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Evaluation of the influence of compaction energy on the resilient behavior of lateritic soil in the field and laboratory

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Article

Keywords
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Pavement subgrade
Undisturbed samples
Resilient modulus

Abstract

This article presents the study of the resilient behavior of three soil horizons from a deposit of lateritic soil employed in a pavement structure in Rio Grande do Sul, Brazil. The use of lateritic soils in pavement layers is a common practice in Brazil and due to its peculiarities, its behavior must be investigated. The methodology consisted of physical and chemical characterization and resilient modulus determination. Samples from the three horizons, compacted at standard, intermediate and modified energy, were analyzed. In addition, undisturbed samples extracted from the interior and top layer of the embankment were submitted to repeated load triaxial tests for resilient modulus determination. The results indicated that the soil exhibit good behavior for pavement subgrade applications, perhaps as subbase or base course layers. The compound and universal models yielded the best correlation coefficients. Furthermore, the results showed that as the compaction energy increased, the resilient modulus also increased, as long as they are within the optimum water content and compaction degree limit. However, when subjected to immersion in water for four days, the resilient behavior decreased about 73% in relation to unsaturated samples.

1. Introduction

The constant search for improvements in pavement projects has led to the adoption of a mechanistic-empirical approach to flexible pavement design in Brazil. This approach is supported by the development of a software program, new M-E pavement design methodology (MeDiNa), which takes into consideration structural efficiency, employment of materials with known performance characteristics and the impact of environmental and traffic conditions (Medina et al., 2006; Ubaldo et al., 2019; Lima et al., 2019; Souza Júnior et al., 2019; Lima et al., 2020; Franco & Motta, 2020).

To validate a design or structural analysis with MeDiNa, it is necessary to carry out laboratory tests to characterize constituent materials, in addition to considering a set of parameters referring to all materials that comprise the flexible pavement structure (Franco & Motta, 2018). Regarding to the subgrade, the resilient modulus (DNIT, 2018a) and the permanent deformation parameters (DNIT, 2018b) are essential, as well as the characterization of the soil physical properties and Miniature Compaction Tropical (MCT) classification (DNER, 1996) of the constituent material. MCT is a Brazilian classification system which was developed specifically to consider the characteristics of fine tropical soils (Nogami & Villibor, 1995). Soils used in subbase and base course layers must be characterized according to MCT methodology and have their elastic and plastic properties determined, regarding resilient modulus and permanent deformation.

The parameter that describes the elastic behavior of materials submitted to cyclic loading is the resilient modulus (RM). Resilience is the capacity of a material to recover from deformations after loading ceases (Huang, 1993; Medina, 1997; Balbo, 2007). In general, the resilient modulus of soils employed in pavement structures exhibit a non-linear behavior, due the variation in the stress state, such as external load variation, changes in layer thickness and the different specific weights of the constituent materials, among others (Hicks & Monismith, 1971; Uzan, 1985).

Previous research on soil behavior under cyclic loading indicates that the resilient modulus depends on the following: soil origin, particle size distribution (percentage of material passing through sieve #200), physical state (water content and dry unit weight), loading conditions (frequency and amplitude of cyclic loading), stress history and state, number of deviator stress solicitations, density, compaction water content, degree of saturation and compaction method, among others (Seed et al., 1967; Medina & Preussler, 1980; Bayomy & Al-Sanad, 1993; Li & Selig, 1994; Guimarães et al., 2001;

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Ceratti et al., 2004; Buttanaporamakul et al., 2014; Razouki & Ibrahim, 2017; Rahman & Gassman, 2017; Lima et al., 2018; Venkatesh et al., 2018; Lima et al., 2019; El-Ashwah et al., 2019; Ackah et al., 2020; de Freitas et al., 2020; Zhang et al., 2020; Zago et al., 2021; Silva et al., 2021).

The use of lateritic soils in pavement layers is a common practice in Brazil, however, their nature is not sufficient to assure a good performance, which is associated with peculiarities of formation and location the deposit (Medina, 2006; Guimarães et al., 2018). According to Camapum de Carvalho et al. (2015) it is necessary to verify the chemical, mineralogical, physical and structural characteristics of tropical soils so that they can be used for highway construction.

In this context, this study evaluates the resilient behavior of a lateritic clay soil deposit, used in a highway project in the state of Rio Grande do Sul, Brazil, by: analyzing the influence of the variation in compaction energy on the behavior of this material; comparing samples compacted in the laboratory to undisturbed samples compacted in the field and extracted from the interior and top layer of the road embankment; and, determining the resilient behavior of samples immersed in water for 96 hours. Due the lack of Brazilian studies about the behavior of undisturbed samples of soil, this article seeks to highlight the importance of compaction energy and the technological control of the process with regard to the behavior of soils used in the subgrade of flexible pavements.

2. Materials and methods

The experimental program for this research was divided into the following steps: sample collection, physical and chemical characterization tests, repeated load triaxial tests, and subsequent analysis of the results.

2.1. Materials

Lateritic soils are very common in humid tropical climates, such as Brazil. According to Nogami & Villibor (1991), the material most frequently used in Brazilian road pavements is fine lateritic soil, due to its abundance in most states.

The study area was located in the municipality of Cruz Alta in the northwest mesoregion of Rio Grande do Sul. The pedological and geological aspects of the area present medium textured, dark red clayey latosols. This material is the result of the weathering process at the upper portion of the Paraná Basin basalt effusion, which belongs to Serra Geral formation and was developed in flat and smooth undulated areas.

Soil from the studied deposit was employed/used in the construction of a 14.20-meter-high road embankment, which served as the subgrade for expansion of an intersection of highway RS-342, located near Cruz Alta. Disturbed samples from the deposit were collected from three pedological horizons (A, B and C) located at 28°37'39.40" S and 53°37'30.50" W, as seen in Figure 1A. The three horizons were used to compose the subgrade of the previous pavement structure. The soils from the horizons were extracted from the deposited and transported to the jobsite to be compacted.

The structure of the intersection of highway studied was made up of: the embankment, a 19 cm sub-base course layer granular material, and a 15 cm granular base course layer. Two asphalt layers were also applied, a 5 cm of conventional asphalt mixture and 5 cm of polymer modified asphalt mixture. This structure was designed to support a total of 3.5 x10^7 ESALs (equivalent single axle load of 80 kN – USACE).

Figure 1B presents the compacted embankment before the extraction of the undisturbed samples. The samples were collected at 28°37'54.00" South and 53°37'31.50" West, from the interior of the embankment, compacted at standard energy, and also from the top layer of the embankment, compacted at intermediate energy.

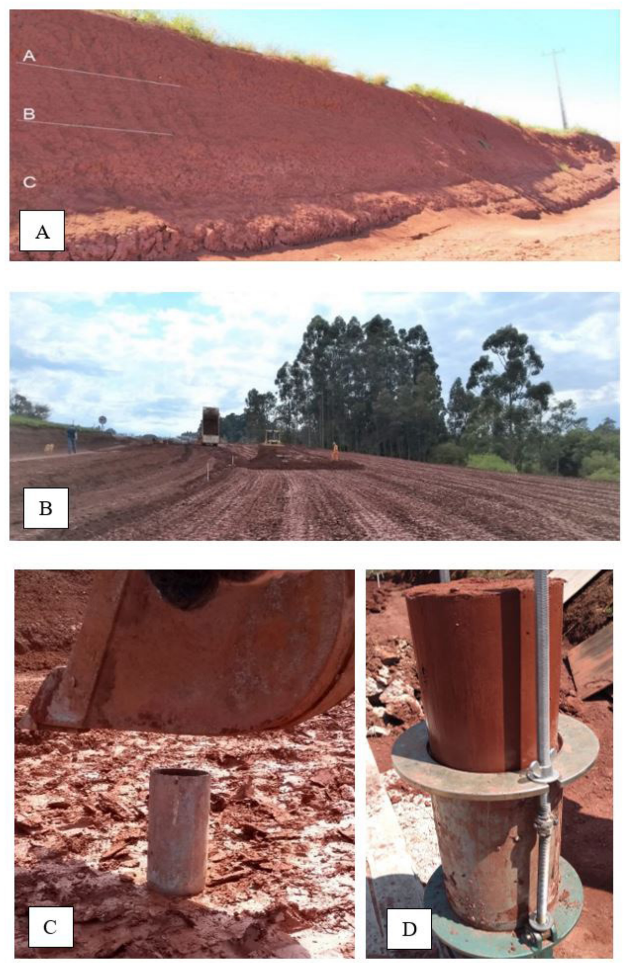

Figure 1. (A) Soil horizons at the Cruz Alta deposit, (B) location of the extraction of undisturbed soil sample, (C) sampler cylinder extraction procedure and (D) undisturbed soil sample.

Cylindrical steel samplers (15 cm diameter x 30 cm height) developed for the extraction of undisturbed samples, were inserted into the subgrade with a backhoe (Figure 1C). The undisturbed samples were extracted with a puller and a hydraulic jack (Figure 1D). Then, they were protected with plastic wrap, aluminum foil and paraffin, to keep the field compaction structure and moisture.

2.2. Physical and chemical characterization

The physical characterization of the soil was developed based on Brazilian national standards and soil mechanics tests (Atterberg limits, grain size analysis and specific gravity of soil grains). In addition, mass loss tests by immersion and Moisture Condition Value Compaction (mini-MCV were performed in order to classify the samples according to the Brazilian MCT methodology (DNER, 1996).

The chemical characterization of the soil was done with energy-dispersive X-Ray Fluorescence (EDXRF), using Bruker S2 Ranger equipment. Energy dispersive X-ray fluorescence provides a qualitative and quantitative analysis to identify elements simultaneously by means of emission detection. Further, a chemical analysis of the horizons was carried out in order to identify the pH, the cation exchange capacity (CEC), the amount of aluminum, magnesium and calcium, the saturation percentage and the percentage of organic matter.

2.3. Mechanical characterization

For the disturbed samples, compaction tests were performed in order to obtain the maximum dry density (MDD) and the optimum moisture content (OMC). A three-part cylindrical mold was employed, as described in the DNIT 134 standard (DNIT, 2018a). For each horizon (A, B and C), compaction curves for standard energy (SE), intermediate energy (IE) and modified energy (ME) were plotted. Then, with the maximum values obtained, three specimens compacted for each horizon, at each compaction energy, were submitted to resilient modulus tests.

Three undisturbed samples from the interior of the embankment (compacted at standard energy) and three undisturbed samples from the top layer (compacted at intermediate energy) were tested. To avoid any change in the structure of the samples due to the contact between the soil and the edge of the sampler, the undisturbed samples were trimmed reducing the extraction dimensions (30 cm in height and 15 cm in diameter) to the test dimensions (10 cm height and 20 cm diameter). The molding procedure for reducing the size of the specimens was done hours before the resilient modulus test, using spatulas and steel lines, controlling the ambient humidity and verifying the moisture content of the specimens every fifteen minutes.

Repeated load triaxial tests were performed on the equipment shown in the Figure 2A and Figure 2B, according to the DNIT 134 (DNIT, 2018a), in order to determine the elastic

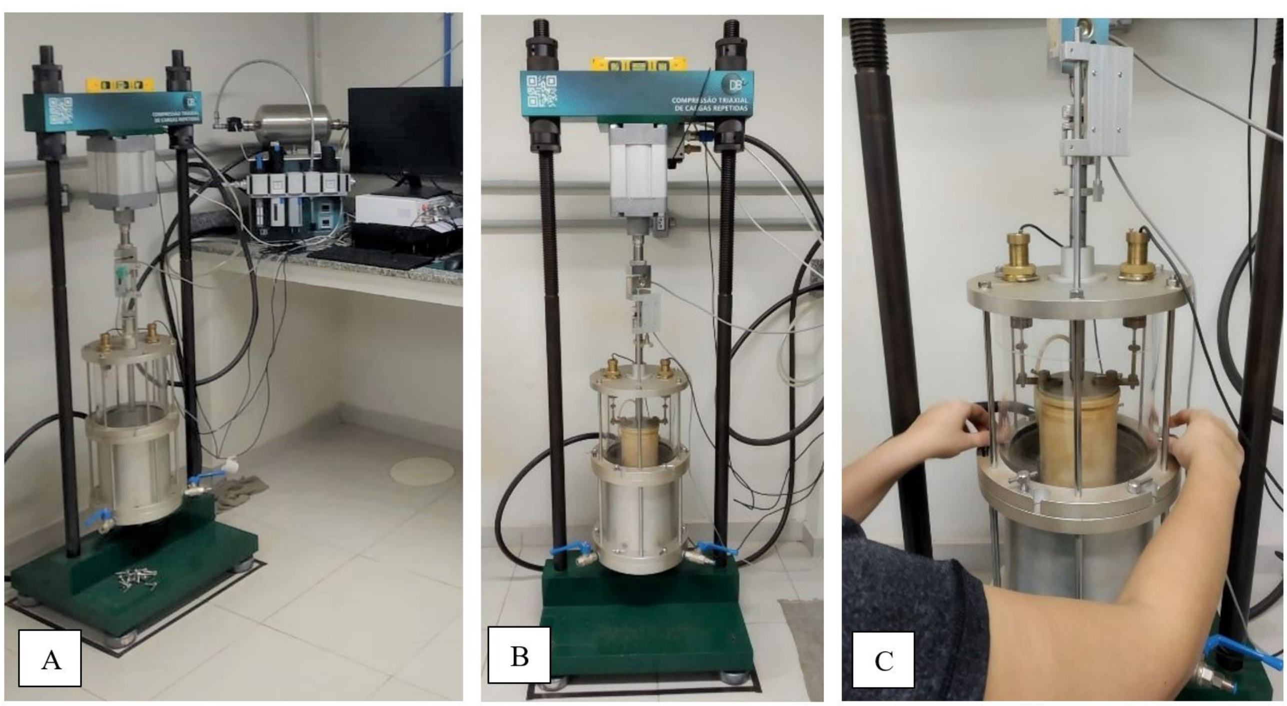

Figure 2. (A) Triaxial equipment of repeated loads, (B) soil sample being positioned on equipment, (C) detail of the two LVDTs inside the triaxial chamber.

properties (resilient modulus test) of both the undisturbed samples, compacted in the field, and the samples taken from the three soil horizons, compacted in the laboratory. In Figure 2C it is possible to observe the two linear variable differential transformers (LVDT) used inside the bipartite triaxial chamber, supported under a top cap that receives the action of the deviator stress through a load cell and a piston. The Brazilian standard DNIT 134 (DNIT, 2018a) presents technical procedures similar to those adopted by American Association of State Highway and Transportation Officials: T 307-99 (AASHTO, 2012) and MEPDG-1 (AASHTO, 2008).

Five hundred cycles were applied for conditioning, with confining stress (σ_3) of 0.07 MPa and deviator stress of (σ_d) 0.07 MPa, at a frequency of 1 Hz. Then, each specimen was submitted to twelve loading sequences, each with 100 cycles, in accordance with the standards, being applied to each sequence of confining stress versus deviator stress: 0.02x0.02 MPa, 0.02x0.04 MPa, 0.02x0.06 MPa, 0.035x0.035 MPa, 0.035x0.070 MPa, 0.035x0.105 MPa, 0.05x0.05 MPa, 0.05x0.10 MPa, 0.05x0.15 MPa, 0.07x0.07 MPa, 0.07x0.14 MPa, 0.07x0.21 MPa.

The determination of the resilient parameters was based on the mathematical models that best describe the behavior of the samples, such as the Biarez model (Biarez, 1962), the Svenson model (Svenson, 1980), the stress invariant model, the Pezo et al. model (Pezo et al., 1992) and the NCHRP 1-37A model (AASHTO, 2004), summarized in Table 1 (Guimarães, 2009; Medina & Motta, 2015; Nguyen & Mohajerani, 2016).

After obtaining the resilient parameters, the relationship between the resilient modulus and soil physical indexes could be identified. For this, the average RM from the model that presented the best fit was correlated with the void ratio, the optimum moisture content and the maximum dry density.

3. Results and analysis

The results of the laboratory tests and analysis of mathematical models are presented here to support the discussions regarding the comparison of the disturbed and undisturbed samples as well as the change in the resilient behavior relative to changes in the compaction energy.

3.1. Physical and chemical characterization

Table 2 shows the average values from the physical and chemical characterization, as well as the soil classification for the three horizons under study. The Atterberg limits and particle size distribution curve are very similar for horizons A and B, however horizon C is different, with a higher Plasticity Index (PI), higher silt content and a lower percentage of sand. Horizon A has a predominance of particles smaller than 0.06 mm and is composed of 64% silt and clay. Horizon B and C exhibit 67% and 72% of the same fractions, respectively.

The particle size distribution sieve analysis for each of the horizons is presented in Figure 3. The tests were performed both with the dispersant sodium hexametaphosphate (WD) and without dispersant (WOD), using only distilled water. The results of the particle size distribution curves without the dispersant shows a tendency for larger particle sizes, in

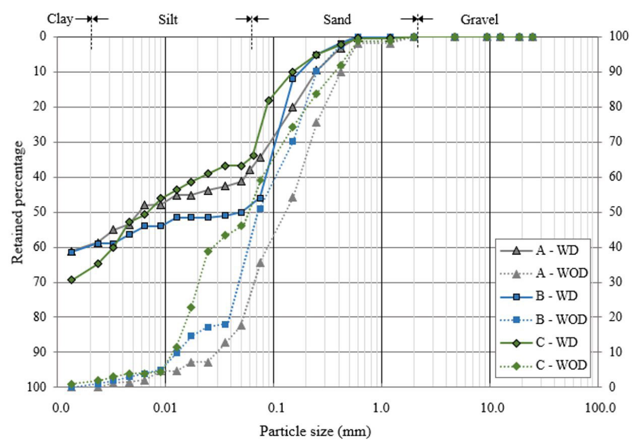

Figure 3. Particle size distribution curves of the horizons.

Table 1. Equations from the models used.

Models	Equation	
Biarez – confining stress	$RM = k_1 . \sigma_3^{k_2}$	(1)
Stress invariant	$RM = k_1 . \theta^{k_2}$	(2)
Svenson – deviator stress	$RM = k_1 . \sigma_d^{k_2}$	(3)
Pezo et al. – compound	$RM = k_1 . \sigma_3^{k_2} . \sigma_d^{k_3}$	(4)
NCHRP 1-37A – universal	$RM = k_1 . \rho_a \left(\frac{\theta}{\rho a} \right)^{k_2} . \left(\rho \frac{\tau_{oct}}{\rho a} + 1 \right)^{k_3}$	(5)

Note: RM: resilient modulus; σ_3 : confining stress; σ_d : deviator stress; θ : principal stress; τ_{oct} : octahedral stress; ρ_a : atmospheric pressure; k_1, k_2 e k_3 : resilient parameters experimentally determined.

addition to not showing the clay particles. This difference between the WOD and WD results is due to the adherence of the clay particles to the larger grains when a chemical dispersant is not used.

According to the Brazilian MCT classification of tropical soils (Nogami & Villibor, 1995), the soil belongs to the clayey lateritic behavior (LG’) group, which infers good behavior for pavement subgrade, exhibiting high bearing capacity, low expansion and permeability. In comparing the MCT classification with the AASHTO, the importance of classifying the behavior of tropical silts is evident. According to the AASHTO road classification, the studied soil is classified in groups A-7-5 or A-7-6, indicating fair to poor behavior for use in pavement structures. Based on the Unified Soil Classification System (USCS), horizon A is classified as a low compressibility inorganic clay, while horizons B and C are classified as high compressibility silt.

Based on the data summarized in Table 2, silicon dioxide, iron oxide and aluminum oxide were present in all three horizons of from deposit. This is consistent with the MCT classification and the physical characteristics of the deposit.

Horizon A which is closer to the surface, had a higher organic matter content. However, as depth increased, organic matter content decreased, with values of 0.2 and 0.1, for horizon B and C, respectively. Organic matter content values are related to cation exchange capacity (CEC). The CEC of the three horizons is less than 6%, indicating low activity clays and little or no presence of organic matter (OM ≤ 2%). As the amount of aluminum in the material increases, the clay content also increases, which reinforces the hypothesis of the clay mineral kaolinite. The pH values of the three horizons, ranging between 4.6 and 5.8, indicate that the deposit presents acidic soils.

3.2. Mechanical characterization of the laboratory samples

Figure 4 presents the optimum moisture content (OMC) and maximum dry density (MDD) for each of the horizons, compacted at standard (SE), intermediate (IE) and modified energy (ME). As compaction energy increases, there is an increase in maximum dry unit weight and a decrease the optimum moisture content (Lambe & Whitman, 1969). Based on the analysis, as closer is the soil to the surface, the lower are the OMC and specific weight of the grains (see Table 2) and the higher is the MDD. As the soil thickness increases, as in the case of horizon C, lower values of specific weight and OMC are observed, and lower values of MDD.

Based on the standard DNIT 134 (DNIT, 2018a), only the tests in which the compacted specimens of the had a maximum variation of ± 0.5% relative to the OMC were considered valid (DNIT, 2018a). Although the standard does not impose a variation limit for maximum dry density, a variation of ±1.0% was adopted to consider the specimen valid.

Table 2. Physical and chemical characterization and soil horizon classification.

Parameters	Horizon A	Horizon B	Horizon C
Liquid Limit (%)	43	55	77
Plastic Limit (%)	28	44	51
Plasticity Index - PI (%)	16	11	26
Specific weight (kN/m^3)	26.13	27.80	28.75
% gravel (>2.0mm)	0	0	0
% coarse sand (0.6 – 2.0 mm)	0	0	0
% average sand (0.2 – 0.6 mm)	15	8	7
% fine sand (0.06 – 0.2 mm)	21	25	21
% silt (2 μm – 0.06 mm)	24	26	38
% clay (%< 2 μm)	40	41	34
Brazilian MCT - c’	2.29	2.35	1.91
Brazilian MCT - d’	48.78	67.00	21.38
Brazilian MCT - e’	1.02	0.69	1.08
Brazilian MCT	LG’	LG’	LG’
AASHTO	A-7-5	A-7-6	A-7-5
USCS	CL	MH	MH
EDXRF - chemical components that prevail	SiO_2/Fe_2O_3 Al_2O_3/Na_2O	Fe_2O_3/SiO_2 Al_2O_3/TiO_2	Fe_2O_3/SiO_2 Al_2O_3/Na_2O
Chemical analysis - CEC	2.0	1.8	3.7
Chemical analysis - basic cations Ca / K / Mg (Cmol$_c$dm^3)	1.4 / 0.05 / 0.6	0.3 / 0.02 / 0.4	0.2 / 0.02 / 0.3
Chemical analysis - saturation Al / base (%)	50.0 / 15.4	55.6 / 9.2	86.6 / 2.6
Chemical analysis - organic matter (%)	2.0	0.2	0.1
Chemical analysis - pH	4.6	5.8	5.6

Note: Results of particle size distribution analysis were obtained with dispersant; Note: Miniature Compaction Tropical – MCT is a classification for tropical soils developed by Nogami e Villibor (1995); Note: AASHTO - American Association of State Highway and Transportation Officials; Note: USCS - Unified Soil Classification System.

As previously mentioned, five resilient modulus prediction models were used to analyze the data obtained by the resilient modulus test for the twelve pairs of confining and deviator stresses previously mentioned. For this, multiple nonlinear regression was performed using Statistica v.10 software, taking into consideration the compaction conditions for each individual sample and for the set of the three samples (01 + 02 + 03). Table 3 shows the prediction model results for the three-sample sets. The criterion used to evaluate the models was the best fit of the coefficient of determination (R^2), obtained by regression analysis.

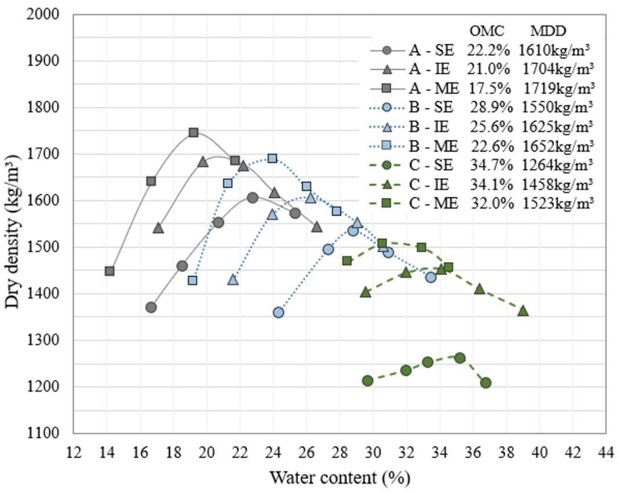

Figure 4. Mechanical characterization of horizons.

Regarding horizon A, in general, the Biarez and stress invariant models presented the worst fit. For the compound model, there was a 57.4% gain in the resilient modulus compacted at intermediate energy, when compared to standard energy. Likewise, the resilient modulus at modified energy was 84.5% higher than the RM at intermediate energy and 190.4% higher than at standard energy.

The universal and compound model, which takes into account deviator stress and confining stress interactions, satisfactorily represented the behavior of horizon A, for the samples compacted at standard and intermediate energy. The Svenson model also showed a good fit based on the nature and particle size distribution curve of the soil, as found in the technical literature (Guimarães et al., 2001; Behak & Núnez, 2017; Bhuvaneshwari et al., 2018; Guimarães et al., 2018).

Table 3. Resilient parameters for the soil horizons for the five models under evaluation.

Models		Horizon A			Horizon B			Horizon C		
		SE	IE	ME	SE	IE	ME	SE	IE	ME
Biarez	k_1	79.72	173.09	736.83	109.76	751.38	1724.20	140.77	523.95	1113.89
	k_2	-0.16	-0.06	0.21	-0.08	0.34	0.50	-0.08	0.30	0.38
	R^2	0.14	0.04	0.61	0.05	0.90	0.91	0.08	0.73	0.90
	RM (MPa)	134.0	211.4	376.4	140.5	250.1	348.7	181.4	202.4	328.3
Svenson	k_1	71.55	143.39	557.70	102.98	387.90	729.83	128.43	302.98	546.45
	k_2	-0.23	-0.15	0.14	-0.15	0.17	0.29	-0.13	0.16	0.20
	R^2	0.62	0.49	0.49	0.41	0.48	0.62	0.43	0.40	0.49
	RM (MPa)	134.2	211.3	391.9	153.4	246.7	349.3	181.4	202.5	328.5
Stress Invariant	k_1	90.21	171.17	541.85	122.03	397.98	721.03	147.27	309.03	559.74
	k_2	-0.24	-0.13	0.20	-0.14	0.30	0.46	-0.13	0.26	0.33
	R^2	0.36	0.21	0.64	0.20	0.80	0.89	0.23	0.66	0.81
	RM (MPa)	134.1	211.3	290.3	153.3	246.8	349.3	181.4	202.5	328.5
Compound	k_1	104.46	208.43	740.80	144.30	739.20	1640.16	163.58	520.12	1105.77
	k_2	0.20	0.20	0.15	0.18	0.34	0.43	0.13	0.29	0.37
	k_3	-0.34	-0.25	0.05	-0.24	0.00	0.08	-0.20	0.01	0.01
	R^2	0.72	0.70	0.65	0.55	0.90	0.93	0.53	0.73	0.90
	RM (MPa)	134.3	211.4	390.1	153.3	246.7	348.4	181.5	202.5	328.1
Universal	k_1	2849.9	3674.9	3245.99	2649.35	2497.19	3016.35	2870.91	1979.15	3271.91
	k_2	0.33	0.33	0.32	0.31	0.54	0.66	0.24	0.43	0.58
	k_3	-0.66	-0.51	-0.006	-0.50	-0.25	-0.21	-0.41	-0.18	-0.26
	R^2	0.81	0.80	0.51	0.64	0.90	0.93	0.64	0.72	0.90
	RM (MPa)	134.1	211.3	368.2	153.4	248.5	350.9	181.9	202.7	330.2

For horizon B, the compound model yielded a RM gain of 60.9% when comparing samples compacted at intermediate energy to those compacted at standard energy. Likewise, due the compaction increase, from standard to modified, there was a gain of 127.3% in stiffness. In comparing intermediate to modified energy compaction, a 41.2% increase was reported. In general, for horizon B, all evaluated models yielded good correlations for samples compacted at IE and ME. However, for SE, the Biarez and stress invariant models did not provide a sufficiently good fit. Therefore, only the compound and universal models presented a good fit.

Among all horizons, horizon C presented the lowest gains in stiffness as the compaction energy increased. For the compound model, an increase in energy from standard to intermediate, yielded a RM gain of 11.6%. In a comparison between intermediate and modified energy, the gain was 62% and between standard and modified it was 80.8%. The precision of fit analysis shows that the behavior of this horizon was similar to horizon B, in terms of the models that best fit each compaction energy. At all energy levels the universal model presented a better fit for this horizon, followed by compound model.

In order to evaluate the resilient behavior of the material under saturation, three specimens from horizon B were compacted at intermediate energy. These specimens remained immersed for 96 hours, according to the procedure performed by Medina et al. (2006) and were subsequently submitted to RM tests. Table 4 presents the specimen properties and the resilient parameters for the set of samples analyzed.

Evaluating the RM obtained from the parameters of the compound model, an average RM of 66.7 MPa was reached, value 72.9% lower than the RM reached in the unsaturated condition of horizon B, compacted at IE (246.7 MPa). This decline in the resilient behavior of the soil is consistent with studies developed by Thadkamalla & George (1995), in which 50-75% reductions in RM were reported depending on the degree of saturation. It therefore follows that if drainage is not designed and executed properly, it can affect the performance of the material, because bearing capacity is drastically compromised on contact with water.

One of the objectives of this article was to determine whether there is a relationship between compaction energy and the coefficient of determination for each model. For the compound and universal model, each sample exhibited different behaviors under the varying compaction conditions, so it was not possible identify any behavior trend for R^2. The Biarez and stress invariant models were the only ones that yielded similar behavior, where, there was not a good fit at low energy levels, whereas at modified energy, the R^2 values were high.

Since the mathematical analysis of horizon B material showed the best fitting, this material was selected to be examined regarding stresses action. Furthermore, this horizon was chosen because it had a lower organic matter content, compared to horizon A, and because it exhibits an absence of sediments from the original rock, unlike horizon C. Figure 5 shows the behavior of the specimens relative to variations in compaction energy levels according to the (A) Biarez, (B) Svenson e (C) stress invariant models.

The resilient behavior at standard compaction energy differs from the other energy levels for the three models under analysis. The samples compacted, at IE and ME energy tests, behaved as follows: as the stresses increased, the RM also increased. The opposite occurred for the samples compacted at SE energy test. The variation of the RM results is higher for samples compacted at standard energy.

3.3. Mechanical characterization of undisturbed samples

After the procedure for reducing the specimen dimensions, three undisturbed soil samples from the interior of the embankment and three from the top layer were subjected to repeated load triaxial test for determination of the resilient

Table 4. Characteristics and resilient parameters of the immersed samples – Horizon B – IE.

Characteristics and parameters	Sample 01	Sample 02	Sample 03
Compaction moisture content (%)	25.20	25.30	25.10
Dry unit weight (kg/m^3)	1630.20	1628.90	1631.50
Compaction degree (%)	100.32	100.24	100.40
Average diameter after compaction (cm)	10.09	10.11	10.11
Average height after immersion (cm)	20.27	20.61	20.40
Moisture content after immersion (%)	31.93	32.38	33.36
Average diameter after tests (cm)	10.20	10.19	10.27
Average height after tests (cm)	20.18	20.37	20.07
Moisture content after tests (%)	30.17	30.04	30.47
Compound model – k_1		116.14	
Compound model – k_2		0.46	
Compound model – k_3		-0.33	
Compound model – R^2		0.84	
RM average (MPa)		66.70	

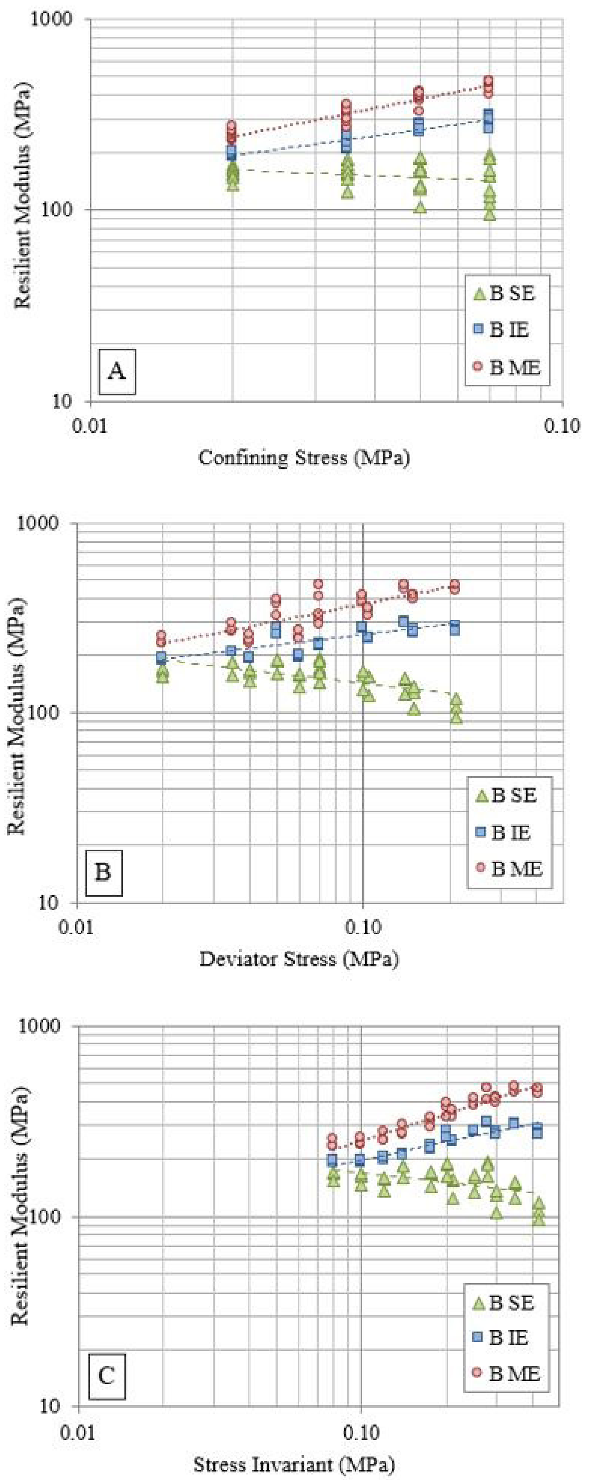

Figure 5. RM behavior for horizon B at three compaction energy levels, based on the (A) Biarez, (B) Svenson and (C) stress invariant models.

modulus. Table 5 presents the quality control for each sample before and after the resilient modulus tests. It is worth noting that the moisture content of the interior of the embankment at the time of collection was 46.07% and the top layer was 21.52%. The maximum dry density of the top layer, obtained with a core-cutter was 1645.30 kg/m^3.

Regarding the measurement of the resilient parameters of the undisturbed soil samples, the results of the 12th pair of stresses from two samples from the interior of the embankment were disregarded. This was due to the interruption of the test at this pair, when the measurement capacity of the linear variable differential transformer (LVDT) had ended. Table 6 presents the parameters of resilience each of the models analyzed, as well as the average resilient modulus.

Note that the moisture contents of the undisturbed field samples, especially those from the interior of the embankment, were 18% to 37.5% higher than the optimum moisture content of the samples from the soil horizons compacted in the laboratory. This may explain the low resilient modulus for the undisturbed samples. In general, for the specimens from the interior of the embankment, the Biarez and stress invariant models presented the worst fit, while other models presented a better fit. The analysis of the parameters obtained from the compound model, for the sample set, reveals a negative value for parameter k3, indicating a decrease in the RM with increases in the deviator stress. The positive values for k2 indicate that increases in confining stress, yields increase in the RM. In order to illustrate the behavior of undisturbed samples taken from the interior of the embankment, Figure 6 A presents a three-dimensional-graph of results from the compound model for these samples. Furthermore, the increase in the deviator stress and confining stresses and the resulting decrease in the resilient modulus values evidence of the non-linear behavior of the material under these specific conditions.

Unlike the undisturbed samples from the interior of the embankment, the samples from the top layer exhibited an improvement in the RM as the stresses increased. In this case, the k2 parameter, for the Biarez, Svenson and stress invariant models produced a positive value, indicating that as the confining, deviator or principal stresses increased, the resilient modulus also increased.

Figure 6 B represents the behavior of undisturbed samples from the top layer using the compound model. As the confining stress increases, the resilient modulus also increases. It is worth mentioning that the universal model presented a better fit than the compound model for the top layer of the embankment.

Based on the parameters obtained from the compound model for undisturbed samples from the top layer of the embankment, this soil presented an average RM of 309.4 MPa, behavior considered satisfactory for the properties of the soil and its application. When compared to the average RM value from the horizon B (246.7 MPa) compacted sample at intermediate energy, the same energy employed in the field, a lower value than the obtained for undisturbed samples from

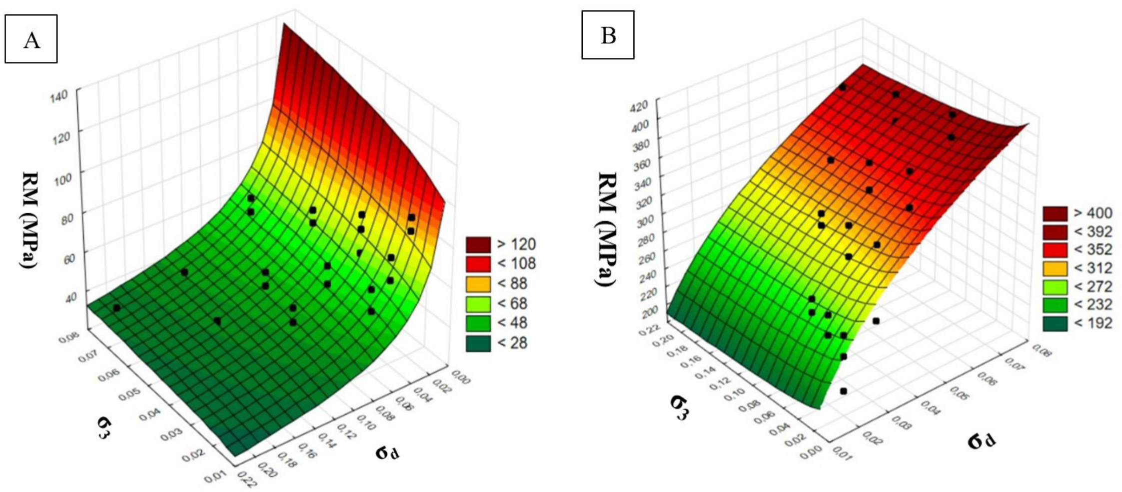

Figure 6. Three-dimensional graph of the undisturbed samples from the (A) interior of embankment and the (B) top layer, using the compound model.

Table 5. Characteristics of the undisturbed samples before and after the RM test.

Sample	Average diameter(cm)	Average height (cm)	Moisture before the test (%)	Average moisture after the test (%)
Interior of Embankment - 01	9.95	19.98	50.25	50.99
Interior of Embankment - 02	10.25	20.21	51.80	51.47
Interior of Embankment - 03	10.02	20.06	51.25	51.36
Top layer – 01	10.03	19.79	20.27	20.03
Top layer – 02	10.00	19.96	20.84	20.08
Top layer – 03	10.05	20.02	20.55	20.15

Table 6. Parameters of resilience for the undisturbed samples.

Models		Interior of Embankment	Top layer
Biarez	k_1	17.70	775.59
	k_2	-0.34	0.29
	R^2	0.26	0.68
	RM (MPa)	53.9	309.5
Svenson	k_1	17.12	433.04
	k_2	-0.42	0.13
	R^2	0.78	0.28
	RM (MPa)	53.4	309.5
Stress Invariant	k_1	24.46	454.16
	k_2	-0.46	0.24
	R^2	0.53	0.55
	RM (MPa)	53.5	309.5
Compound	k_1	21.57	792.87
	k_2	0.12	0.32
	k_3	-0.48	-0.03
	R^2	0.80	0.69
	RM (MPa)	53.4	309.4
Universal	k_1	1476.72	3394.95
	k_2	0.18	0.51
	k_3	-0.78	-0.29
	R^2	0.81	0.71
	RM (MPa)	53.3	310.4

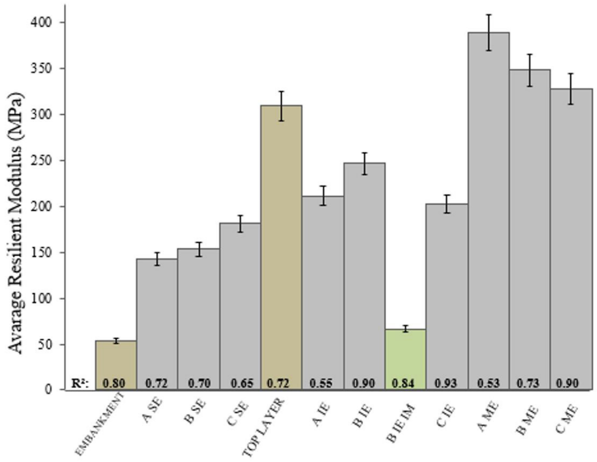

Figure 7. Average Resilient modulus determined by the compound model.

the top layer. This behavior can be explained by the fact that the compaction moisture in the field samples is lower than the optimum moisture content of the laboratory samples for all horizons. The field moisture content of the top layer specimens was near the OMC of the samples compacted at modified energy. Therefore, the resilient modulus values are similar, presenting good performance in terms of resilient behavior.

Figure 7 shows an average resilient modulus for each condition studied, as well as the coefficient of determination, based on the compound model. The values expressed within the bars refers to the R^2 for sample condition. The difference in the average RM for the undisturbed samples from the embankment interior is evident, when compared to the soil horizon specimens compacted at standard energy. Moreover, the loss of resilience in the immersed samples from horizon B, compacted at intermediate energy (B IE IM), can be seen when compared to other compacted samples at the same energy level.

The soil deposit horizons, with varying compaction energy levels, presented average resilient modulus values between 134 and 390 MPa, and the average resilient modulus values for the embankment layers were between 53 and 309 MPa. The variation in the RM for the three horizons of the deposit, with the increase of the compaction energy, tends to show significant impact on the bearing capacity, directly affecting structural design and performance.

In order to determine the influence of the physical indexes on resilient modulus behavior, the relationship between the RM of each sample to its void ratio (e), optimum moisture content (OMC) and maximum dry density (MDD) was investigated. Table 7 presents the data from the samples that were subjected to resilient modulus tests, as well as their respective compaction energy and origin. These relationships are illustrated in Figure 8, the relationship between RM

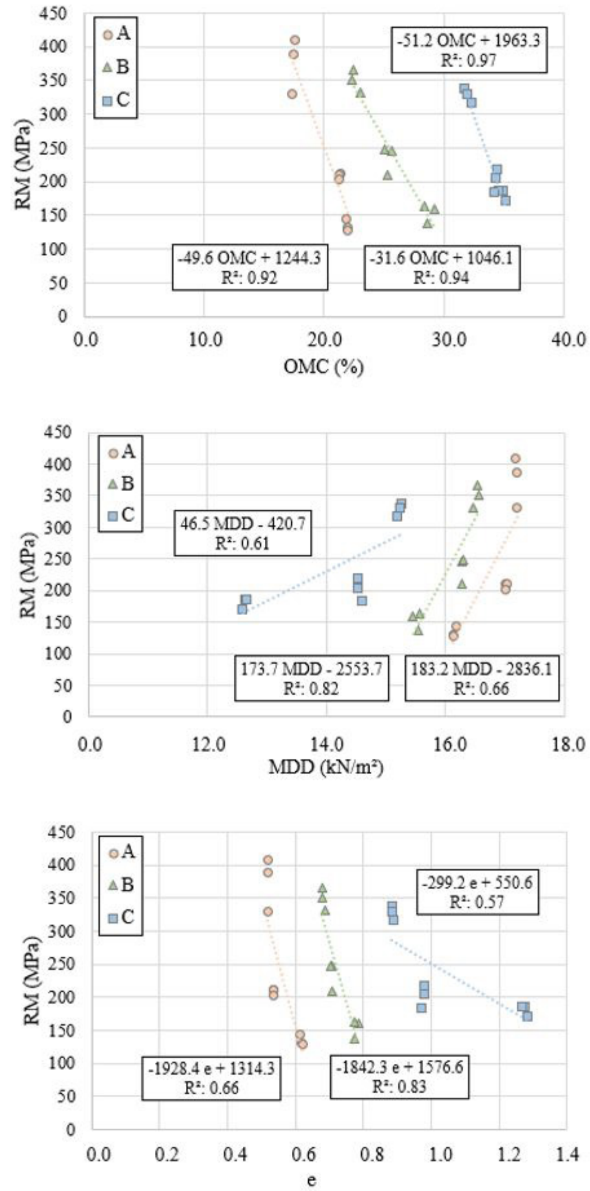

Figure 8. Correlations between the RM and the physical indexes for the samples analyzed with compound model.

and OMC, between RM and MDD and the relationship between RM and void ratio. Note that the RM of each sample corresponds to the average for all of the stresses, based on the compound model.

Among the correlations performed, the relationship between the RM and the OMC yielded the best R^2, indicating that the compaction moisture has a higher influence on the resilient behavior of this deposit, although the density and the void index are related to this physical index. Analyzing simultaneously the three correlations and the three horizons, horizon B presented the strongest relationships and best fit. All of the correlations were considered satisfactory.

Table 7. Physical indices of samples compacted in the laboratory, submitted to RM tests and analyzed with the compound model.

SOIL		Standard Energy			Intermediate Energy			Modified Energy		
Horizon A	RM (MPa)	131.0	128.0	143.6	211.2	210.6	202.4	330.3	408.5	387.7
	e	0.62	0.62	0.61	0.54	0.53	0.54	0.52	0.52	0.52
	OMC (%)	21.94	22.02	21.89	21.43	21.29	21.33	17.35	17.61	17.43
	MDD (kN/m^3)	16.13	16.13	16.19	17.01	17.03	17.02	17.21	17.17	17.20
Horizon B	RM (MPa)	159.6	163.4	137.2	246.5	248.1	209.4	351.3	331.5	366.0
	e	0.79	0.77	0.77	0.71	0.70	0.71	0.68	0.69	0.68
	OMC (%)	29.25	28.42	28.58	25.70	25.10	25.31	22.33	23.01	22.48
	MDD (kN/m^3)	15.46	15.57	15.56	16.27	16.32	16.29	16.55	16.47	16.54
Horizon C	RM (MPa)	187.0	170.9	186.4	218.6	204.5	184.2	338.2	329.8	316.8
	e	1.28	1.28	1.27	0.98	0.98	0.97	0.88	0.89	0.89
	OMC (%)	34.87	35.14	34.55	34.41	34.33	34.20	31.69	32.00	32.26
	MDD (kN/m^3)	12.63	12.60	12.67	14.53	14.53	14.59	15.26	15.24	15.20

Note: void ratio – e.

4. Final considerations

The performance of a pavement is directly correlated with the performance of the materials that compose it. Given that relationship, a new M-E pavement design methodology (MeDiNa) has been developed in Brazil, aimed at analyzing materials under a mechanistic-empirical approach, ensuring durability and quality parameters. For materials that compose the base, sub-base, subgrade and subgrade reinforcement for pavement layers, this analysis is performed by tests and modeling of the resilient modulus. The present study aimed to evaluate the physical and chemical properties and the resilient behavior of a soil deposit used as subgrade in an embankment for a stretch of highway RS 342, in Cruz Alta, using disturbed and undisturbed samples.

The MCT classification and the chemical analyses showed that the deposit under study is composed of lateritic soils, rich in silicon, iron and aluminum oxides, which offers a good behavior as pavement subgrade. The MCT classification is more suitable for tropical soils, since according to the traditional classifications, USCS and AASHTO, the soil in question would be classified as having fair to poor behavior for use in pavement structures.

The mechanical characterization was carried out by means of resilient modulus tests, for compacted specimens at standard, intermediate and modified compaction energies for three horizons of a soil deposit, and then fitted according to the Biarez, Svenson, compound, universal and stress invariant models. As expected, the resilient behavior increases with the increase in compaction energy, although it is not proportional for all horizons. Based on analysis with the compound model, soil Horizon B had the highest percentage increase in RM from standard energy to intermediate energy; and the smallest increase from intermediate to modified energy. The material from this horizon was used to study of resilience loss after sample saturation, demonstrating the behavior of subgrades subject to poor drainage. The RM declined considerably, showing that, sometimes, the material completely loses its bearing capacity, leading to total rupture.

For the undisturbed samples, the top layer of the embankment, which exhibited a degree of compaction of 100%, presented good resilient modulus values, while the values from the interior of the embankment were not as satisfactory. This behavior can be attributed to the moisture content of the extracted samples, considerably different from the optimum wet content found in laboratory tests. Thus, it is evident the need to control the compaction.

Based on these findings, the compound or universal models are the best options when working with a variety compaction energies and materials; and when it is important to use a standardized model.

The gain in RM, as compaction energy increases, can directly affect the distribution of internal stress of a pavement and it can be correlated with the parameters of compaction curves and soil physical indices. This fact reinforces the need for executive control and influences the design of the structure as well as its performance over its service life.

Finally, the present study contributes to the consolidation of the methodologies for pavement design and evaluation according to MeDiNa. It also contributes to increasing the database of pavement construction materials widely used in southern Brazil, such as the red latosols, present throughout Brazilian territory.

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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

Paula Taiane Pascoal: conceptualization, methodology and experimental procedures, formal analysis, writing – original draft, review and editing. Amanda Vielmo Sagrilo: validation, experimental procedures, writing – review e editing. Magnos Baroni: advisor, supervision, validation, writing – review e editing. Luciano Pivoto Specht: supervision, funding acquisition, project administration, writing – review. Deividi da Silva Pereira: funding acquisition, project administration, writing – review.

List of symbols

θ	Principal Stress
τ_{oct}	Octahedral Stress
k_1, k_2, k_3	Resilient Parameters Experimentally Determined
ρ_a	Atmospheric Pressure
σ_3	Confining Stress
σ_d	Deviator Stress

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