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A study on the deformability behavior of clayey lateritic soils through statistical and correlational analysis

Luigi Tavares Gomes[1], Patricia Rodrigues Falcão[1], Paula Taiane Pascoal[1#], Leonardo Alberto do Nascimento[1], Magnos Baroni[1], Luciano Pivoto Specht[1]

Article

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Database

Abstract

This study investigated the mechanical behavior of tropical soils, specifically lateritic clays (LG') compacted under intermediate energy, with a focus on the analysis on resilient modulus (RM) and permanent deformation (PD). A database was compiled including 20 Brazilian soils, comprising physical properties (maximum dry density, optimum moisture content, particle size distribution, and MCT classification indices) and mechanical properties data from repeated load triaxial tests. RM and PD regression parameters were evaluated for different stress states, adhering to Brazilian regulations. RM results showed high variability (mean: 351 MPa; CV: 42%), demonstrating a strong influence of deviatoric stress, which significantly reduced the elastic response with increasing stress levels. PD followed a log-normal distribution (mean: 0.635%; CV: 141%), with greater deformation correlating to elevated stress states. Pearson's correlation revealed associations between RM and physical properties: positive with sand content and negative with clay content and optimum moisture content. Kruskal–Wallis tests confirmed RM's significant dependence on geotechnical variables, whereas PD showed no statistically significant with these factors. These findings underscore the importance of integrated physical–mechanical characterization for predicting the structural performance of LG' soils. Furthermore, they highlight PD's high variability and the necessity for global analyses to achieve more representative estimates in mechanistic–empirical pavement design.

1. Introduction

Due to its continental dimensions, Brazil exhibits a wide diversity of tropical soils, which predominate across much of its territory because of the prevailing climatic, geological, and pedological characteristics. Through intense decomposition and mineralogical transformation processes, these soils acquire distinctive mechanical and hydraulic properties (Carvalho et al., 2015). Given complexity and specific nature of tropical soils, the Miniature, Compacted, Tropical (MCT) is considered the most suitable classification method for assessing their particularities. (Nogami & Villibor, 1995; Sousa et al., 2021; Coutinho & Sousa, 2021). This methodology classifies soils as either lateritic or non-lateritic. Within this framework, and highly relevant to pavement engineering, soils belonging to the LG' group are particularly noteworthy. They are characterized by low permeability and expansion coefficients, high bearing capacity, medium to high plasticity, and low mass loss by immersion (Medrado, 2009; Villibor & Alves, 2019; DNIT, 2023).

Owing to their favorable geotechnical properties, LG' soils are ranked among the top three performing groups in the MCT classification and are extensively used in road paving, with proven practical effectiveness (Lima et al., 2018; Freitas et al., 2020; Santos, 2020; Sousa et al., 2021; Pascoal et al., 2023). Within pavement structures, compaction is a fundamental geotechnical step because it significantly alters soil's physical and mechanical behavior, resulting in greater structural stability, increased bearing capacity, reduced permeability, and enhanced shear strength. These benefits stem from the application of mechanical energy, which promotes the rearrangement and densification of solid particles, thereby reducing the void ratio (Crispim et al., 2011; Carvalho et al., 2015).

[#]Corresponding author. E-mail address: ptpascoal@hotmail.com; paulatpascoal@gmail.com
[1]Universidade Federal de Santa Maria, Departamento de Transportes, Santa Maria, RS, Brasil.
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In Brazil, intermediate compaction energy is widely adopted for the final layers of road subgrades. Characterizing the elastic and plastic behavior of these materials is crucial for implementing empirical-mechanistic pavement designs, such as the National Design Method (MeDiNa). For this purpose, repeated load triaxial tests are performed to determine both the resilient modulus (RM) and permanent deformation (PD), assessing the materials' elastic and plastic responses under varying load conditions (DNIT, 2018a; DNIT, 2018b).

For RM, the resilient parameters (k_1, k_2 and k_3) are determined post-test using the composite model proposed by Pezo et al. (1992), which relates RM to the confining stress (σ_3) and deviatoric stress (σ_d) using experimental data. Similarly, the Guimarães model (2009) is used for PD, yielding plastic parameters (ψ_1, ψ_2, ψ_3, and ψ_4) that relate PD to σ_3, σ_d, and the number of load applications (N).

While these RM and PD triaxial tests provide representative mechanical results, their high cost and requirement for specialized infrastructure limit their application in early project stages.

Consequently, predictive models utilizing statistical regression and multivariate analysis have emerged as viable alternatives. These models estimate mechanical behavior using easily obtainable variables, such as particle size distribution, compaction moisture content, California Bearing Ratio (CBR), plasticity index, and data from in situ non-destructive tests (e.g., DCP). (AASHTO, 2021; Sadrossadat et al., 2018; Ikechukwu et al., 2019; Hanandeh et al., 2020; Onyelowe et al., 2023; Indraratna et al., 2023; Shah et al., 2024; Khawaja et al., 2024; Fan et al., 2024).

Considering this, numerous Brazilian studies have investigated the relationship between MCT classification and the results of repeated load triaxial tests for tropical soils (Marangon, 2004; Guimarães, 2009; Norback, 2018; Dalla Roza et al., 2018; Dornelles et al., 2018; Gomes et al., 2018; Lima et al., 2018; Freitas et al., 2020; Santos, 2020; Pascoal et al., 2021; Sousa et al., 2021; Pascoal et al., 2023).

The present study contributes to this context by developing and analyzing a database of compacted tropical soils, classified by the MCT system and characterized by their deformability. More specifically, from a dataset of 94 soils characterized in accordance with current Brazilian standards for pavement applications, the subset of lateritic clay soils (LG') compacted under intermediate energy was selected. Statistical analyses were then carried out, focusing on the regression parameters of RM and PD to assess the influence of different stress-strain combinations on their respective elastic and plastic responses. In addition, the physical and mechanical parameters included in the database were correlated using Pearson's method to identify potential interrelationships within this soil group and to support the reliability of mechanistic analyses.

2. Materials and methods

The database used in this study was compiled from theses, dissertations, and peer-reviewed papers that reported mechanical testing of Brazilian tropical soils in accordance with the DNIT standards for resilient modulus (DNIT 134/2018a) and permanent deformation (DNIT 179/2018b). Only studies explicitly describing compaction under intermediate energy and providing sufficient experimental information for regression analysis were included. The selection focused on lateritic clay soils (LG′), as defined by the Miniature, Compacted, Tropical (MCT) classification system (DNIT 259/2023).

To ensure methodological consistency across the different sources, all datasets were reviewed and harmonized before integration. The following criteria were adopted: only results obtained from repeated load triaxial tests with controlled confining (σ_3) and deviatoric (σ_d) stresses were considered; all physical properties — including maximum dry density (MDD), optimum moisture content (OMC), particle size fractions, Atterberg limits, and MCT parameters (c', d', e') — were converted to standardized units (kN/m^3, %). When multiple replicates were available, mean values were used to represent each soil. Missing mechanical parameters were excluded from the correlation analyses but retained in descriptive statistics to preserve representativeness.

Only datasets reporting compaction near the optimum moisture (± 1.0%) and maximum dry density obtained from the intermediate Proctor test were accepted. Each sample was compacted and cured according to DNIT recommendations, typically at ambient temperature for 24 h prior to testing. Differences between laboratories regarding test temperature, equipment type, or sample preparation were qualitatively documented but not used as exclusion criteria, given their minor influence compared to applied stress conditions.

Mechanical behavior was described using the regression parameters for resilient modulus (RM) — k_1, k_2, k_3 — based on the composite model proposed by Pezo et al. (1992), and for permanent deformation (PD) — ψ_1, ψ_2, ψ_3, ψ_4 — following Guimarães (2009). Both models relate RM and PD to confining and deviatoric stresses, and the corresponding equations are presented below (Equations 1 and 2).

$$RM = k_1 \sigma_3^{k_2} \sigma_d^{k_3} \tag{1}$$

$$PD = \psi_1 \left(\frac{\sigma_3}{\rho_0}\right)^{\psi_2} \left(\frac{\sigma_d}{\rho_0}\right)^{\psi_3} N^{\psi_4} \tag{2}$$

RM: resilient modulus; σ_3: confining stress; σ_d: deviator stress; *PD*: specific permanent deformation; ρ_0: reference stress (atmospheric stress); N: number of load cycles; k_n: resilient modulus parameters; ψ_n: permanent deformation parameters.

With the *RM* and *PD* regression parameters compiled, the values of resilience modulus and specific permanent deformation were obtained for the stress trajectories recommended by DNIT (2018a, b), as shown in Table 1.

Subsequently, frequency histograms were generated for each dataset, and distribution analyses were performed considering different stress pair configurations. This allowed the determination of the minimum, maximum, mean, and standard deviation values for the *RM* and *PD* of the 20 LG' soils compacted with intermediate energy.

Furthermore, the database was processed for the application of Pearson's method to analyze the correlation relationships among the various variables. Based on this analysis, a correlation matrix was constructed. This matrix provides deeper insight into the interactions and mutual influences between the physical and mechanical properties of the tropical soils studied.

3. Results and analysis

3.1 LG' soil database

The database consists of 20 LG' soils collected from eight distinct locations across Brazil, as shown in Figure 1. This figure illustrates the spatial distribution of the samples superimposed on the map of fine, sandy, and clayey soils lateritic soils in Brazil, as proposed by Villibor & Nogami (2009). This spatial contextualization highlights the representativeness of the samples analyzed relative to the typical geological settings where lateritic soils are commonly found in the country.

Table 2 presents the database, which includes key physical and mechanical properties relevant to pavement geotechnical studies, and the deformability behavior of the materials. The table contains conventional classification data alongside the MCT classification parameters (*c'*, *d'*, *e'*). Furthermore, mechanical parameters derived from the regression analyses for the resilient modulus and permanent deformation for each material are also provided.

Table 2 presents, among other data, the coefficients of determination (R^2) obtained from the regression analyses for the RM and PD. For the RM, the R^2 values ranged from 0.44 to 0.95. For the PD, the range was from 0.860 to 0.990. The dispersion in the RM R^2 values indicates that, for some soils, the composite model by Pezo et al. (1992) provided a limited fit to the observed variability in elastic behavior. Particularly, cases with low R^2, such as soil LG' 14 (R^2 = 0.44), suggest that the predictive capacity of the model may

Table 1. Stress sequence for determining RM and PD for subgrade soils (DNIT, 2018a, b).

Property	Tension pairs (MPa)	1	2	3	4	5	6	7	8	9	10	11	12
Resilient Modulus	σ_3	0.020	0.020	0.020	0.035	0.035	0.035	0.050	0.050	0.050	0.070	0.070	0.070
	σ_d	0.020	0.040	0.060	0.035	0.070	0.011	0.500	0.100	0.150	0.070	0.140	0.210
Permanent Deformation	σ_3	0.040	0.040	0.040	0.080	0.080	0.080	0.120	0.120	0.120	-	-	-
	σ_d	0.040	0.080	0.120	0.080	0.160	0.240	0.120	0.240	0.360	-	-	-
Stress ratio (σ_1/σ_3)		2	3	4	2	3	4	2	3	4	2	3	4

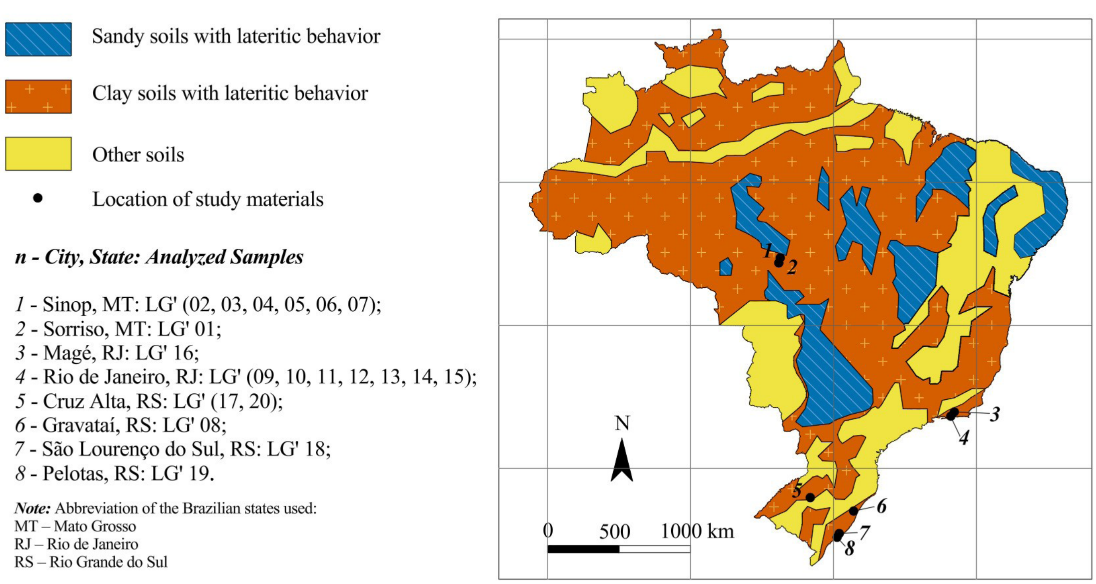


Figure 1. Source locations of the LG' soils investigated in this study.

Table 2. Database of LG’ soil parameters.

Material		LG’ 1	LG’ 2	LG’ 3	LG’ 4	LG’ 5	LG’ 6	LG’ 7	LG’ 8	LG’ 9	LG’ 10
Maximum dry density - *MDD* (kN/m³)		16.58	15.99	16.25	15.65	15.34	14.34	15.43	16.77	17.75	16.52
Optimum moisture content - *OMC* (%)		19.9	20.6	20.5	22.5	22.5	28.7	23.5	21.4	17.8	21.5
Particle size distribution (%)	Silt-S	66	50	41	29	67	24	35	30	36	35
	Clay-C	18	19	12	7	16	24	20	17	4	12
	Sand-SC	15	31	47	63	16	51	45	53	60	53
Atterberg	w_L	-	-	-	-	-	-	-	30	-	-
	w_P	-	-	-	-	-	-	-	50	-	-
	PI	-	-	-	-	-	-	-	20	-	26
Classification	AASHTO	-	-	-	-	-	-	-	A-7-5	-	A-7-5
	USCS	-	-	-	-	-	-	-	MH	-	-
MCT index	*c’*	2.24	2.18	2.24	2.2	2.66	2.66	2.31	2.4	2.94	2.84
	d’	60	85.7	102.5	68.8	291.7	142.9	75	40	89.3	49.6
	e’	1.2	1.1	1.1	1.2	1.0	1.0	1.1	1.1	0.6	0.7
RM - Regression parameters	k_1	315.45	207.60	309.97	147.52	370.71	123.74	283.04	268.53	424.17	363.01
	k_2	0.32	0.15	0.34	0.19	0.30	0.36	0.28	0.13	0.23	0.38
	k_3	-0.43	-0.40	-0.46	-0.56	-0.46	-0.66	-0.49	-0.23	-0.39	-0.44
	R^2	0.50	0.47	0.68	0.63	0.56	0.63	0.63	0.45	0.95	0.60
PD -Regression parameters	ψ_1	0.140	0.180	0.180	0.110	0.080	0.210	0.180	0.019	0.093	0.143
	ψ_2	0.540	-0.570	-0.600	0.050	-0.220	0.450	0.000	0.957	0.314	-0.221
	ψ_3	0.940	2.130	1.720	1.760	1.900	1.930	1.400	1.882	0.936	0.998
	ψ_4	0.050	0.020	0.040	0.050	0.040	0.040	0.050	0.116	0.045	0.066
	R^2	0.930	0.920	0.980	0.970	0.950	0.990	0.960	0.920	0.940	0.890
Author		Dalla Roza et al. (2018)							Schreinert (2021)	Lima (2020)	

Material		LG’ 11	LG’ 12	LG’ 13	LG’ 14	LG’ 15	LG’ 16	LG’ 17	LG’ 18	LG’ 19	LG’ 20
Maximum dry density - *MDD* (kN/m³)		17.05	16.65	16.51	18.16	17.59	16.75	16.25	16.85	17.6	15.9
Optimum moisture content - *OMC* (%)		21.3	22.5	20.5	11	17.8	20.5	25.6	20.1	18	26
Particle size distribution (%)	Silt-S	36	27	34	21	-	34	33	37	39	30
	Clay-C	16	17	23	19	-	17	26	19	12	24
	Sand-SC	46	56	43	37	-	48	41	36	43	46
Atterberg	w_L	40	19	20	20	22	24	44	20	32	41
	w_P	69	42	58	36	68	64	55	46	44	61
	PI	29	23	38	16	46	40	11	26	12	20
Classification	AASHTO	A-7-5	A-7-6	A-7-6	A-7-6	-	A-6	A-7-6	A-7-6	A-7-5	A-7-5
	USCS	MH	CL	CH	CL	-	ML	MH	CL	ML	MH
MCT index	*c’*	2.2	2.19	2.35	2.05	-	-	2.35	2.45	1.72	1.96
	d’	37.2	54	38.5	51.2	-	-	67	43.8	56.3	37.7
	e’	1.0	0.9	1.1	1.0	-	-	0.7	0.8	0.7	0.8
RM - Regression parameters	k_1	153.4	118.4	122.1	109.6	531.5	109.4	739.2	826.7	1892.5	355.8
	k_2	0.32	0.26	0.14	0.56	0.61	0.17	0.34	0.53	0.57	0.16
	k_3	-0.73	-0.63	-0.55	-0.73	-0.73	-0.68	0	-0.11	0.03	-0.16
	R^2	0.86	0.94	0.82	0.44	-	0.9	0.9	0.88	0.87	0.71
PD -Regression parameters	ψ_1	0.146	0.583	0.162	0.136	0.094	0.359	0.083	0.179	0.109	0.083
	ψ_2	-0.585	1.022	0.321	-0.151	0.380	-0.090	0.699	1.074	0.726	0.529
	ψ_3	1.776	0.628	1.318	1.078	0.946	1.215	0.517	0.739	0.615	1.244
	ψ_4	0.046	0.048	0.048	0.042	0.042	0.058	0.103	0.076	0.089	0.090
	R^2	0.930	0.960	0.980	0.970	-	0.960	0.930	0.860	0.960	0.970
Author		Lima (2020)				Lima et al. (2018)	Norback (2018)	Pascoal (2020)	Pascoal (2024)		Santos (2020)

be insufficient for certain LG' samples. This insufficiency may be related to the material's intrinsic variability or to factors not captured by the model's stress variables.

3.2 Resilient modulus

Using the resilient regression parameters, RM values were calculated for the 12 stress pairs recommended by DNIT (2018a). Table 3 displays the resulting 240 RM values for the 20 LG' soils.

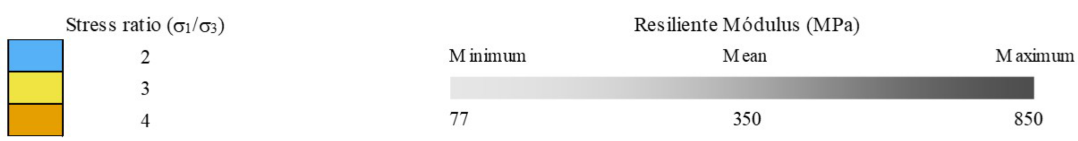
The frequency histogram of these values is presented in Figure 2 along with a normality assessment using a QQ-plot with 99% confidence intervals. Although the histogram visually suggests a normal distribution, the QQ-plot reveals points outside the expected range, indicating that the raw database values are not normally distributed. This is further confirmed by the Shapiro-Wilk normality test (Shapiro & Wilk, 1965), which yielded a p-value of 1.69×10^{-7}, confirming the non-normality of the dataset.

Analysis of these values reveals a dispersion range of 773 MPa between the minimum and maximum RM values. The RM mean is 351 MPa, with a standard deviation of approximately 145 MPa, yielding a coefficient of variation of 42%. This overall assessment, which considers all materials and stress levels, demonstrates that the stress state significantly influences RM results. Furthermore, high variability persists even when comparing materials subjected to identical stress conditions, suggesting that soils of the same classification and compaction energy may exhibit considerable dispersion in these parameters.

The elastic response of the evaluated soil group is strongly influenced by deviatoric stress. For a given confining stress, an increase in the deviatoric stress (and thus the stress ratio) leads to a substantial reduction in RM values. This reduction

Table 3. Resilient modulus values in MPa for different stress pairs.

Pairs	Tension pairs (MPa)		Resilient Modulus (MPa) - Soil Classification: LG'																			
	σ_3	σ_d	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.020	0.020	485	552	496	627	693	400	644	407	793	454	754	504	607	213	850	804	192	161	182	344
2	0.020	0.040	360	418	360	425	504	253	458	346	605	335	454	325	415	128	512	502	193	149	185	309
3	0.020	0.060	302	356	299	339	418	194	376	315	517	280	338	252	332	96	381	381	193	143	188	290
4	0.035	0.035	456	480	463	510	634	338	572	383	725	439	600	409	482	194	795	605	233	204	254	345
5	0.035	0.070	339	364	337	346	461	214	407	326	553	324	362	265	330	117	479	377	234	189	259	310
6	0.035	0.105	284	309	280	276	382	164	334	297	473	272	269	205	264	87	356	286	234	180	262	291
7	0.050	0.050	439	439	444	447	599	304	531	369	685	431	519	359	417	182	761	504	264	236	315	346
8	0.050	0.100	326	333	323	303	435	192	378	314	523	318	313	232	285	110	459	315	264	219	321	311
9	0.050	0.150	273	283	268	242	361	147	310	286	446	266	233	180	228	82	341	239	265	209	325	292
10	0.070	0.070	423	404	426	395	567	275	495	356	649	422	453	317	363	172	731	425	296	272	385	347
11	0.070	0.140	314	306	310	268	412	174	352	303	495	312	273	205	248	104	441	265	297	252	393	312
12	0.070	0.210	264	260	257	213	342	133	289	276	423	261	203	159	198	77	328	201	297	241	397	293



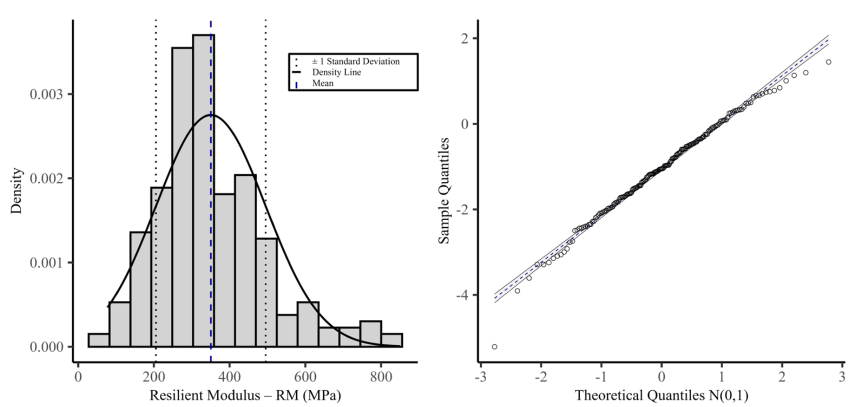


Figure 2. Frequency histogram of RM.

reaches approximately 50% when comparing stress ratios of 2 and 4 in some materials, specifically soils 6, 11, 12, 14, 15, and 16. Conversely, holding the stress ratio constant while increasing only the confining stress results in only a slight decrease in RM.

However, deviatoric stress does not always dominate this behavior; some fine-grained soils, such as LG'17 and LG'19, exhibit resilient responses predominantly governed by confining stress. This phenomenon has been previously documented by researchers investigating the resilient behavior of compacted soils under intermediate and/or modified compaction energies (Amare et al., 2025; Pascoal et al., 2021; Santos, 2020; Schreinert, 2021).

Figure 3 presents the frequency histograms of the RM values obtained for each stress pair. These histograms are accompanied by the respective fitted frequency distribution curves and the theoretical normal distribution curves, which were calculated from the means and standard deviations of the 12 pairs. This analysis allows for a clearer understanding of the variation in RM values as a function of the different applied stress state conditions.

It is observed that the stress pairs with a stress ratio (σ_1/σ_3) equal to 2 (pairs 1, 4, 7, and 10), the presented significantly higher standard deviation values compared to those with stress ratios of 3 (pairs 2, 5, 8, and 11) and 4 (pairs 3, 6, 9, and 12). This is indicated by the wider ranges of the theoretical normal distribution curves. Furthermore, a trend of decreasing standard deviations was noted as the stress ratio increased, suggesting this soil class exhibits greater RM variability when subjected to deviatoric stresses close to the confining stresses.

As deviatoric stress increases, RM values display a narrower range of variation, which results in greater reliability in representing resilient behavior. This indicates that RM variability becomes less pronounced under higher stress ratios and elevated confining stress levels, thus allowing for more consistent estimates of the elastic response.

However, it must be emphasized that the stresses acting on lateritic clay soil layers do not always follow this pattern. In certain situations, these layers may be subjected to relatively low stress states that yield in high standard deviations. This underscores the need for prior knowledge of the loading conditions affecting these layers. Such an approach is essential for establishing more accurate reliability parameters, particularly when considering the intrinsic variability of these materials under different loading conditions.

3.3 Specific permanent deformation

Table 4 presents the specific permanent deformation values for the 20 LG' soils. These values were calculated using

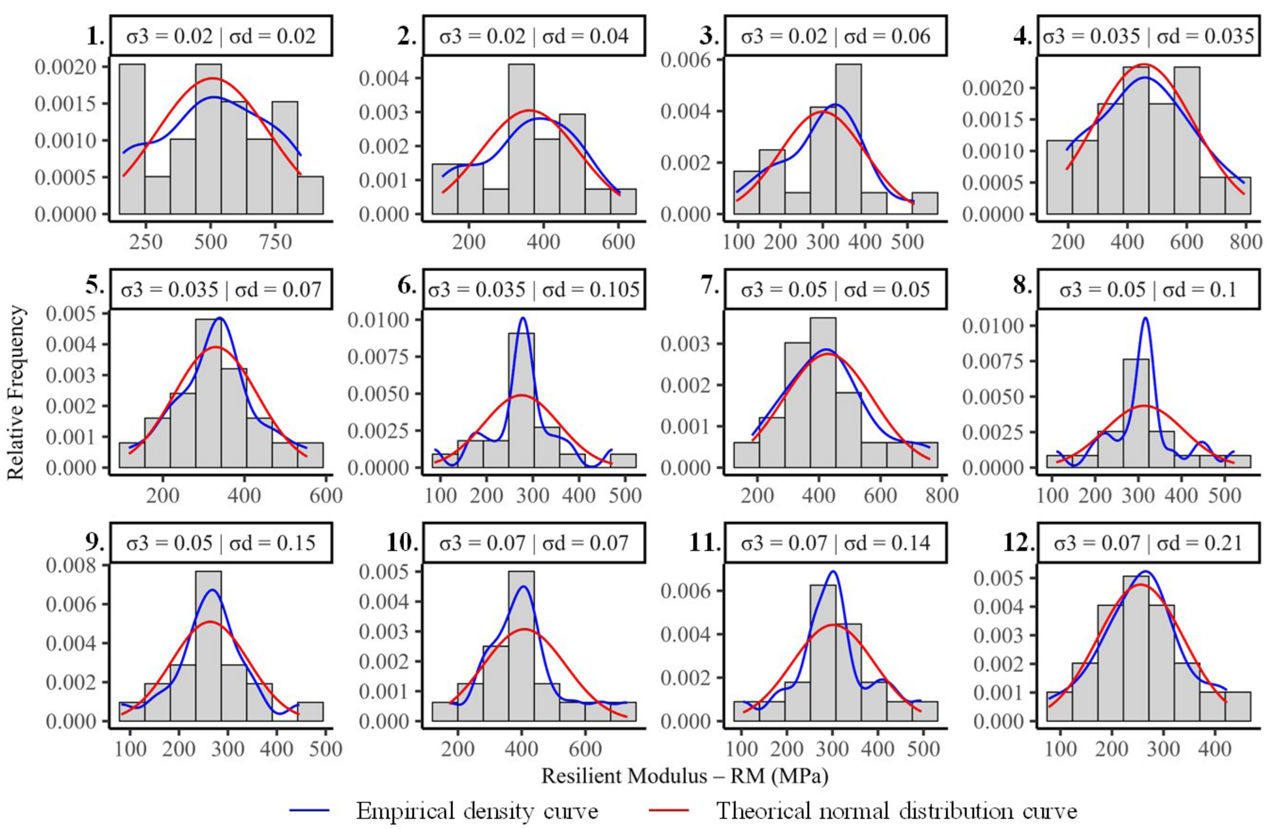


Figure 3. Frequency distribution of RM values (grouped for all 20 LG' soils) for each of the 12 evaluated stress pairs.

the regression parameters of the Guimarães (2009) model and the nine stress pairs specified in the DNIT (2018b) regulations.

Unlike the resilient modulus values, the frequency distribution of the specific Permanent Deformation (PD) dataset visually follows a log-normal pattern, as illustrated in Figure 4. This figure presents both the frequency histogram of the 180 values and a QQ-plot with 99% confidence bands, which confirms adherence to a log-normal distribution.

To verify this, the Shapiro-Wilk test was applied to the log-transformed PD dataset. The test yielded a p-value of 0.198, which is higher than the significance level of 0.05. This indicates the normality of the transformed data and, consequently, confirms that the original values follow a log-normal distribution.

Given the log-normal distribution of the permanent deformation (PD) dataset, the mean, standard deviation, and coefficient of variation (CV) were calculated using the logarithmically transformed data. Accordingly, the mean PD value on the original scale is 0.635%, with a standard deviation of 0.897% and a CV of 141.2%. This high variability highlights the broad range of PD values exhibited by soils of the same classification and compaction energy, emphasizing both the stress state's influence on deformability and the significant intrinsic variability of these materials.

As previously discussed, an increase in deviatoric stress significantly reduces the elastic response (RM). This trend is reflected in deformability behavior: under higher deviatoric stresses, lower elastic responses lead to greater plastic responses (Table 4). Furthermore, increasing the stress ratio (σ_1/σ_3) from 2 to 4 can increase the average PD values by more than seven times compared to a ratio of 2. Soil LG' 2 exhibited the largest increase, approximately ninefold, with notable increases also seen in soils LG' 5, 6, and 8.

Figure 5 presents the frequency histograms of the specific permanent deformation values obtained for the nine stress pairs recommended by DNIT (2018b). It is observed that data distribution follows a log-normal trend, as evidenced by the greater adherence of the experimental values to the theoretical log-normal distribution curve compared to the density curve fitted directly to the original data.

Moreover, for all stress pairs, a higher frequency concentration is associated with low *PD* values, with decreasing frequency as these values increase. However, the curves for this dataset do not converge as satisfactorily as those observed in the resilient modulus distributions.

This behavior highlights that the *PD* data, when analyzed separately and grouped by stress pairs, tend to exhibit greater dispersion and less defined patterns. This reinforces the highly variable nature of *PD* in LG' soils, which is directly influenced by the stress state, and indicates the need for integrated and global analyses (considering all stress pairs) to achieve a more representative interpretation of this parameter.

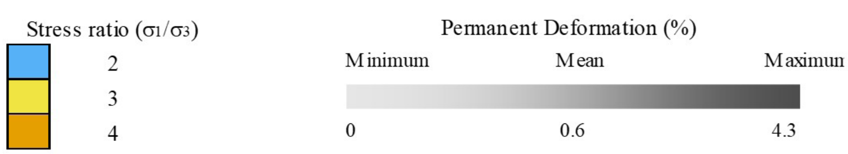
3.4 Correlation between database variables

The correlation matrix was constructed using the Pearson correlation coefficient, considering only the numerical variables from the experimental dataset. This statistical method quantifies the strength and direction of the linear relationship between two continuous variables. Figure 6 presents the resulting correlation coefficients, which illustrate the relationships between mechanical parameters (i.e., resilient modulus and permanent deformation) and the materials' physical properties.

A strong negative correlation is observed between *MDD* and optimum moisture content (*OMC*) (-0.84). This is a well-documented and expected behavior in compacted soils, where higher dry densities are typically associated

Table 4. Percent Permanent Deformation for Different Stress Pairs.

Pairs	Tension pairs (MPa)		Permanent Deformation, ε_p (%) - Soil Classification: LG'																			
	σ_3	σ_d	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.040	0.040	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.1	0.2	0.1	0.1	0.0	0.3	0.1	0.1	0.1	0.0
2	0.040	0.080	0.1	0.2	0.3	0.1	0.1	0.1	0.2	0.0	0.1	0.3	0.3	0.3	0.2	0.2	0.1	0.6	0.1	0.1	0.1	0.1
3	0.040	0.120	0.2	0.6	0.7	0.3	0.2	0.3	0.4	0.0	0.1	0.5	0.6	0.4	0.3	0.3	0.1	1.0	0.2	0.2	0.2	0.2
4	0.080	0.080	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.0	0.1	0.3	0.2	0.7	0.2	0.2	0.1	0.6	0.2	0.3	0.2	0.2
5	0.080	0.160	0.3	0.7	0.7	0.4	0.3	0.7	0.6	0.1	0.2	0.5	0.7	1.1	0.5	0.4	0.2	1.3	0.3	0.5	0.4	0.4
6	0.080	0.240	0.5	1.6	1.5	0.9	0.7	1.6	1.1	0.3	0.3	0.8	1.3	1.4	0.8	0.6	0.3	2.1	0.4	0.7	0.5	0.6
7	0.120	0.120	0.3	0.3	0.4	0.3	0.2	0.5	0.4	0.1	0.2	0.4	0.3	1.4	0.4	0.3	0.2	0.9	0.3	0.6	0.4	0.3
8	0.120	0.240	0.6	1.3	1.2	0.9	0.6	1.9	1.1	0.5	0.4	0.7	1.1	2.1	0.9	0.6	0.4	2.0	0.5	1.0	0.6	0.8
9	0.120	0.360	0.9	3.1	2.3	1.9	1.4	4.2	1.9	1.0	0.6	1.1	2.2	2.7	1.6	0.9	0.6	3.3	0.6	1.4	0.8	1.3



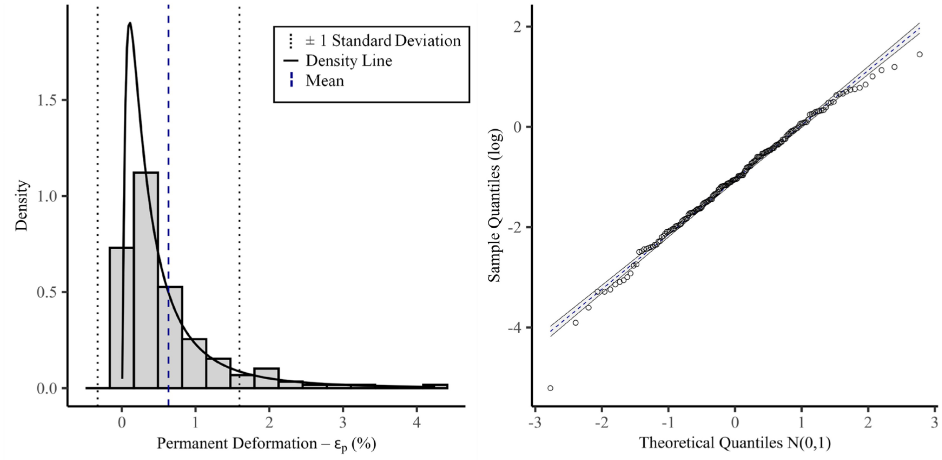


Figure 4. Frequency histogram of PD.

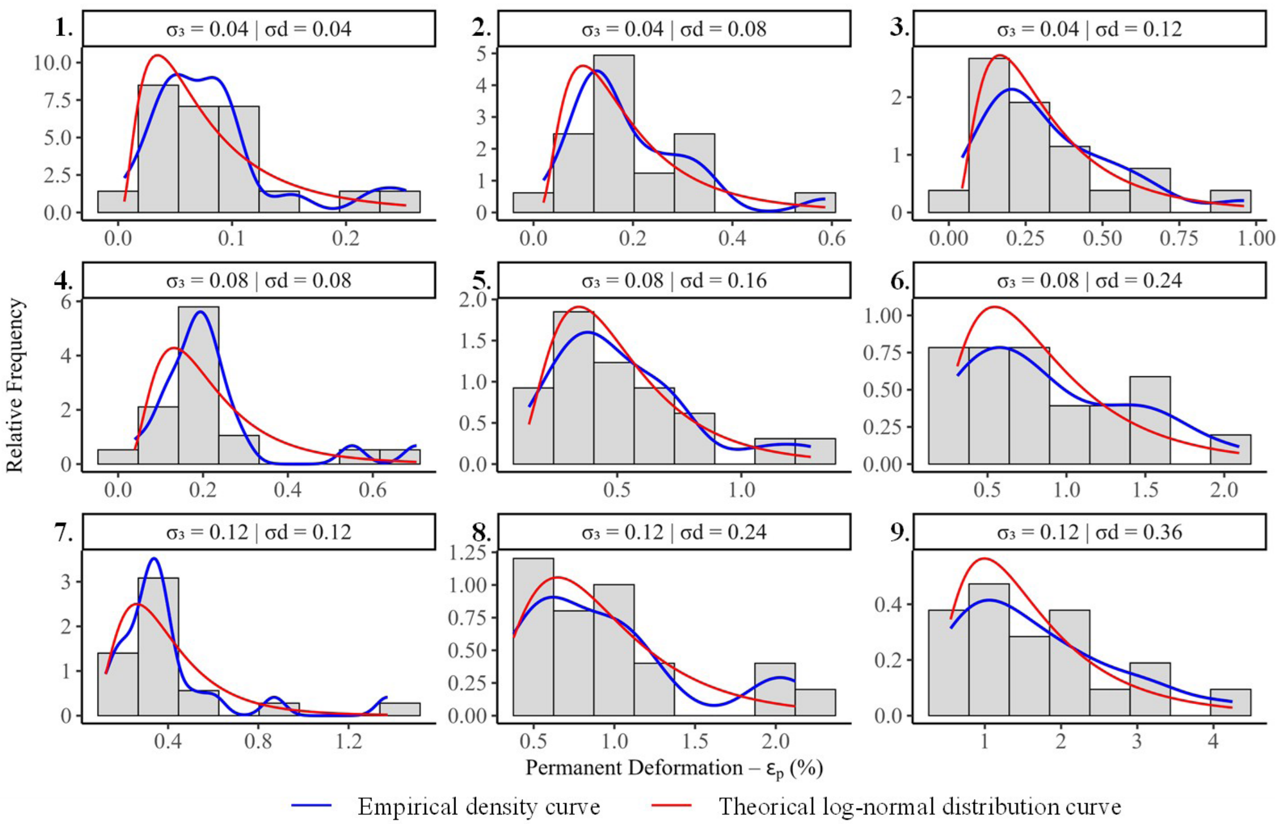


Figure 5. Frequency histograms of the specific permanent deformation values (grouped for all 20 LG' soils) for each of the 9 evaluated stress pairs.

with lower optimum moisture contents. Regarding particle size distribution, an inverse correlation is identified between sand and silt contents (-0.79), reflecting the complementary nature of these fractions. Moreover, silt content shows a positive correlation with both the *d'* parameter (0.53) and *RM* (0.48), suggesting that higher silt content may enhance elastic behavior, possibly due to improved interparticle structuring.

Clay content, in turn, shows a positive correlation with *OMC* (0.41) and a negative correlation with *RM* (-0.53), These results indicate that clay-rich soils generally require higher moisture levels to achieve maximum compaction and tend to exhibit reduced elastic response, in agreement with findings widely reported in the literature, Additionally, *RM* displays a positive correlation with the *c'* parameter (0.43), associated with the MCT classification, suggesting that intrinsic characteristics of this soil type influence its resilient behavior, In the case of *PD*, lower correlation magnitudes were observed overall, reinforcing the high variability previously discussed for this dataset, Nevertheless, notable trends include a negative correlation with *MDD* (-0.46), indicating that higher densities tend to reduce plastic deformation, and a positive correlation with *OMC* (0.37), suggesting that wetter compaction conditions may promote greater accumulation of permanent strain.

Figure 7 shows boxplots of *RM* for compacted LG′ soils, where continuous variables were stratified into terciles to ensure balanced group sizes. Soils with higher *MDD* exhibit slightly increased *RM* values, reflecting the greater stiffness associated with enhanced particle contact. Similarly, lower *OMC* is associated with higher *RM*, likely due to drier, denser states that promote interparticle friction and elastic response. For the silt fraction, the intermediate range yields the highest *RM*, followed by a decreasing trend as silt content increases. This suggests that excessive silt may impair structural rearrangement and increase deformation susceptibility. Lower clay contents are associated with higher *RM* values, indicating that a high fines content may reduce resilient stiffness. A slight positive trend with sand content is also noted, although *RM* values remain relatively uniform across terciles.

To assess statistically significant differences in *RM* across groups defined by terciles of continuous variables such as *MDD*, *OMC*, and particle size fractions, the Kruskal–Wallis test was applied, This non-parametric method is used to compare three or more independent groups without assuming data normality or homogeneity of variances, The test is based on ranking the data and comparing the sum of ranks across groups, making it particularly suitable for datasets with skewed distributions or the presence of outliers, which are common in soil strength and deformability parameters, The test statistic (*H*) follows a chi-square distribution, and *p*-values lower than 0,05 were considered indicative of statistically significant differences among the evaluated groups, The Kruskal–Wallis test results confirmed that *RM* exhibits statistically significant variations as a function of the physical properties of the analyzed soils, Significant differences were identified among *MDD* groups ($H = 8.77$; $p = 1.25 \times 10^{-2}$) and *OMC* groups ($H = 11.40$; $p = 3.34 \times 10^{-3}$), reinforcing the strong statistical association between compaction density, moisture content, and resilient behavior. The silt fraction showed a strong effect on *RM* ($H = 20.64$; $p = 3.29 \times 10^{-5}$), as did the clay fraction, whose influence was even more pronounced ($H = 30.19$; $p = 2.78 \times 10^{-7}$), Sand content also exhibited a significant impact ($H = 9.65$; $p = 8.01\times 10^{-3}$), These results reinforce that variations in gradation and compaction conditions of LG′ soils are directly related to the stiffness observed under repeated loading, Following the Kruskal–Wallis

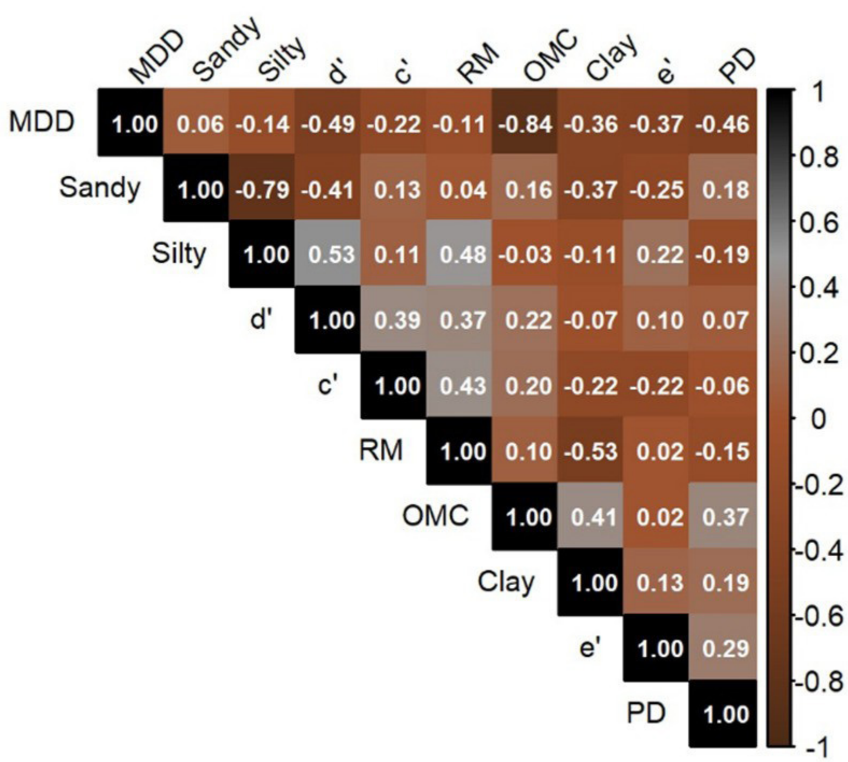


Figure 6. Correlation between parameters of LG' soils.

test, Dunn's post-hoc comparisons with Holm adjustment were performed to identify specific group differences,

Soils with high *MDD* exhibited significantly higher *RM* values than those with low *MDD* (p = 0.0135). For *OMC*, significant differences were found in both medium vs. high and medium vs. low comparisons, reinforcing that lower moisture content increases stiffness. Regarding fines content, both the silt and clay fractions showed pronounced contrasts: higher contents were consistently associated with lower *RM*, particularly in low vs. medium comparisons ($p < 0.001$). Sand content also influenced *RM*, with significant differences observed between the low vs. high and low vs. medium groups ($p < 0.05$).

Figure 8 presents boxplots relating geotechnical variables to *PD*, Kruskal–Wallis analysis revealed no statistically significant differences among groups, *MDD* terciles yielded H = 4.91 (p = 0.0859), suggesting a moderate trend short of the 5% threshold, OMC (p = 0.6802), silt (p = 0.9947), clay (p = 0.9455), and sand (p = 0.4241) show high p-values, indicating no significant *PD* influence, Dunn's post-hoc with Holm adjustment found no significant pairwise *PD* differences at the 5% level, The lowest adjusted p-value was 0.0918 (High vs, Medium *MDD*), indicating a non-significant trend, All other adjusted p-values exceeded 0.58, confirming the absence of contrasts, These findings align with the global Kruskal–Wallis results and suggest that, in contrast to *RM*, *PD* is not significantly influenced by individual geotechnical variables.

4. Conclusion

The integrated analysis of the database, comprising 20 lateritic clay soils compacted under intermediate energy, provided valuable insights into the interaction among physical properties, MCT classification parameters, and mechanical behavior under applied stress conditions. The characterization demonstrated that, despite belonging to the same geotechnical class, subtle variations in gradation, physical indices, and compaction moisture significantly influence their elastic and plastic responses, thereby highlighting the inherent complexity of tropical soils.

The *RM* results exhibited a strong dependence on the applied stress state. Higher stress ratios and increased confining stress levels reduced *RM* variability, which improved the reliability of resilient behavior representation. However, the fact that some soils did not uniformly follow this trend, even when classified as LG′ and compacted under the same energy, underscores their intrinsic variability.

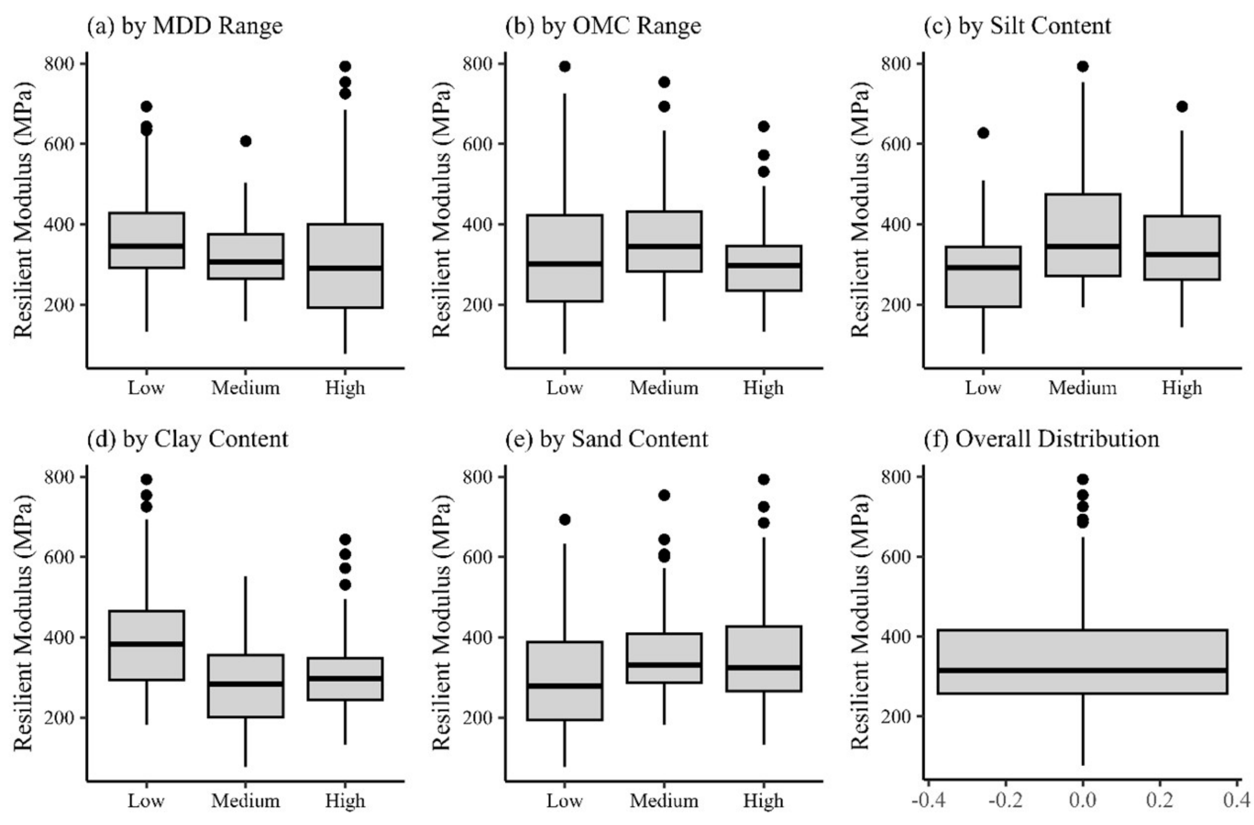


Figure 7. Boxplots of *RM* values (all 240 values grouped) for compacted LG' soils, stratified by terciles of continuous variables: (a) *MDD* Range; (b) *OMC* Range; (c) Silt Content; (d) Clay Content; (e) Sand Content; and (f) Overall Distribution.

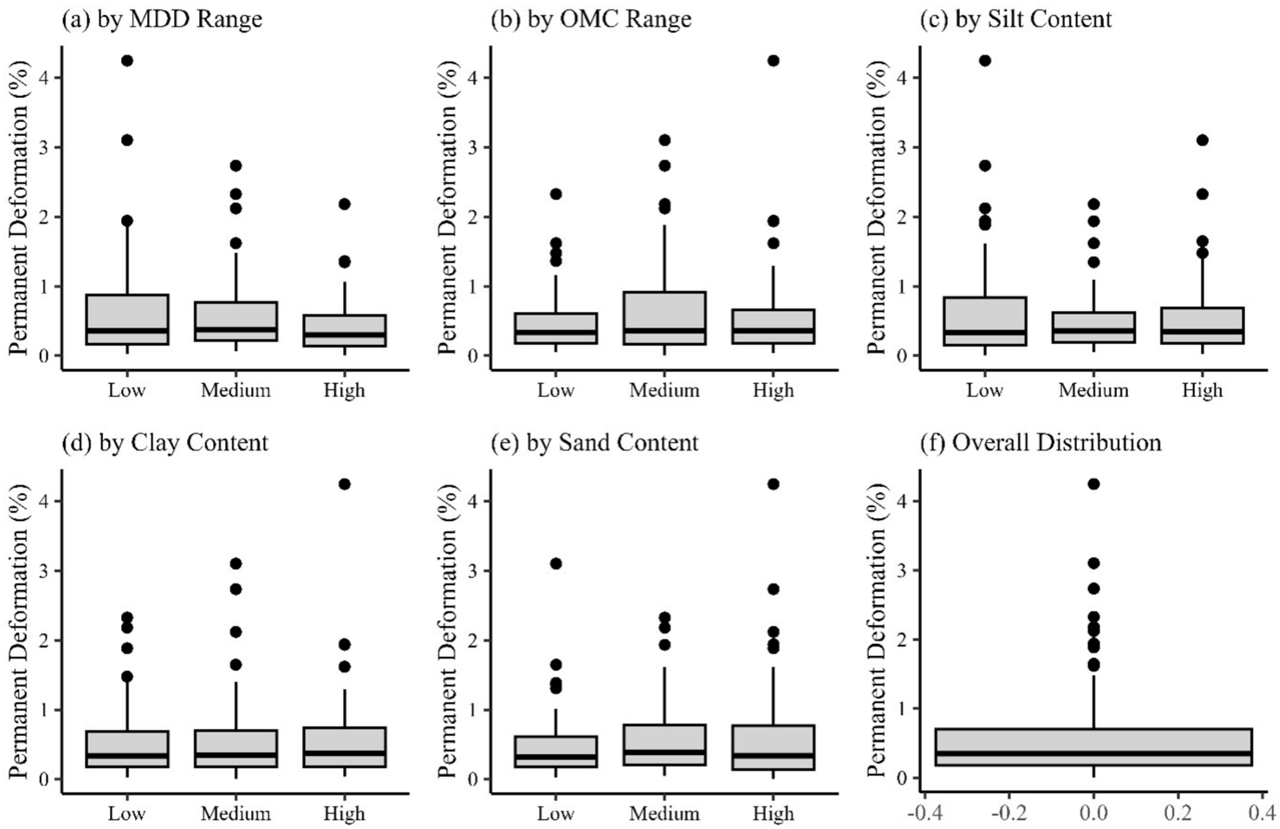


Figure 8. Boxplots of permanent deformation values (all 180 values grouped) for compacted LG' soils, stratified by terciles of continuous variables: (a) *MDD* Range; (b) *OMC* Range; (c) Silt Content; (d) Clay Content; (e) Sand Content; and (f) Overall Distribution.

Pearson correlation analysis confirmed consistent patterns, including the negative relationship between clay fractions and *RM* and the positive influence of sand fractions on the elastic response. Moreover, the inverse relationship between maximum dry density and optimum moisture content aligned with the classical behavior of compacted soils. These findings reinforce that soil texture and compaction conditions play a decisive role in material stiffness, and are strongly associated with material stiffness, which is a key factor in pavement layer performance under traffic loading.

Conversely, the Permanent Deformation (*PD*) results exhibited substantial dispersion across the dataset, even when grouped by stress pairs. This variability, although partially inherent, may also stem from external factors such as methodological differences between laboratories, equipment calibration, sample handling procedures, and operator influence. These factors emphasize the necessity for strict standardization of testing methodologies and well-established protocols to minimize experimental variability and enhance result reliability.

The significant variability observed in the permanent deformation (*PD*) results, even among soils of the same classification and compaction energy, highlights intrinsic limitations in global predictive models for this parameter. Possible sources of this high dispersion may include external factors not captured in the models, such as methodological differences between laboratories, equipment calibration, sample handling procedures, and operator influence. Furthermore, while the statistical analysis identified strong associations and significant influences of physical properties on the resilient modulus (*RM*), the nature of the database compilation (secondary data) and the statistical methods used, such as Pearson's correlation and Kruskal–Wallis tests, do not establish a definitive causal link. Therefore, these findings should be interpreted as reinforcing the importance of integrated physical–mechanical characterization for pavement design, recognizing the necessity for site-specific experimental investigations to achieve the highest level of reliability.

Therefore, understanding the mechanical behavior of LG′ soils require a combination of detailed physical characterization, representative laboratory testing, and robust statistical analyses. The database developed advances knowledge of compacted tropical soils and serves as a useful tool to support future research and improve mechanistic-empirical pavement design methodologies by providing parameters related to the variability of properties such as RM and PD. These parameters can refine reliability-based analyses but do not replace the need for site-specific experimental investigations for each material to be effectively used.

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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

Luigi Tavares Gomes: conceptualization, data curation, methodology, visualization, software, writing – original draft. Patricia Rodrigues Falcão: conceptualization, data curation, methodology, validation, software, writing – original draft. Paula Taiane Pascoal: conceptualization, data curation, methodology, validation, writing – original draft. Leonardo Alberto do Nascimento: conceptualization, data curation, methodology, writing – original draft. Magnos Baroni: methodology, project administration, resources, supervision, writing – review & editing. Luciano Pivoto Specht: supervision, writing – review & editing.

Data availability

The datasets generated analyzed during the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

No generative artificial intelligence (GenAI) assistance was used to develop this work.

List of symbols and abbreviations

c'	Clay coefficients
d'	Correlation coefficient between specific mass and humidity
e'	Laterization index
k_n	Resilient modulus parameters
LG'	Lateritic clay soils
MCT	Miniature, compacted, tropical
MDD	Maximum dry density
N	Number of load cycles
OMC	Optimum moisture content
PD	Permanent deformation
RM	Resilient modulus
ε_p	Specific permanent deformation
ρ_0	Reference stress (atmospheric stress)
σ_3	Confining stress
σ_d	Deviator stress
ψ_n	Permanent deformation parameters

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