Modification of a Lateritic Soil with Lime and Cement: An Economical Alternative for Flexible Pavement Layers

F.H.M. Portelinha, D.C. Lima, M.P.F. Fontes, C.A.B. Carvalho

Abstract. Lateritic soils are widely spread in the Brazilian territory and they have been used as subgrade of pavement layers. Specifically, the Red-yellow latosols are usually clayey soils and are characterized as low bearing capacity materials for flexible pavement layers. As a conventional solution, soil stabilization with hydrated lime or Portland cement has been used as pavement layers reinforcement. However, the addition of low contents of stabilizers, referring to the soil modification, has not been applied on regular basis in highway designs. The purpose of this paper is to evaluate the use of low contents of lime and cement in the modification of a lateritic soil properties concerning the behavior of mixtures since of the beginning of construction to the resulting final product. At this point, the workability, chemical properties, mechanical behavior and mineralogical composition were evaluated. Mechanistic analyses were performed in order to verify fatigue failures on asphalt layers in roadways structural layers. Experimental results showed that addition of 2% and 3% of lime or cement was enough to change the soil workability and mechanical strength. Additionally, mechanistic analyses supported the soil modification technique as valuable practice with low elastic strains in the asphalt layer when applied in pavement base layers.
Keywords: soil modification, hydrated lime and Portland cement, lateritic soil, flexible pavement layers; mechanistic analysis.

1. Introduction

Pavement designers have always been searching for technical and economical solutions for roadway applications. Soil stabilization technique, which is normally used for the improvement of local soils, is considered an economical solution in places where granular materials are not available. Hydrated lime and Portland cement have been considered excellent stabilizers for the improvement of different soils and have been extensively used in the past decades. Beneficial effects of compacted soil-lime and soil-cement mixtures on geotechnical properties have been discussed in the technical literature (Herrin & Mitchell, 1961; Moh, 1965; Kennedy *et al.*, 1987; Bhattacharja *et al.*, 2003; Felt & Abrams, 2004; Galvão *et al.*, 2004; Kolias *et al.*, 2005; Osinubi & Nwaiwu, 2006; Consoli *et al.*, 2009; Sariosseri & Muhunthan, 2009; Cristelo *et al.* 2009). Ordinarily, these stabilizers can promote plasticity reduction, grain size distribution alterations caused by flocculation reactions, and expressive mechanical strength increase. Thereby, benefits of the soil stabilization for pavement applications can be available since the construction phase until to the final product.

The geotechnical behavior of lime or cement treated soils depends on physical and chemical properties of soils, in which are directly related with soil formation conditions and mineralogical composition of the matrix rock (Kennedy *et al.*, 1987; Consoli *et al.*, 2009). In general, temperate soils, usually composed of active clayey soils (montmorillonites and smectites minerals) can respond better than tropical soils (kaolinitic soils) after lime stabilization. However, Brazilian experiences have shown excellent mechanical improvement in lateritic soils treated with lime or cement in roadways applications.

Regarding lateritic soils, they are widely spread in the Brazilian territory and appear in almost all regions in different climatic conditions, topography and matrix rock (Fig. 1a). Lateritic soils have been extensively used in roadways, embankments and retaining walls due to the excellent improvement after compaction. However, Red yellow latosols normally appear as clayey soils with relatively low bearing capacity for flexible pavement structural layers. Considering that these soils cover almost a third of the Brazilian territory (Fig. 1b), soil modification technique come up as an economical solution in these situations.

In this study, the term “soil stabilization” refers to a substantial improvement of the mechanical behavior, whereas the term “soil modification” applies to a significant improvement of the soil workability and compaction characteristics, and to a minor improvement of the soil mechanical strength using low contents of stabilizers, as visu-

F.H.M. Portelinha, MSc, Setor de Geotecnia, Departamento de Engenharia Civil, Universidade Federal de Viçosa, 36570-000 Viçosa, MG, Brazil. e-mail: fernando@sc.usp.br.
D.C. Lima, Professor, Departamento de Engenharia Civil, Universidade Federal de Viçosa, 36570-000 Viçosa, MG, Brazil. e-mail: declima@ufv.br.
M.P.F. Fontes, Professor, Departamento de Solos, Universidade Federal de Viçosa, 36570-000 Viçosa, MG, Brazil. e-mail: mpfontes@ufv.br.
C.A.B. Carvalho, Associate Professor, Departamento de Engenharia Civil, Universidade Federal de Viçosa, 36570-000 Viçosa, MG, Brazil. e-mail: cabraz@ufv.br.
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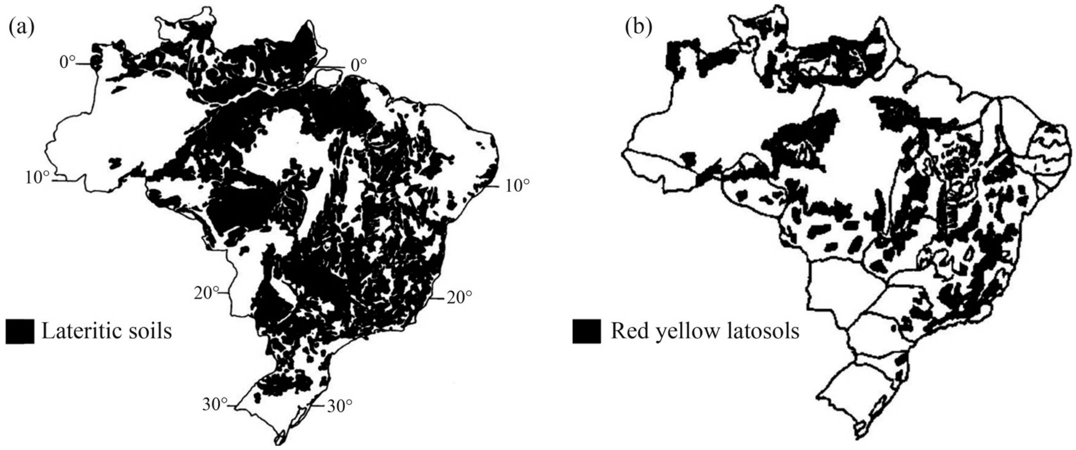

Figure 1 - Distribution of lateritic soils in Brazil: (a) Lateritic soils; (b) Red Yellow latosol (Ker, 1998).

alized by Osula (1996) and Sariosseri & Muhunthan (2009). From this point, it must be emphasized that the use of mixtures with high contents of lime or Portland cement (as stabilized soils) generally produces materials with excellent mechanical behavior, as well as the application of mixtures with low contents of these stabilizers (as modified soils) can represent an economical and efficient solution for flexible pavement design, as reported by Sariosseiri & Muhunthan (2009) and Solanki *et al.* (2009).

This paper presents the evaluation of the workability, mineralogical composition and mechanical behavior of a lateritic soil (Red-yellow latosol) modified with hydrated lime and with Portland cement (percents of 1%, 2% and 3%), for highway engineering applications. The experimental program was directed to the evaluation of the soil and its mixtures index properties, unconfined compressive strength (UCS), initial tangent modulus at strain levels up to 0.1%, California bearing ratio (CBR), and mineralogical composition. The behavior of the mixtures in flexible pavement design was evaluated through mechanistic analysis of two different pavement configurations using, respectively, the modified soil as subbase or base layer.

2. Experimental Program

The experimental program was conducted in three steps. The first addressed the application of low contents of hydrated lime (HL) and of Portland cement (PC) in order to promote soil workability modification. The following parameters were used in these analyses: plastic and liquid limits, grains size distribution and compaction parameters (Proctor tests). In the second step, UCS tests were conducted in order to access the improvement in strength and initial tangent modulus (at strain levels up to 0.1%); additionally, CBR and cyclic triaxial tests were implemented to verify the potential applications of materials in roadways. In the third step, X-ray diffraction analyses were carried out to study the mineralogical modification in the lateritic soil after treatment. Thereafter, mechanistic analyses of modified soil layers were performed using the finite difference computational program ELSYM5.

2.1. Materials

A lateritic fine-grained soil from Viçosa city, located in the Minas Gerais state, Brazil, was used in this study. Table 1 summarizes the geotechnical properties of the soil, whereas Table 2 introduces chemical soil properties. The material is a residual gneiss soil, pedologically classified as Red-yellow latosol, which commonly appears in B horizons of soft slopes and classified as silty sand clay. Follow-

Table 1 - Geotechnical properties of soil.

Properties		Standard method
Clay (%)	66	
Silt (%)	6	
Fine sand (%)	13	NBR 7181/84
Medium sand (%)	13	
Gravel sand (%)	2	
Liquid limit (%)	69.5	NBR 6459/84
Plasticity limit (%)	40.9	NBR 7180/84
Plasticity index (%)	28.6	
Specific gravity	2.725	NBR 6508/84
Maximum dry unit weight (kN/m^3)	14.9	NBR 7182/86
Optimum water content (%)	27.9	

Table 2 - Chemical properties of soil.

Properties	
pH	6.76
ZPC	6.02
CEC (cmol$_c$/dm^3)	1.25
BS (%)	80

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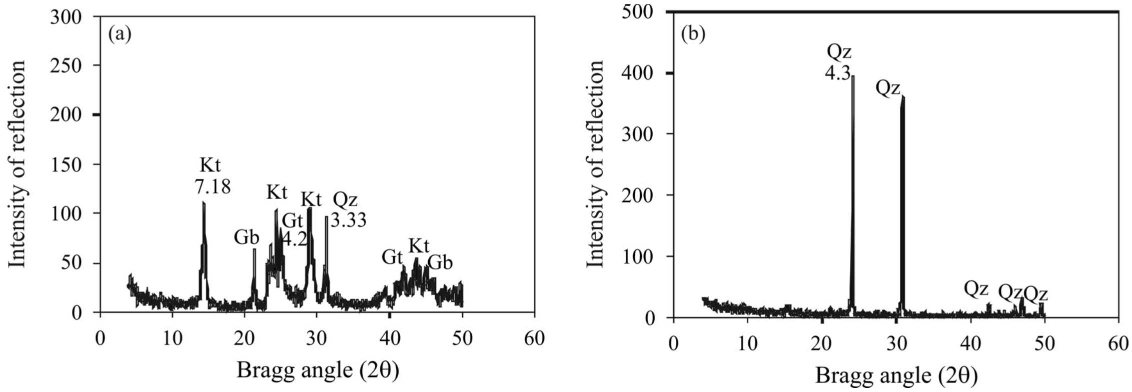

Figure 2 - XRD of untreated soil samples: (a) clay-silt and (b) sand fractions.

ing the USC and the TRB soil classifications systems, the soil is classified as a CL and A-7-5 soil, respectively. According to MCT soil classification system (*Miniature, Compacted, and Tropical*), the soil is a lateritic sandy clay. (LG'). Figure 2 presents X-ray diffraction data, in which kaolinite, goethite and gibbsite were identified as the main minerals.

A commercial chemically pure powdered hydrated lime (CH-III), and Portland cement (PC II-E-32) were used throughout the study.

2.2. Methods

Contents of 1%, 2% and 3% in weight of hydrated lime and Portland cement were mixed to dry soil samples. Thereafter, water contents were added to each mixture in order to reach its optimum water content (Standard Proctor compaction effort). Samples of homogeneous mixtures were put into plastic bags and rested during one hour before running chemical analysis, particle size distribution, Atterberg limits and compaction tests. Specimens for UCS, CBR and cyclic triaxial tests were molded at the optimum water content and maximum dry unit weight of each mix, and subsequently cured during 7 days and 28 days. In addition, stabilizers contents of 0.5%, 1%, 2%, 4%, 8% and 12% were used in the determination of plastic (w_p) and liquid limits (w_L) of mixtures, in order to compare the plasticity index changes provided by soil modification and soil stabilization techniques, as well as in the classification of mixtures following the Unified Soil Classification (UCS) and the Transportation Research Board (TRB) systems. XRD analyses were performed in post-failure specimens from UCS tests; on the other hand, specimens for CBR tests were prepared using 2% and 4% of stabilizers, and for cyclic triaxial tests using only 2% of stabilizers.

2.2.1. Workability properties

The workability improvement of soils in field applications is related to its plasticity, finer fraction, optimum water content reductions and maximum dry density increases (Osula, 1996; Sariosseri & Muhunthan, 2009). Therefore, workability modifications assessed through particle size distribution, plasticity index, and compaction tests parameters. Particle size distribution was carried out by sieve analyses and sedimentation test using sodium hexametaphosphate as dispersant solution.

Compaction test was performed at the Standard Proctor compaction effort (NBR7182, 1986) in order to determine compaction curves, and, consequently the optimum water content and maximum dry unit weight of soil and mixtures.

2.2.2. Chemical parameters

The chemical analyses of soil and mixtures were conducted according to EMBRAPA (1997). Samples from

Table 3 - TRB classification of mixtures.

Materials	Passing #200 (%)	LL (%)	PI (%)	GI (%)	TRB classification	OBS
Soil	66	73.4	32.6	17	A-7-5	
Soil + 1% HL	59	65.1	28.1	18	A-7-5	
Soil + 2% HL	59	67.8	22.0	16	A-6	Clayey soils
Soil + 3% HL	49	72.0	24.3	13	A-6	
Soil + 1% PC	57	60.0	25.4	16	A-6	
Soil + 2% PC	48	59.5	20.1	11	A-5	Silty soils
Soil + 4% PC	41	58.1	14.1	6	A-4	

plastic bags were used in these analyses. The hydrogenionic potential (pH) of soil and mixtures were determined in potassium chloride (KCl) solution in ratio of soil/solution suspension of 1/2.5 (volume/volume), at minimum of one hour of contact time and agitation before the potentiometric readings. Cation exchangeable capacity (CEC) of soil and mixtures were carried out in order to quantify the Calcium, Magnesium, Aluminum, Sodium and Potassium exchangeability. Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) exchangeable were extracted by chloride potassium (KCl) solution (1 mol/L), with ratio of 1:20, and determined by an atomic absorption spectrometer, *Varian Spectra*, model 2020 FS. Aluminum (Al^{3+}) cations were extracted in similar solution that was used in calcium and magnesium extraction; however, determination was performed by titration in NaOH (0.025 mol/L). Cations of Sodium (Na^{+}) and Potassium (K^{+}) were extracted by Mehlich-1 solution and determined via flame photometry.

2.2.3. Mechanical behavior parameters

UCS tests have been used in most of the experimental programs reported in the literature in order to verify the effectiveness of the stabilization, to access the importance of influencing factors in the strength of treated soils and to choose the best stabilizer percentage. Therefore, UCS failure and initial tangent modulus (up to 0.1%) were used in analyses of mechanical response after soil modification. UCS tests were carried out according to ASTM D2166/94 in cylindrical specimens with 10 cm diameter and 12.7 cm high, molded at the optimum compaction parameters of soil and mixtures. The tested specimens were rested during 7 days and 28 days. In accordance to DNER-ME 129 (1994), acceptance criteria of specimens were $\pm$ 0.30 kN/m^3 for maximum dry unit weight, and $\pm$ 0.5% for optimum water content. Average of the failure stresses of three specimens were adopted as UCS values, and the acceptance criteria of UCS average value was $\pm$ 10% for each specimen. Initial tangent modulus was obtained from UCS tests stress-strain curves at strain levels up to 0.1%. Duncan & Chang (1970) hyperbolic models were fitted in order to eliminate inaccuracies and subjectivity of tests at these strain levels. Mechanical strength and swelling parameters from CBR tests were performed as recommended in DNIT-ME 049/94.

Resilient modulus (RM) tests were performed using cyclic triaxial tests following the procedure DNIT-ME 134/10, and were carried out in specimens of the lateritic soil treated with 2% of lime and cement that were cured during 7 days and 28 days. Bilinear models were fitted in the values obtained from triaxial tests, which were used in the mechanistic analyses.

2.2.4. X-ray diffractometry investigation (XRD)

Mineralogical characterizations of soils and mixtures were carried out using XRD analyses. Mixtures samples used in this analysis were extracted from post-failure of UCS specimens after 7 days and 28 days of curing times, and prepared by breaking, sieving through the 2 mm sieve, and oven-drying at 105 °C. Clay-silt (diameter $\leq$ 0.05 mm) and sand (0.05 < diameter $\leq$ 2 mm) fractions were separated by sedimentation with sodium hexametaphosphate dispersant. The XRD analyses were conducted using an X-ray diffractometer from the Department of Soils at the Federal University of Vicosa. All samples were irradiated using Cobalt laminas (Co-kα) and scanning intervals ranging from 4° to 50° 2θ. The sand fraction samples were installed in excavated glass lamina without mineral orientation, and the clay-silt fraction samples were installed in flat glass lamina with mineral orientation (Gibbs, 1965).

2.2.5. Research data application in flexible pavement design

In the mechanistic analyses, it was used the finite-difference computational program ELSYM5 applied to two typical pavement configurations using modified soil mixtures as base and subbase layers. The main objective of these analyses was to evaluate fatigue failure conditions and elastic strains generated in asphalt layers. The two design configurations were here named as Design 1 and 2 (Fig. 3). Design 1 was composed of the following layers and thicknesses: asphalt (12.5 cm), granular base (15 cm), modified soil subbase (10 cm, 30 cm, 40 cm and 50 cm), and subgrade of untreated soil. Design 2 was a pavement structure with the layers: asphalt (12.5 cm), modified soil base (10 cm, 30 cm, 40 cm and 50 cm) and untreated local subgrade.

In this study, it was adopted the 82 kN axle dual wheel and the load repetition number of 5 x 10^7 (for heavy traffic, the Brazilian standard requires at least a 12.5 cm thick hot mix asphalt concrete layer). The input elastic properties were obtained through iterative analyses by the relationship between the stress differences resulting from the mechanistic analyses and the RM calculated by the bilinear model. Therefore, the convergence between the inputs RM values (ELSYM5) and RM from bilinear models was considered in each configuration. RM parameters from bilinear fit are showed in Table 4.

Soares *et al.* (2000) refers to asphalt layer fatigue failure (hot mix asphalt concrete) of 0.55 MPa of allowable stress determined in the cyclic diametric compression test. Stress differences σ_{zz}, σ_{xx} and σ_{yy} are indirectly related to tension stresses and elastic deformations of asphalt layers near fatigue failure. In this study, these stresses differences ($\sigma_d = \sigma_{zz} - \sigma_{xx} - \sigma_{yy}$) were determined using the finite-difference computational program ELSYM5; however, fatigue failures of the modified soil layers were not evaluated in this work. Although, the fatigue failure of these layers may occur, it is expected that the modified soil layers do not show the high stiffness of the stabilized soil layers. Therefore, cracks may not occur. Further tests must be performed

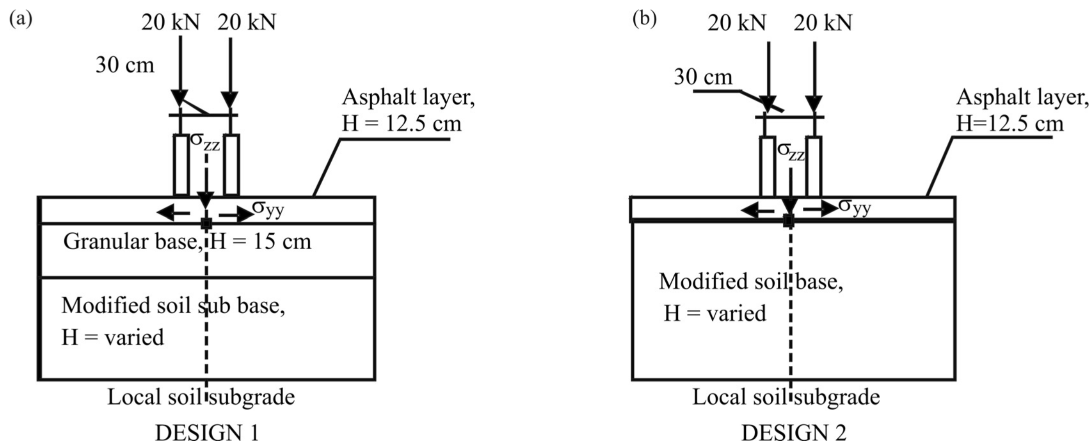

Figure 3 - Pavements mechanistic analyses: (a) Design 1 and (b) Design 2.

Table 4 - RM parameters from bilinear model.

Mixtures	RM parameters – bilinear model			
	K1	K2	K3	K4
Soil	130	73000	958	-79
Soil + 2% HL - 7 days	115	225000	5057	-579
Soil + 2% HL - 28 days	140	1175000	16111	-1591
Soil + 2% PC - 7 days	120	255000	10292	-1178
Soil + 2% PC - 28 days	140	720000	10389	-343

in order to assess the fatigue behavior of the modified soil layers.

3. Results and Discussion

3.1. Workability

3.1.1. Particles size distribution

Figure 4 shows particle size distribution curves of soil and mixtures. Results present reductions on the clay fraction (Fig. 4 and Table 3) and increases on the silt and fine sand fractions (Fig. 4), probably resulting from flocculation reactions. The alteration of particle size distribution curves occurs for all stabilizers. In general, the soil-lime mixtures showed higher reductions in the clay fraction than soil-cement mixtures, mainly with 3% of lime. Another interesting aspect is that addition of 1% of lime was as efficient as 3% of cement in the clay fraction reduction. Probably, calcium exchangeable concentration from hydrated lime favored the flocculation reaction. Additionally, the clay fractions reduced from 60% to 38% after addition of 3% lime even using dispersant in the sedimentation analysis.

3.1.2. Atterberg limits

Figure 5 illustrates alterations on liquid (w_L) and plastic (w_p) limits promoted by addition of 0.5%, 1%, 2%, 4%,

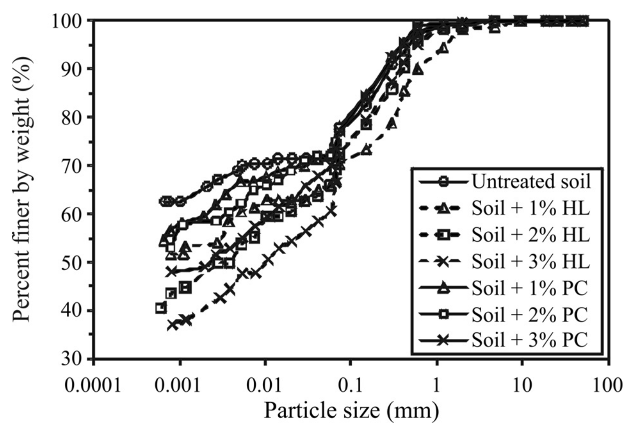

Figure 4 - Particle size distribution of lime (HL) and cement (PC) mixtures.

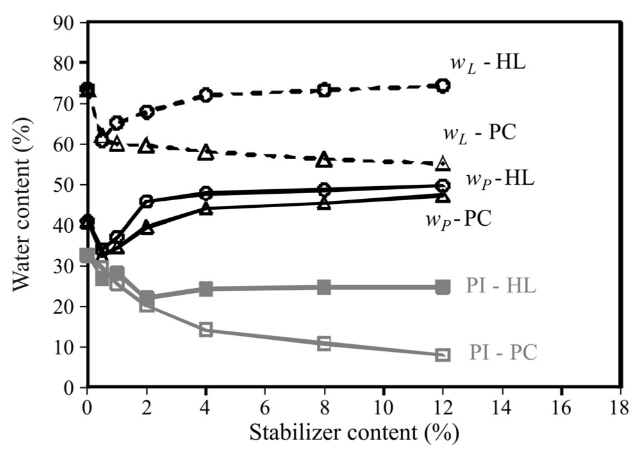

Figure 5 - Atterberg Limits *vs.* stabilizers contents.

8% and 12% of cement and lime. In general, content of 0.5% of both modifiers caused sudden decreases of w_p and w_L of soil. Thereafter, the w_L suffered increases after lime modification, whereas the cement promoted decreases. Probably, hydration reactions of cement can favor for this behavior. On the other hand, w_p of soil increased after modification with lime and cement. In this set of results, curves in Fig. 5 showed that the modification of soil workability occurred with both modifier agents, and alterations promoted by lime were similar to cement when low contents were applied (up to 2%). In addition, the highest rates of decrease on PI occurred up to 2% of lime and cement, and soil stabilization with cement (from 4% to 12%) could provide higher alterations on PI due to hydration reaction effects. Chemical properties of mixtures supported the results from Atterberg limits, in which the CEC of mixtures with stabilizers contents from 1% to 3% did not change considerably (Fig. 6), and, simultaneously, PI of the lime mixture did not suffer significant alteration.

3.1.3. Chemical properties

The relationship between soil physic alterations and chemical parameters has been largely discussed in the technical literature (Bell & Coulthard, 1990; Rogers & Glendinning, 2000). Specially, pH alterations of soils can establish mineralogical formations due to dissolution of soil mineral components, while the cationic exchangeable capacity (CEC) can explain cationic change reactions occurrence and, consequently, soil flocculation. Figure 5 presents pH and CEC values of soil modified with lime and cement. The effects of pH in a clayey silt sand soil stabilized with lime are explicitly presented by Rogers & Glendinning (2000), which reported that the minimum lime content to characterize the soil stabilization was 3%. After this lime content, called lime fixation point (LFP), further addition of lime did not produce significant change in the plastic limit, as reported previously by Hilt & Davidson (1960). In Fig. 6, CEC values of soil-lime mixtures were higher than soil-cement, which supports the highest particle size distribution changes showed by 3% lime mixtures. The pH of soil solution increased considerably after lime and cement modification (from 5.5 to 13), which can favor the minerals dissolution and, possibly, a formation of a new mineral gel.

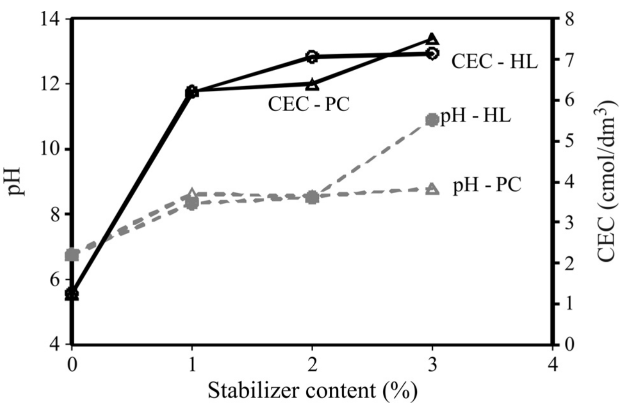

Figure 6 - pH and CEC values of soil modified with 1, 2 and 3% of lime and cement.

3.1.4. Classification for roadway application

In order to quantify the modifications of soil caused by addition of lime and cement ranging from 0.5% to 12% in the roadways context, the mixtures were classified according to the USC (Fig. 7) and TRB (Fig. 7 and Table 3) systems. In the Unified system, plasticity modification did not promote changes in the classification groups of Casagrande plasticity chart, maintaining the material on the MH and OH group. Although cement did not change the classification group of the USC system, the cement modification caused dispersion of points inside the plot, and large contents of cement (4%, 8% and 12%) changed the mixture classification to the group OH. On the other hand, lime mixtures kept the classification in the group MH.

Figure 7b illustrates the TRB classification of soil after modification with lime and cement, while Table 3 presents the TRB classification considering the group index of mixtures. Lime and cement modification did not change the classification group. On the other hand, contents of 4%, 8% and 12% of cement provided w_p increases and w_L decreases, fitting these mixtures next to the A-5 group. The TRB classification considering group index reveals that the soil changes from A-7-5 to A-4 with addiction of 4% of cement. Addition of lime showed to be less effective, since classified the soil as A-6.

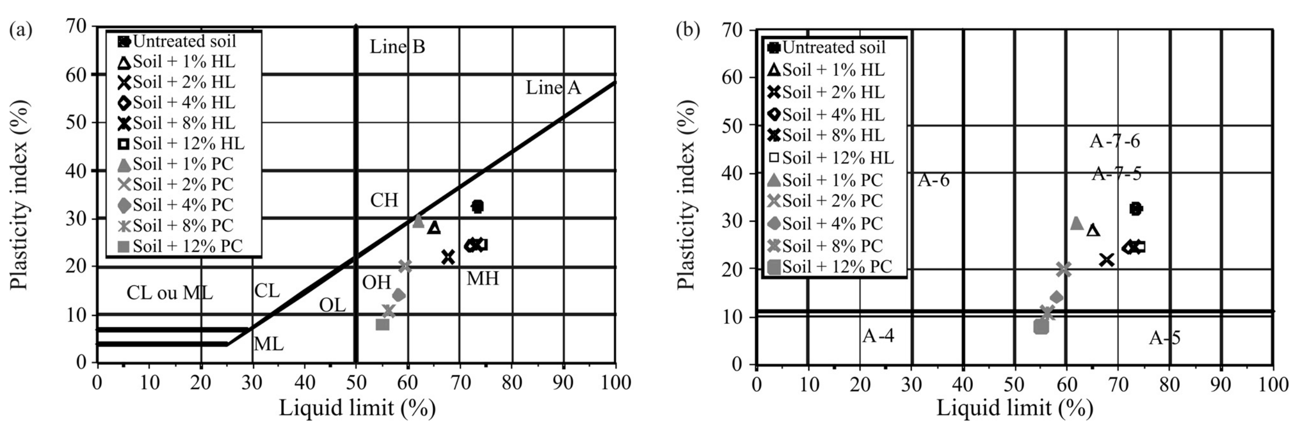

Figure 7 - Geotechnical classifications of modified soils: (a) USC, and (b) TRB systems.

3.1.5. Compaction parameters

Figure 8 presents the compaction curves of soil and its mixtures with 1%, 2% and 3% of lime and cement. Soil-cement mixtures showed higher values of maximum dry unit weight than the untreated soil, while soil-lime presented lower values when compared to untreated soil. The addiction of lime caused increase of optimum water contents, while the addiction of cement, in general, promoted decrease. In addition, gradual increases on both stabilizers percentage caused decreases of maximum dry unit weight in accordance with Osula (1996) and Osinubi & Nwaiwu (2006).

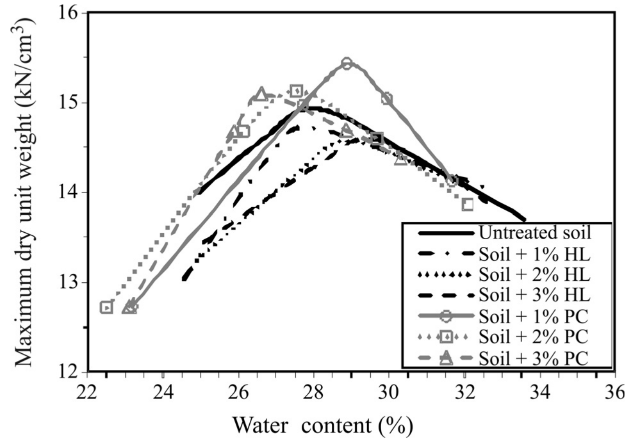

Figure 8 - Compaction curves of soil and mixtures.

3.2. Mechanical behavior

3.2.1. Unconfined compressive strength

Figure 9 shows results of unconfined compression tests at failure (Fig. 9a) and initial tangent modulus (Fig. 9b) for lime and cement soil modification, after 7 days and 28 days of curing times. Cement modification promoted higher increases in unconfined compressive strength (UCS) when compared with lime modification, for both curing times. Also, for both stabilizers, strength values after 28 days of cure were higher than for 7 days. In Fig. 9b, the variation of initial tangent modulus with addiction of 1%, 2% and 3% of modified agents showed similar trends to those reported for maximum UCS (Fig. 9a).

Figures 10 and 11 illustrate the increase rates in mechanical strength and initial tangent modulus at 0.1%, respectively, caused by modification with 1%, 2% and 3% of lime and cement after 7 days (a) and 28 days (b) of curing. Increases rates were determined in relation to the untreated soil strength. Strength increases promoted by the addition

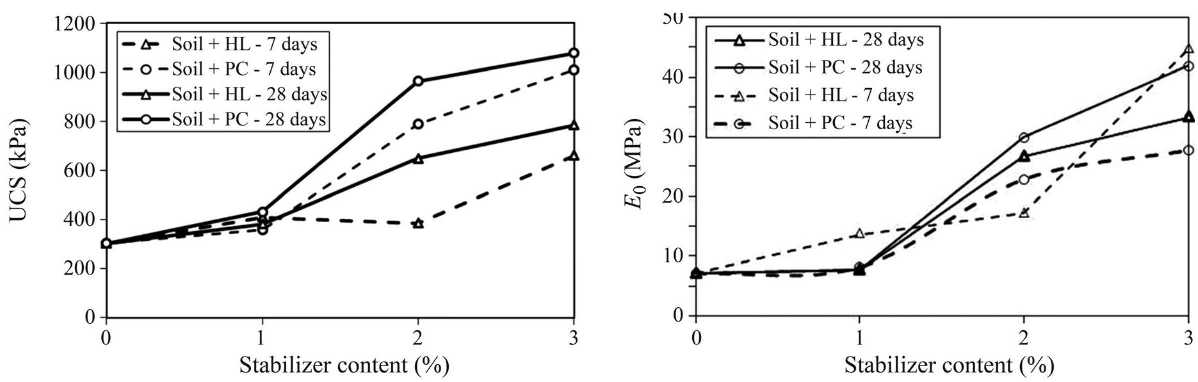

Figure 9 - UCS (a) and initial tangent modulus (b) of lime and cement mixtures, after 7 and 28 days of curing.

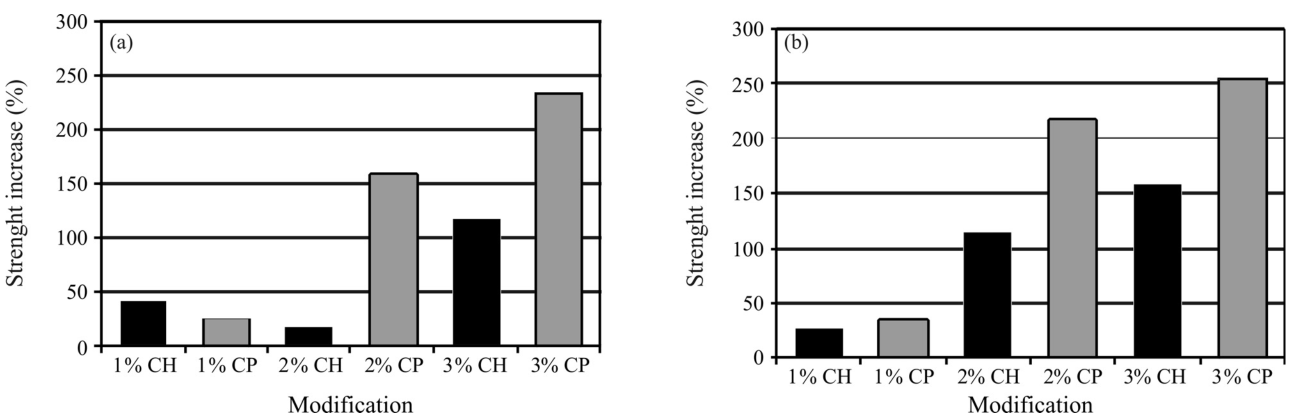

Figure 10 - Strength increase of mixtures specimens after 7 (a) and 28 (b) days of curing.

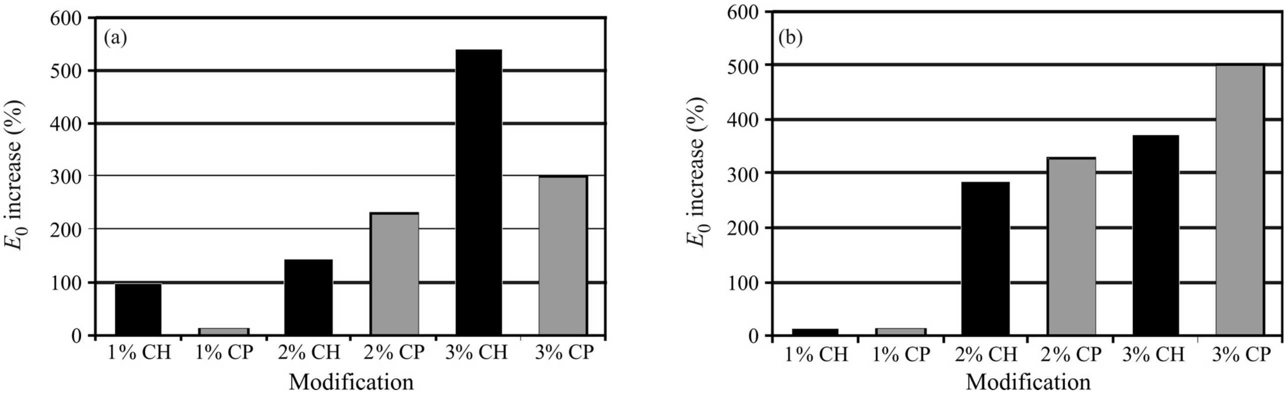

Figure 11 - Initial tangent modulus increases of mixtures specimens after 7 (a) and 28 (b) days of curing.

of 1%, 2% and 3% of lime, in specimens cured after 7 days, were 42%, 17% and 118%, respectively. On the other hand, addiction of 1%, 2% and 3% of cement provided increments of 26%, 166% and 233%, respectively (Fig.10a). For specimens cured during 28 days, the addiction of 1%, 2% and 3% of lime reveals increases of 26%, 114% and 159% in strength, while cement promoted increment of 35%, 218% and 255%, respectively (Fig. 10b). Therefore, the use of low contents of cement showed to be more effective than lime to improve the lateritic soil strength. In Fig. 11 increments of initial tangent modulus of soil-cement and soil-lime mixes are compared. Results show that the stiffness increments were higher than strength increments, presenting values around 500%.

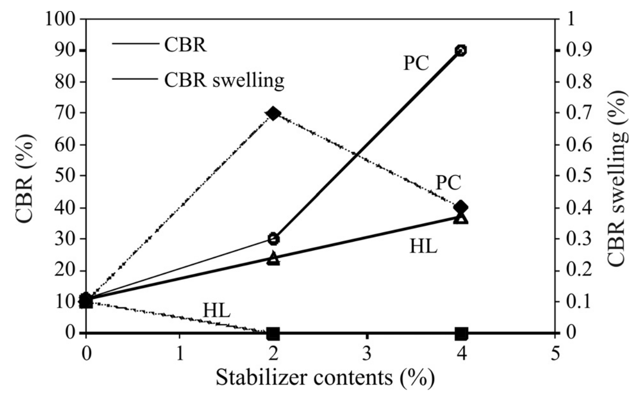

Figure 12 - CBR results of modified soils.

3.2.2. CBR and swelling

CBR results and swelling parameters of mixtures with 2% and 4% of stabilizers are presented in Fig. 12. Results show that the cement modification is more efficient than the lime modification on the CBR responses, highlighting the highest increase of CBR in the mixture of lateritic soil with 4% of cement. Swellings of mixtures were very low in lime mixtures when compared to cement mixtures. Actually, lime modification eliminated the soil swelling. On the other hand, cement modification with 2% caused increases on the CBR swelling, and a sudden decrease after 4% of treatment.

3.3. XRD analysis

Figures 13 and 14 presents XRD analysis data of mixtures of clay-silt fractions (a) and sand fractions (b) at contents of 1%, 2% and 3% of lime and cement, respectively, after 7 days curing, while Figs. 15 and 16 show results of

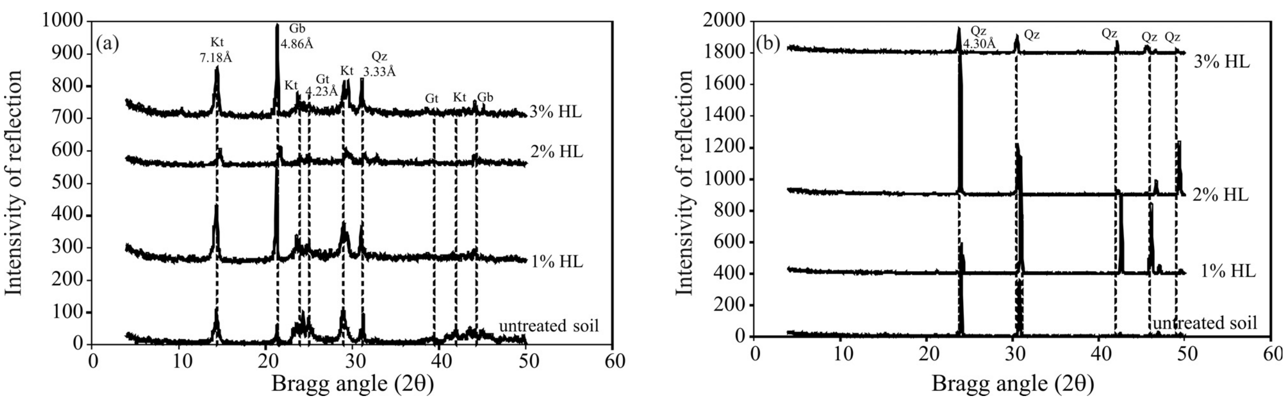

Figure 13 - XRD data of silt-clay (a) and sand fraction (b) of the latosol and its mixtures with lime contents of 1%, 2% and 3% after 7 days of curing time.

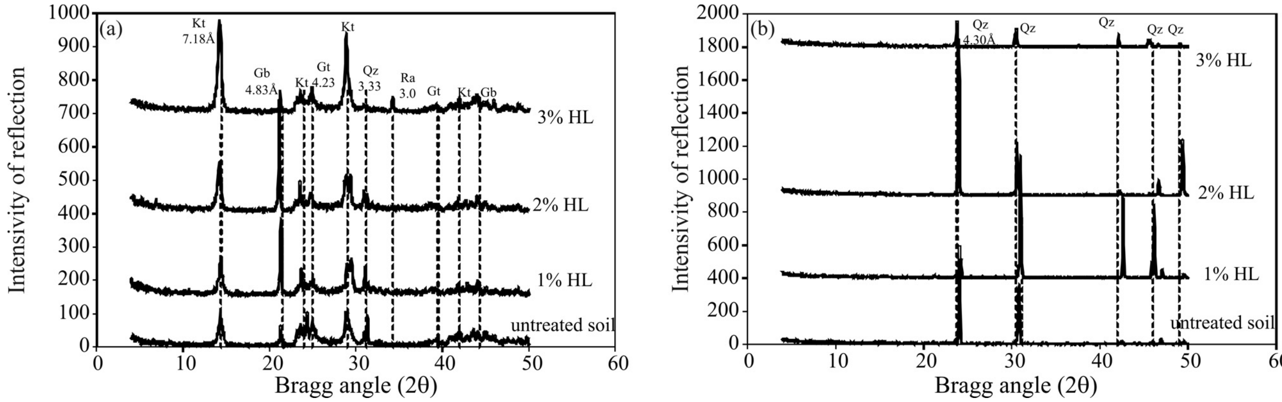

Figure 14 - XRD data of silt-clay (a) and sand fraction (b) of the latosol and its mixtures with cement contents of 1%, 2% and 3% after 7 days of curing time.

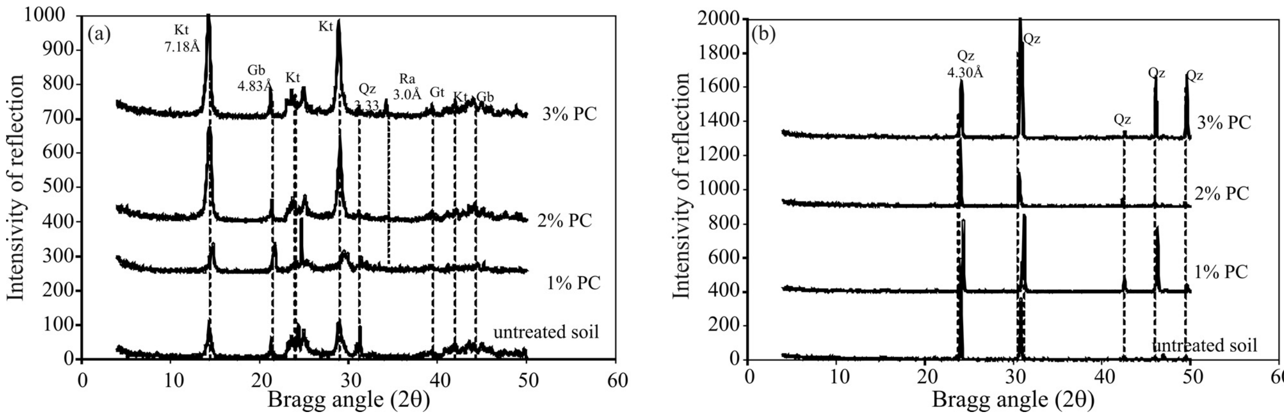

Figure 15 - XRD data of silt-clay (a) and sand fraction (b) of the latosol and its mixtures with lime contents of 1%, 2% and 3% after 28 days of curing time.

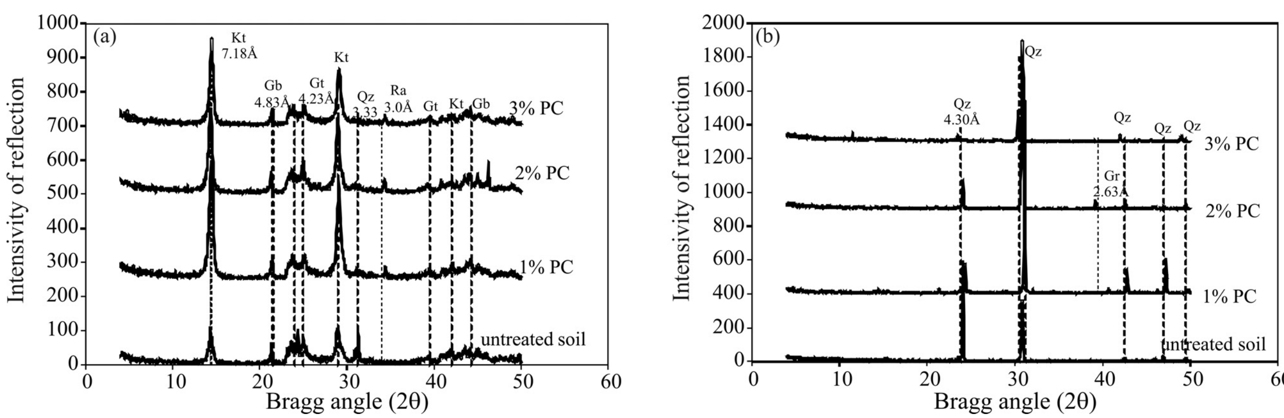

Figure 16 - XRD data of silt-clay (a) and sand fraction (b) of the latosol and its mixtures with cement contents of 1%, 2% and 3% after 28 days of curing time.

clay-silt fractions and sand fractions of mixtures after 28 days of curing time. Results show that the utilization of low contents of lime in samples after 7 days of curing did not cause significant mineralogical alterations in the clay-silt and sand fractions. On the other hand, addiction of 3% of cement favored formation of Calcium silicate, identified as Rankinite, still after 7 days of curing (Fig. 14). For samples cured during 28 days, in the clay-silt fractions Calcium silicate appeared in mixtures of 3% of lime and 1%, 2% and 3% of cement. In the sand fractions, the formation of Calcium silicate aluminate was noted just in samples with 2% of cement. This mineral was identified as Grossular (Fig. 16).

3.4. Mechanistic analysis of flexible pavement layers with modified soil

Results from mechanistic analyses for the Designs 1 and 2 are showed in Figs. 17, 18 and 19. Figure 17 presents the resilient modulus (RM) values obtained from the iterative process for the Designs 1 and 2. It can be noticed that soil modification applied in subbase of pavements (Fig. 3a) showed higher RM values than for base application as presented in Design 2 (Fig. 3b). Even though the cement modi-

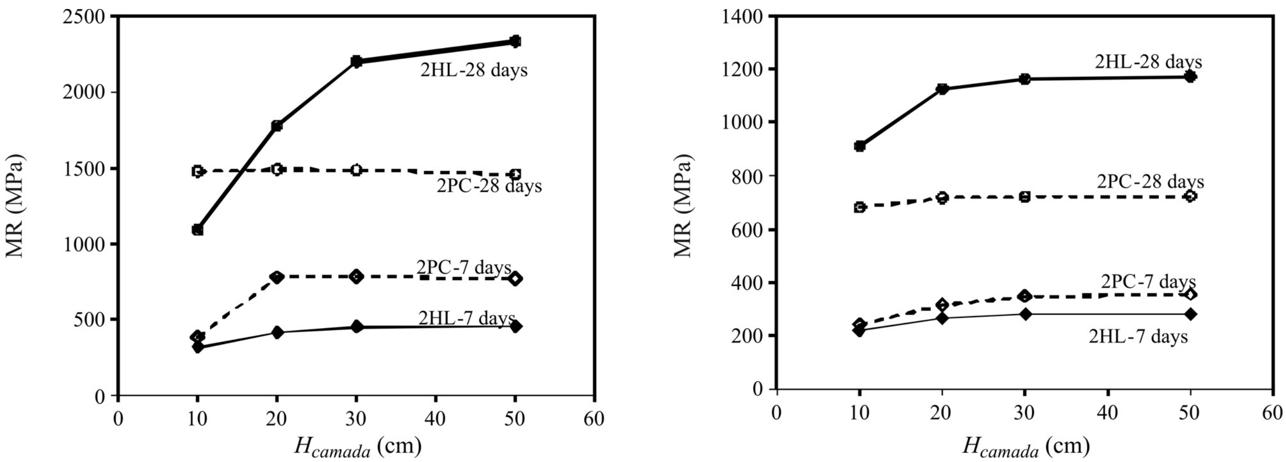

Figure 17 - RM values of mixtures of 2% of stabilizers and soil in the Design 1 (a) and Design 2 (b).

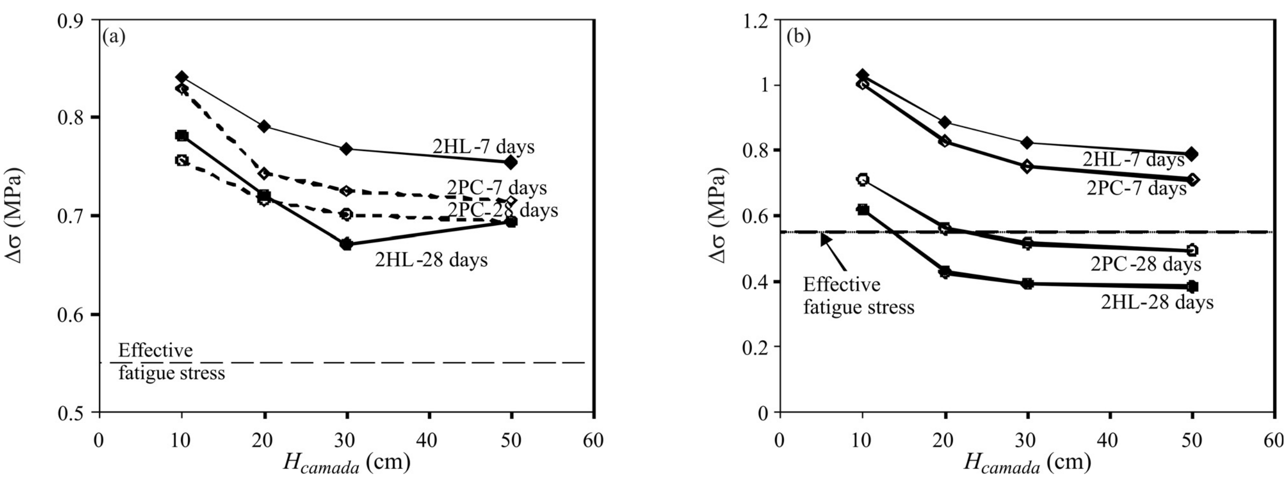

Figure 18 - Stress (Δσ) and strain *vs.* base thickness of the Design 1.

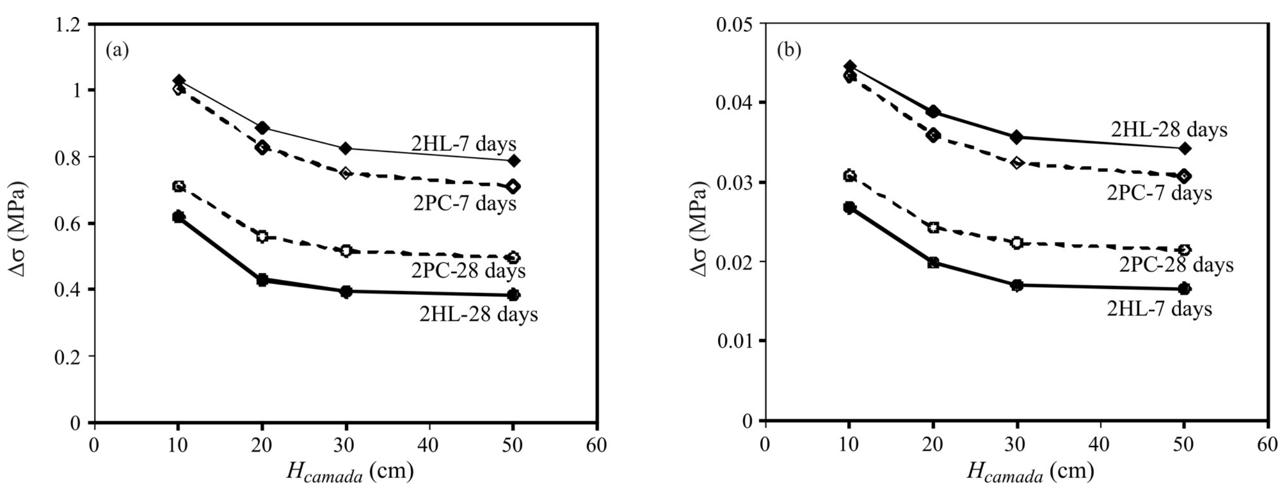

Figure 19 - Stress (Δσ) and strain *vs.* base thickness of the Design 2.

fication has showed higher UCS values than lime modification, the RM values from lime modification were higher than those from cement modification after 28 days of curing. However, cement modification showed better response after 7 days of curing.

Input elastic properties are presented in Table 5.

Generally, the RM values of the modified soil with lime and cement after 28 days of curing were similar to the values of RM of sand soils with high bearing capacity. Nevertheless, the soil modification should be a good solution in situation where sand soils are not available.

Figure 18 shows the performance of Design 1 in the mechanistic analyses. The uses of higher layers favored to the decrease of the stress levels in the asphalt layer. However, regarding that the allowable stress level in asphalt layers with 12.5 cm is around 0.55 MPa, the configuration adopted in the Design 1 probably will results in cracking on the asphalt layer, even using higher subbase layers. Problems in this Design are higher resilient modulus in the subbase layer than in the base layer, favoring the cracking development.

In Fig. 19, it can be noticed that cracks can appear only when RM values with 7 days of curing time are considered in the designs. After 28 days of curing, cement and lime modification showed an excellent performance when considering modified base layers constructed with heights from 20 cm to 50 cm. Theoretically, fatigue failure will not occur and the stresses and strains levels were lower than that in Design 1. Hence, the use of 2% and 3% of lime and cement modifications may be an economical alternative for flexible pavement layers.

Table 5 - Input elastic parameters of materials used in mechanistic analyses.

Layers		Design 1		Design 2	
		RM (MPa)	ν	RM (MPa)	ν
Asphalt layer	3000	0.3	3000	0.3	
Granular layer	300	0.35	300	0.35	
	10 cm	201	0.25	197	0.25
2% HL	20 cm	203		212	
(7 days)	30 cm	203	0.25	212	0.25
	50 cm	204		213	
	10 cm	1330	0.25	760	0.25
2% HL	20 cm	1190		1010	
(28 days)	30 cm	1170	0.25	1030	0.25
	50 cm	1155		1025	
	10 cm	215	0.25	200	0.25
2% PC	20 cm	218		230	
(7 days)	30 cm	217	0.25	229	0.25
	50 cm	219		228	
	10 cm	750	0.25	645	0.25
2% PC	20 cm	720		693	
(28 days)	30 cm	719	0.25	697	0.25
	50 cm	717		697	
Untreated soil	130	0.4	130	0.4	

4. Final Discussion

The use of low contents of lime and cement, here named soil modification technique, improved workability and mechanical behavior of the lateritic soil. Workability improvements were noted from analyses of plasticity properties and particle size distribution of mixtures. Lime and cement addition up to 2% of the stabilizers brought the highest alterations on plastic limit, and further additions did not change this parameter significantly. This behavior was confirmed by pH and CEC determinations. Additionally, cement was a more effective modifier of soil workability than lime after the lime fixation point. Explanations around this can come from hydration reactions of cement in short term. In contrast, the addition of lime provides higher alteration on grain size distribution than cement. In general, both stabilizers promoted improvement in soil handling with maximum alterations around 3% of lime and cement.

The cement provided significant improvement of strength and stiffness, and increased on compaction maximum dry unit weight. Nevertheless, the lime modification promoted increases in soil strength that can be useful in the applications suggested in this work. Still, the swelling elimination and initial tangent modulus increases can be a considerable advantage of this modifier. In general, both materials demonstrated to be efficient with addition of 3%.

Findings from XRD analyses support the mechanical improvement of mixtures using low contents of lime and cement. Identification of new minerals forms was observed at the same stabilizers contents, responding for significant strength increases. Therefore, pH alterations of mixtures were sufficient to promote the dissolution of some minerals of soil and cementation of new formed gels.

This study was directed to the Brazilian regions showing occurrence of Red-yellow latosol; however, it is expected that the findings can apply to soils with similar mineralogical characteristics, chemical and physics properties. Regarding the RM and Poisson coefficient values adopted in the mechanistic analyses, soil modification in bases of pavement were efficient against asphalt layer fatigue failure, and showed to be an economical solution for local soil application. Applications in subbase of flexible pavement (asphalt) layers were not efficient in the mechanistic analyses because the subbase presented higher RM than the granular base layer. However, if the elastic properties were inverted, the cracking problem could be avoided.

Even though the advantages of the lateritic soil modification, homogeneity of mixture in field applications can be an adverse aspect of the technique. Therefore, an intensive mixture process must be required in the field. Actually, the authors do not recommend the applications of contents of 1% of the modifiers. Probably, problems around homogeneity can be come up. However, the use of 2% and 3% and an intensive process of mixture can make the soil modification a good technique. The authors have not evaluated this aspect; however, they recommend implementation of an experimental field test before the final application.

5. Conclusions

Results support that modification of the tested soil with lime and cement is an efficient and economical technique for flexible pavement design and construction, and conclusions of the study are as follows:

- Low contents of lime and cement were efficient in workability changes of the Red-yellow latosol, highlighting highest alterations provided by addition of 3% of cement. Further additions of lime and cement do not change the soil PI.
- Chemical properties of mixtures were compatible with the plasticity behavior, showing that the lime fixation point is around 3% in this soil. Therefore, it can support the mineralogical alterations. Hydration reaction of cement favored to PI decreases;
- Lime modification eliminated the swelling of soil, while cement increased it with addition of 2% of cement;
- The soil modification promoted increase in strength and initial tangent modulus, mainly after 28 days of curing, where cement was more efficient material. The highest alterations in strength occurred at 2% and 3% of lime and cement, although addition of 1% was sufficient to provide 50% of the unconfined compressive strength increase compared to the untreated soil. Initial tangent modulus increases were significantly higher than the unconfined compressive strength increases generated by addition of low contents of stabilizers.
- It was noted that mineralogical alterations have occurred in samples that showed significant strength increases.
- Mechanistic analyses showed that the soil modification can be applied to the design of base of flexible pavements producing low elastic strain and stress levels. Additionally, the most efficient (economically and mechanically) configuration of pavements suggested in this study was the sub-grade improvement or modified soil base.

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List of Symbols

Fd: Feldspate
Gr: Grossular
Gb: Gibbsite
Gt: Goethite
Kt: Kaulinite
Mi: Mica
UCS: Unconfined Compression Strength
Qz: Quartz
Ra: Rankinite
HL: Hydrated Lime
PC: Portland Cement
LFP: Lime fixation point
CBR: California Bearing Ratio
CEC: Cation Exchangeable Capacity
pH: Potential Hydrogenionic
TRB: Transportation research board
USC: Unified Soil Classification
MCT: Miniatura, Compactado, Tropical
RM: Resilient modulus