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Lime Stabilization of Tropical Soils: Mechanical Parameters for Mechanistic–Empirical Pavement Design

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Abstract

The mechanical behavior of lime-stabilized layers is essential for mechanistic–empirical pavement design, particularly in tropical regions where soil behavior differs from that of temperate residual soils. This study investigated three tropical soils (Argisol, Luvisol, and Latosol) stabilized with two hydrated lime sources (calcitic and dolomitic) at contents of 3% and 5%, compacted at standard or modified effort. Unconfined compressive strength (UCS) was measured at 7, 28, and 90 days, while flexural tensile strength (FTS) was obtained at 28 days, from which the flexural static modulus (FSM) and strain at break (ε_b) were derived. The results showed a strong soil-dependent response to lime treatment, with Argisol and Latosol behaving as lime-stabilized materials, whereas Luvisol exhibited more moderate improvements typical of soil modification. Compactive effort, lime type, and lime content significantly influenced UCS, FTS, and FSM, with compactive effort being the dominant and operationally achievable factor. Higher compactive effort, calcitic lime, and a 5% lime content consistently resulted in improved mechanical behavior, while curing time strongly influenced compressive strength due to progressive pozzolanic reaction. In contrast, strain at break was not significantly affected by the studied controllable factors and converged toward approximately 200 microstrain for soil–lime mixtures with UCS > 1 MPa, indicating a less brittle behavior relative to cement-stabilized materials and providing a representative input for preliminary design. Finally, significant correlations were established between UCS and FTS and between UCS and FSM, enabling the estimation of flexural parameters directly from compressive strength and supporting design simplifications when flexural testing is unavailable.

Keywords: soil–lime stabilization; tropical soils; mechanical parameters; mechanistic–empirical pavement design; cemented layers

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1. Introduction

The mechanical performance of asphalt pavements is strongly influenced by the stiffness and deformability of the supporting subgrade [1]. In tropical regions, such as Brazil, where more than 80% of the territory is composed of tropical and subtropical soils [2], soil behavior differs significantly from that of temperate regions due to distinct weathering processes and mineralogical characteristics. The electrochemical nature of tropical soils and the mineralogical composition of their active clay fraction, therefore, require soil evaluation under site-specific geotechnical and environmental conditions [3].

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This is aligned with Carvalho et al. [4], who highlighted the importance of the chemical and mineralogical composition of tropical soils as well as the structural characteristics along the soil profile. Similarly, Nogami and Villibor [5] emphasized that tropical soils, particularly those from humid environments, exhibit complex and less predictable behavior that cannot be adequately described solely by conventional index properties. Accordingly, they proposed the MCT (Miniature, Compacted, Tropical) methodology, which adopts characterization procedures specifically developed to represent the behavior of tropical soils in the compacted state, as typically considered in pavement structures, and provides more reliable guidance for geotechnical applications.

To overcome the limitations associated with the engineering behavior of fine-grained tropical soils, chemical stabilization techniques have been widely applied, with lime being one of the most commonly used binders. In the short term, lime addition leads to a reduction in plasticity and swelling potential as well as an improvement in workability [6–12]. These effects are collectively referred to as soil modification by lime. In addition, lime can promote long-term strength gain through pozzolanic reactions, a process known as soil stabilization with lime [3,8,13–16]. Depending on the soil characteristics, these improvements may be sufficient not only to guarantee adequate subgrade support but also to enable the use of lime-stabilized soils as subbase or even base layers [17].

Although previous research has evaluated the mechanical behavior of soil–lime mixtures, most studies focused on compressive properties such as unconfined compressive strength (UCS) [9,18–31], owing to the simplicity of such tests. However, lime-stabilized soils behave as cemented materials, which typically fail due to shrinkage and/or fatigue cracking [32–40]. The former is mainly addressed during mix design and construction, whereas the latter also depends on traffic and is addressed during the structural design phase. The structural performance of such materials under traffic loading is governed by tensile stress states, and the most common way to evaluate this is by using the indirect tensile strength (ITS) test, for which a substantial number of studies can be found in the literature [41–49]. Nonetheless, the flexural tensile strength (FTS) test produces a more faithful representation of the material's tensile behavior and, importantly, provides essential parameters for mechanistic–empirical pavement design, such as flexural static modulus (FSM) and strain at break (ε_b). Although numerous FTS results exist in the literature for other cemented and chemically stabilized materials [36,38,50–59], the availability of flexural data for soil–lime mixtures remains limited [36,60,61]. There is a lack of studies that jointly evaluate flexural strength, stiffness, and strain capacity of lime-stabilized soils and relate these parameters to compressive strength, especially considering the variability of tropical soils.

Furthermore, mechanistic–empirical pavement design procedures, such as the South African Mechanistic–Empirical Design Method (SAMDM), require the determination of the following parameters to evaluate fatigue and crushing mechanisms in cemented layers: modulus, tensile strain at break, and unconfined compressive strength [62,63]. The availability of robust flexural-derived parameters, therefore, enables more realistic pavement modeling and allows the formulation of optimized structural solutions. Since soil composition directly influences lime reactivity and the development of cementitious bonding, examining different tropical soil types is essential for establishing reliable design parameters applicable to lime-stabilized layers.

In this context, the objective of this study was to investigate the lime stabilization of three distinct tropical soils through a comprehensive experimental program. The effects of lime content, lime type, and compactive effort on compressive strength, flexural tensile strength, strain at break, and flexural static modulus were evaluated, with curing effects analyzed through UCS. A second objective was to provide mechanical parameters suitable for mechanistic–empirical pavement design and to establish correlations between compressive strength and flexural properties that may support preliminary engineering estimations and design simplifications.

The main contributions of this study are as follows: (i) the evaluation of lime-stabilized layers considering different tropical soils within a unified experimental framework; (ii) the assessment of compressive and flexural mechanical parameters, including strength, stiffness, and strain capacity, addressing the limited availability of flexural data for soil–lime mixtures; and (iii) the establishment of a consistent experimental basis to support mechanistic–empirical pavement design, including the investigation of relationships between compressive and flexural parameters.

2. Experimental Program

This section presents the materials, mixtures, and testing procedures used in the experimental phase of the study.

2.1. Materials and Mixtures

Laboratory tests were conducted on mixtures composed of tropical soil and hydrated lime. Three soils from distinct pedological groups were selected: Red–Yellow Argisol (PVA), Haplic Luvisol (TX), and Red Latosol (LV), according to the Brazilian Soil Classification System [64]. Soil samples were collected in the tropical areas of Southeastern Brazil. Figure 1 illustrates the soils used in this study. The main geotechnical and physicochemical properties of the soils are summarized in Table 1, along with their classification according to the Unified Soil Classification System (USCS), the American Association of State Highway and Transportation Officials (AASHTO) classification system, and the MCT methodology. Their grain-size distributions are presented in Figure 2.


(**a**) (**b**) (**c**)

Figure 1. Tropical soils used in the study: PVA (**a**), TX (**b**), and LV (**c**).

Table 1. Geotechnical and chemical properties of the soils used in the study.

Property		**Argisol (PVA)**	**Luvisol (TX)**	**Latosol (LV)**
% passing through #200 sieve (0.075 mm)		53	95	95
Plasticity Index (%)		17	28	15
Classification	AASHTO [65]	A-7-5	A-7-5	A-7-5
	USCS [66]	ML	MH	MH
	MCT [67]	NS′	NG′	LG′
Chemical properties	pH (H_2O)	5.1	6.8	4.6
	P (mg/dm^3)	0.2	17.0	0.7
	K (mg/dm^3)	6	>400	51
	$Al_{exchangeable}$ ($cmol_c/dm^3$)	1.2	0.0	0.8
	CEC ($cmol_c/dm^3$)	2.6	27.3	7.3
	Organic matter (%)	0.2	1.5	0.7
	Base saturation (%)	16.0	94.0	33.0

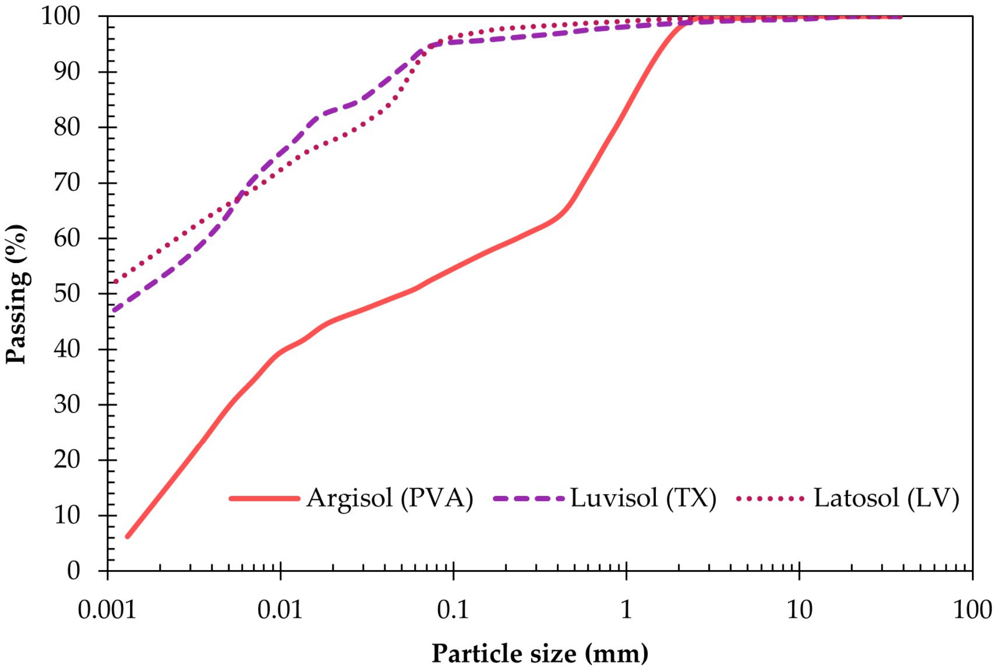

Figure 2. Grain-size distribution of the soils used in the study.

Based on the results presented in Table 1, the three soils studied, although all classified as A-7-5 according to the AASHTO system, exhibited markedly different characteristics. As shown in Figure 2, the TX and LV soils have similar grain-size distributions, being finer than PVA. TX is the most plastic soil and the only one with no exchangeable aluminum. According to the MCT classification, LV is the only lateritic soil. Regarding chemical attributes, TX presents notably high potassium (K) and phosphorus (P) contents, high cation exchange capacity (CEC), high base saturation, and the greatest amount of organic matter. In contrast, LV shows intermediate behavior for these parameters, while PVA consistently exhibits the lowest values.

To evaluate the effect of lime type on soil–lime mixtures, two industrial hydrated limes were used: one calcitic (C) and one dolomitic (D). The calcitic lime is predominantly composed of calcium hydroxide $Ca(OH)_2$ (93%), while the dolomitic lime contains 44% of $Ca(OH)_2$ and 40% of magnesium hydroxide $Mg(OH)_2$. The unit mass of the calcitic lime is 0.398 g/cm^3, with 0.2% retained on the 0.075 mm sieve, indicating a finer material. In contrast, the dolomitic lime has a unit mass of 0.606 g/cm^3 and 17.2% retained on the 0.075 mm sieve, reflecting a coarser gradation. Figure 3 illustrates the limes used in this study.


(**a**) (**b**)

Figure 3. Hydrated lime used in the study: calcitic (**a**) and dolomitic (**b**).

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The mix design of soil–lime mixtures was defined based on the pH procedure [68], which indicated that all three soils reached a pH of 12.4 with 3% of calcitic hydrated lime. This lime content is also in accordance with the minimum value recommended by Thompson [17] and by the National Lime Association [16] while mitigating potential issues related to the uniform distribution of very lime content. To evaluate the effect of lime content, two lime levels were adopted for both calcitic and dolomitic hydrated limes: 3%, defined based on the mix design, and 5%, corresponding to an additional 2% used to assess the effect of increased lime content.

Among the selected soils, Red–Yellow Argisol exhibited the highest reactivity, reaching a pH of 12.4 with only 2% of either lime type. Owing to this higher reactivity, PVA was selected as the reference soil to assess the influence of compactive effort, and both standard and modified efforts were, therefore, adopted for this material. Based on the soil properties previously presented in Table 1 and considering practical and experimental constraints, a single compactive effort was defined for the remaining soils. The Haplic Luvisol mixtures were compacted under standard effort, as its higher organic matter content (1.5%) may delay pozzolanic reactions [3,16,69], indicating a greater suitability for soil modification rather than stabilization. Conversely, the Red Latosol mixtures were compacted under modified effort, since higher compactive effort is required to promote representative mechanical improvement. This experimental design reflects soil-specific behavior and practical considerations, while acknowledging that the effects of soil type and compactive effort are not fully isolated for all materials.

The compaction tests were performed to establish the optimum moisture content (OMC) and maximum dry unit weight (MDUW) of the mixtures, which were used as reference conditions for specimen preparation. The procedure followed ASTM D698 [70] and ASTM D1557 [71] for standard and modified compactive efforts, respectively. Table 2 summarizes all mixtures studied as well as the corresponding compaction parameters, including those of the untreated soils. For stabilized mixtures, differences in MDUW and OMC are shown relative to standard mixtures.

Table 2. Soil–lime mixtures studied and associated compaction parameters (OMC and MDUW).

Soil	Lime Type	Lime Content	Compactive Effort	ID	MDUW (kN/m^3)	Relative MDUW Difference	OMC (%)	Absolute OMC Difference
Argisol	-	-	Standard	PVA-S	16.28		18.9	
Argisol	Dolomitic	3%	Standard	PVA-S-3D	15.68	(−3.7%)	21.8	(+2.9 p.p.)
Argisol	Dolomitic	5%	Standard	PVA-S-5D	15.63	(−4.0%)	20.8	(+1.9 p.p.)
Argisol	Calcitic	3%	Standard	PVA-S-3C	15.49	(−4.9%)	21.2	(+2.3 p.p.)
Argisol	Calcitic	5%	Standard	PVA-S-5C	15.41	(−5.4%)	22.0	(+3.1 p.p.)
Argisol	-	-	Modified	PVA-M	18.58		9.6	
Argisol	Dolomitic	3%	Modified	PVA-M-3D	18.46	(−0.6%)	13.4	(+3.8 p.p.)
Argisol	Dolomitic	5%	Modified	PVA-M-5D	18.22	(−2.0%)	13.4	(+3.8 p.p.)
Argisol	Calcitic	3%	Modified	PVA-M-3C	18.25	(−1.8%)	13.2	(+3.6 p.p.)
Argisol	Calcitic	5%	Modified	PVA-M-5C	18.05	(−2.9%)	13.5	(+3.9 p.p.)
Luvisol	-	-	Standard	TX-S	14.08		28.0	
Luvisol	Dolomitic	3%	Standard	TX-S-3D	13.98	(−0.7%)	29.5	(+1.5 p.p.)
Luvisol	Dolomitic	5%	Standard	TX-S-5D	13.94	(−1.0%)	28.3	(+0.3 p.p.)
Luvisol	Calcitic	3%	Standard	TX-S-3C	13.91	(−1.2%)	29.2	(+1.2 p.p.)
Luvisol	Calcitic	5%	Standard	TX-S-5C	13.87	(−1.5%)	28.4	(+0.4 p.p.)
Latosol	-	-	Modified	LV-M	15.17		29.7	
Latosol	Dolomitic	3%	Modified	LV-M-3D	15.56	(+2.6%)	27.4	(−2.3 p.p.)
Latosol	Dolomitic	5%	Modified	LV-M-5D	15.50	(+2.2%)	27.0	(−2.7 p.p.)
Latosol	Calcitic	3%	Modified	LV-M-3C	15.25	(+0.6%)	28.4	(−1.3 p.p.)
Latosol	Calcitic	5%	Modified	LV-M-5C	15.00	(−1.1%)	29.8	(+0.1 p.p.)

Based on the compaction parameters summarized in Table 2, the three soils exhibited distinct responses to lime addition. For Argisol (PVA), the addition of lime reduced MDUW and increased OMC for both compactive efforts, with more pronounced reductions in MDUW prepared with calcitic lime. A substantial difference was also observed between standard and modified efforts: modified effort resulted in markedly higher MDUW and lower OMC, reflecting the increased densification expected from higher compactive effort.

Luvisol (TX) compacted only at standard effort, showing similar trends but with smaller magnitude: lime incorporation reduced the MDUW and increased the OMC, although the variations were less expressive than those observed for PVA. Both soils, therefore, followed the typical behavior reported for lime-stabilized soils [15,72–75]. In contrast, Latosol (LV), compacted only at modified effort, did not exhibit this conventional response. Except for the mixture with 5% calcitic lime, most LV mixtures exhibited higher MDUW and lower OMC compared with the natural soil, particularly when dolomitic lime was used. This response aligns with behaviors previously reported for some lateritic soils, which may exhibit increased MDUW and reduced OMC upon lime addition [76].

2.2. Methods

The test methods employed in the present study are described in this section.

2.2.1. Specimen Preparation and Curing

The mixing procedures adopted for specimen preparation were the same as those used for compaction tests. Water was added to reach OMC, and the specimens were compacted until reaching MDUW. Compaction was performed in three layers, and the surface of each layer was lightly scarified before placing the next layer to improve interlayer bonding. The acceptance criteria was OMC ± 1% for the moisture content and MDUW ± 0.5 kN/m^3 for the dry unit weight. After demolding, the specimens were sealed in plastic bags to prevent moisture loss and cured at room temperature and relative humidity (RH) above 95%.

2.2.2. Unconfined Compressive Strength Tests

Unconfined compressive strength (UCS) tests were carried out in triplicate for each mixture. Cylindrical specimens 50 mm in diameter and 100 mm in height were compacted according to the compactive effort adopted for each mixture: dynamic compaction was used for mixtures under standard effort, while static compaction was used for mixtures under modified effort. After demolding, the specimens were cured for 7, 28, and 90 days. The UCS tests followed Procedure A of ASTM D5102 [77], using an automatic loading machine with a constant displacement rate of 1.14 mm/min. The UCS results were analyzed using Minitab® 22.4.0, in which regression models were fitted and evaluated. Analysis of Variance (ANOVA) was used to assess the significance of each model and its individual factors, considering a significance level (α) of 0.05.

2.2.3. Flexural Tensile Strength Tests

Flexural tensile strength (FTS) tests were carried out in triplicate for each mixture. Prismatic beams with dimensions of 100 mm × 100 mm × 400 mm were molded by dynamic compaction, using a manually operated rammer and the same compactive effort for each mixture. After the curing period (28 days), the beams were carefully removed from storage and tested in a four-point bending configuration, following the procedures reported in the National Cooperative Highway Research Program (NCHRP) [36,78,79]. A testing machine with 250 kN capacity was used for the flexural tests.

During testing, the temperature and relative humidity were kept at 24 ± 3 °C and 55 ± 15%, respectively, in accordance with Castañeda López et al. [58]. The load was applied under controlled stress conditions at a constant rate of 0.69 MPa/min until failure.

The flexural tensile stress was calculated using Equation (1), with the FTS defined as the maximum stress sustained by the specimen.

$$\sigma_i = \frac{P_i \cdot L}{w \cdot h^2} \tag{1}$$

where σ_i (MPa) is the flexural tensile stress corresponding to force P_i (N); L is the distance between supporting rollers (300 mm); and w and h are the average width and height of the specimen (mm), respectively.

In addition to FTS, the strain at break (ε_b) was determined based on the recommendation of Austroads [80], which defines ε_b as the strain corresponding to 95% of the peak load. This criterion is adopted because strains measured beyond this point are associated with specimen fracture and, therefore, exhibit higher variability [81]. The strain at break was calculated using Equation (2).

$$\varepsilon_i = \frac{108 \cdot h \cdot \delta_i \cdot 10^6}{23 \cdot L^2} \tag{2}$$

where ε_i (microstrain) is the flexural tensile strain corresponding to LVDT's average displacement δ_i (mm); L is the distance between supporting rollers (300 mm), and w and h are the average width and height of the specimen (mm), respectively.

The flexural static modulus (FSM) was estimated from the normalized stress–strain curve using Equation (3), considering the secant modulus corresponding to 40% of the flexural tensile strength, as recommended by Austroads [81].

$$FSM = \frac{\sigma_j}{\varepsilon_j} \cdot 10^6 \tag{3}$$

where FSM (MPa) is the flexural static modulus; σ_j is the corresponding tensile stress (MPa); and ε_j is the strain (microstrain) at the selected stress level.

The FTS, ε_b and FSM results were evaluated through analysis of variance (ANOVA) using Minitab® 22.4.0 software. The statistical significance of the main effect and interactions was assessed at a significance level (α) of 0.05.

3. Results and Discussion

This section presents the experimental results.

3.1. Unconfined Compressive Strength

Figure 4 presents the UCS results for all soil–lime mixtures, including the effects of lime content (3% and 5%), lime type (calcitic and dolomitic), compactive effort (for PVA mixtures), and curing time (7, 28, and 90 days). Each data point corresponds to the mean UCS value, with error bars representing the standard deviation.

In all cases, strength increased with curing time, reflecting the progressive development of pozzolanic reactions. Red–Yellow Argisol (PVA) presented the highest reactivity, with clear gains associated with both lime content and compactive effort, particularly for mixtures with 5% of calcitic lime. This finding is consistent with the observations reported by Rezende [82], who showed that among the soils investigated, the one with the highest exchangeable aluminum content exhibited superior mechanical behavior. Red Latosol (LV) also showed strength improvement, although to a lesser extent, and it was mainly influenced by lime content rather than lime type. In contrast, Haplic Luvisol (TX) exhibited limited strength development over time, regardless of lime content or type. This reduced reactivity is attributed to its relatively high organic matter content (1.5%) combined with extremely elevated potassium concentration (>400 mg/dm^3), which likely inhibited the progression of pozzolanic reactions.

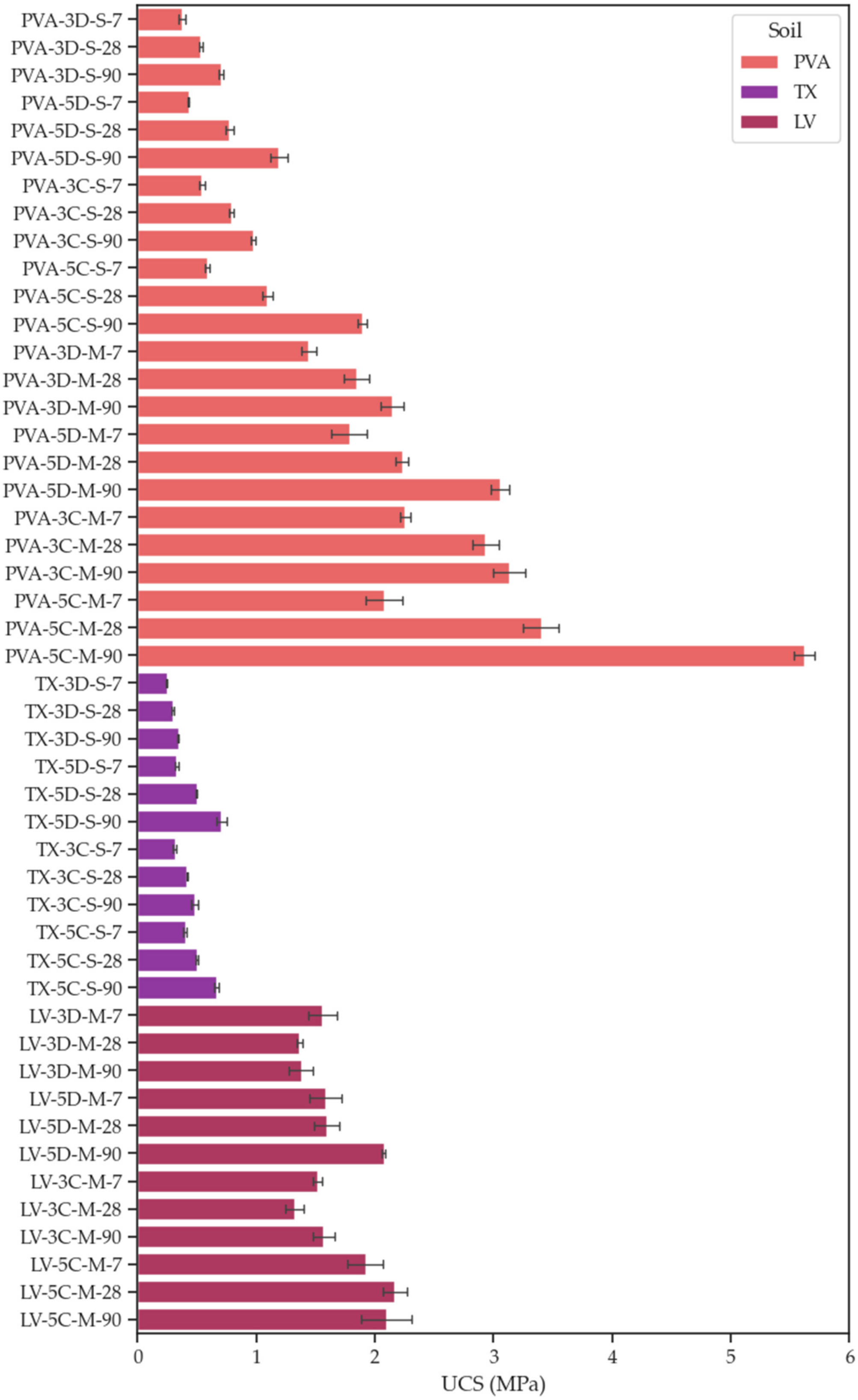

Figure 4. Unconfined compressive strength results of the studied mixtures.

Figure 5 presents the main effects obtained from regression analysis of UCS results for all soil–lime mixtures. The fitted models showed excellent goodness of fit for Argisol (PVA) and Luvisol (TX), with determination coefficient (R^2) of 96.6% and 96.8%, respectively, and a moderate fit for Latosol (LV), with an R^2 of 77.2%.

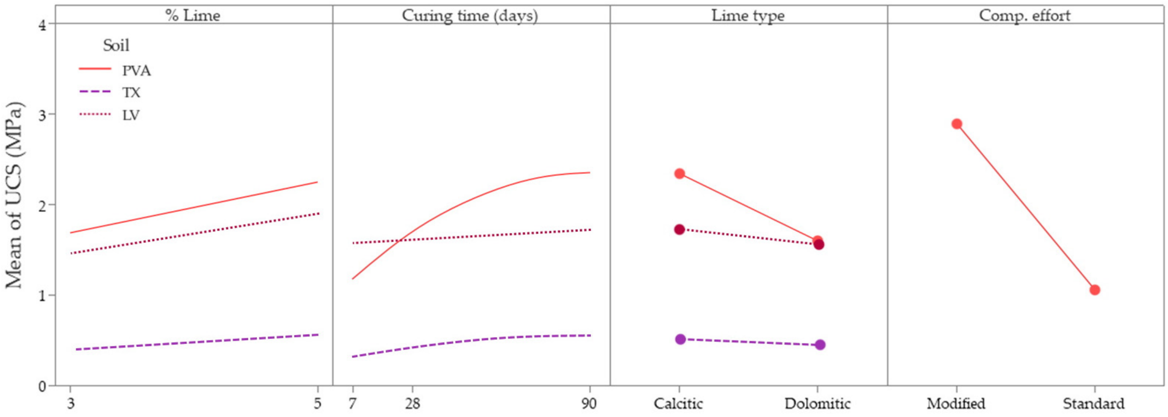

Figure 5. Main effects of the control factors on the mean of UCS of the PVA, TX, and LV mixtures.

Considering the main effects (Figure 5), compactive effort was the factor with the greatest influence on UCS for PVA mixtures. Specimens compacted at modified effort exhibited substantially higher UCS values than those compacted at standard effort. This behavior is consistent with the increase in maximum dry unit weight and the reduction in moisture content discussed in Section 2.1. This densification promotes closer particle contact and enhances cementation, leading to faster and more intense strength gain [15,16,83]. For TX and LV mixtures, tested at standard and modified effort, respectively, the effects of lime content, curing time, and lime type were all statistically significant. Although the magnitude of these effects was more pronounced for PVA mixtures, a consistent increase in UCS was observed for all soils with higher lime content, longer curing time, and the use of calcitic lime instead of dolomitic lime.

Figure 6 presents the interaction plots derived from the regression analysis of UCS results for all mixtures. A consistent interaction pattern was observed between lime content and curing time across the three soils. At 7 days, the UCS values for 3% and 5% lime are similar, indicating that the available lime has not yet been fully reacted. However, at 90 days, the mixtures containing 5% lime show markedly higher strengths, reflecting the progressive reaction of lime over time and the continued development of cementitious products [27].

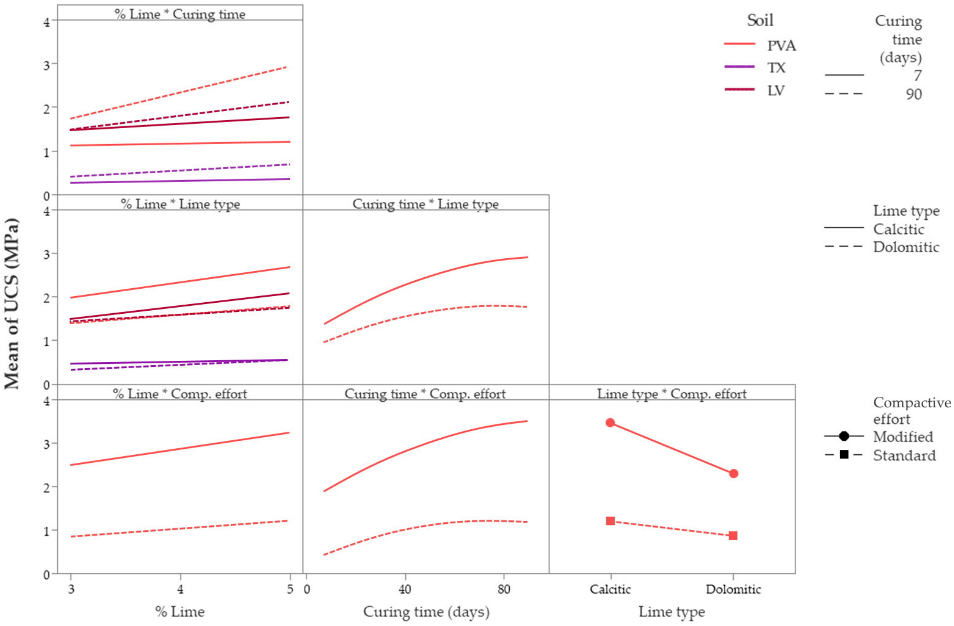

Figure 6. Interaction effects of the control factors on the mean of UCS of the PVA, TX and LV mixtures.

In addition, an interaction between lime content and lime type was identified for all soils. For the PVA and LV mixtures, the distinction between calcitic and dolomitic lime became more pronounced at 5% lime content, whereas for the TX mixtures this difference was more evident at 3% lime. Other interactions, such as between lime type and compactive effort and between curing time and lime type, for PVA mixtures, reinforce the superior behavior of calcitic lime [6,7,84,85], likely associated with its higher $Ca(OH)_2$ content and finer particle size, which results in more effective reaction kinetics, especially under denser packing conditions.

3.2. Flexural Tensile Behavior

Figure 7 shows the 28-day FTS mean strength and standard deviation.

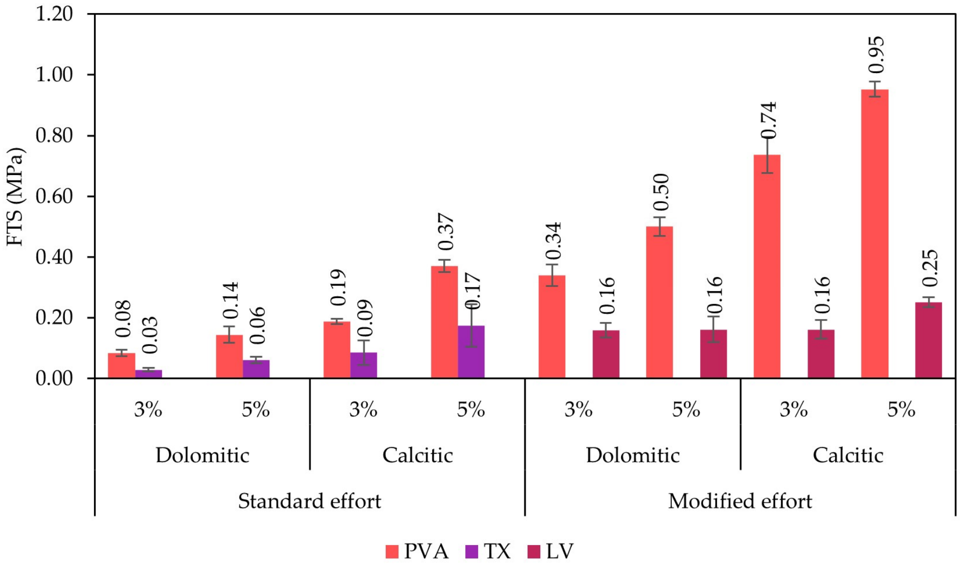

Figure 7. Flexural tensile strength results of the studied mixtures.

The FTS results demonstrate for all three soils a clear trend of improved flexural strength with the use of calcitic lime with the higher lime content of 5%. For Argisol (PVA), a significant increase in FTS was observed when specimens were compacted using modified effort compared with standard effort, reinforcing the sensitivity of the soil to densification effects noted in the UCS results. Additionally, the flexural strength of the PVA mixtures was markedly superior to that obtained for Luvisol (TX compacted at standard effort) and for Latosol (LV compacted at modified effort), indicating a higher pozzolanic reactivity and a more favorable response to lime stabilization with the PVA soil.

Figure 8 presents the main effects obtained from ANOVA of FTS results for all mixtures. The regression models yielded R^2 values of 99.1%, 67.3%, and 72.2% for PVA, TX, and LV mixtures, respectively, indicating excellent goodness of fit for PVA and moderate adjustment for TX and LV. In the PVA mixtures, compactive effort exhibited the strongest effect, followed by lime type and lime content. A similar pattern was observed for TX mixtures compacted at standard effort, although lime type exerted a greater influence than lime content. For the LV mixtures, compacted at modified effort, lime type and lime content presented similar influence magnitudes, reflecting comparable contributions to the flexural response. Across all soils, higher lime content (5%) and calcitic lime consistently resulted in superior FTS values. Additionally, for PVA mixtures, modified compactive effort produced higher FTS values than standard effort.

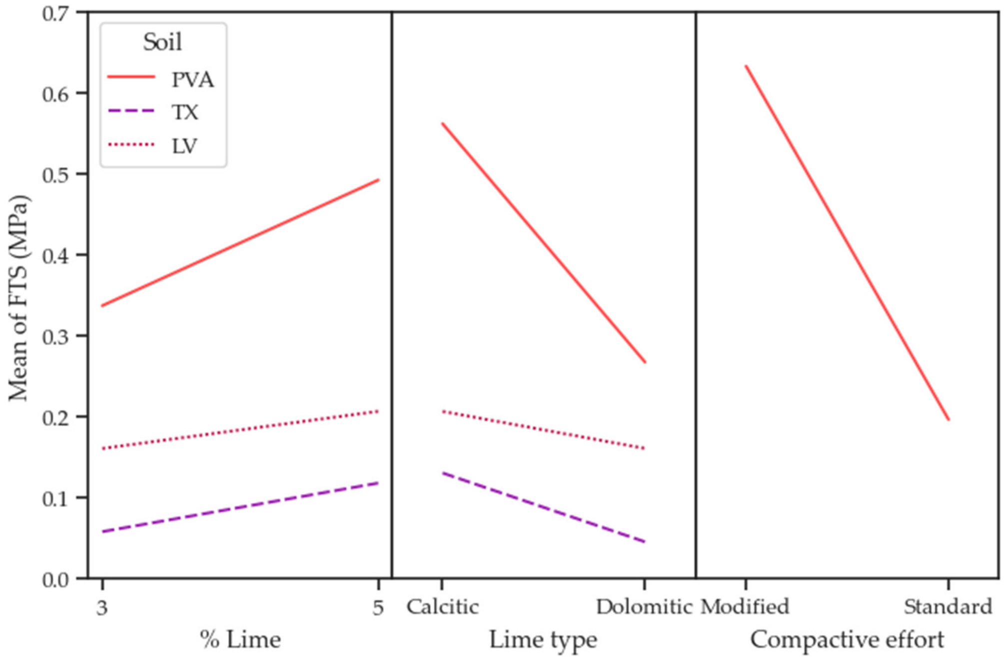

Figure 8. Main effects of the control factors on the mean of FTS of the PVA, TX, and LV mixtures.

Figure 9 presents the interaction effects derived from the ANOVA of FTS for PVA and LV mixtures. For the TX mixtures, the interaction between lime type and lime content was not statistically significant and was therefore excluded. For the PVA mixtures, the most pronounced interaction occurred between lime type and compactive effort, indicating that the beneficial effect of increased compactive effort was substantially amplified when using calcitic lime. For the TX mixtures, the interaction between lime type and lime content revealed that with 3% lime, the FTS values were essentially independent of lime type, whereas with 5% lime, a clear divergence was observed, with calcitic lime yielding markedly higher flexural strength than dolomitic lime.

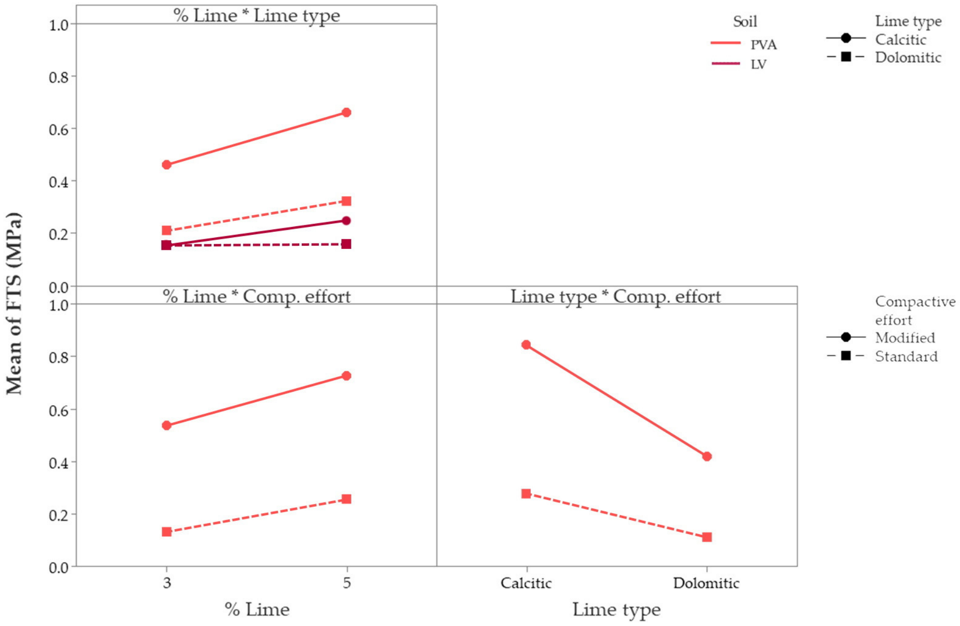

Figure 9. Interaction effects of the control factors on the mean of FTS of the PVA and LV mixtures.

Figure 10 presents the strain at break (ε_b) obtained for all mixtures after 28 days of curing. For the PVA mixtures, except for the 3% dolomitic lime mixture, the ε_b values were similar between specimens compacted with standard and modified effort. For the TX and LV mixtures, the ε_b values obtained with dolomitic lime exhibited comparable magnitudes regardless of lime content. The ANOVA performed for ε_b across the three soils yielded low statistical significance, with R^2 values of 56.6% for PVA, 54.8% for TX, and 20.2% for LV. These results indicate that strain at break is not meaningfully affected by the controllable factors evaluated in this study. For the mixtures compacted at modified effort (PVA and LV), ε_b values tended to stabilize around 200 microstrain. When compared with the reference values adopted by SAMDM [63] for cemented materials (125 and 145 microstrain), all studied mixtures exhibited ε_b values exceeding 145 microstrain. This suggests the potential for improved fatigue performance, as these mixtures can sustain larger tensile strain prior to cracking.

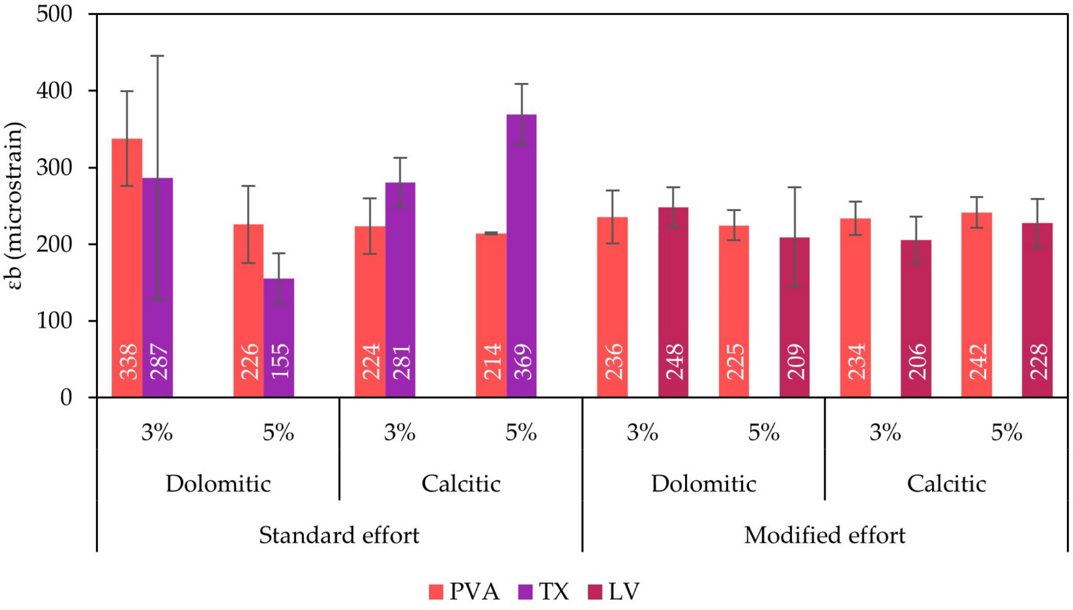

Figure 10. Strain at break results of the studied mixtures.

Figure 11 presents the flexural static modulus (FSM) results for all mixtures after 28 days of curing. The trends generally follow those observed for FTS: in all three soils, mixtures prepared with calcitic lime exhibited higher FSM than those stabilized with dolomitic lime, and use of 5% lime resulted in visibly stiffer materials compared with 3%. For the PVA soil, the effect of compactive effort was again evident, with specimens compacted under modified effort presenting substantially higher modulus values than those compacted under standard effort, reflecting the improved stiffness associated with increased densification. Across the TX and LV mixtures, FSM values were consistently lower than those with PVA, but the same hierarchy of influencing factors, lime type and lime content, was maintained.

Figure 12 presents the main effects obtained from ANOVA of FSM for all mixtures. The regression models yielded R^2 values of 99.2%, 81.1%, and 81.1% for PVA, TX, and LV, respectively, indicating excellent adjustment for PVA and strong adjustment for TX and LV. Among the main effects, the PVA mixtures showed the same ordering; as for FTS, compactive effort was the dominant factor, followed by lime type, and lastly lime content, with visibly distinct magnitudes among the three. In the TX mixtures, lime content and lime type displayed nearly equivalent effect magnitudes, indicating that both contributed similarly to flexural stiffness. For all soils, higher lime content (5%) and the use of calcitic lime consistently resulted in higher FSM values, and for PVA mixtures, the modified compactive effort yielded substantially superior stiffness values relative to standard effort.

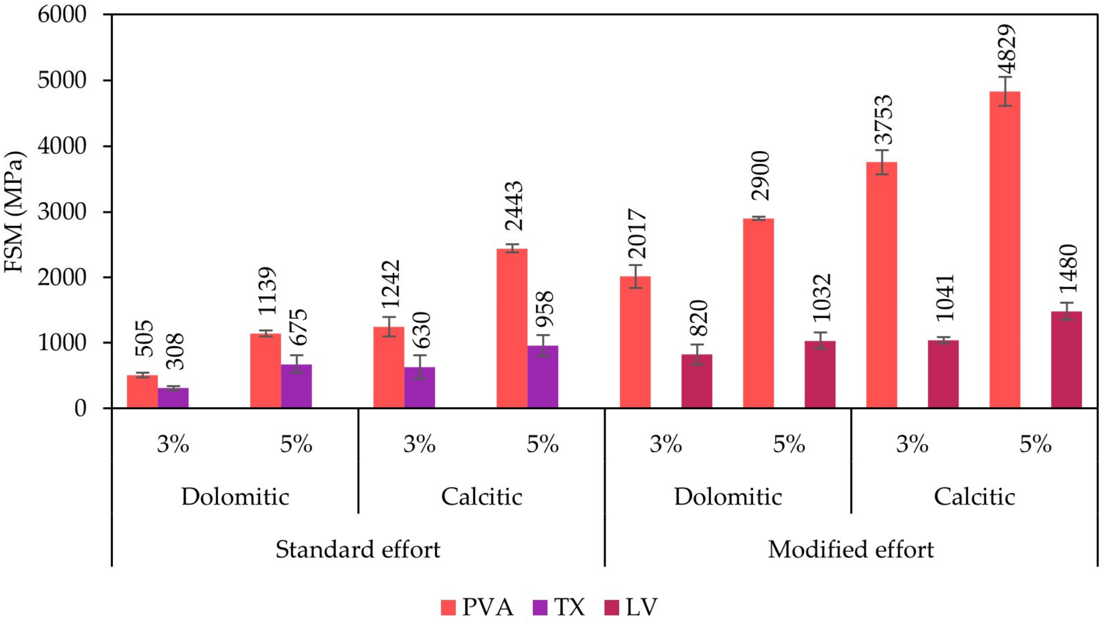

Figure 11. Flexural static modulus results of the studied mixtures.

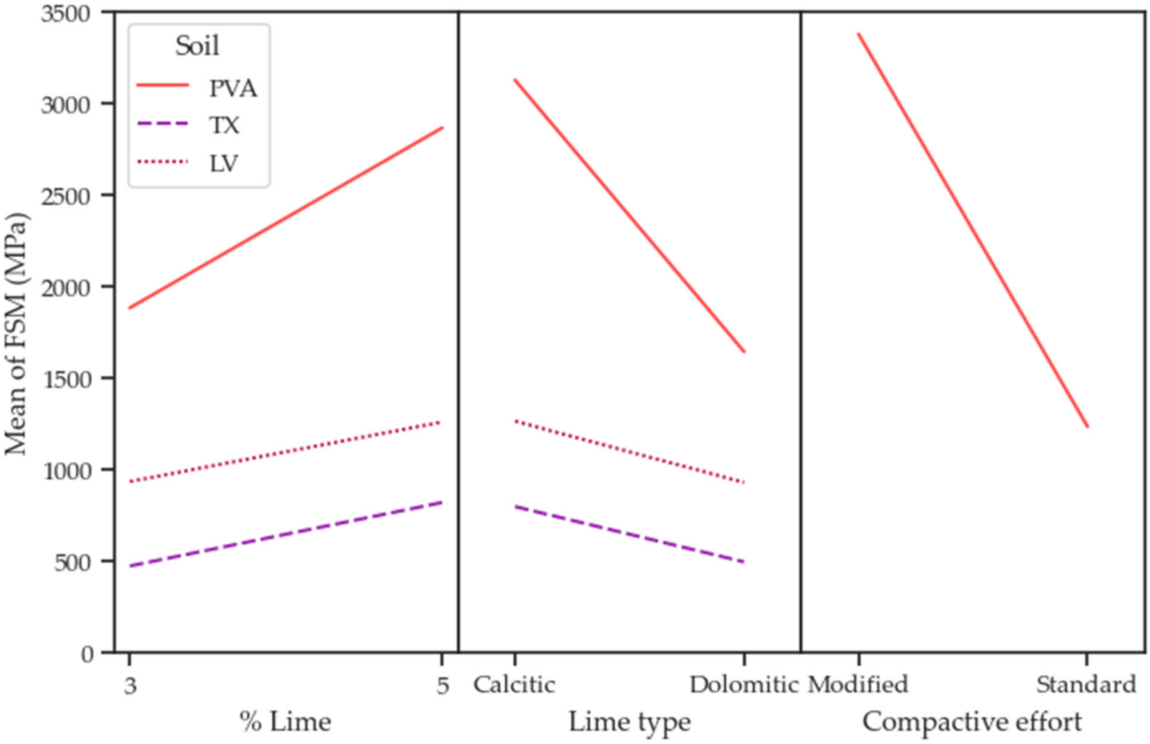

Figure 12. Main effects of the control factors on the mean of FSM of the PVA, TX, and LV mixtures.

Figure 13 presents the interaction effects derived from the ANOVA of FTS for the PVA mixtures. For TX and LV mixtures, the interaction between lime type and lime content was not statistically significant and was, therefore, excluded from the analysis. Within the PVA mixtures, the interaction between lime content and compactive effort also did not display statistical significance. Conversely, the interaction between lime type and compactive effort demonstrated a strong effect: the beneficial impact of modified effort was substantial when calcitic lime was used, resulting in higher FSM values compared with dolomitic lime.

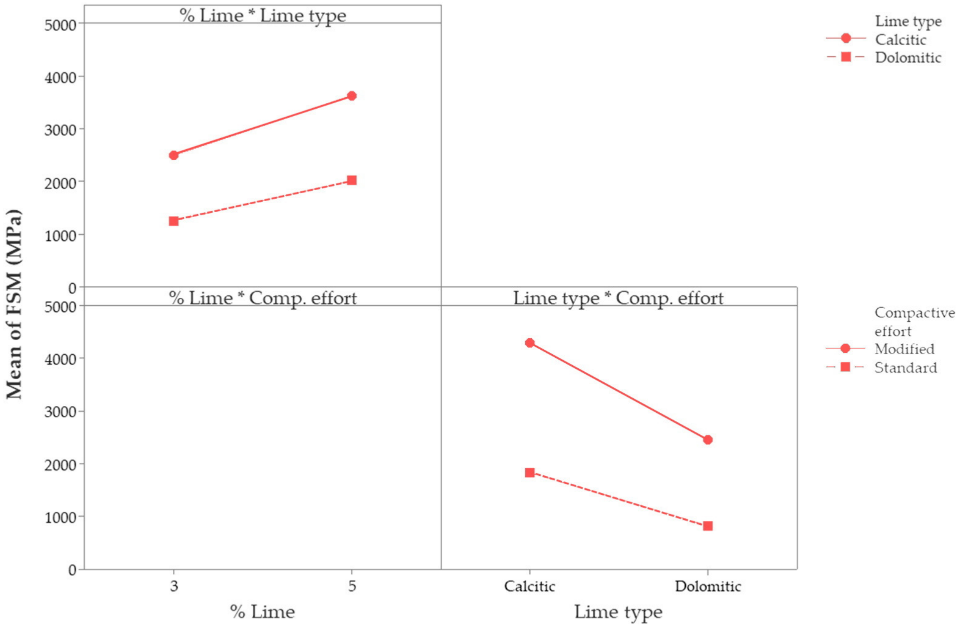

Figure 13. Interaction effects of the control factors on the mean of FSM of the PVA mixtures.

3.3. Correlations Between Compressive Strength and Flexural Properties

Even though the FSM and strain at break are parameters used in the mechanistic–empirical design of pavements with cement-treated layers, there are limited results for soil–lime mixtures reported in the literature. Therefore, the possibility of estimating these parameters, along with the FTS, from UCS results after 28 days of curing was analyzed. Linear, logarithmic, exponential, and power models were tested.

Ordinary least squares method was used to fit a linear regression model to the data. For non-linear models, a linearized equation was derived using logarithmic relationships, which was then fitted to the data. The determination coefficient (R^2) from both linearized and original models were calculated to evaluate the goodness of fitness, along with the mean absolute error (MAE) and root mean squared error (RMSE) between the fitted and observed flexural parameters. Note that each of the sixteen data points represents the average value from six separate specimens—three for the flexural tests and three for the UCS test.

Table 3 summarizes the four regression models considered for the correlation between UCS and FTS results for all mixtures evaluated. Although the power model resulted in the highest R^2 inside the transformed linear space (0.83), the best R^2, MAE, and RMSE between fitted and observed FTS were found using the exponential model (0.87, 0.06, and 0.09, respectively). Figure 14 shows the resulting exponential model plotted over the observed data. It is worth noting that the relationship between UCS and FTS for a given set of soil and compactive effort is intrinsically linear, with an intercept close to zero. Even though a linear relationship may better represent the physical correlation between both strengths, the exponential model was ideal to capture the variability in the results of the mixtures studied.

The relationship between FSM and UCS was also evaluated using linear regression. The resulting models and their corresponding metrics are given in Table 4. Within the transformed linear space, the linear model showed the highest R^2 (0.78). However, when comparing fitted and observed FSM values directly, the exponential model presented the best metrics, with 0.84 R^2, 370 MAE, and 494 RMSE. Figure 15 shows the resulting exponential model plotted with the observed data. Once again, a linear trend can be observed within each given soil and compactive effort group (i.e., PVA-S, PVA-M, TX-

S, and LV-M). However, the exponential model was able to capture the variation in all variables combined.

Table 3. Regression models correlating flexural tensile strength (FTS) and unconfined compressive strength (UCS).

Model	Linear Equation	a	b	Linear R^2	k_1	k_2	Model R^2	MAE	RMSE
$FTS = k_1 + k_2 \cdot UCS$	$FTS = a + b \cdot UCS$	−0.07	0.25	0.83	−0.07	0.25	0.83	0.08	0.10
$FTS = k_1 + k_2 \cdot \ln UCS$	$FTS = a + b \cdot \ln UCS$	0.25	0.28	0.65	0.25	0.28	0.65	0.11	0.15
$FTS = k_1 \cdot e^{k_2 \cdot UCS}$	$\ln FTS = a + b \cdot UCS$	−2.91	0.89	0.79	0.05	0.89	0.87	0.06	0.09
$FTS = k_1 \cdot UCS^{k_2}$	$\ln FTS = a + b \cdot \ln UCS$	−1.77	1.16	0.84	0.17	1.16	0.82	0.08	0.11

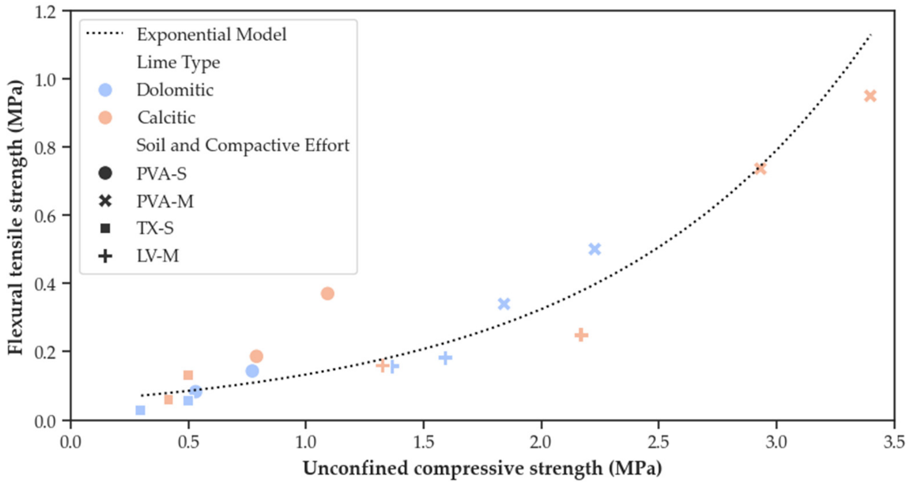

Figure 14. Exponential model correlating flexural tensile strength (FTS) and unconfined compressive strength (UCS).

Table 4. Regression models correlating flexural static modulus (FSM) and unconfined compressive strength (UCS).

Model	Linear Equation	a	b	Linear R^2	k_1	k_2	Model R^2	MAE	RMSE
$FSM = k_1 + k_2 \cdot UCS$	$FSM = a + b \cdot UCS$	−21.31	1202.74	0.7805	−21.31	1202.74	0.78	450.78	580.59
$FSM = k_1 + k_2 \cdot \ln UCS$	$FSM = a + b \cdot \ln UCS$	1528.28	1351.54	0.6231	1528.28	1351.54	0.62	595.55	760.82
$FSM = k_1 \cdot e^{k_2 \cdot UCS}$	$\ln FSM = a + b \cdot UCS$	6.20	0.68	0.7413	490.60	0.68	0.84	369.88	494.38
$FSM = k_1 \cdot UCS^{k_2}$	$\ln FSM = a + b \cdot \ln UCS$	7.07	0.86	0.7447	1174.22	0.86	0.72	499.71	651.20

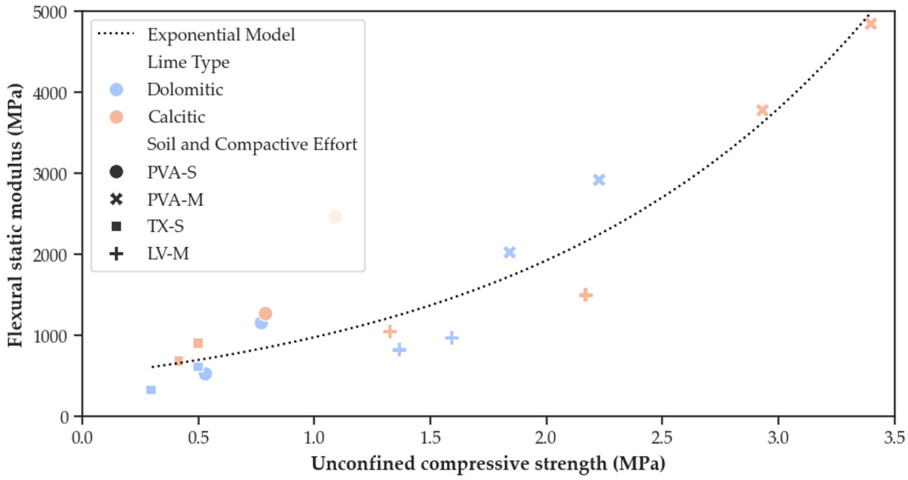

Figure 15. Exponential model correlating flexural static modulus (FSM) and unconfined compressive strength (UCS).

Strain at break (ε_b) was the only flexural parameter without a clear correlation to UCS. All regression models resulted in an R^2 close to zero, meaning that the prediction model performed as good as a simple average of all observations. As a result, Figure 16 presents a linear model fitted to the data with an intercept of 203 microstrain, a coefficient of 0.4, and an R^2 equal to zero. The ε_b value around 200 microstrain is particularly true for all mixtures considered slightly cemented by Austroads [86], with UCS varying between 1 and 4 MPa at 28 days of curing.

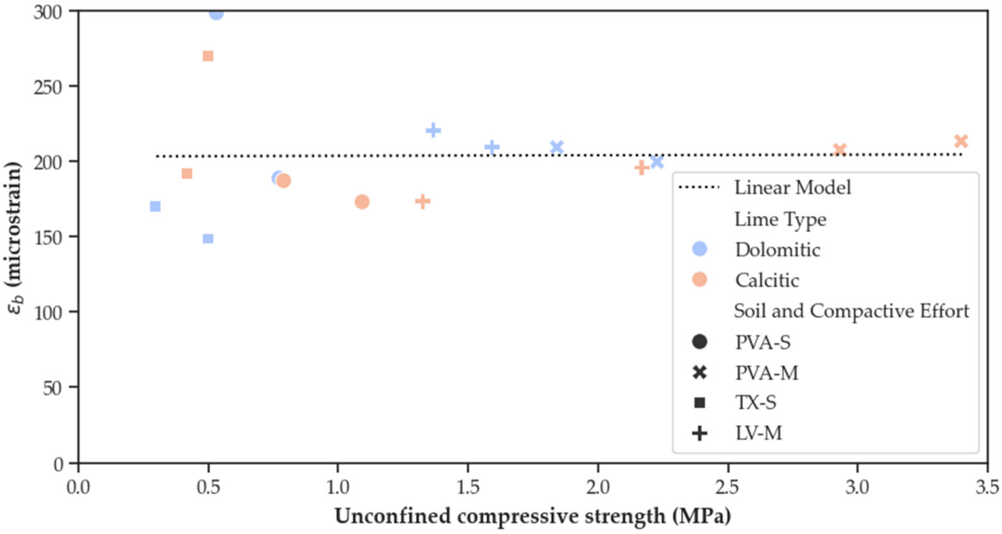

Figure 16. Linear model correlating strain at break (ε_b) and unconfined compressive strength (UCS).

4. Conclusions

This paper investigated lime stabilization of three tropical soils through a comprehensive experimental program, evaluating the effects of lime type, lime content, and compactive effort on unconfined compressive strength (UCS), flexural tensile strength (FTS), strain at break (ε_b), and flexural static modulus (FSM), with curing time assessed through UCS. The results support the advancement of mechanistic–empirical design parameters for lime-treated soils and the development of compressive–flexural correlations. Based on the analyses, the following conclusions can be drawn:

- All three soils responded positively to lime treatment, though to different extents. Argisol (PVA) and Latosol (LV), particularly when compacted with modified effort, achieved high strength and stiffness and demonstrated performance consistent with lime-stabilized materials. In contrast, Luvisol (TX) showed more moderate improvements, consistent with soil modification. These trends are likely associated with its elevated organic matter content (1.5%) and high potassium concentration (>400 mg/dm^3), both of which may inhibit pozzolanic reactions. These findings emphasize that lime treatment performance is soil-dependent, and that stabilization feasibility must be evaluated for each soil according to its reactivity with lime.
- Mechanical behavior of soil–lime mixtures was influenced by the study's controllable factors, with compactive effort emerging as the dominant factor within the evaluated experimental framework, followed by lime type and lime content. The use of higher lime content (5%) resulted in increased strength and stiffness, especially in combination with calcitic lime and modified compactive effort. These results have direct implications for field construction: increasing compactive effort, an operationally achievable measure in practice, provides substantial performance gains without requiring excessive lime contents, which may induce shrinkage, thereby promoting both cost-effectiveness and structural reliability.

- Curing time significantly influenced unconfined compressive strength, confirming the time-dependent development of pozzolanic reactions. A strong interaction between lime content and curing time was observed: lime content exerted minimal influence at 7 days but became increasingly significant after 28 and 90 days, indicating progressive lime consumption and cementitious development as curing advances. Overall, longer curing time yielded higher UCS values.
- Calcitic lime produced superior mechanical behavior compared with dolomitic lime. This effect is attributed to higher $Ca(OH)_2$ content (93% vs. 44%), lower retained fraction on the 0.075 mm sieve (0.2% vs. 17.8%), and lower particle density (0.4 vs. 0.6 g/cm^3), resulting in greater surface area and higher dissolution rate. These properties contributed to enhanced reactivity and cementation, particularly when combined with higher compactive effort.
- Strain at break was the only measured parameter not significantly affected by the studied controlled factors. For soil–lime mixtures with UCS > 1 MPa at 28 days, ε_b converged toward approximately 200 microstrain. This indicates that lime-stabilized mixtures in this study exhibit a more ductile response than typical cement-treated materials, tolerating greater deformation before cracking and, thus, providing desirable stress–strain behavior for mechanistic–empirical pavement applications.
- Statistically significant correlations were established between UCS, FTS, and FSM, facilitating the estimation of flexural properties directly from compressive strength values. Thus, when flexural testing is unavailable, engineers may use the proposed estimation equations to estimate flexural modulus and strength from UCS and may adopt $\varepsilon_b = 200$ microstrain for preliminary pavement design assessments.

Finally, these conclusions are applicable to the materials, procedures, and experimental conditions employed in this study. Since soil–lime interaction is inherently dependent on the soil characteristics, the results should not be broadly generalized. Further research with the same soils may include durability, resilient modulus for lime-modified mixtures, and mechanistic–empirical applications of the parameters obtained in this paper to verify structural performance. Additionally, studies should be extended to other tropical soils and complemented with field-scale evaluation to support the refinement and calibration of mechanistic–empirical design of lime-treated layers in tropical environments.

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Abbreviations

The following abbreviations are used in this manuscript:

$Al_{exchangeable}$	Exchangeable Aluminum
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
AASHTO	American Association of State Highway and Transportation Officials
C	Calcitic Lime
$Ca(OH)_2$	Calcium Hydroxide
CEC	Cation Exchange Capacity
D	Dolomitic Lime
ε_b	Strain at Break
FSM	Flexural Static Modulus
FTS	Flexural Tensile Strength
IDT	Indirect Tensile Strength
K	Potassium
LG′	Lateritic Clayey Soil
LV	Red Latosol
M	Modified Effort
MAE	Mean Absolute Error
MCT	Miniature, Compacted, Tropical
MDUW	Maximum Dry Unit Weight
$Mg(OH)_2$	Magnesium Hydroxide
MH	High-Plasticity Silt
ML	Low-Plasticity Silt
NG′	Non-Lateritic Clayey Soil
NLA	National Lime Association
NS′	Non-Lateritic Silty Soil
OMC	Optimum Moisture Content
P	Phosphorus
PVA	Red–Yellow Argisol
R^2	Determination Coefficient
RMSE	Root Mean Squared Error
S	Standard Effort
SAMDM	South African Mechanistic–Empirical Design Method
TX	Haplic Luvisol
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System

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