Contribution to the Study of Brazilian Tropical Soils as Pavement Materials

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ABSTRACT

Among the main factors that affect the predictive capability of pavement design and analysis methods, one can mention the proper definition of representative loads, layer geometry, and material properties, obtained from well-designed experimental testing protocols. Several properties and parameters have been selected to represent the constitutive behavior of the materials in the different layers of the pavements. The design method currently employed in Brazil is based on the California Bearing Ratio (CBR) parameter, which is not the most appropriate choice. For instance, the generally well-performing lateritic soils, which are typically found in tropical regions and successfully used in low cost pavements, are often considered inadequate for base and subbase. In addition, the study of permanent deformation of flexible pavements based on laboratory triaxial load tests is critically important to properly characterize and classify tropical soils. In this paper, a lateritic soil was analyzed based on an experimental program that included conventional characterizations, Miniature, Compacted, Tropical (MCT) procedures, and cyclic loading tests performed to assess permanent deformation (PD) and resilient modulus (RM) of the soil. During the tests, key parameters, such as stress levels, moisture, and compaction energy were varied. A further study using the SisPavBR software was conducted to analyze the mechanical responses of the lateritic soil in a pavement structure. The soil evaluated presented good resistance to PD after 150,000 load cycles and high RM for both tested energies and can possibly be regarded as a good pavement material. In addition, this research also aims to generate a relevant database information about lateritic soils which can be useful for next generations of mechanistic-empirical pavement design guides.

Keywords: pavement material, lateritic soil, repeated load triaxial test, resilient modulus.

1. INTRODUCTION

Brazil is a large country with vast tropical areas where the so-called lateritic soils are abundant. These materials are highly weathered soils and have been applied satisfactorily in pavements with light or medium traffic, presenting some advantages such as small deflections and absence or low incidence of rupture when used for subbase/base layers [1].

For many years, the design method employed in Brazil was based on the California Bearing Ratio (CBR) parameter. However, the newly released Brazilian mechanistic - empirical design guide has adopted a more scientifically - sound strategy that is based on a mechanistic stress analysis procedure. The mechanistic analysis requires the determination of material characteristics from repeated load triaxial tests. The resistance to permanent deformation of the materials is then modeled following the so-called Guimarães model [2].

The mechanical characteristics of soils, such as the resilient modulus (RM), vary with many factors, including the material mineralogy, moisture content, compaction energy, and stress state [2, 3, 4]. The proper characterization of permanent deformation (PD) and elastic deformation through repeated load triaxial (RLT) tests is very important for the analysis of unbound materials of the pavement layers. The RLT tests are currently the most popular procedures to determine the PD and the RM. In Brazil, they have been performed routinely for a long time.

As for moisture, the environmental and drainage conditions of the pavement can greatly affect the physical characteristics of the soil and this directly influences the value of RM. According to [5], in a humid tropical environment, it is not surprising that the in situ moisture content in subgrade, subbase, and base is relatively low.

Some researchers [6-8] aimed to study the moisture variation in the field, changing the moisture of the already compacted test specimen in the optimum moisture. [2] varied the moisture content by increasing it from the optimum for a laterite specimen from Rondonia (Brazil) and that resulted in excessive permanent deformation during the initial phase of the permanent deformation test. For the other soils (clayey or clayey sand) studied by [2], the assumed moisture variation generated a larger difference of accumulated permanent deformation values than for the resilient modulus test results. [9] studied the permanent deformation in sandy granular soils that constituted the subgrade of some highways in Kuwait. The samples were prepared with three levels of compaction moisture. They observed that the permanent deformation increased with the humidity of compaction. In addition to these, [3] performed a total of 12 tests varying 5% by weight the fine amount and 1% by weight the moisture content (OMC-1% and OMC+1%) for each fine variation. They found for all fine contents that the increase in moisture content resulted in the increase in the permanent deformation and in the decrease of the resilient modulus. It is worth noting that the Brazilian technical standards admit a field variation of 2% from the optimum moisture regardless of the nature of the soil.

The testing samples are often compacted in the normal Proctor energy for the subgrade, although the intermediate Proctor energy has also been applied to the subgrade considering that higher tire pressures may create larger stress levels in that layer. The energy denominated intermediate differs from the modified energy only by the number of blows being applied normally in the intermediate layers of the pavement. [10] observed that the predominance of fine materials together with the low compaction energy (normal) resulted in high rates of deformation, which motivated the study of one of the soils also using intermediate energy. The researchers suggested that studies about the use of the intermediate compaction energy for the subgrade should be pursued.

Although research is being carried out on PD and RM in Brazil, an effort is required to increase the database to further improve project procedures. Thus, the primary objective of this research is to present a discussion of results from the RLT test for one fine lateritic soil. The specific objectives are:

- To analyze and classify the PD accumulation according to [13] and the shakedown theory,
- To compare the two loading conditions proposed by the Brazilian standard [11] of RM,
- To investigate the influence of the compaction energy and of the moisture content on the RM of the lateritic soil,

- To analyze the applicability of the lateritic soil in numerical simulations using the SisPavBR software.

2. MATERIALS AND METHODS

The soil evaluated in this research was collected in a subgrade in different segments of BR-493, a federal Brazilian highway. Traditional characterization tests were performed to determine the liquid limit (LL), plastic limit (LP), and the gradation of the material. The sample was analyzed according to the MCT classification methodology [12], which has the main purpose of distinguishing soils of lateritic behavior from those of non-lateritic behavior, given that the lateritic ones exhibit properties that are not taken into account by traditional soil classification approaches, such as high resistance, low deformability, and low expansibility. The mechanical behavior of the material was characterized based on RLT tests to determine RM and PD.

In addition to the laboratory tests, a parametric analysis was conducted using the SisPavBR software to illustrate the effects of the RM of the base layer on the mechanical responses of the pavement structure. For this analysis, the RM tests were performed in the intermediate energy for the two sets of loading at OMC (568 MPa for the largest pairs of loading evaluated and 466 MPa for the other pairs), and for the highest set of loading at OMC+2% (609 MPa) and OMC-2% (232 MPa). The traffic level adopted was 5.27×10^6 ESALs. The asphalt concrete layer was assumed to be composed of an elastic and isotropic material with elastic modulus of 9588 MPa, Poisson ratio of 0.30, and thickness of 10 cm. The base had Poisson ratio of 0.35 and thickness of 30 cm. The subgrade layer had elastic modulus of 189 MPa, Poisson ratio of 0.35, and infinite thickness. PD characteristics of the base and subgrade layers were obtained from the calibration of the Guimarães model [2] parameters.

2.1 Permanent Deformation Test

To assess the permanent deformation resistance of the soils, cyclic loading tests were performed at 2 Hz (0.1 s loading and 0.4 s unloading), with at least 150,000 cycles of load application and nine different stress levels (one stress state for each specimen). The conditioning of 50 repeated cyclic loads with confining and deviator stresses of 30 kPa was applied to all specimens. The intermediate compaction energy was selected because it was used in the compaction of the segments from which the samples were extracted. The OMC was 17.8% and the maximum dry density (MDD) was 17.59 kN/m³.

From the information obtained in these tests, it was possible to find the parameters of Eq. 1, the Guimarães model [2], by nonlinear multiple regression, and to classify the behavior of this type of material based on the shakedown theory following the suggested graphical model and classification by [14, 15].

$$\varepsilon_p(\%) = \psi_1 . \left(\frac{\sigma_3}{\rho_0}\right)^{\psi_2} . \left(\frac{\sigma_d}{\rho_0}\right)^{\psi_3} . N^{\psi_4} \quad (1)$$

where
$\varepsilon_p(\%)$: specific permanent deformation;
$\psi_1, \psi_2, \psi_3, \psi_4$: regression parameters;
σ_3: static confining stress (kgf/cm²);
σ_d: deviator stress (kgf/cm²);
ρ_0: reference pressure (atmospheric pressure - 1 kgf/cm²);
N: number of load application cycles.

2.2 Resilient Modulus Test

In this research, in addition to tests performed in the OMC and in the intermediate energy, other four conditions of humidity and another compaction energy were adopted to evaluate the behavior of the lateritic material.

The test specimens were homogenized considering different moisture contents to verify the influence of moisture on the soil resistance in the triaxial test: OMC-2%, OMC-1%, OMC+1%, and OMC+2%. The chosen energies were normal and intermediate because they are the most used for subgrade layers and base/subbase with soils. Three tests were performed at a frequency of 1 Hz (0.1 s loading and 0.9 s unloading) to determine the RM for each moisture condition.

Another aspect analyzed was the possibility of performing the RM tests on the lateritic soil using high stress levels that the new Brazilian standard [11] recommends to avoid when subgrade soils are tested, as shown in Figure 3. For this analysis, the tests were performed using the normal and the intermediate energies and considering only on optimum moisture.

3. RESULTS AND DISCUSSION

In addition to the soil evaluated in this paper, characteristics of other five lateritic soils from different Brazilian states were found in the literature. Those materials were tested in the OMC in RLT experiments. Relevant properties are summarized in Table 1. Although they are materials from different places, the RM values for the normal compaction energy were smaller and the ψ_1 are considerably higher than for the intermediate energy.

TABLE 1 Summary of data of Brazilian fine lateritic soils

Reference	State	MCT Classification	LL(%)	LP(%)	Compaction Energy	OMC (%)	MDD (kN/m³)	RM average (MPa)	PD			
									ψ_1	ψ_2	ψ_3	ψ_4
This study	RJ	LG'	68	22	Intermediate	17.8	17.59	568	0.094	0.380	0.946	0.042
[2]	SP	LG'	-	-	Normal	24.0	16.65	258	0.206	-0.240	1.340	0.038
[16]	MA	LG'	45	18	Intermediate	26.5	14.58	393	0.021	0.606	2.048	0.091
[17]	MA	LG'	-	21	Intermediate	24.0	16.30	305	0.088	-0.146	1.618	0.063
[17]	MA	LG'	68	26	Intermediate	23.0	16.70	425	0.048	0.033	2.154	0.045
[2]	ES	LG'	60.3	22.5	Normal	18.0	-	176	0.453	-0.186	1.084	0.058

Note: RJ = Rio de Janeiro; SP = São Paulo; MA = Maranhão; and ES = Espírito Santo.

Figure 1a shows the evolution of PD with the number of load applications for several ratios between the confining and the deviator stresses. The same moisture content and compaction energy were used in these cases. As expected, PD increases with the applied stresses. Figure 1b shows the PD rate, which is often used for the evaluation of the shakedown behavior of granular materials and soils. As shown, the material presents a predominantly elastic behavior after a long period of load application, which indicates that the material reached the shakedown region. Finally, Figure 1c shows the evolution of RM with the load cycles. For most cases, RM became constant after 150,000 cycles with magnitudes ranging between 500 and 1,000 MPa. The exception was the 40/40 case, which presented variability between 100,000 and 150,000 cycles.

The parameters presented in Table 2 were obtained considering the new Brazilian RM standard. The experimental results and the sets of loading are shown in Figure 3. The material resisted the most critical stress set and the RM results presented percentage differences of up to 35%. The greatest differences were observed when larger deviator stresses were applied. It was identified that the RM results from subgrade stresses levels were smaller and this could be due to the fact that only the lower stress state was applied in the conditioning stage.

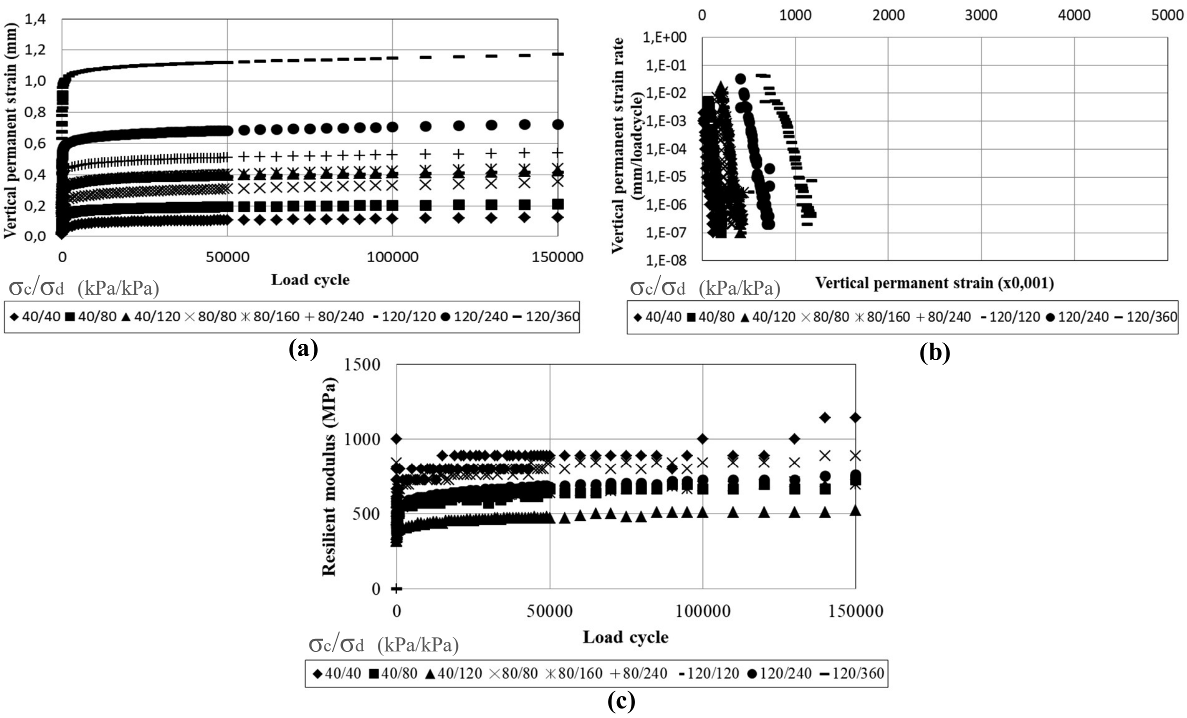
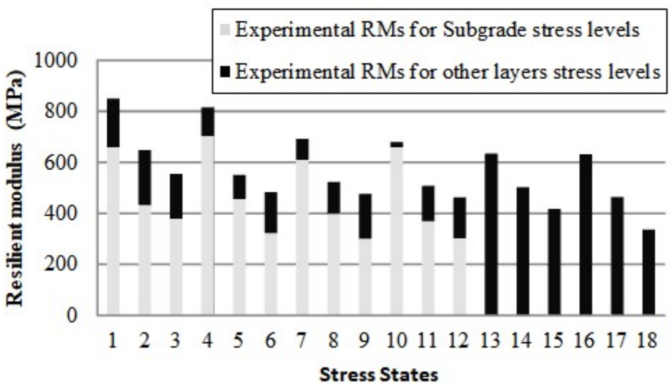


FIGURE 1 Results from PD tests (a) PD in mm (b) Shakedown analysis (c) RM

TABLE 2 Regression parameters of RM model for the two stress sequences

Model: $RM = k_1\sigma_3^{k_3}\sigma_d^{k_3}$							
From sets of loading for others layers				From sets of loading for subgrade			
Coefficients	k_1	k_2	k_3	Coefficients	k_1	k_2	k_3
Average	430.2	0.2420	-0.4160	Average	531.5	0.6125	-0.7330



	σ_3 (MPa)	σ_d (MPa)
1	0,020	0,020
2	0,020	0,040
3	0,020	0,060
4	0,035	0,035
5	0,035	0,070
6	0,035	0,105
7	0,050	0,050
8	0,050	0,100
9	0,050	0,150
10	0,070	0,070
11	0,070	0,140
12	0,070	0,210
13	0,105	0,105
14	0,105	0,210
15	0,105	0,315
16	0,140	0,140
17	0,140	0,280
18	0,140	0,420

Conditioning Stage

Sets of loading for others layers

	σ_3 (MPa)	σ_d (MPa)
1	0,070	0,070
2	0,070	0,210
3	0,105	0,315

Set of loading for subgrade

	σ_3 (MPa)	σ_d (MPa)
1	0,070	0,070

FIGURE 3 Experimental RM results by the Brazilian standard loading conditions

The compaction curves presented the known tendency of decreasing OMC and MDD when higher compaction energies are applied. The change from normal to intermediate energy allowed RM results to increase up to 42% at the intermediate energy, with an average percentage difference of 23%.

Finally, Figure 4 shows the effects of moisture on the RM for the normal and intermediate compaction energies. The ratio between RM and RM at OMC increased when the moisture content decreased. The average percentage difference in modulus between the OMC case for intermediate energy and the OMC-2%, OMC-1%, OMC+1%, and OMC+2% cases were, respectively, 42%, 16%, 21%, and 68%. For the normal energy these differences were, respectively, 38%, 7%, 46%, and 71%. It is clear that RM was more susceptible to the compaction energy when higher moisture contents were used.

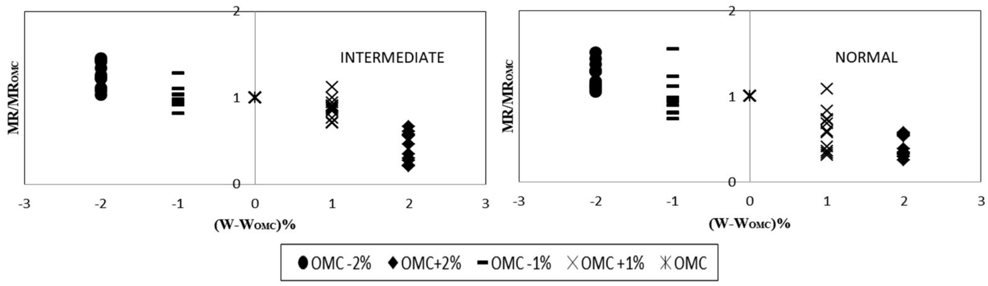


FIGURE 4 Relationships between RM from the different moistures content for intermediate and normal compaction energies

The substitution of the aforementioned structure for OMC condition in the SisPavBR resulted on PDs below 12.5 mm, which is the maximum permissible value for a highway project with high traffic volume. However, the four RM conditions of the lateritic soil presented different results regarding the predicted cracked area of pavement at the end of the established period: 3,67%, 15,18%, more than 40%, and 2,29%, respectively. The most critical position analyzed for PD was the middle of the layer, between wheels of an axle.

4. CONCLUSIONS

This paper presented a study on the characteristics of the so-called lateritic soils, typically found in tropical countries, such as Brazil. This type of soil presents few problems in pavement construction and typically performs better during the pavement service life than the clays of cold and temperate climates. The few studies found in the literature show the need for more tests on the RLT equipment for future pavement design using this high quality tropical soil.

The results indicated that the lateritic soil evaluated could resist the high loads that the new Brazilian standard recommends to avoid in RM laboratory tests of subgrade soils. In addition, the material was not very sensitive to the compaction energy although the resistance increased with the change from normal to intermediate energy. Regarding the moisture content, it was observed that water contents above the OMC reduced the stiffness and consequently increased the PD. However, OMC+2% was not enough to generate considerably low RM results (232 MPa and 163 MPa). Preliminary numerical simulations performed in the SisPavBr software showed that the pavement structure simulated could have a large cracked area in the asphalt concrete for the OMC+2 case. Finally, the evaluation of different compaction energies and moisture contents showed that the lateritic soil can potentially be used as a good pavement material.

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