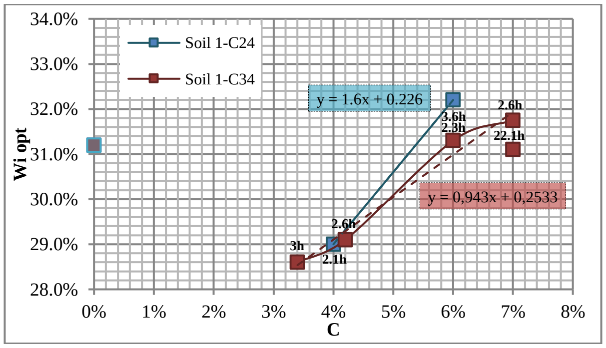


Figure 3. Maximum density evolution with lime dosage



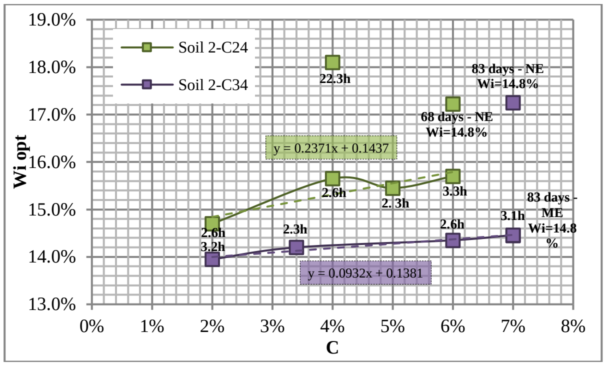


Figure 4. Optimum moisture content evolution with lime dosage

4 DISCUSSION

The tests reveal that the addition of lime by-product to clayey soils reduces soil density. This can be attributed primary to the cation exchange reaction, which modifies the electrostatic charge of the clay, leading to a decrease in the double water layer and the formation of calcium bonds between clay particles (flocculation) (Osula 1996) (Al-Mukhtar, Lasledj, and Alcover 2010) (Kavak and Baykal 2012). As a result, the flattening effect observed is more pronounced in soils with higher clay content and when lime with higher levels of calcium is used (Di Sante 2020). Indeed, the dosage of calcium solution plays a crucial role in the compaction behavior of treated soils. When the soil is saturated with calcium solution, it leads to a substantial reduction in soil density. This reduction can be attributed to the enhanced flocculation process of clay particles, primarily facilitated by the increased cationic substitution of calcium. Consequently, the treated soil exhibits greater friability and reduced plasticity, resulting in a decrease in soil density and minimizing the water effect (flattening phenomena) (Hilt and Davidson 1960) (Eades and Grim 1960) (Choquette, Berube, and Locat 1987).

The mineralogy of the clay fraction and the chemical components of the soil and lime play a crucial role in the cation exchange reaction in clayey soils treated with lime (Diamond and Kinter 1965) (Ali and Mohamed 2017). The combination of these factors determines the extent and nature of the cation exchange process, which, in turn, influences the changes in soil density and compaction behavior. The observed displacement of optimum compaction points along specific saturation curves (75%, 80%, or 85%) with increasing lime by-product dosage further highlights the significance of this interaction. Supporting this, a study conducted on three different soils (Nguyen 2015) revealed that highly plastic soils exhibit optimum points near the natural saturation curve of 80%, while clays and silts with lower plasticity have optimum points closer to the natural saturation curve of 85%. Thus, these findings highlight the intricate relationship between mineralogy, chemical components, cation exchange, and compaction behavior in lime-treated clayey soils.

The time before compaction significantly affects soil density and the effectiveness of lime by-product treatment. Compacting the soil earlier generally produces better results by promoting optimal cementation and development. Increasing the tbc leads to a decrease in soil density and a shift in the optimum compaction points towards lower saturation curves. This is influenced by the dynamic cation exchange reaction, which takes longer to reach equilibrium with increasing tbc. The extended duration allows for enhanced clay agglomeration due to the ongoing formation of cementitious compounds, resulting in increased resistance to compactability (Ali and Mohamed 2017). However, excessively delaying compaction can hinder the development of cementation at particles contact and between clay flocs, potentially impacting the effectiveness of lime treatment (Ali and Mohamed 2017). This finding can help explain the significant increase in density observed after changing the compaction energy of treated soil 2 with a tbc of 83 days. Therefore, finding the right balance between allowing sufficient time for the cation exchange reaction and ensuring timely compaction is crucial for achieving the desired density and compaction characteristics. Based on the findings of the study, an optimal compaction time within the range of two to three hours is recommended.

Within the defined dosage range, linear equations can estimate the variation of optimum points (W_{iopt}, ρ_{dmax}) along specific saturation curves. These equations exhibit distinct slopes (S), which vary depending on the soil type and the type of lime used. For instance, a 1% lime content results in density decreases of 20.2 kg/m3, 37.5 kg/m3, 7 kg/m3, and 9.7 kg/m3 respectively for the treatment of soil1 with C34, soil 1 with C24, soil 2 with C34, and soil 2 with C24. The following equation $S = (\%< 2\mu m) \times CEC\ (meq/g) \times (CaO \text{ or } Ca(OH)_2)\ (\%) \times \rho_{dmax}\ (C=0\%) \times 10^{-5}$ can be used to estimate the decrease in slope of maximal densities during dosage transitions. This preliminary equation, utilizing an estimated Cation Exchange Capacity (CEC) (McBratney et al. 2002), closely aligns with the experimental slopes obtained from compaction curves of treated soils. However, further research is necessary to validate and refine this equation.

Over a certain dosage, lime products' effect becomes negligible in reducing ρ_{dmax} and increasing W_{iopt}. This dosage represents the chemical fixation point (PFC) identified by Eades and Grim (1966). The PFC satisfies cation exchange reactions, creating an alkaline environment that enhances soil resistance and facilitates the transition from improvement to stabilization (Hilt and Davidson 1960) (Bell 1996). Thus, Proctor curves can help to determine the minimum lime dosage for soil treatment, ensuring a favorable environment for soil resistance.

5 CONCLUSION

Lime by-products give similar results compared to pure lime and appear as an economic option for lime treatment. The study focuses on the effects of lime by-product treatment on clayey soils, yielding the following findings:

Lime by-product addition reduces soil density and flattens Proctor curves. This is attributed to the cation exchange reaction and flocculation, with greater impact observed in soils with higher clay content and when using lime with higher calcium levels.

The interaction between mineralogy, chemical components, and lime dosage determines the efficiency of the cation exchange reaction. This interaction influences the compaction behavior, causing a shift in optimal compaction points along specific saturation curves as lime dosage increases.

The time before compaction significantly affects soil density and lime treatment effectiveness. Increasing tbc leads to a shift in the optimal compaction point towards lower saturation curves. Excessive delay in compaction hinders cementation and compromises lime treatment. An optimal compaction time within the range of two to three hours is recommended.

At a specific lime by-product dosage, the excessive impact of lime on reducing soil density and increasing water content becomes negligible.

Increasing the compaction energy of lime-treated soil shifts it along the same compaction curve, resulting in higher soil density. Moreover, a longer tbc enhances this effect, leading to even greater soil density.

6 ACKNOWLEDGEMENTS

The authors extend their thanks to the Natural Sciences and Engineering Research Council of Canada for providing funding for this research.

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