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Effect of quarry dust (QD) particle on the strength, durability, and microstructure of lime stabilized lateritic sandy soil

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Article

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Abstract

Chemical soil stabilization by lime addition is used to improve soil properties and to ensure a suitable performance of natural soil. Sometimes chemical and granulometric stabilization combined is required to meet the requirements imposed by the geotechnical design. In this context, reusing waste materials in large-scale projects, besides improving the characteristics of the soil, can reduce the environmental impact of irregular disposal. Considering the importance of this issue, this paper presents the results of an experimental study of quarry dust (QD) addition on a lime-stabilized lateritic soil. The mixtures were prepared using soil, quarry dust proportions of 25%, 50%, and 75%, and lime contents of 7%, 9%, and 11%. The unconfined compressive strength was evaluated at 7, 14, 21, and 28 days of cure, and wetting-drying cycles were performed after 14 days of cure. The microstructure of samples with 9% lime and 28 days of cure was also considered. Regarding the results, it was observed that incorporating 25% of QD and 9% or 11% of lime into a lateritic soil is a viable material in terms of unconfined compressive strength and durability with better performance than natural soil. However, proportions of 50% and 75% of quarry dust decreased the soil strength. The microstructure of the natural soil and soil with 25% QD presented a more closed and interconnected structure. In contrast, the 50% and 75% QD soil mixtures presented a porous structure. Therefore, the proportion of the quarry dust addition demonstrated a critical parameter to be considered.

1. Introduction

Soil stabilization is widely used to improve soil properties and to ensure a suitable geotechnical performance of natural soil (Kumar & Kumar, 2018; Tom et al., 2023; Portelinha et al., 2012). Regarding chemical stabilization, the hydrated lime presents some positive effects on the soil geotechnical properties, such as plasticity reduction, particle size change due to the flocculation reactions, compressive strength and the bearing capacity increase, the improvement of the compaction parameters besides the low cost and abundantly available in many parts of the world (Portelinha et al., 2012; Celauro et al., 2012; Mukhtar et al., 2010; Al-Mukhtar et al., 2012).

The soil-lime stabilization is based on the cation exchange, flocculation/agglomeration, lime carbonation, and pozzolanic reactions between clay fraction and lime (Eades & Grim 1960; Cuisinier et al., 2011). The pozzolanic reactions depend on an alkaline environment, temperature, and mineralogy. These reactions develop more slowly over a long period of time (Al-Mukhtar et al., 2012; Wild et al., 1993). The high pH is responsible for dissolving the silica and the alumina of the clay fraction, which reacts with the calcium and forms cementitious products, such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) (Ingles & Metcalf, 1972).

Moreover, technical literature presents several materials that are suitable for improving soil properties, such as construction wastes, old tires, asphalt materials, and mining waste, among others. Additionally, the researchers have indicated different kinds of industrial wastes, used alone or in combination with other materials, for soil stabilization (Soosan et al., 2005). Regarding the quarry dust (QD), this specific waste presents a high shear strength and suitable permeability and can be used as a substitute for natural soil to improve the particle size distribution in lateritic soils (Soosan et al., 2001a; Soosan et al., 2001b; Godfrey et al., 2023).

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The application of quarry dust for base and subbase materials shows an improvement in geotechnical properties, such as the decreasing of liquid limit, plasticity, optimum water content, and increasing of maximum dry density and unsoaked and soaked California Bearing Ratio (CBR) values (Soosan et al., 2005). However, Kanoo et al. (2014) pointed out that few studies present the influence of quarry dust content on geotechnical soil properties. The authors recommend additional experimental investigation to evaluate the use of quarry dust waste as a replacement for natural soil.

Considering the potential of quarry dust (Nakayenga et al., 2021) associated with the reduction in environmental impact, a study of the feasibility of a mixture composed of quarry dust and hydrated lime seems to be an interesting option. The combination of both materials results in the reduction of the exploitation of natural soil deposits, reducing lime consumption and contributing to the suitable disposal of quarry dust. Therefore, this paper presents an experimental study of quarry dust used to partially replace lateritic sandy soil for geotechnical applications. The study evaluated the behavior of lime-stabilized soil and soil-QD-lime mixtures. The performance of the mixtures was evaluated using unconfined compressive strength, durability tests (wetting-drying cycles), and microstructure analyses. The hydrated lime was added to the soil and soil-quarry dust mixtures in proportions of 7, 9, and 11% in dry mass. The results enabled the evaluation of the suitable proportion of QD to the lime-stabilized soil and the effect on the strength and durability.

2. Materials and experimental program

2.1 Materials characteristics

The disturbed soil selected for this study is a lateritic sand soil (S) collected at a site at Xambrê, Parana State, Brazil. The lateritic sand soil, classified as LA (MCT Methodology), is from Arenito Caiuá rock. It presents a low hygroscopic water content and high susceptibility to water and wind erosion. The samples were air-dried until they reached a hygroscopic water content, which was about 0.5%, sieved in a #2.0 mm sieve, and stored in containers.

The quarry dust (QD) was collected from a mining site in Maringa, Parana state, Brazil. The material originates from basaltic flows of the Paleozoic Era, composed of silicates and aluminum oxides. The samples were air-dried until hygroscopic water content and sieved in a #2.0 mm sieve. The hydrated lime selected was the commercial CHI, composed of carbonic anhydride, calcium and magnesium oxides, and total oxides. The particle density of the lime grain is 24.3 kN/m^3, and the particle size distribution shows the predominance of particles between 1μm - 10μm (54%). Moreover, particle sizes between 10μm - 100μm (34%) are also detected.

Tables 1 and 2 present the materials' geotechnical properties and the soil's chemical parameters, respectively. The geotechnical tests were performed using ASTM standards.

X-ray mineralogical (XDR) results indicate that the soil is composed of quartz, feldspar, and kaolinite, a low-activity clay mineral frequently found in lateritic soils. The absence of iron oxides is consistent with the specific gravity value observed in the experimental test. Regarding the QD sample, the XDR results detected the predominance

Table 1. Geotechnical properties of the materials.

Geotechnical parameters	S	QD
Gravel content (%)	-	-
Sand content (%)	76	45
Silt content (%)	7	49
Clay content (%)	17	6
Liquid limit (%)	Non-plastic material	Non-plastic material
Plasticity index	Non-plastic material	Non-plastic material
HRB/AASHTO classification	A-2-4	A-3
General rating as a subgrade	good	excellent - good
Unified Soil Classification System (USCS)	SC	SW-SC
MCT Classification	LA	-
Particle density (γ_s) – fine fraction (kN/m^3)	26.0	29.2

Legend: see List of Symbols.

Table 2. Chemical parameters of the natural soil.

Chemical parameters	
Organic matter (%)	0.27
CEC (cmol$_c$/Kg)	4.06
Calcium (Ca^{2+}) (cmol$_c$/dm^3)	1.03
Magnesium (Mg^{2+}) (cmol$_c$/dm^3)	1.02
Potassium (K^+) (cmol$_c$/dm^3)	0.32
Phosphor (P) (mg/dm^3)	1.79
Copper (Cu) (mg/dm^3)	2.28
Iron (Fe) (mg/dm^3)	36.42
Manganese (Mn) (mg/dm^3)	39.12
Zinc (Zn) (mg/dm^3)	0.96

Legend: see List of Symbols.

of feldspar, iron oxides (magnetite, hematite, iron, and magnesite), mica, and muscovite. The presence of iron oxides justifies the slightly higher value of specific gravity. Additionally, the diffractogram of hydrated lime indicates the predominance of dolomite and calcium hydroxide, which is consistent with the commercial information.

2.2 Mixtures

Table 3 presents the different proportions of the materials for each mixture, where *S* is the natural soil, *L* is the lime, and QD is the quarry dust. The mixtures were prepared based on dry mass. The proportion of the materials was defined based on the particle size distribution of each material, which promotes the replacement of the natural soil and ensures a well-graded grain size distribution mixture.

Figure 1 shows the particle size distribution of S, QD and S-QD mixtures without lime (Table 3). As expected, the silt and coarse contents increased with the QD addition, while the clay and fine sand contents decreased. Results also show that the $S_{25}QD_{75}$ mixture presented a well-graded grain size distribution since the coefficient of uniformity (*Cc*) is 1.94 ($1 < Cc < 3$). The other mixtures presented *Cc* higher than 3 and were classified as poorly graded soil.

The particle density (γ_s) of the mixtures $S_{75}QD_{25}$, $S_{50}QD_{50}$ and $S_{25}QD_{75}$ were 26.9, 27.6 and 28.6 kN/m^3, respectively. The increase in the γ_s is associated with iron oxides detected in the QD composition. Additionally, the studied mixtures presented a non-plastic (NP) behavior.

2.3 pH

The pH test results, assessed based on ASTM (2017), are presented in Table 4 and indicate that the ideal lime amount to stabilize the natural soil and the mixtures (Eades & Grim, 1960) was achieved when 7, 9, or 11% of lime was used. The incorporation of lime promotes an alkaline environment where pozzolanic reactions, flocculation, and particle agglomeration are observed.

The pH values indicate that natural soil, quarry dust, and lime exhibit alkaline behavior, and consequently, the mixtures with lime also display this behavior. The lime incorporation resulted in a pH mixture increase, contributing to the occurrence of the pozzolanic reaction.

Table 3. Proportion of the materials for the studied mixtures.

Mixtures	S (%)	L (%)	QD (%)
S	100.00	0	0
SL_7	93.00	7	0
SL_9	91.00	9	0
SL_{11}	89.00	11	0
$S_{75}QD_{25}$	75.00	0	25.00
$S_{75}L_7QD_{25}$	69.75	7	23.25
$S_{75}L_9QD_{25}$	68.25	9	22.75
$S_{75}L_{11}QD_{25}$	66.75	11	22.25
$S_{50}QD_{50}$	50.00	0	50.00
$S_{50}L_7QD_{50}$	46.50	7	46.50
$S_{50}L_9QD_{50}$	45.50	9	45.50
$S_{50}L_{11}QD_{50}$	44.50	11	44.50
$S_{25}QD_{75}$	25.00	0	75.00
$S_{25}L_7QD_{75}$	23.25	7	69.75
$S_{25}L_9QD_{75}$	22.75	9	68.25
$S_{25}L_{11}QD_{75}$	22.25	11	66.75

Legend: see List of Symbols.

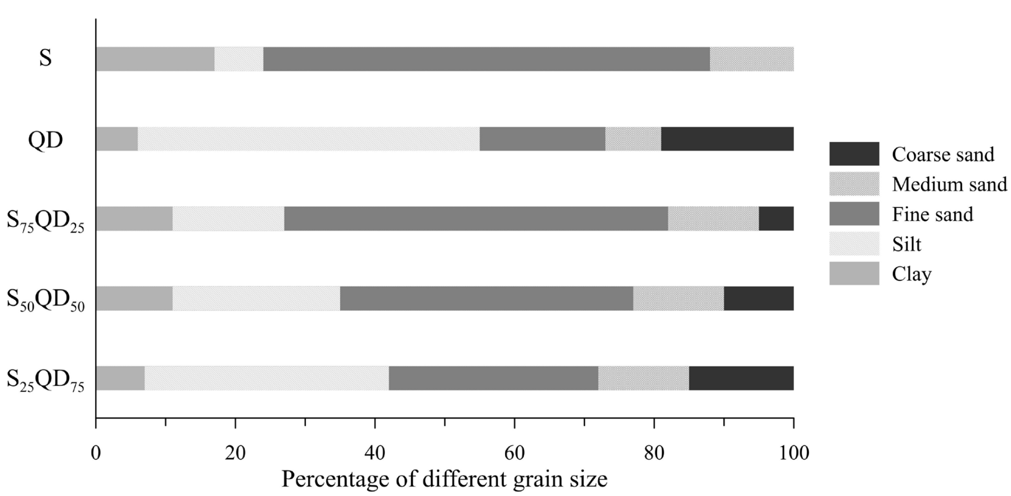


Figure 1. Particle size distribution of the materials and mixtures.

Table 4. pH of the materials.

Mixtures	H_20	$CaCl_2$
S	9.57	8.25
SL_7	12.46	12.70
SL_9	12.54	12.70
SL_{11}	12.52	12.71
$S_{75}QD_{25}$	8.72	7.10
$S_{75}L_7QD_{25}$	12.51	12.68
$S_{75}L_9QD_{25}$	12.50	12.67
$S_{75}L_{11}QD_{25}$	12.49	12.69
$S_{50}QD_{50}$	9.38	9.08
$S_{50}L_7QD_{50}$	12.44	12.66
$S_{50}L_9QD_{50}$	12.38	12.67
$S_{50}L_{11}QD_{50}$	12.36	12.67
$S_{25}QD_{75}$	9.46	8.16
$S_{25}L_7QD_{75}$	12.49	12.65
$S_{25}L_9QD_{75}$	12.43	12.65
$S_{25}L_{11}QD_{75}$	12.51	12.65
QD	10.14	8.47
L	12.62	12.73

Legend: see List of Symbols.

2.4 Molding and curing of the specimens

Cylindrical specimens for the strength and durability tests were molded at the optimum water content (OWC) and maximum dry unit weight (MDW) estimated by Proctor compaction tests using Brazilian standard effort (600 kJ/m^3). The specimens were prepared using different proportions of the materials (Table 3) and mixed manually until a homogeneous aspect was observed. Then, distilled water was added in an amount equivalent to the optimum water content correspondent. Then, the mixture was compacted in three layers, and the final specimens had diameters and heights of 50 and 100 mm, respectively. The mass and dimensions of the specimens were checked; they were protected using waterproof plastic and stored in a humid room for curing for 7, 14, 21, and 28 days before testing. The moist room keeps a humidity value greater than 95% and a temperature between 21.0-25.0 ºC.

As acceptance criteria for the unconfined compressive strength and durability tests, at least three specimens were molded with a mass of ± 2% and water content of ± 0.5% to the estimated values. After the curing time, the specimens were measured and weighed, and the tests were carried out.

2.5 Unconfined compressive strength (UCS)

The specimens' unconfined compressive strength (UCS) was assessed based on ASTM (2016) and represented by average values. The tests were carried out with a load cell with a maximum capacity of 20 kN (± 0.25%) and two linear variable displacement transducers (LVDTs) with a maximum capacity of 5 mm (± 0.2%). The UCS values were calculated using the maximum force values (rupture). As a criterion for acceptance of UCS values, at least three specimens molded under the same conditions should present the same results with a 10% variation from the average.

2.6 Durability tests

The durability tests were conducted using the method proposed by Hoover et al. (1958), where the compacted specimens were subjected to wetting-drying cycles. The process of wetting-drying cycles was carried out according to the following steps: a) specimens were molded at the water content and dry density desired, then cured for 14 days; b) each wetting-drying cycle is composed of the dried during 24 hours at room temperature and then completed immersed in distilled water for 24 hours. Additional cycles are a repetition of this procedure; c) After 12 completed cycles, the specimens were wiped to ensure a surface dry condition, measured the height and weight and submitted to the UCS test; d) the UCS values were compared with the strength of the specimens which are not subject to the wet-dry cycles.

2.7 Scanning electron microscopy (SEM)

The equipment used was the Shimadzu Superscan SS-550, which works with an acceleration voltage of 10 kV and has a magnification capacity of 20 to 300,000 times. The samples used for SEM analyses consist of fragments of the UCS specimens after the tests. The samples were placed in a carbon tape fixed in aluminum support and subjected to metallization. The microstructure analysis was carried out for mixtures with 9% lime and 28 days of curing.

3. Results and discussion

3.1 Compaction test results

Figure 2 presented the compaction curves for the studied mixtures (Table 3). The addition of lime in the natural soil caused a decrease in maximum dry unit weight (MDW) while the optimum water content (OWC) increased (Figure 3). Similar behavior was observed in the research works (Osinubi & Nwaiwu 2006; Portelinha et al., 2012; Osula 1996; Osinubi & Nwaiwu 2006; Haji Ali et al., 1992). The resistance of flocculated soil structure during applying effort compaction decreases the maximum dry density. At

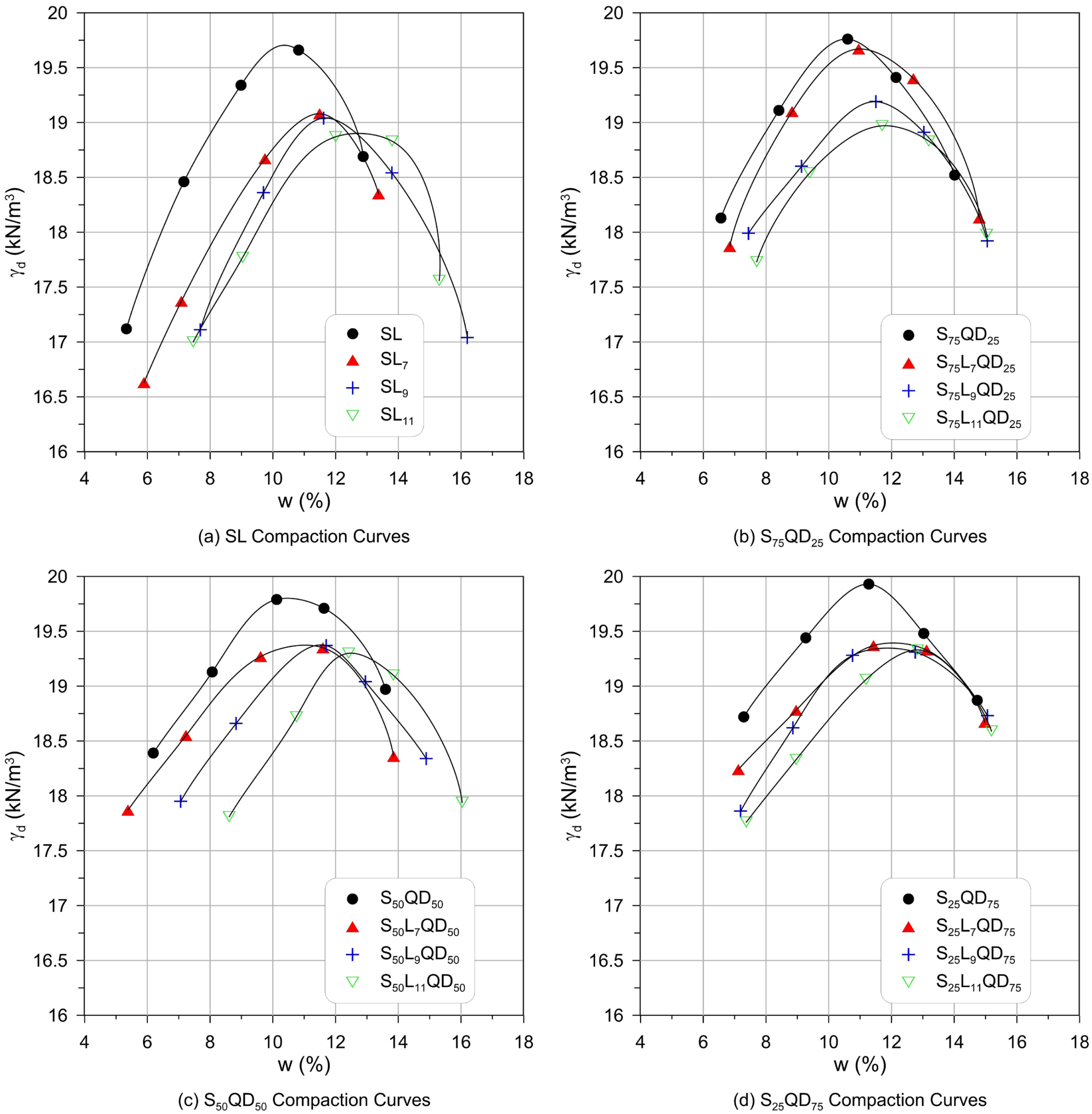


Figure 2. Compaction curves for the studied mixtures.

the same time, the reaction between soil structure and lime held an amount of additional water, increasing the optimum water content (Nagaraj, 1964).

The behavior of the compaction parameters, through the addition of lime, is consistent with other research works (Osinubi & Nwaiwu 2006; Portelinha et al., 2012), mainly due to the effect of fine hydrated lime particles. When fine materials are added to the soil, an increase in the optimum water content during compaction is obtained so that all contact surfaces are completely involved, and the reaction of hydration requires a more significant amount of water.

Adding quarry dust to the natural soil increased the maximum dry unit weight and the optimum water content (Figure 4). The results are consistent since the MDW and OWC of the quarry dust were 21.0 kN/m³ and 11.8%, respectively. Despite fluctuations, the results indicate that the increase of lime in the soil-QD mixtures decreases the MDW and increases the OWC, as discussed in Figure 3.

The highest value of MDW (19.85 kN/m³) was observed for 25% of soil, 75% of QD, and 0% of lime, while the lowest value (18.90 kN/m³) was observed for 100% of soil and 11% of lime. The highest value of OWC (12.80%)

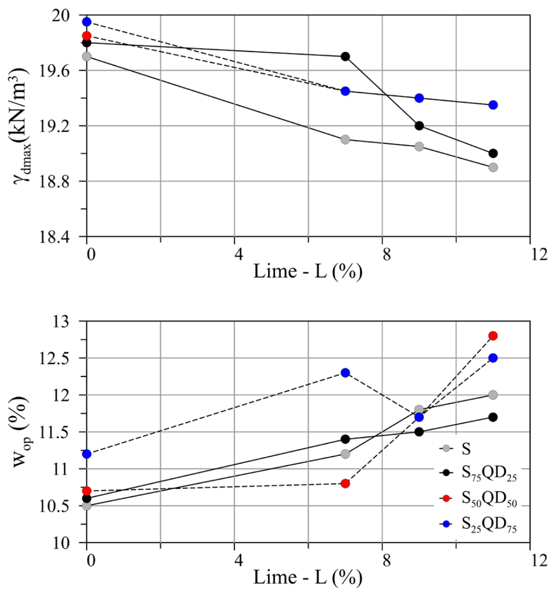


Figure 3. Effect of lime addition on the compaction parameters.

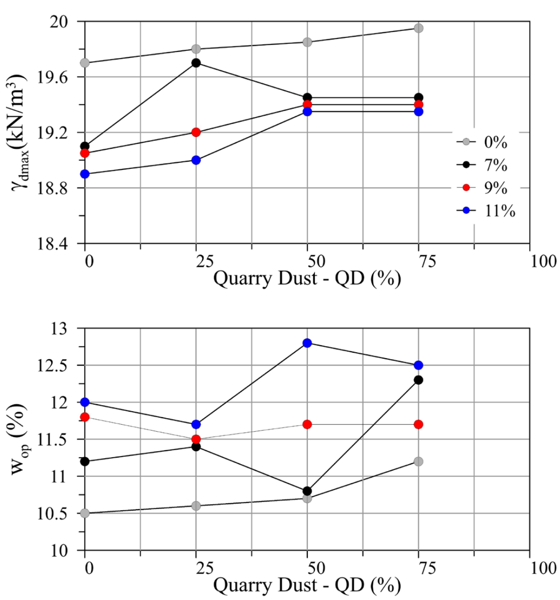


Figure 4. Effect of quarry dust addition on the compaction parameters.

was observed for 50% of the soil, 50% of QD, and 11% of lime, while the lowest value (10.50%) was observed for the natural soil.

3.2 Unconfined compressive strength (UCS)

The unconfined compressive strength (UCS) of the studied mixtures for different curing times was represented by average values (Figure 5). As acceptance criteria, at least four specimens molded at the same conditions had to present the same results within a 10% variation from the mean. After UCS tests, the water content measurements were taken per sample, and the results indicated 3.4%, 3.6%, 2.8% and 1.9% average decrease in the water content value for 7, 14, 21 and 28 days of cure, respectively.

As seen from Figure 5, the UCS of the materials gradually increases as the curing time and lime content increase. The effect of curing time on the strength is due to the pozzolanic reactions, which strongly depend on the time. The optimum lime content, which corresponds to the maximum UCS for the materials, was 11% lime after 28 days of cure. For S and $S_{75}QD_{25}$, the lime addition of 11% lime

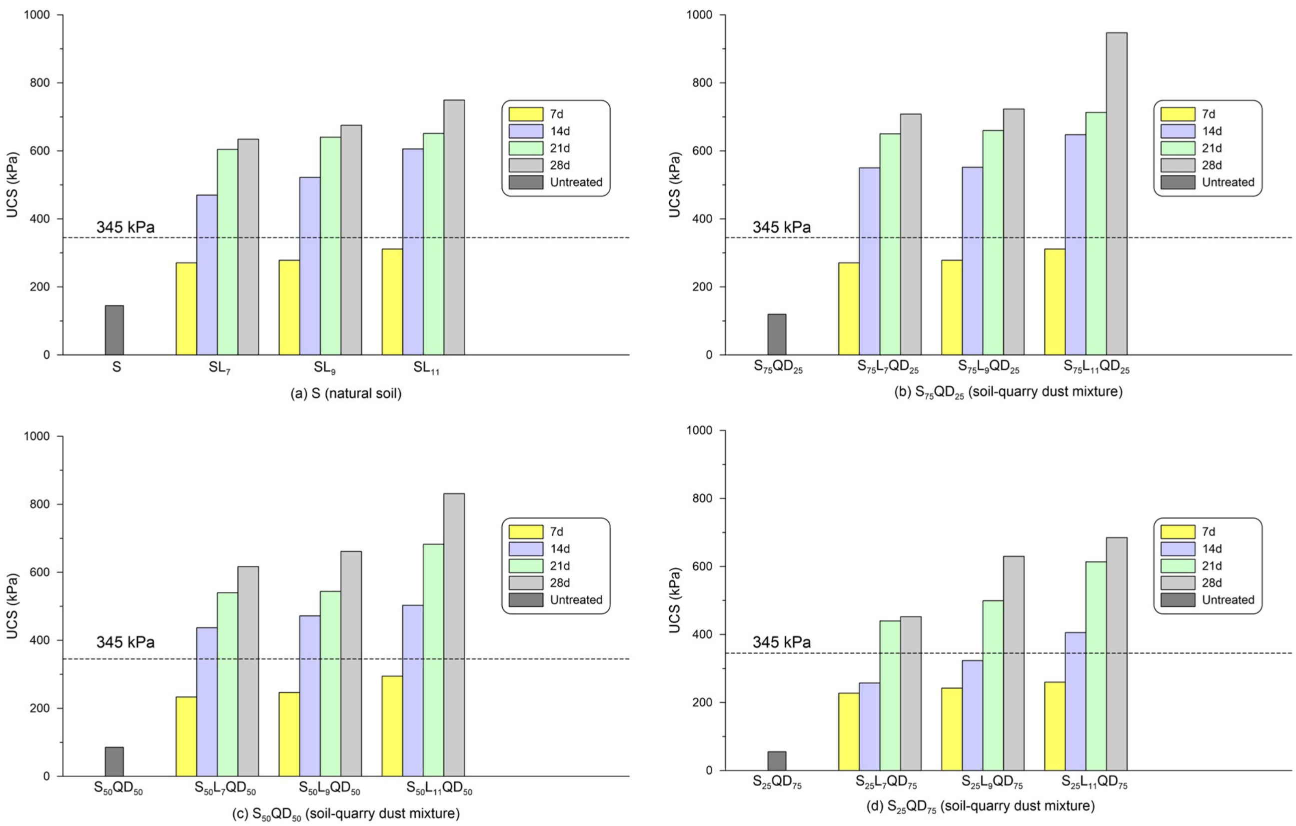


Figure 5. The influence of different curing times and lime content on the strength of the studied mixtures.

after 28 days of cure enhanced the unconfined compressive strength to 749.5 and 947.3 kPa, which increased by 5.2 and 7.9 times compared to the parent material, respectively. Whereas in the case of $S_{50}QD_{50}$ and $S_{25}QD_{75}$ materials, the maximum strength is 831.2 and 684.8 kPa after treating with 11% lime and 28 days of cure, which corresponds to 9.7 and 12.4 times the strength of the parent material, respectively. The lime treatment was satisfactory because the UCS results presented values higher than the minimum value of 345 kPa recommended by ASTM (2008). The S, $S_{75}QD_{25}$, and $S_{50}QD_{50}$ mixtures enhanced the minimum compressive strength after 14 days of the cure, while the $S_{25}QD_{75}$ mixture required a cure timing of 21 days.

The strength improvement is associated with the structural modification of the soil or mixture, which occurs during lime stabilization (Dhar & Hussain, 2021). Furthermore, curing, represented by time, temperature, and relative humidity, is well discussed as a relevant factor influencing strength increase (Mitchell & Hooper, 1961; Bell, 1996). As shown in Figure 5, the higher growth in the UCS occurs in the first 7 days, corresponding to the period when cementitious reactions are most active (Bell, 1996). The water content also influences the rapid increase in the strength. Lowering the water content causes strength to occur in a short period. Therefore, the use of water content above the optimum content ensures complete hydration, and the resistance continues to increase as the curing time also increases (Bell, 1996).

The effect of lime content on the strength of cured mixtures was represented by the strength growth rate (θ_L), defined as:

$$\theta_L = \frac{\beta_x - \beta_0}{\beta_0} \times 100\% \tag{1}$$

where θ_L is the strength growth rate, which represents the influence of lime content on the strength of soil mixtures, β_x is the strength of the soil and soil-quarry dust mixtures with varying lime contents (7, 9, and 11%), and β_0 is the strength of the soil and soil-quarry mixtures without lime.

The β_0 is strongly dependent on the granulometric characteristics of the materials. This is because the unconfined compression test is unsuitable for measuring the strength of cohesionless materials. The β_0 was reduced by 17%, 41%, and 62% proportionally to the addition of quarry dust to the natural soil. Figure 6 shows the lime influence on the strength growth rate (θ_L). The effect of lime addition was more evident when clay content decreased and coarse sand increased, associated with the quarry dust incorporation into the natural soil. Results also showed that for the S, $S_{75}QD_{25}$, and $S_{50}QD_{50}$, the strength growth development was higher between 7 to 14 days of cure, while for the $S_{25}QD_{75}$, it was

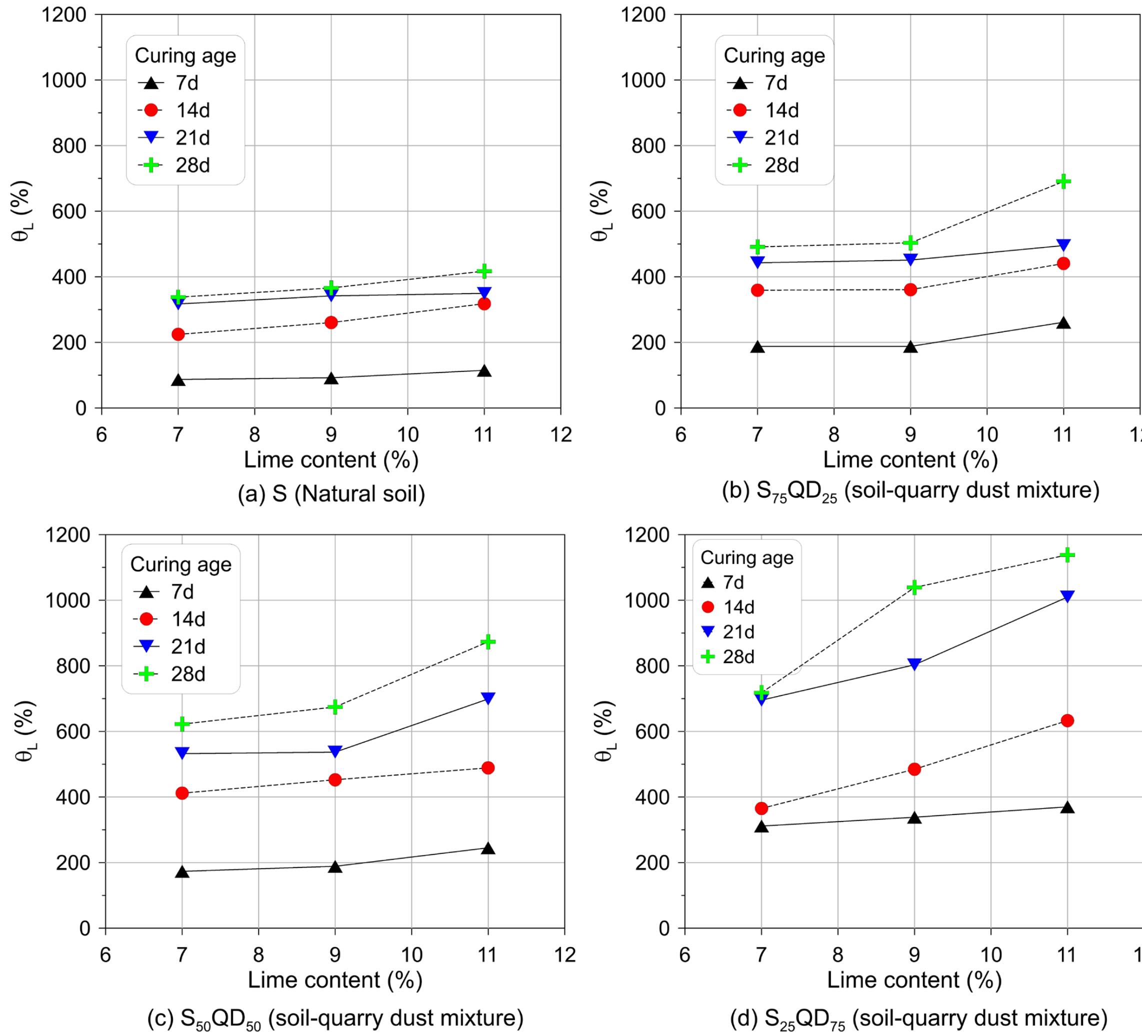


Figure 6. The strength growth rate of the soil mixtures with varying lime contents.

observed between 14 to 21 days of cure. Generally, the lowest strength growth was observed between 21 to 28 days of cure.

Additionally, the effect of quarry dust content on strength of cured mixtures was represented by the strength growth rate (θ_{QD}), defined as:

$$\theta_{QD} = \frac{\beta_y - \beta_1}{\beta_1} \times 100\% \tag{2}$$

where θ_{QD} is the strength growth rate, which represents the influence of quarry dust content on the strength of soil mixtures, β_y is the strength of the soil mixtures with varying quarry dust contents (25, 50, and 75%), and β_1 is the strength of the soil without quarry dust.

The β_1 increased as the lime content and the cure days also increased, and the period between 14 and 21 days showed the highest increase for the parameter. Figure 7 shows the influence of quarry dust on the strength growth rate (θ_{QD}). Incorporating 25% of quarry dust improves the soil strength, while 50% and 75% decrease the soil strength (negative values). An exception was observed when 11% lime and 50% quarry dust were added to the natural soil for 21 and 28 days of cure (Figure 7c). Regarding the θ_{QD} strength growth rate, results also demonstrated that the best performance was for 9% and 11% of lime during the early cure (7 days).

The comparison between θ_L and θ_{QD} strength growth rates demonstrated that the lime influence is strongly higher than the quarry dust influence. For the θ_L, the values vary from 87% to 1140%, while for the θ_{DQ}, the values vary from -45% to 39%.

3.3 Durability tests

Figure 8 presents the percentual loss mass of the studied mixtures after 14 days of cure and exposure to wetting-drying

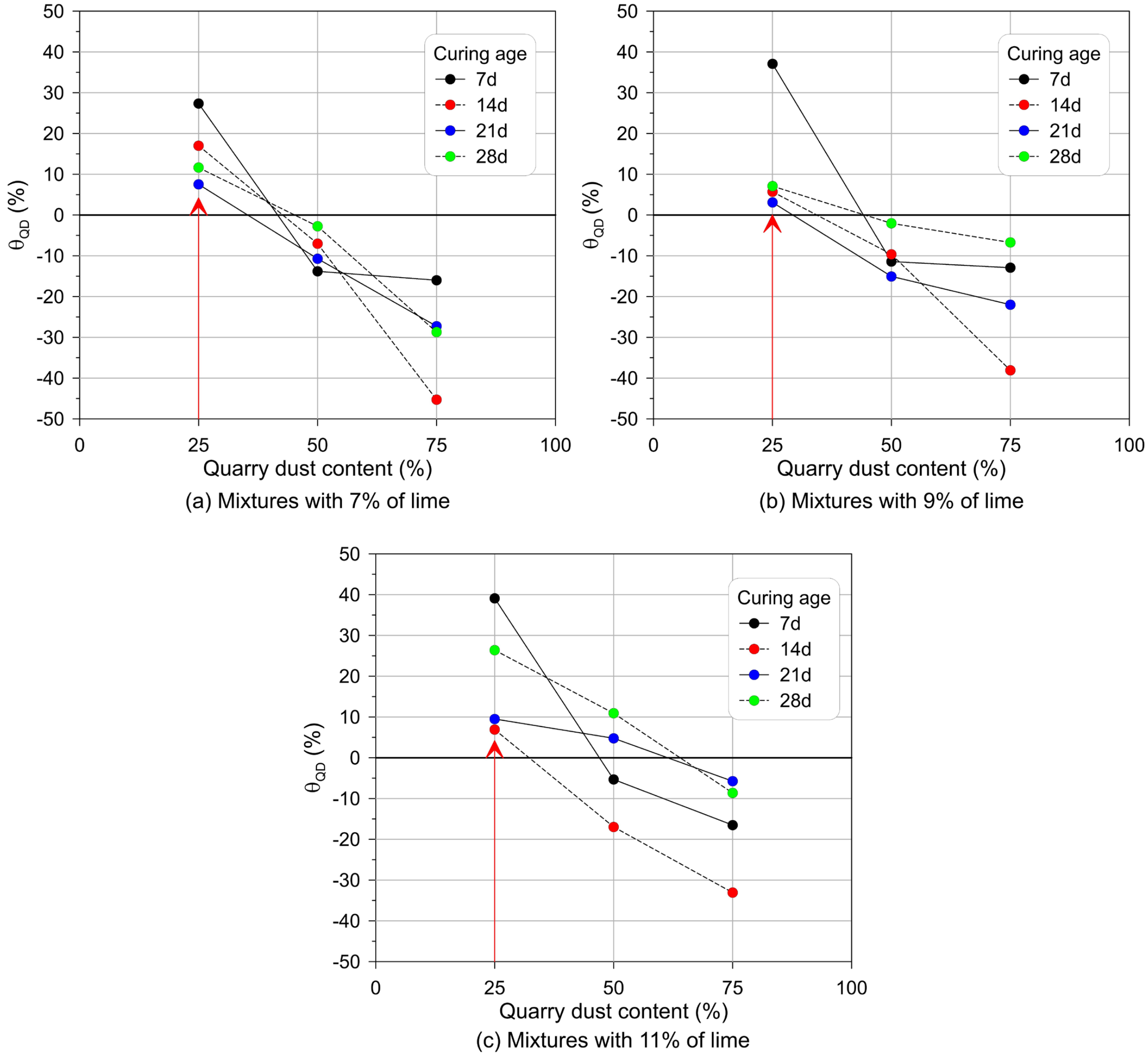


Figure 7. The strength growth rate of the soil mixtures with varying quarry dust contents.

cycles. Despite the fluctuation, results show a mass loss for all the studied mixtures. The water content variation during the wetting-drying cycles can influence the loss mass fluctuation. The natural soil with 9% lime presented the highest mass loss (± 12%) from the 4th cycle, and $S_{75}QD_{25}$ with 9% lime presented a mass loss of 10% from the 8th cycle. However, as the quarry dust content increased ($S_{50}QD_{50}$ and $S_{25}QD_{25}$), the mixtures treated with 9% lime presented a favorable behavior during wetting-drying cycles, with a mass loss of about 6-7%. The mixtures with 11% lime presented the lowest mass loss (7%) between the 4th and 5th cycle compared with other lime contents. In general, results demonstrated that quarry dust and lime contribute to avoiding the loss of mass.

The mixtures' visual degradation (Figure 9) confirms the loss of mass measured during the wetting-drying cycles (Figure 9b). The SL_9 and $S_{75}L_9QD_{25}$, composed of a lower percentage of quarry dust, presented a more evident visual degradation when compared to the $S_{50}L_9QD_{50}$ and $S_{25}L_9QD_{75}$ mixtures.

The strength improvement factor (UWD) presented by Nabil et al. (2020) was used to evaluate the degradation of unconfined compressive strength after 12 wetting-drying cycles. The UWD is a non-dimensional parameter represented by the ratio between the unconfined compressive strength of the samples after 14 days of cure and 12 wetting-drying cycles (UCS_{12}) and the unconfined compressive strength of the samples kept in a humid room for curing (UCS) (Equation 3).

$$UWD = \frac{UCS_{12}}{UCS} \times 100\% \tag{3}$$

The degradation of the unconfined compressive strength was not observed when the quarry dust was

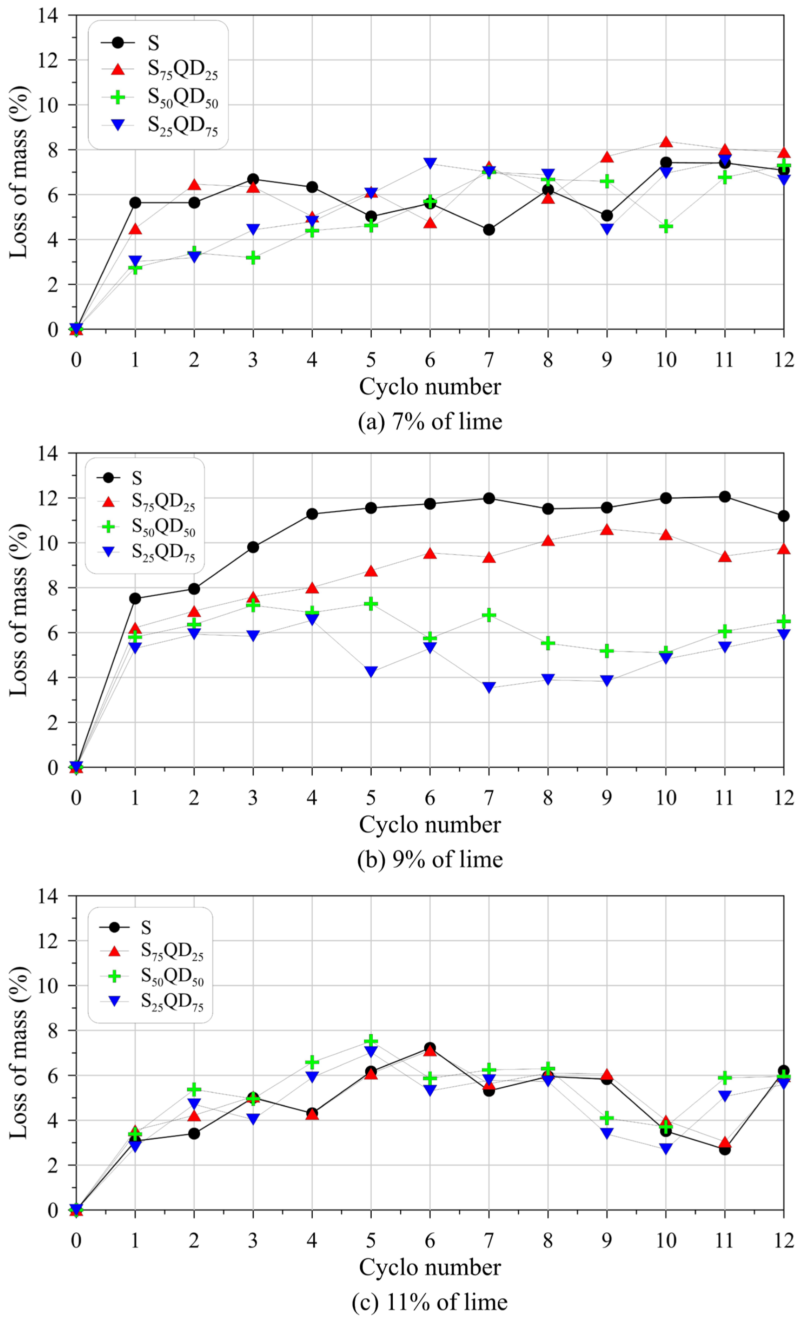


Figure 8. Percentual loss of mass of the studied mixtures during wetting-drying cycles.

combined with 9% and 11% lime (Figure 10). For these mixtures, the UWD values were about 100%, indicating that UCS_{12} and UCS values are the same. The natural soil presented UWD of 80% and 90% when 9% and 11% lime were used. Therefore, incorporating quarry dust in the natural soil prevents strength degradation. Regarding using 7% lime, the natural soil presented a higher value of UWD, and as the quarry dust content increased, the UWD value decreased. Therefore, the results indicate that 7% lime is not enough to develop pozzolanic reactions with the quarry dust to improve the strength of the treated mixtures.

3.4 Microstructure and porosity of the mixtures

The porosity (η) of the mixtures was evaluated based on the ratio between void (V_V) and total volumes (V_T). The volumes were calculated using the physical index of the

(a) SL_9 (b) $S_{75}L_9QD_{25}$ (c) $S_{50}L_9QD_{50}$ (d) $S_{25}L_9QD_{75}$

Figure 9. The visual degradation aspect for the mixtures.

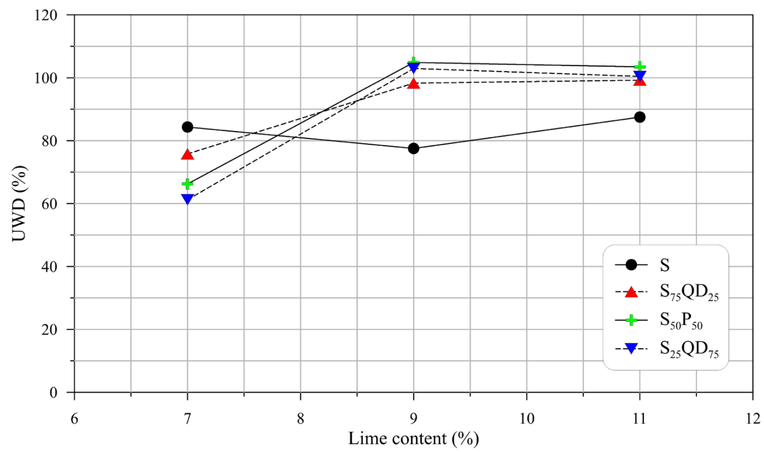


Figure 10. Strength improvement factors (UWD) treated with lime after wetting-drying cycles.

samples. Figure 11 presents the average porosity of the samples, considering the different lime contents and curing times. The results show that the lime content and curing time did not influence the porosity of the mixtures. The lower porosity values were observed for the $S_{75}QD_{25}$ (≅ 26%), while higher values were for the $S_{25}QD_{75}$ (≅ 60%). The granulometric characteristics strongly influenced the porosity since the $S_{75}QD_{25}$ presented a well-graded size distribution (Figure 1). The porosity of the samples is directly related to the unconfined compressive strength. Therefore, the results in the 3.2 section are consistent with the porosity of the samples.

The microstructure was compared using mixtures with 9% lime content and 28 days of cure. The natural soil (S) and $S_{75}QD_{25}$ mixture presented a more closed and interconnected structure. In contrast, the $S_{50}QD_{50}$ and $S_{25}QD_{75}$ mixtures presented a porous structure (Figure 12) and reinforced the results in Figure 11. The micrograph also shows the formation of cementitious calcium silicate hydrate phases (C-S-H) on the surface of particles.

The magnification of 2000 times (Figure 13) confirms the impregnation of the particles with a C-S-H gel and a closed package for S and $S_{75}QD_{25}$. Besides the C-S-H gel, the mixtures $S_{50}QD_{50}$ and $S_{25}QD_{75}$ indicate the presence of macropores, which are associated with the particle size composition. Adding lime and the consequent dispersion of calcium, associated with the pH, induces the formation of pozzolanic components and increases strength. It was observed for the studied mixtures, and the strength results were presented and discussed in section 3.2. The proportion of the quarry dust addition also demonstrated an important parameter to be considered.

3.5 Application of the findings for untested mixtures

The geotechnical behavior findings presented in this paper can be extended to untested materials with chemical, mineralogical, and granulometric characteristics similar to those of the tested materials. The amount of lime consumed for chemical stabilization depends on the materials' pH. A

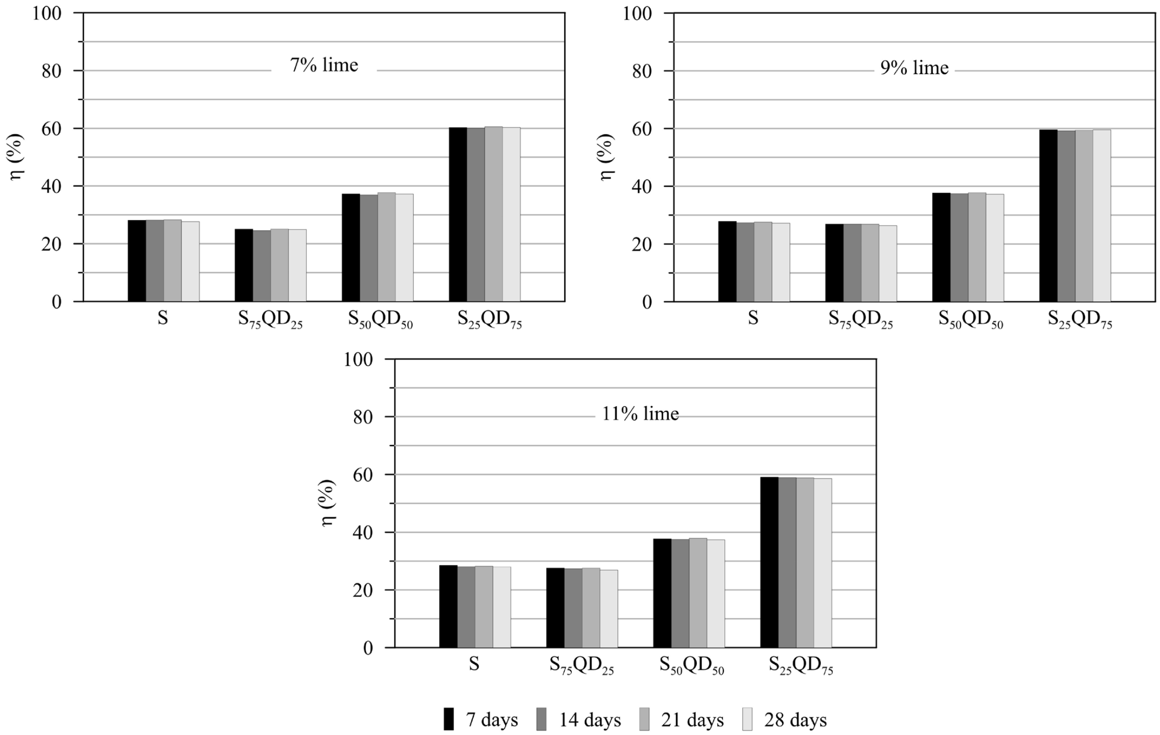


Figure 11. Influence of lime content and curing time in the porosity (η) of the mixtures.

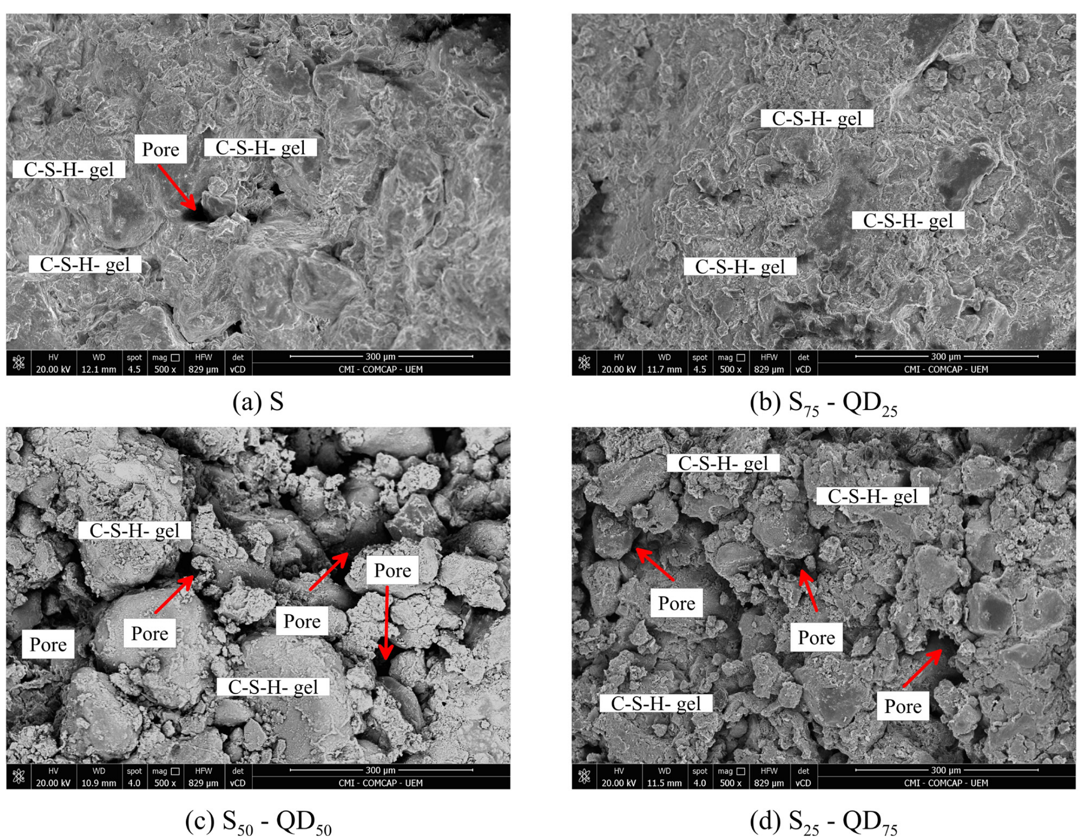
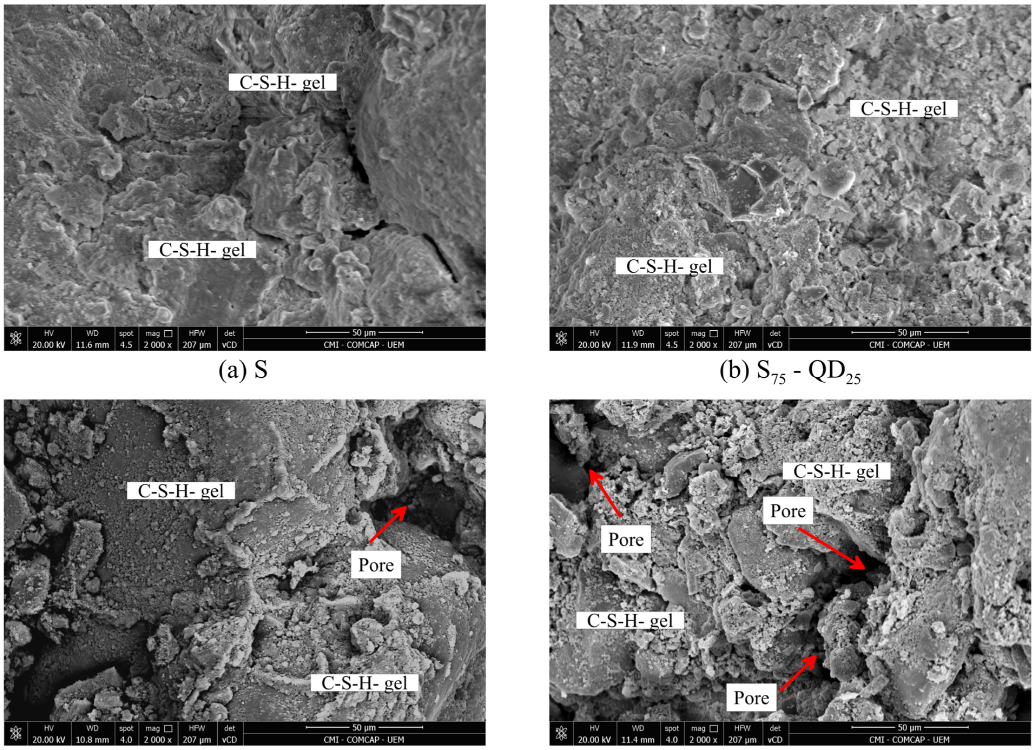


Figure 12. Micrograph for the mixtures with 9% lime and 28 days of cure (500 ×).



(a) S

(b) S_{75} - QD_{25}

(c) S_{50} - QD_{50}

(d) S_{25} - QD_{75}

Figure 13. Micrograph for the mixtures with 9% lime and 28 days of cure (2000 ×).

small amount of lime for alkaline soil and quarry dust induces an environment favorable to chemical reactions. This way, natural soils and waste with pH alkaline values can ensure a small amount of lime consumption.

Another critical parameter is the mineralogical composition of the materials, which influences the chemical reaction on the particle surface. This paper used a lateritic sandy soil composed of a low-activity clay mineral. Additionally, the quarry dust presents iron oxides, feldspar, and muscovite. Therefore, the results presented here can be extended to untested materials if they have a similar mineralogical composition, especially regarding other clay minerals.

The presented work also discussed the importance of the grain size distribution of the materials to ensure a suitable granulometric stabilization of the mixtures. Therefore, untested mixtures should use materials with proportions that present a final grain size distribution like the tested mixtures. Results presented here indicate that the best performance was observed for a mixture of 11% clay, 16% silt, 55% fine sand, 13% medium sand, and 5% coarse sand. Aiming for similar results, it is recommended that these proportions be established for other materials.

The authors highlight that the parameters θ_L and θ_{QD} are dependent on the lime amount and granulometric characteristics, which indicates that the same result behavior of this paper can be ensured for untested mixtures that present an alkaline environment with equivalent lime consumption to tested mixtures and a grain size distribution similar to tested mixtures.

However, it is essential to consider the composition of the materials, especially waste, which may affect the experimental results under different conditions.

4. Conclusion

This paper presents key experimental findings on the influence of lime treatment and quarry dust granulometric stabilization at variable dosages. The study draws conclusions based on geotechnical characterization, unconfined compressive strength, durability from wetting-drying cycles, and microstructure tests.

When it comes to granulometric stabilization by quarry dust addition, our results revealed some intriguing patterns. We found that silt and coarse contents increased with the QD addition, while the clay and fine sand contents decreased. The use of 25% quarry dust presented a well-graded grain size distribution, and the other mixtures were classified as poorly graded soil. These findings underscore the importance of evaluating different dosages to determine the ideal quarry dust content.

The influence of lime and quarry dust on the compaction parameters demonstrated that adding lime to natural soil decreased the maximum dry unit weight (MDW) while increasing the optimum water content (OWC). Adding fine materials increases water content during compaction, and hydration reactions require a significant amount of water to develop. The compaction curves also showed that adding quarry dust to the natural soil increased the maximum dry unit weight (MDW) and the optimum water content (OWC).

The unconfined compressive strength of the mixtures increases as the curing time and lime content increase. The curing time is an important parameter contributing to pozzolanic reactions, and consequently, strength improvement is observed. The mixture $S_{75}QD_{25}$ presented a higher unconfined compressive strength, which increased about 7.9 times compared to the parent material. This behavior confirms that 25% of quarry dust is a suitable dosage for this specific soil. Regarding the strength growth rate, results showed that the effect of lime addition depends on the granulometric characteristics of the mixtures associated with the quarry dust incorporation into the natural soil. Incorporating 25% of quarry dust improves the soil strength, while 50% and 75% decrease the soil strength. The influence of lime is strongly higher than that of quarry dust.

Regarding the durability tests, the studied mixtures demonstrated that they could resist 12 wetting-drying cycles without significant strength degradation. The degradation of the unconfined compressive strength was not observed when the quarry dust was combined with 9% and 11% lime. The natural soil presented 20% and 10% strength decreased when 9% and 11% lime were used. Therefore, incorporating quarry dust in the natural soil prevents strength degradation. Results also showed that quarry dust and lime contribute to avoiding the loss of mass of the samples.

Finally, the porosity and microstructure analyses confirm the strength results, the lower porosity values were observed for the $S_{75}QD_{25}$ while higher values were for the $S_{25}QD_{75}$. The granulometric characteristics strongly influenced the porosity since the $S_{25}QD_{75}$ presented a well-graded size distribution. The microstructure of the natural soil (S) and $S_{75}QD_{25}$ mixture presented a more closed and interconnected structure. In contrast, the $S_{50}QD_{50}$ and $S_{25}QD_{75}$ mixtures presented a porous structure. The micrograph also shows the formation of cementitious calcium silicate hydrate phases (C-S-H) on the surface of particles.

This study demonstrates that the partial replacement of lateritic sandy soil with QD and treated with lime can lead to a better-performing alternative material for granulometric and chemical stabilization. The findings also suggest that this solution can help reduce the depletion of natural soil deposits. The laboratory results from this study indicate that the proportion of the quarry dust addition is a crucial parameter to be considered. Adding 25% of QD and 9% or 11% of lime to a lateritic sandy soil produces a viable alternative material in terms of unconfined compressive strength and durability (wetting-drying cycles), with better performance than natural soil and other alternative materials. However, it is important to consider field conditions, which may vary from laboratory conditions, and to confirm the effect of quarry dust on strength values under field conditions.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Gislaini Bezerra: investigation, data curation, writing – original draft. Matheus de Souza Bertoco: investigation, data curation. Jeselay Hemetério Cordeiro dos Reis: conceptualization, methodology. Juliana Azoia Lukiantchuki: conceptualization, methodology, supervision, writing, revision.

Data availability

The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was not prepared with the assistance of Generative Artificial Intelligence (GenAI).

List of symbols

AASHTO	American Association of State Highway and Transportation Officials
Cc	coefficient of uniformity
CEC	cation exchange capacity
C-S-H	cementitious calcium silicate hydrate phases
HRB	highway research board classification of soil.
L	hydrated lime
LA	ateritic sand soil
LVDT	linear variable displacement transducer
MCT	miniature, compacted, tropical
MWD	maximum dry unit weight
NP	non-plastic
OWC	optimum water content
QD	quarry dust
S	natural soil

SEM	scanning electron microscopy
UCS	unconfined compressive strength (humid room for cure)
USCS	unified soil classification
UWD	strength improvement factor
V_T	total volume
V_v	void volume
XDR	X-ray mineralogical
β_0	strength of the soil and soil-quarry mixtures without lime.
β_x	strength of the soil and soil-quarry dust mixtures with varying lime contents (7, 9, and 11%)
β_1	strength of the soil without quarry dust.
β_y	strength of the soil mixtures with varying quarry dust contents (25, 50, and 75%)
γ_s	particle density
η	porosity
θ_L	strength growth rate (lime effect)
θ_{QD}	strength growth rate (quarry dust effect)

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