

EXPERIMENTAL AND STATISTICAL ANALYSIS OF SOIL STABILISATION TO AVOID LANDFILLING

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ABSTRACT. Clayey soil is a moisture-sensitive material whose properties pose geo-environmental challenges in the construction sector. Soil stabilisation through lime treatment offers the possibility of using local unsuitable soils without landfilling. This study investigates the lime treatment and stabilisation of sensitive reddish clay soils from the Setif region, Algeria. Geotechnical, chemical, and physico-chemical characterisation of the clayey soils with different percentages of dry lime (i.e. 0% to 9% by weight with intervals of 3%) were conducted. The standard plasticity test shows that the lime treatment causes a decrease in the plasticity index (from 30.7 to 22.1%) and methylene blue value (from 5% to 2.71%). Furthermore, the compressive strength test showed a 16-fold increase in unconfined compressive strength (UCS) after 28 days for the clay with 6% lime (130 kPa versus 2100 kPa). However, a decrease in dry density was also observed (16 kN m⁻³ versus 15.7 kN m⁻³). Chemical and physico-chemical analyses using X-ray fluorescence and diffraction revealed the appearance of other chemical elements and mineral phases. Finally, ANalysis Of VAriance (ANOVA) was used to evaluate the effect of curing time and lime content on UCS. Both variables affected the strength development positively. The lime content was two times more efficient than the curing time.

KEYWORDS: Soil stabilisation, clays, lime, curing, compressive strength.

1. INTRODUCTION

Natural clayey soils are not suitable for subgrade or embankments due to their geotechnical properties under moisture variations. According to [1], clay compaction is difficult as its consistency ranges from hard to very hard when the soil is dry and quite sticky when wet. Generally, inferior geotechnical properties (e.g. low bearing capacity, low permeability, high compressibility, and volume instability) are common for this type of soil [2, 3], which poses technical challenges for road construction [4, 5]. Thus, several techniques are used for improving these properties (e.g. surface compaction, grouting, injection, soil reinforcement, and chemical stabilisation) [6–8] to avoid expensive damages [9] and avoid landfilling. The service life of the soil, the relevant local environment, and the soil type are directly related to the selected technique [10]. For example, calcium-based stabilisers (i.e. cement and lime) are used for their effectiveness [11–13]. However, cement is not suitable for stabilising soils with a plasticity index higher than 30% due to mixing [14] and Ca²⁺ depletion during cation exchange [15]. Clayey soils treated with lime lose their cohesive properties and behave as a granular material in a short period [14]. In the literature, several studies have demonstrated that lime treatment improves soil workability by decreasing plasticity in-

dex (PI) and methylene blue value (MBV). Hussain and Dash [16] found that high-plasticity soil became silt after a 3% lime addition. Aziz et al. [17] found that adding up to 4% of lime to low plasticity clays significantly decreased PI. Bhattacharja and Bhatta [18] tested three clayey soils and found that the effectiveness in the short period of 3% lime depends on their starting PI. Long-term stabilisation effects increase the unconfined compressive strength (UCS) due to chemical reactions, including lime hydration and pozzolanic reaction [19, 20]. Specifically, the hydration forms hydrated lime (HL), which causes a secondary soil stabilisation due to the pozzolanic reaction [15]. When Ca(OH)₂ is in an over-saturated state, it will precipitate, fill the soil pores, and improve its mechanical performance [21]. Bell [7] found that lime hydration caused a significant increase in UCS up to 14 days. Bouras et al. [22] showed that 2% of lime added to a low plasticity soil is sufficient to achieve 1 MPa UCS after 7 days of curing. Anburuvél [15] observed that UCS of inorganic and organic soils treated with 5% of all common stabilisers ranges between 700 and 1500 kPa.

X-ray diffraction (XRD) analyses [7, 23, 24] confirmed that the addition of lime to clays promotes the formation of new mineral phases (i.e. new cementitious compounds) and provides a denser structure [25].

Generally, the main cementitious compounds are hydrated calcium silicate (C-S-H), hydrated calcium aluminate (C-A-H), and calcium alumina-silicate hydrate (C-A-S-H) [26–28]. Bell [7] and Russo and Modoni [29] showed that the treatment produces smaller pores due to the formation of nano-cementitious products. Ying et al. [30] studied lime-treated clays with low clay fractions over 90 days of curing. They found an increase in nanopores, probably due to the production of cementitious compounds, which coated the aggregates and gradually closed the pores. Mixing, mellowing, curing time [31], and mineral soil composition affect compound formation. Al-Mukhtar et al. [32] showed that the pozzolanic reaction of a lime-treated soil containing 86 % of clay minerals (i.e. 48 % of bentonite and 38 % of kaolinite) caused the formation of C-A-H after 1 day and C-S-H after 7 days. Wang et al. [24] observed the C-S-H content after 1 year of curing in a lime-treated soil with a clay content of Wang et al. [24] observed the C-S-H content after 1 year of curing in a lime-treated soil containing 27 %. However, after 150 days of curing [30], residual portlandite was found in the soil. Meaning that no cementitious compound was identified due to the slow pozzolanic process and low clay fraction content in the tested soil.

Although several researchers investigated lime stabilisation of clayey soils, there is a lack of studies on the hydration of ferrite/iron oxides [15, 33] in haematite-rich red clay soils. Amiri et al. [33] investigated cement-stabilised haematite-rich red clay through XRD analyses and scanning electron microscope (SEM) images. They suggested that the haematite in red soils accelerates the hydration process and improves C-S-H and C-A-H production. The haematite particles exhaust the $\text{Ca}(\text{OH})_2$ and form C-F-H and C-F-S-H nanostructures. These nanostructures reduce porosity and increase the strength of cement-stabilised soil samples. Therefore, red clay deposits, a distinctively geological feature of the Setif region in northeastern Algeria [34], could be used for infrastructure projects (e.g. roads, dams, and industrial zones). Usually, in-situ clayey soils are removed and replaced by other unbound materials. However, soil substitution is costly because it requires quarrying and transportation [35] with significant environmental burdens [36] and non-renewable resource consumption [37]. Stabilisation has improved prospects for reusing by-product soil, improving the circular economy, and reducing the carbon footprint of construction projects [38]. The improvement of subgrade layers in road construction is essential to ensure the durability and performance of pavements, particularly in areas with naturally weak or unstable soils. The subgrade layer, located directly beneath the base and surface layers, supports and distributes traffic-induced loads, while minimising deformations [35]. When stabilised with binders such as lime or cement, the subgrade gains enhanced strength, stiffness, and durability. The

addition of binders to the soil in the subgrade initiates chemical reactions that reinforce the structure of the soil. For example, lime stabilisation is highly effective for clayey soils, as it reduces plasticity and increases load-bearing capacity by forming durable cementitious compounds through pozzolanic reactions. This process minimises the impact of moisture and temperature variations, thereby reducing the risks of soil swelling and shrinkage that can compromise the pavement stability.

Improving the subgrade layer offers long-term benefits, including reduced maintenance frequency and extended pavement lifespan. Optimising the quality of lower layers also reduces the required thickness of base and surface layers, contributing to lower construction costs and environmental impact [37]. Ultimately, subgrade improvement significantly contributes to the construction of more reliable and resilient roads, capable of withstanding high traffic demands and challenging environmental conditions.

This study presents the physical, chemical, and geotechnical properties of clayey soils treated with 0 % to 9 % dry lime by weight. In particular, this study consists of a before-after characterisation of the Atterberg's limits, methylene blue value, standard Proctor, UCS tests, and X-ray fluorescence and diffraction analyses of a reddish clay from the Ain Azel industrial zone in Setif (Figure 1). Additionally, a statistical ANalysis Of VAriance (ANOVA) has been carried out to verify the reliability of the proposed method to predict UCS of the treated soil from curing time and lime content.

2. MATERIALS AND METHODS

Three 1.5–2 m deep open-air boreholes were drilled to test soil near a road where severe damages (e.g. chipping, settling, and longitudinal cracks) were observed. The boreholes revealed the presence of reddish clay.

Table 1 lists the geotechnical characteristics of the soil that consists of 60 % silt, 20 % sand, and 20 % clay. Given its plasticity index of 31 % and over 88 % passing through 80 μm , it is a marly clay or very plastic silt (A3) according to [39], and requires a lime treatment according to the Road Earthwork Guide [40].

Figure 2a shows the mineral composition from XRF spectrometry using a Rigaku spectrometer (ZSX PrismaIV) [46]. Silica (SiO_2), calcium oxide (CaO), and iron oxide (Fe_2O_3) are dominant. However, there are also small quantities of other metal oxides (e.g. magnesium oxide-MgO, potassium oxide- K_2O , and alumina- Al_2O_3). Figure 2b presents the XRD results from a Siemens D500 powder diffractometer with a nickel anti-cathode ($\delta K\alpha = 1.5406 \text{ \AA}$) and a microcomputer for automated control of goniometer rotation, data acquisition, and data processing. The power used was 600 W, with a voltage of 30 kV and an intensity of 20 mA. According to Figure 2b, the natural soil contains quartz (42.4 %), calcite (35.4 %), and clay minerals, such as kaolinite (7.1 %) and illite (13.1 %).



FIGURE 1. Workflow of the research study.

Soil parameters	Symbol	Method	Value	Unit
Optimum moisture content	w_{opt}	[41]	22	%
Maximum dry density	$\gamma_{d,opt}$	[41]	16	kN m^{-3}
Liquid limit	LL	[42]	56	%
Plastic limit	PL		25.3	%
Plasticity index	PI		30.7	%
Methylene blue value	MBV	[43]	5	-
Fraction ≤ 2 mm	$P_{2\text{ mm}}$	[44]	100	%
Fraction ≤ 80 μm	$P_{80\text{ }\mu\text{m}}$		88	%
Fraction ≤ 2 μm	$P_{2\text{ }\mu\text{m}}$	[45]	22	%

TABLE 1. Geotechnical characteristics of the soil.

The presence of haematite mineral phase Fe_2O_3 (2%) explains the red colour of the clay [47]. The XRF spectrum and X-ray diffractogram in Figure 2 are coherent: the high CaO values are consistent with the presence of calcite, while silica, alumina, and potassium oxide are consistent with the presence of quartz, kaolinite, and illite, whereas iron oxide is consistent with the presence of haematite.

Table 2 shows the chemical composition of the lime used, produced in the Constantine area, Algeria. The percentages of lime used in the mixtures were 0%, 3%, 6%, and 9% by weight.

Figure 3 shows the lime diffractogram; black stars highlight the diffraction peaks of CaO at 18.2, 29.8, 32.45, 33.45, 37.34, 47.8, 51.0, 54.23, 64.67, and 67.57 degrees.

Laboratory tests were conducted before and after the lime treatment to study its effects on short-term (workability) and long-term (stabilisation) soil properties:

- Dry sieving and hydrometer granulometric tests according to [44] and [45] to obtain the gradation curve of the natural soil;
- Atterberg's limits according to [42] to determine PL, LL, and PI;
- methylene blue value (MBV) tests according to [43] to investigate the effect of lime on the specific surface area of clay;
- standard Proctor tests according to [41] to determine the optimum dry density and moisture content

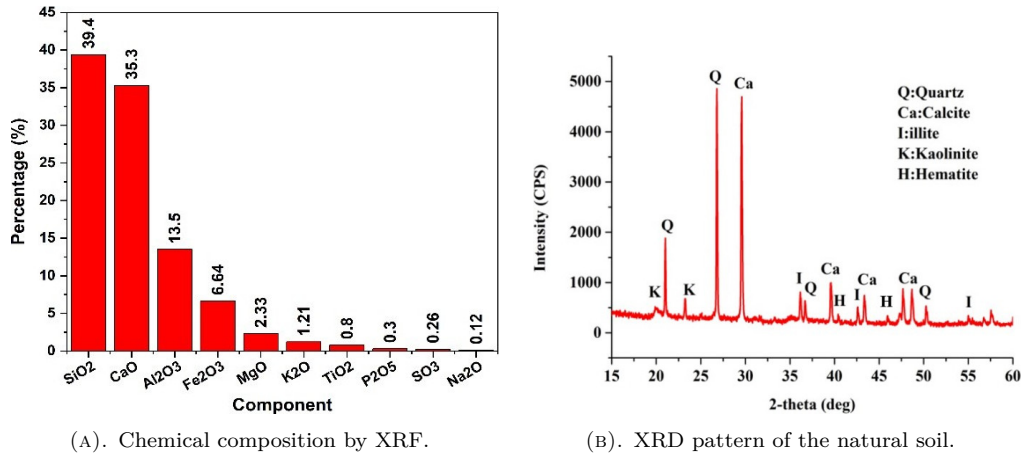


FIGURE 2. XRF spectrum and X-ray diffractogram.

Component	Weight [%]
Sodium oxide (Na ₂ O)	0.04
Magnesia (MgO)	0.43
Alumina (Al ₂ O ₃)	0.17
Silica (SiO ₂)	0.60
Phosphorus pentoxide (P ₂ O ₅)	0.00
Sulfate (SO ₃)	0.10
Potassium oxide (K ₂ O)	0.02
Lime (CaO)	98.40
Iron oxide (Fe ₂ O ₃)	0.12
Strontium oxide (SrO)	0.02

TABLE 2. Chemical composition of lime used.

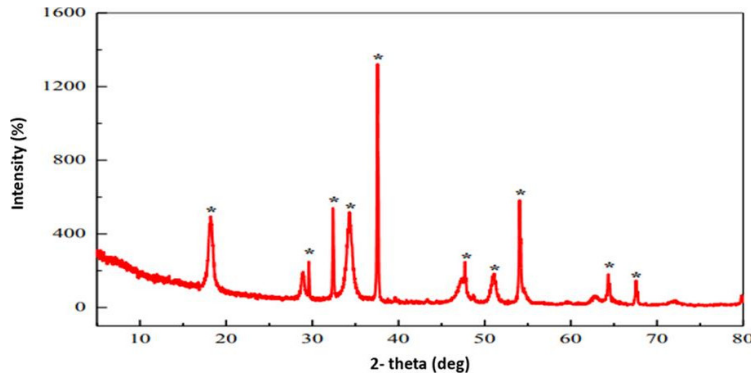


FIGURE 3. Diffractogram of lime.

by varying the lime content. The soil-lime mixtures were thoroughly mixed for 1 hour before the compaction test (i.e. mellowing period);

- UCS tests according to standards [48] and [49] on samples with the optimum moisture content obtained from the standard Proctor tests. The prepared soil was then placed in a 37.5 mm diameter cylindrical mould with a height-to-diameter ratio of 2. Static compaction was performed in four layers at 1.27 mm min⁻¹ to achieve $\gamma_{d,opt}$ for each lime content. The samples were wrapped in plastic film and stored in a humid chamber for 1, 7, 14, or 28 days before testing. After curing, the axial load-

ing press was used at a constant displacement rate of 1 mm min⁻¹ to determine the maximum rupture force from the force-deformation curve. In particular, UCS is the stress at failure resulting from the ratio (Equations (1) and (2)) between the rupture force (F) and the average cross-sectional area of the sample (A):

$$UCS = \frac{F}{A}, \tag{1}$$

$$A = \frac{A_0}{1 - \epsilon_I}, \tag{2}$$

where A_0 is the starting average cross-section, and ϵ_I is the axial strain for the applied rupture force.

In addition, chemical and mineralogical analyses have been carried out on dried, ground samples subjected to compression tests before and after the treatment with different lime content (i.e. 0 %, 3 %, 6 %, and 9 %).

Statistical analyses of UCS results assessed the influence of each variable and their interaction on the mechanical performance of the treated soil. A full factorial approach has been proposed to predict the UCS from two independent factors: curing time in days (T) and lime content percentage by weight of dry soil (L). The coefficient of determination (R^2), adjusted coefficient of determination (Adjusted R^2), and root mean square error (RMSE) have been calculated to test the relationship between the experimental compressive strength values and the independent variables.

ANOVA was used to compare the obtained means from two independent variables using the F -distribution [50]. The Fisher test (F -test) was used to compare the computed F value (F -ratio) to the critical F value (F_{crit}) from the Fisher-Snedecor table with a significance level of 0.05. In particular, the degrees of freedom for the F -test were DOF_1 , DOF_2 , and DOF_3 according to the Sum of Squares due to Error Lack, Sum of Squares due to Error Residuals, and Sum of Squares Total Corrected Error, as shown in Equations (3)–(5), respectively:

$$\text{DOF}_1 = p - 1, \quad (3)$$

$$\text{DOF}_2 = n - p, \quad (4)$$

$$\text{DOF}_3 = n - 1, \quad (5)$$

where p is the number of estimated coefficients (i.e. 4 in the model), and n is the number of training samples (i.e. 12 in the model) [51].

The Student's t -test compared the sample and population means according to:

$$t = \frac{\bar{x} - \mu}{\frac{S_{\bar{x}}}{\sqrt{n}}}, \quad (6)$$

where t is the test statistic, \bar{x} is the sample mean, μ is the population mean, and $S_{\bar{x}}$ is the sample standard deviation. Then, t has been compared to a critical value (t_{crit}) corresponding to a significance level (α) and DOF_2 . The critical value is obtained from the Student's t -distribution table [50]. If the absolute value of t is higher than t_{crit} , the variable effect is significant; otherwise, it is non-significant.

3. RESULTS AND DISCUSSION

Table 3 shows Atterberg's limits for different lime contents. PI significantly decreases with 3 % lime content and stabilises with 6 % and 9 % lime content. Since LL is stable with the increase in lime content except for a slight increase at 3 %, the increase in LP drives the benefits in terms of PI. Therefore, the highest level of improvement in the consistency of this soil is for a lime content of 6 % (PI is 15 % with 6 % of lime

Lime content [%]	LL [%]	PL [%]	PI [%]
0	56	25	31
3	60	40	20
6	60	41	19
9	61	45	16

TABLE 3. Effect of lime addition on plasticity properties of the tested soil.

and 20 % with 3 % of lime). Under such conditions, the soil changes classification from clayey soil (class A3) to slightly plastic marls or clayey silts (class A2) according to [36]. Chemical reactions between lime and soil, including ion exchange and flocculation reactions [32, 52, 53], change the clay texture and improve the consistency of the treated soil [54]. The incorporation of lime into the soil matrix exhibited distinct effects on the soil's plasticity characteristics. The plastic limit (PL) demonstrated a notable increase at a dosage of 3 % lime content, primarily attributed to the lime-induced flocculation-agglomeration mechanism. This phenomenon occurs due to the cation exchange process, where calcium ions (Ca^{2+}) from the lime replace the existing monovalent cations in the clay minerals. This leads to improved interparticle attraction and subsequent resistance to particle movement [54]. Beyond the 3 % lime dosage, the PL values maintained a relative constant values, indicating that the workability of soils cannot be improved further; however, the small variation in PL is likely due to the manipulation during the trial. On the contrary, the liquid limit (LL) exhibited minimal fluctuations throughout the lime addition range, maintaining a relatively consistent trend. This stability in LL values, despite the varying lime content, suggests that the influence of lime on the soil's maximum water-holding capacity at a liquid state was less pronounced.

In natural soils, clay surfaces holding negative charges attract water directly or through cation exchange. This effect leads to electroneutrality forming a diffuse double layer (DDL), responsible for soil plasticity. Ca^{2+} ions have a lower affinity than monovalent cations, induce lower DDL thickness, and thus reduce plasticity [55].

Figure 4 shows the results of the MBV measurement for each lime content. An increase in lime content causes a decrease in MBV values.

For example, a 6 % lime content causes a 40 % decrease in MBV compared to the untreated samples (3 % vs 5 %). The amount of MB absorbed by clay particles depends on their surface specific area (SSA) and their type of minerals [20]. In addition, the hydrates from the pozzolanic reaction coat the surface of soil particles and act as binders between soil particles, inducing flocculation and agglomeration of aggregates and reducing SSA and MBV. The linear regression curve reveals a strong correlation (i.e. R^2 value of 0.954) between MBV and the lime content. How-

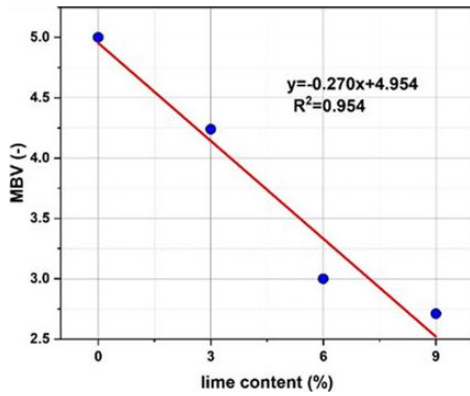


FIGURE 4. MBV as a function of lime content.

ever, the drop in MBV was found more pronounced for 6% than for any other lime content.

Figure 5 shows the soil $\gamma_{d,opt}$ and w_{opt} as a function of lime content.

The increase in w_{opt} with lime content is due to high water retention capacity in flocculated soils and the water needed for the pozzolanic reaction between clay and lime [56]. The decrease in $\gamma_{d,opt}$ is due to the lower density of lime compared to the treated soil [57, 58]. The observed behaviour is in accordance with [57].

The UCS tests were carried out on samples at 1, 7, 14, and 28 days of curing. Table 4 shows that adding 3% and 6% of lime increases UCS, especially at 28 days of curing. Whatever the curing period, UCS for 9% lime content is less than 6%. Therefore, the optimal lime dosage to achieve the highest strength at 28 days of curing is 6%. At 1 and 7 days of curing, a crucial increase in UCS is observed compared to the natural soil, and the optimal lime dosage remains at 6%. Bell [7] studied compacted soils stabilised with lime and showed that at 6% lime addition and 7 days of curing, fat clay, elastic silt, and silt soils had 1.5, 2, and 6 times higher UCS, respectively, compared to untreated samples. According to Amiri et al. [33], soils containing iron oxide treated with 6% of calcium stabiliser have a 17 times higher 7-day compressive strength than the untreated. In this study, the red soil stabilised with 6% of lime showed an 11.5-fold increase in UCS compared to the control samples after 7 days of curing.

The increase in UCS at 1 and 7 days of curing is attributed to short-term chemical reactions (cation exchange and flocculation/agglomeration) that make the soil more granular and friable [59]. The cation exchange capacity depends on the availability of free Ca^{2+} , which affects the continuous increase of UCS with lime content. However, the increase in 28-day UCS after a 6% treatment is attributed to the slow pozzolanic reaction and cementation between lime and soil [60]. Additionally, Yong and Ouhadi [61] attributed the increase in UCS to changes in the mineralogical composition of the soil after treatment. In this study, the reduction in UCS at 28 days of curing

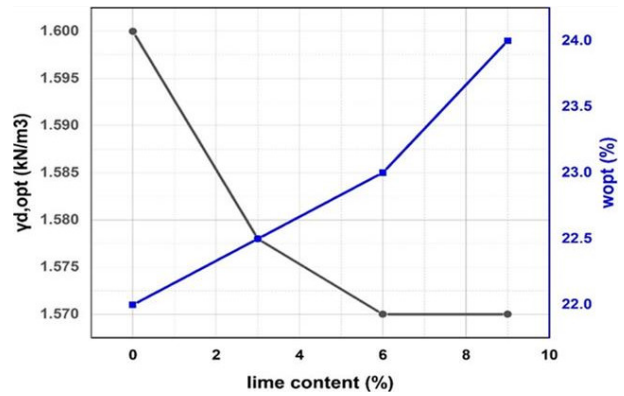


FIGURE 5. Lime Content vs soil properties.

Curing period [day]	Lime content [%]			
	0	3	6	9
1	130	910	1 100	1 090
7	130	1 200	1 480	1 430
14	130	1 375	1 700	1 590
28	130	1 480	2 100	1 890

TABLE 4. Development of UCS [kPa] with increasing curing period.

for the 9% lime content compared to 6% is due to the pozzolanic reaction. At this stage, the water content [62] causes residual anhydrite lime particles responsible for weakening the soil structure.

XRD patterns of specimens treated with the optimum content of lime (i.e. 6%) highlight mineralogical changes at different curing periods. For the sake of brevity, only specimens cured for 28 days are discussed. Figure 6a compares the XRD patterns of natural (red curve) and treated with 6% lime soil (blue curve). The XRD patterns between two angles of 2θ (i.e. from 15 to 23°C and from 32 to 40°C) are focused on in Figure 6b and Figure 6c, respectively.

Figure 6b and Figure 6c show the appearance of two new peaks at $2\theta = 18.2^\circ$ and 34.18° due to portlandite produced during the lime hydration. According to [30], portlandite transforms into cementitious compounds (e.g., C-A-H and C-S-H) after reacting with silica and alumina from clay minerals. In this study, C-A-H, C-S-H, C-F-H, and C-F-S-H are absent due to their slow crystallisation [24, 32]. In addition, as long as portlandite ($Ca(OH)_2$) is oversaturated, it will fill the soil pores through precipitation, leading to a denser and stronger soil structure [21]. The peaks at $2\theta = 42.60^\circ$, 46.03° , and 64.49° corresponding to the haematite phase have almost disappeared in Figure 6a.

Figure 7 compares the chemical composition of samples treated with 6% of lime after 28 days of curing with the untreated ones. Data reveal a significant decrease in Al_2O_3 and SiO_2 of 19.2% and 9.6%, respectively, and an increase in CaO of 16.9%. The hydration of lime releases OH^- ions, which raise the pH to around 12.4. This basic environment promotes the

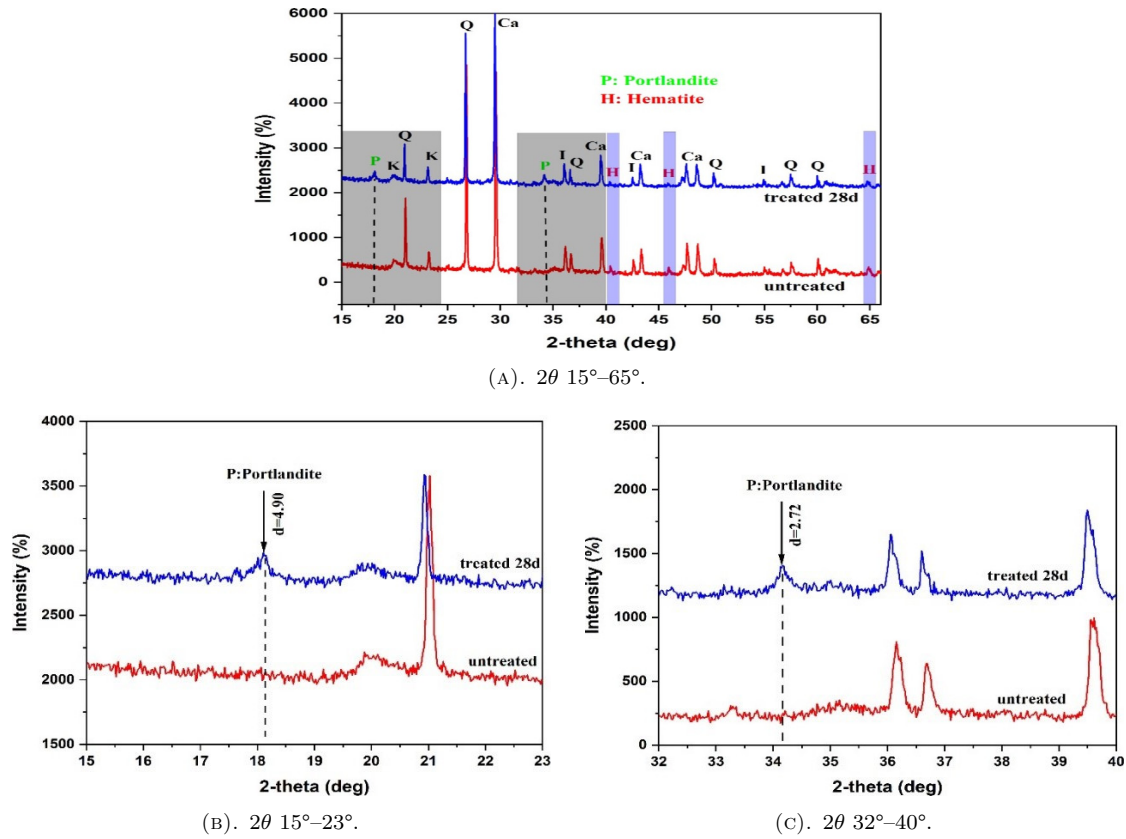


FIGURE 6. Comparison of XRD patterns: natural vs treated at 28 days curing soil (red vs blue curves).

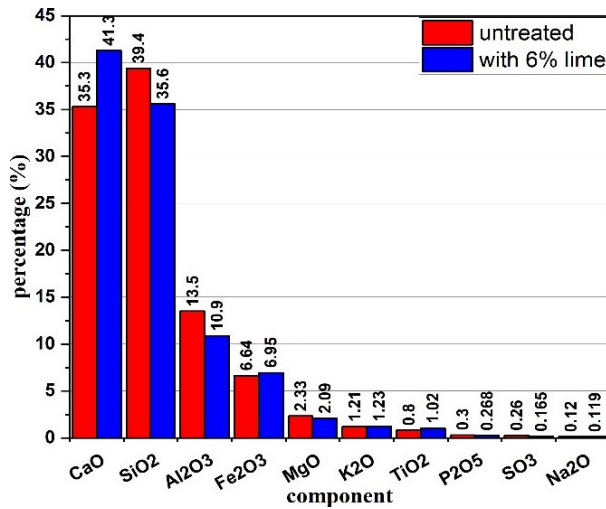


FIGURE 7. Chemical composition by XRF of untreated and treated with 6% lime soil at 28 days.

dissolution of aluminates and silicates from clay minerals (i.e. reduction of SiO₂ and Al₂O₃), which later react with calcium from lime, and thus pozzolanic reactions occur [61, 63, 64].

In addition, an increase in Fe₂O₃ of 4.7% was observed whose solubility depends on the pH values. In particular, the haematite dissolution rate increases at high pH values, releasing more iron over time [65, 66]. This phenomenon complies with the haematite peaks in the XRD analysis (Figure 6a).

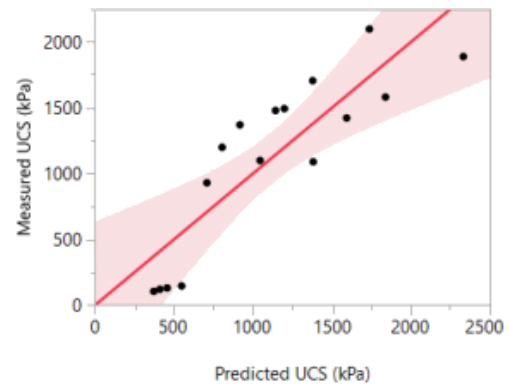


FIGURE 8. Correlation between measured and predicted UCS values.

Finally, Equation (7) has been implemented to predict the UCS from the curing time between 1 to 28 days and lime content from 0% to 9%:

$$\begin{aligned}
 \text{UCS} = & 1158.40 + 281.98 \left(\frac{T - 14.5}{13.5} \right) \\
 & + 699.09 \left(\frac{L - 4.5}{4.5} \right) \\
 & + 193.51 \left(\frac{T - 14.5}{13.5} \right) \left(\frac{L - 4.5}{4.5} \right).
 \end{aligned} \tag{7}$$

Figure 8 shows the correlation between the predicted and measured UCS values. The bold red line is the linear regression curve, and the red area is the 85% confidence region.

Statistical parameter	Symbol	Value
Coefficient of determination	R^2	0.75
Adjusted coefficient of determination	Adjusted R^2	0.68
Root Mean Square Error	RMSE	371.39

TABLE 5. Results of the fit indices for the UCS modelReg.

Term	Estimate	Std Error	t
Intercept	1 158.40	94.67	12.24
Time [days] ($1 \div 28$)	281.98	124.57	2.26
Lime content [%] ($0 \div 9$)	699.09	127.01	5.50
Time [days] \times Lime content [%]	193.51	167.13	1.16

TABLE 6. Regression analysis.

Source	Degree of freedom	Sum of squares	Mean square	F -ratio	t
Model	$DOF_1 = 3$	4 887 001.6	1 629 001	11.81	12.24
Error	$DOF_2 = 12$	1 655 196.1	137 933		2.26
Total	$DOF_3 = 15$	6 542 197.8			1.16

TABLE 7. Results of ANOVA test.

The proposed model exhibits a high R^2 value (i.e. 0.75), showing a good correlation between the experimental and analytical values (Table 5).

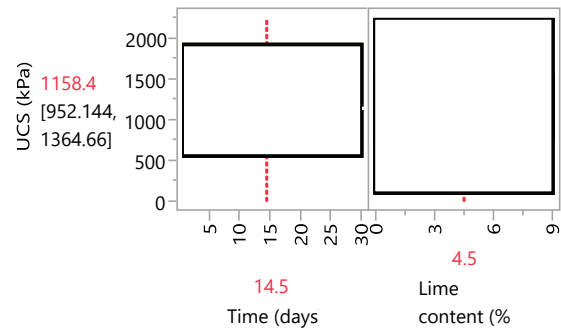
Table 6 presents the contribution of each independent variable (i.e. T and L) and their interaction with UCS according to Equation (7). In this study, the t_{crit} for $n = 16$ experiments and $p = 4$ coefficients was 2.179.

According to Table 6, T and L affect the UCS because the absolute t -values are higher than the t_{crit} . Nevertheless, the Student’s t -test indicates that the interaction effect between T and L lacks significance ($|t| < t_{crit}$). The proposed regression relationship retains its validity without the interaction between T and L .

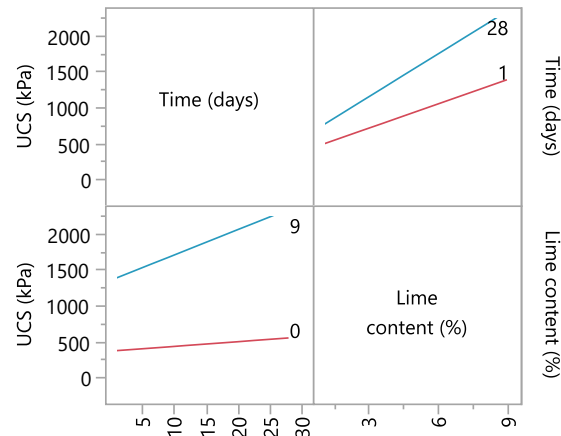
Table 7 summarises the results of the ANOVA test. The calculated F -ratio (11.81) is greater than the Fisher’s ratio (critical F -value), which is 3.49. As a result, the regression model (Equation (7)) is correct.

Regarding the first-order polynomial regression curve (Equation (7)), Figure 9a shows the influence of the curing time and lime content on UCS. The UCS rate due to L is higher than T , as confirmed by the coefficients in Table 6 (699.09 and 281.98, respectively). The change in the soil plasticity and the onset of pozzolanic reactions confirm the results (Figure 6a). Figure 9b represents the interaction response diagrams for UCS. Both interaction diagrams are not crossed and confirm that the interaction effects are not significant according to the Student’s t -test.

The residual plot for the predicted UCS in Figure 10a shows a random distribution. In Figure 10b the random distribution of studentised residual values falls between ± 3.0 , and no data records high error [67]. The error does not form a pattern and is assumed



(A). Main effects plot for UCS.

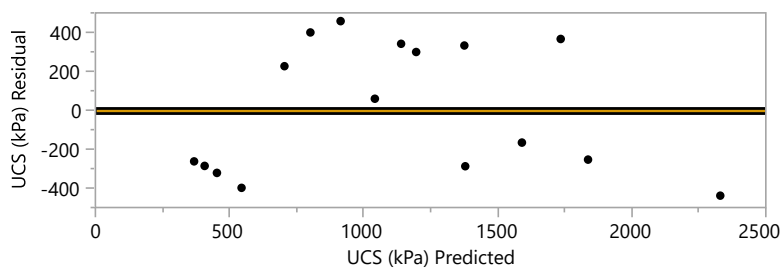


(B). Interaction plot for UCS.

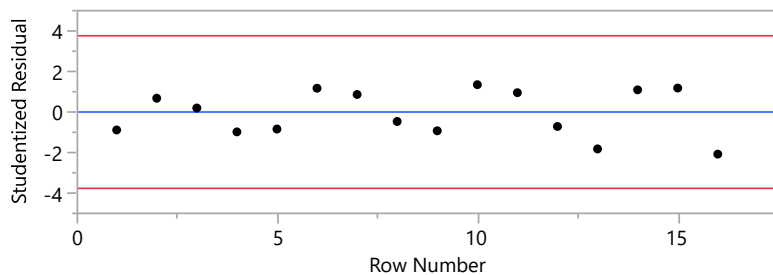
FIGURE 9. Interaction diagrams.

homoscedastic [68] suggesting that the fitted model is valid to predict the response [69].

Further investigations are necessary to implement a complete factorial design based on a second-degree full-factorial design (Equation (7)).



(A). Residuals by predicted plot.



(B). Studentised residuals.

FIGURE 10. Diagram of residuals.

4. CONCLUSION

In construction, silty and clayey soils affect the physical and mechanical performance over the service life. Their natural state is therefore unsuitable for embankments and roadworks and requires disposal in landfill. However, the increasing concern for the environment and the need to limit costs encourage an in-situ lime treatment to improve the strength of clayey soils. This approach is a sustainable alternative to sending waste soil to landfills because it ensures environmental and economic benefits. When lime is exposed to water, a hydration reaction occurs, resulting in the formation of C-S-H and C-A-H, which fill the voids between clay particles.

This paper investigates the geotechnical, physical, chemical, and mechanical properties of reddish clayey soil treated with 0% to 9% of lime. Atterberg's limits, methylene blue value, standard Proctor, and unconfined compression strength tests have been conducted. In addition, chemical and mineralogical analyses with XRF and XRD were performed to interpret geotechnical data. The laboratory results led to the following conclusions:

- After 28 curing days, a 6% lime content changes the soil classification from clayey to low-plasticity soil with a decrease in the specific surface area, as confirmed by a reduction of methylene blue value.
- The maximum dry density of lime stabilised soil decreases from 16 kN m^{-3} (natural soil) to 15.7 kN m^{-3} at 6% and 9% lime content. The optimum moisture content increases from 22% (natural soil) to 24% with 9% lime content.
- The addition of 6% lime results in a 16 times increase in UCS at 28 days compared to untreated soil (2100 kPa vs 130 kPa).

- X-ray diffraction (XRD) analysis shows the almost complete disappearance of the haematite phases, indicating their contribution to cementitious reactions and a new mineral phase (portlandite) after 28 days of curing. However, no C-S-H or C-A-H were found in the XRD patterns.
- After 28 days of treatment with a 6% lime content, XRF analyses show a relative release of iron oxide and a significant decrease in Al_2O_3 and SiO_2 of 19.2% and 9.6%, respectively.
- Finally, the ANOVA test demonstrated that both the lime content and curing time were significant predictors of the UCS of the treated soil and the Student's *t*-test indicates that the interaction effect between Time (measured in days) and Lime content [%] lacks significance. It was also observed that the lime content had a greater impact on the UCS than the curing time. The statistical analysis results agree with the experimental data, demonstrating that adding lime to clay increases its compressive strength.

Another extended model is required to predict UCS for additional time, and possibly introduce more independent variables (e.g. temperature and drying-rewetting cycles).

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