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Mechanical characterization of an alternative laterite gravel used as pavement material

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Article

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Permanent deformation
Resilient modulus
Shakedown theory

Abstract

Laterite gravels have been successfully adopted as pavement materials in the field. Despite that, they are often rejected in material selection processes because of its base on traditional gradation and consistency limits requirements. To allow a deeper evaluation of such material found abundantly in tropical countries, along to characterizing traditional parameters, repeated load triaxial tests were performed in a Laterite Gravel from Acre/Brazil to evaluate its elastic and plastic behavior through Resilient Modulus (*RM*) and Permanent Deformation (*PD*), respectively. In addition, a simulation was conducted in the MeDiNa software, based on the test results considering stress states that are usually applied in pavement layers. The material showed *RM* values higher than 500 MPa, which was considered high compared to materials such as Quartz and Granite. It was also observed low permanent deformation (below 1 mm for higher tensions applied) and accommodation of displacement (shakedown) for most specimens. The simulation results showed low rutting prediction for the Laterite Gravel applied in highway pavement layers. Thus, the results indicated that the lateritic gravel can be adopted in the composition of base or subbase layers of flexible pavements, even though some limits of the parameters specified by traditional specifications were violated, as expected. In addition, we also highlight the need for adoption of new material selection strategies that are based on key mechanical characteristics to avoid discarding potentially well performing materials.

1. Introduction

The laterites or lateritic gravels are low-cost materials typically found in African and Asian countries. They are also abundant in Brazil, especially in the northern part of the country, and have been successfully used in the composition of unbound layers of Brazilian flexible pavement structures since the 1970s. Despite that, they are often discarded or recommended only after stabilization by material selection processes based on traditional parameters such as the particle size requirements and the Atterberg limits.

Several studies indicated the importance of the mechanical characterization of the laterites in experimental programs that go beyond the typical tests required by specifications. Cardoso (1987) studied Brazilian laterites and showed possible applicability for this material; Grace (1991) studied laterites from Kenya and Malawi in experimental sections concluding that although the laterites used do not fit any specification evaluated, such materials showed good behavior as base layer; Indraratna & Nutalaya (1991) studied laterites from Southeast Asia and concluded that in general such materials have promising use in geotechnical works.

Mahalinga-Iyer & Williams (1997) studied laterites from southeastern of Queensland (Australia) and they confirmed that laterites, in fact, performed well as paving material, proposing a material selection criterion; Seixas (1997) described characteristics of a laterite used as a sub-base at the airport in Rio Branco/AC and validated as a good material to be applied; Santos (1998) described physical and mechanical characteristics of laterites used on highways in Mato Grosso State (Brazil) which showed high Resilience Modulus (*RM*) and low permanent deformation; Vertamatti (1998) studied laterites used in several aerodromes in the Amazon region (Brazil), showing that such materials proved to be suitable for base layers of that type of pavement.

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Guimarães (2001) showed that a laterite from Brasília (Brazil) has a high resilient modulus and low permanent deformation even submitted to testing up to 1,000,000 load cycles; Omotosho (2004) investigated the influence of exclusion, or scalp, of part of laterite samples, indicating an important influence on its mechanical properties; Sunil et al. (2006) researched the influence of the water *pH* used for the *CBR* test immersion on laterites on the west coast of India, showing that the *pH* variation can generate significant changes in chemical characteristics of lateritic soils, Guimarães & Motta (2008) studied a laterite from Acre (Brazil) which does not fit the criteria of DNIT, standard DNIT 098 (DNIT, 2007), specific for laterites and showed that this material presented an average *RM* of 650 MPa, higher than some graded gravels, and total Permanent Deformation (*PD*) below 2 mm, for a sample test of 200 mm of height, considering various stress states, that is, very low values, corroborating the fact that this kind of material has a promising use in that region of Brazil.

In addition to these studies, Carvalho et al. (2015) and Barbosa et al. (2018) researched tropical soils in Brazil and showed that their physical, mineralogical, and chemical characteristics, including the soil structure, depend on the type of soil, and influence its geotechnical behavior. However, many authors such as Menezes et al. (2021), Silva et al. (2021), Lima et al. (2021a), and Freitas et al. (2020) have also been concerned with moisture content in lateritic soils and observed a deterioration of mechanical properties associated with its variation, especially for moisture content above optimum.

Paige-Green et al. (2015) argue that many laterites do not meet traditional standards for pavement layers, but experience indicates that it is a good material considering other specifications, concluding that the criteria used in Brazil are probably the ones most relevant. Dalla Roza (2018), in addition to studying the mechanical behavior of some laterites, also proposed pavement solutions as a structural catalog for her region in Brazil.

Analyses of laterite genesis aspects can also be found in Melfi & Carvalho (1983) and a review of specifications around the world for the selection of lateritic materials is provided by Paige-Green et al. (2015). More recent research efforts have analyzed the mechanical behavior of lateritic gravels for flexible pavements based on accelerated pavement testing and Finite Element Methods (FEM) simulations for M-E Pavement Design (Samb et al., 2018; Qian et al., 2019).

Since the research efforts by Morin & Todor (1975) and Gidigasu (1976), it is known that laterites that satisfy traditional criteria of *CBR*, gradation, and plasticity index present good performance as pavement materials, as long as they do not generate cracks after the construction. However, according to Netterberg (2014), laterites have not been used to their fullest extent in African upper layers (base and subbase) of paved roads for several reasons, and sometimes this happens in Brazil too. Those include the inadequacy with respect to the technical standard due mainly to the high plasticity index (*PI*), the difficulty of establishing gradations within the standard curves, and the low *CBR* values. In addition, the Los Angeles abrasion results are often unsatisfactory.

Mechanical tests performed by many researchers indicates good behavior for laterites and other tropical soils. Bona & Guimarães (2021) reported excellent behavior of *RM* and *PD* for a Brazilian laterite with satisfactory performance for pavement base layer, despite its low *CBR* value. Similar results were presented by Sousa et al. (2021), Lima et al. (2021b) and Guimarães et al. (2018). Guimarães et al. (2021) shows the result of field tests that corroborates with the mechanical properties predicted for a sandy lateritic soil, which was a low penetration rate and *PD*.

To overcome the shortcomings of traditional requirements and their inability to identify well-performing laterite gravels, alternative characterizations based on mechanical tests to assess the *RM* and the resistance to *PD* can be pursued.

It is worth noting that lateritic tropical soils can have a high amount of clay fraction, and this may intensify the plastic responses. However, such clay is composed of iron and aluminum sesquioxides, as well as minerals of the kaolinite group, which, besides not being expansive, provide good cohesion characteristics to the soil because they are natural cements. In other words, the significant existence of this clay fraction causes an increase in soil resistance when applied in the field. Based on this plastic peculiarity of laterite gravels, the specification of low allowable values for the plasticity index (*PI*) has caused high rejection of this type of material. For instance, the Brazilian standard DNIT 098 (DNIT, 2007) requires *PI* values smaller than 15%, although it has been observed that the use of materials with *PI* higher than 15% does not necessarily affect the field performance (Guimarães & Motta, 2008; Dalla Roza, 2018).

The practical regional experience indicate that laterite soils can be used in pavements layers without any type of stabilization for low to medium traffic volumes. However, additional studies are required to demonstrate that feasibility based on more scientifically sound characterizations. Thus, this study evaluates the mechanical characteristics of a specific material, the Acre laterite, which is very abundant in the northern part of Brazil.

Some early studies have analyzed certain aspects of gravel lateritic soils from the Acre State, including a geological characterization by Costa (1985) and the description of general aspects of the occurrences of these materials in the Amazon by Costa (1991). This material is usually locally employed in base layers of pavement structures after granulometric or chemical stabilizations. For the granulometric stabilization, unbound granular materials from the state of Rondônia are often used. The chemical stabilization, in turn, induces an increase in the natural cracking process of the layer with the addition of cement or hydrated lime, and this can cause a significant increase in the pavement final cost.

The accumulation of data with general characteristics of this type of material, as well as a deeper understanding on its mechanical behavior is important not only for the local knowledge, but also for the whole country, as the new Brazilian mechanistic-empirical asphalt pavement design (MeDiNa) has been recently proposed and focuses on the adoption of modern material selection methods. This study also aims to expand the knowledge on laterite gravels with good mechanical properties to other tropical countries, given that there is a limited number of research efforts documented in the literature about these materials.

2. Materials and methods

One Brazilian laterite, named in this study as Acre laterite gravel, was selected and characterized based on the laboratory tests. Some geological characteristics of this material, such as physical indexes, gradation, absorption, and results of and additional microscopic analysis are provided in this section.

To further evaluate the applicability of the Acre laterite gravel in the composition of pavement layers, mechanical tests were also performed on a repeated load triaxial (RLT) equipment to characterize its resilient modulus (*RM*) and resistance to permanent deformation (*PD*) based on its elastic and plastic behaviors, respectively. The testing results were used to calibrate regression coefficients for the predictive performance models implemented in the MeDiNa program. Simulations were performed considering the shakedown theory, which categorizes soils based on their ability to stabilize permanent deformations after a certain number of loading cycles.

2.1 Material selection and basic characterization

The Acre laterite gravel evaluated in this study was collected in the George Moura quarry, located along highway BR-317, in the State of Acre, between the cities Senador Guiomard and Epitaciolândia, as illustrated in Figure 1.

The physical indexes of the Acre laterite gravel are shown in Table 1. These indexes are analyzed based on the fraction passing sieve No. 40 (0.42 mm). The liquid limit was consistent with the Brazilian standard, i.e., $LL \leq 40\%$. However, as shown, the plasticity index (*PI*) of the material was 20.9%, which violates the maximum limit of 15% allowed in Brazil. Thus, the material would be rejected based on this criterion.

Table 2 summarizes the grain size distribution of the material and indicates the presence of 30% of fine material - silt or clay - passing sieve No. 200 (0.075 mm), 30% of the intermediate sand size, and 40% of the gravel fraction. The grain size distribution is also shown graphically in Figure 2.

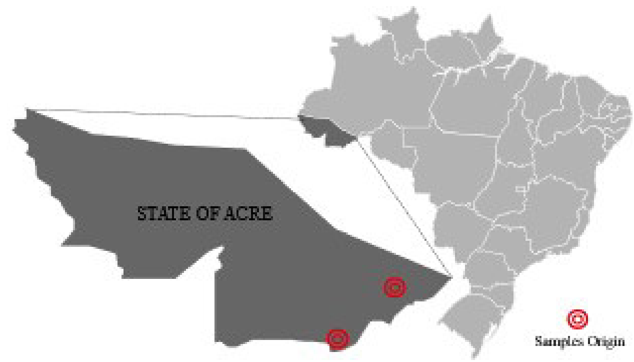

Figure 1. Location of the city of Rio Branco within the Brazilian Amazon.

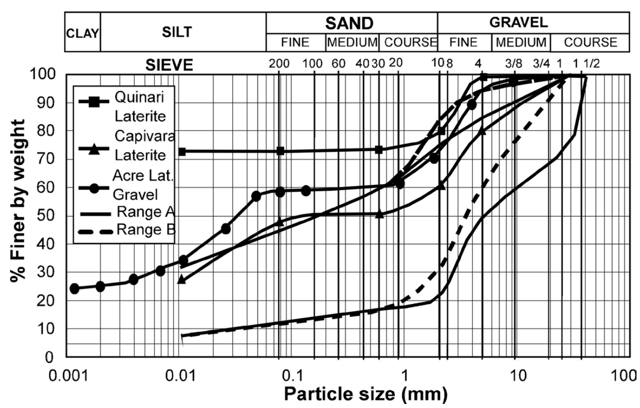

Figure 2. Gradation distributions of three Acre laterite gravels, including the one evaluated in this study, and two gradation envelopes from the Brazilian standard DNIT 098 (DNIT, 2007).

Table 1. Physical indexes of the Acre laterite gravel evaluated in this study.

Material	Plastic Limit – *LP* (%)	Liquid Limit – *LL* (%)	Plastic Index – *PI* (%)
Acre Laterite Gravel	13.6	34.5	20.9

Table 2. Physical indexes of the Acre laterite gravel of this study using the ABNT standard (ABNT, 2016) reference.

Material	Clay (%)	Silt (%)	Sand			Gravel (%)
			Fine (%)	Medium (%)	Coarse (%)	
Acre Laterite Gravel	19	11	21	8	1	40

In addition to the laterite evaluated in this study, Figure 2 also shows the gradation distributions of two extra laterites from the same state of Acre to improve the understanding on the characteristics of this material. It is noteworthy that, according to Guimarães (2009), although the two additional laterites do not meet the standardized technical requirements completely, both their plastic and elastic deformability characteristics are compatible with those from materials successfully adopted in the composition of pavement layers.

It is presented, along with the gradations, the limits for the gradation envelopes A and B specified by the Brazilian standard DNIT 098 (DNIT, 2007), as well as the gradation curves of the three Acre laterites, i.e., that evaluated in this study (Acre Laterite Gravel) and the other two additional materials (Quinari Laterite and Capivara Laterite). The figure emphasizes the variability of this type of material in the Amazon region.

Among the three laterites, the one from the Capivara deposit has the largest number of coarse aggregates and its gradation curve fits better within the limits for both envelopes specified by DNIT 098 (DNIT, 2007). This laterite is an exception to the general rule of the studied Acre laterites, being characterized and adopted since 1998, and present excellent results in the field as a pavement layer material. The laterite from the Quinari deposit is more representative of laterite occurrences in the Amazon region. It has been continuously used for urban paving in Rio Branco, the capital of the Acre state. It is a fine material with approximately 70% of the particles passing sieve No. 200.

It can be observed that there is usually a lack of particles with intermediate sizes, creating a plateau in the gradation curves. This is quite typical of the laterization process. The figure also illustrates that the laterite investigated in this study presents gradation between those of the other two laterites. For better visualization, Figure 3 illustrates the laterite gravel of this study.

Another important physical aspect to be analyzed in the study of laterites is absorption. Santos et al. (2012) demonstrated that such property may vary between 2% and 12%. They also compared the absorption of the laterite of this study with the absorption of a granite sample from Rondônia (another Brazilian state) that is often applied in pavements of Acre State. As shown in Table 3, the absorption of the Acre laterite is much higher than that of the Rondônia laterite.

Unlike the crushed granite, during the absorption experiment, air bubbles emerged from the pores of the Acre laterite gravel, forming a foam on the water surface, which is a consequence of the higher number of larger pores within the laterite. Figure 4 illustrates that the laterite in fact is a more porous material, for which several pores are visible to the naked eye. It is noteworthy that absorption interferes significantly in the determination of the optimum moisture content of the pavement layer.

Figure 3. Illustration of the Acre taterite gravel evaluated in this study.

Figure 4. Visual comparison between the porosities of the Acre laterite pores (above) and the crushed granite (below).

Table 3. Absorption results for the Acre laterite gravel and the Rondônia granite laterite (Santos et al., 2012).

Material	Wet sample mass (g)	Dry sample mass (g)	Absorption (%)
	294.8	271.0	9
Acre	298.8	277.7	8
	289.1	266.8	8
Granite	367.0	362.0	1
	365.4	363.4	1

A microscopic study was also carried out to determine the size of the pores. Figure 5 shows some images of the Acre laterite gravel and one image of the crushed granite. As shown, the Acre laterite gravel material indeed presents large pores that affect its absorption.

2.2 Mechanical characterization

In addition to the traditional characterization, mechanical *PD* and *RM* tests were performed to evaluate the mechanical behavior of the Acre laterite and to identify the plastic and elastic model parameters required by the MeDiNa program.

Table 4 shows information about moisture content, applied stresses (deviatoric, σ_d, and confining, σ_3), number of loading cycles (*N*), as well as plastic displacements obtained in the *PD* tests. The main differences between the two testing procedures are the number of loading cycles and the stress states that are applied to the specimens. The *RM* is a multi-stage test and is already well described in the literature (ASTM, 2003; NCHRP, 2004a, b). There are standards in different countries, including Brazil, which had some updates over the years (AASHTO, 2003; CEN, 2004; AG, 2006; DNIT, 2018a). On other hand, the *PD* testing procedures may vary significantly and thus the protocol followed in this research is described in this section.

The sample preparation procedure for both *PD* and *RM* tests was the same. The laterite gravel was homogenized in the optimum moisture content for at least 12 hours and was stored in a humidity chamber. The specimens were prepared in a tripartite cylindrical mold measuring 100 mm × 200 mm (diameter × height), indicated for particle sizes smaller than 25.4 mm. Scalping was not necessary because the maximum aggregate size of the Acre laterite gravel was 12.5 mm and its gradation is compatible with the dimensions of the mold used. All samples were compacted in the intermediate Proctor compaction energy, which is commonly adopted in Brazil.

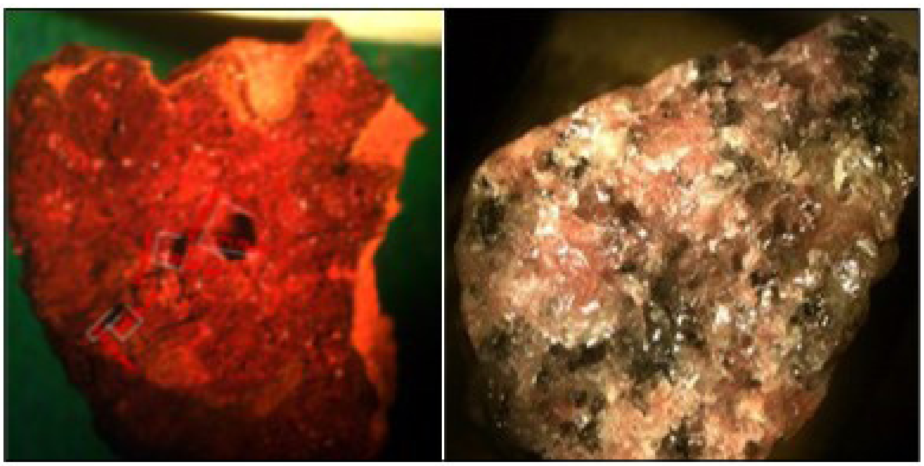

Figure 5. A microscopic image (magnification factor of 6.5) of (a) a sample of the Acre laterite gravel evaluated in this study and (b) a sample of crushed granite for comparison.

Table 4. Information about the *PD* test performed in this study.

Sample	Stresses		Moisture (%)	N	Permanent displacement (mm)	
	σ_d (kPa)	σ_3 (kPa)			$\varepsilon_{p10,000}$	$\varepsilon_{p100,000}$
Lat AC 01	105.0	105	11.03	161,312	0.220	0.220
Lat AC 02	210.0		11.04	245,252	0.635	0.635
Lat AC 03	315.0		10.68	257,200	0.864	0.952
Lat AC 04	157.5		10.90	257,200	0.719	0.734
Lat AC 05	300.0	150	10.80	245,500	0.735	0.760
Lat AC 06	100.0		11.84	415,000	0.832	0.824
Lat AC 07	200.0		10.20	111,500	0.501	0.534
Lat AC 09	100.0		10.26	243,418	0.316	0.328
Lat AC 10	50.0	50	9.50	56,295	0.116	-
Lat AC 11	100.0		9.80	150,300	0.225	0.236
Lat AC 12	400.0	150	10.56	72,658	0.619	-
Lat AC 14	157.5	105	10.49	231,453	0.581	0.598

The cyclic triaxial tests were conducted at 1 Hz (60 cycles per minute, with a pulse of 0.1 s and rest interval of 0.9 s). To allow the evaluation of the long-term potential of the material to stabilize the plastic deformations, at least 50,000 cycles were applied. In fact, most tests were performed with more than 150,000 loading cycles per stress state, which has been considered adequate for the characterization of the *PD* responses of the material.

One stress state was applied to each specimen. A total of 12 stress states were selected to represent field stresses typically occurring in the base and subbase layers of flexible pavement structures considering the standard axle of 820 kN. These values were selected based on backcalculations performed on Brazilian highways and *PD* publications and standards (CEN, 2004; AG, 2006).

Regarding specimen humidity, it can usually vary about 0.5% for fine materials and 1% for granular materials. The optimum moisture content of this material obtained with the compaction curve was 11.5%.

In cases of granular soils, the moisture variability is often considerably high and the process of checking the moisture of the samples by small capsules turns it more evident due to the gradation distribution. Thus, there are errors in the measurements and samples were considered valid if their moisture content was within OMC ± 2%, following the field practice adopted in Brazil. Therefore, out of the 14 samples tested, two were outside this range and consequently discarded: samples 8 and 13.

It is worth noting that the testing procedures adopted in this research follow the recommendations by the Brazilian standards for tests in the RLT equipment: DNIT 134 (DNIT, 2018a) and DNIT 179 (DNIT, 2018b) for *RM* and *PD*, respectively.

The testing results were used as input parameters to calibrate predictive models and to evaluate the potential applicability of the Acre laterite gravel in comparison with other laterites and different materials. Based on Werkmeister (2003) and Guimarães (2009), the shakedown theory was considered to identify the four plastic behaviors (A, B, C, and AB) according to the evolution and accumulation of permanent deformation.

With respect to the predictive models, the selected *RM* model is commonly used in the international literature, while the *PD* model follows procedures developed in Brazil by Guimarães (2009) and has been adopted by several researchers in the country (Guimarães et al., 2019; Dalla Roza, 2018; Lima et al., 2019). Both models are implemented in the MeDiNa program, which was used to simulate the mechanical responses of the Acre laterite gravel for the configurations shown in Figure 6.

All the materials, except the asphalt mixture and the surface treatment, were tested by the authors of this work. The asphalt mixture, the lateritic clayey material in the layers, and the clay subgrade were considered the same for all situations. A total of four structures and three different traffic levels were analyzed.

3. Analysis and results

3.1 Plastic behavior

Figure 7 shows the results of *PD* tests performed with the Acre laterite gravel. As expected, the largest plastic displacement of 1.018 mm (*PD* of about 0.5%) was obtained for the testing sample 12, which was subjected to the most severe stress state, i.e., deviatoric and confining stresses of 400 kPa and 150 kPa, respectively. As shown in Figure 7, test 12 was the only one for which it was not possible to identify a clear trend of *PD* accommodation because it was performed considering a small number of loading cycles (72,658).

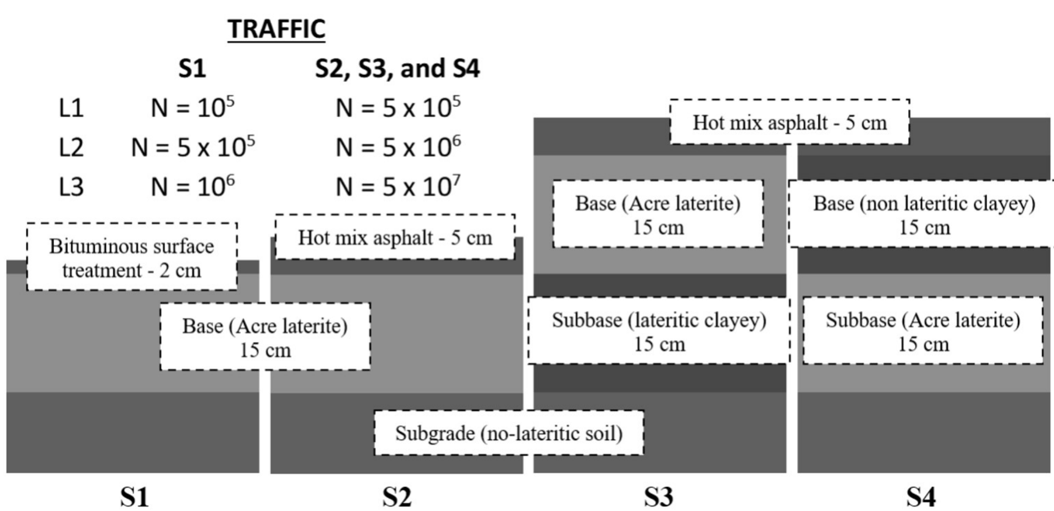

Figure 6. Information about the four sections analyzed in this study.

Table 5 presents the four cases (tests 1, 2, 3, and 14) for which the confining stress of 105 kPa was applied. The ratios σ_d/σ_3 were 1, 1.5, 2, and 3. These ratios were adopted so that a wide range of stress levels was applied to the samples.

The *PD* curves for tests 1, 2, 3, and 14 presented similar shapes with a clear trend of significant growth for the initial 10,000 cycles. After that, as shown in Figure 7, the *PD*s converged asymptotically to constant values. Another observation was on the relationship between the permanent displacements at 10,000 and at 100,000 cycles. In general, the test variations were lower than 11%, ranging between 1.36% and 10.19% for tests 1 and 3, respectively. The other samples results, except for test 12, also presented some *PD* accommodation trend.

Table 6 and Figure 7 also indicate that the *PD* increased with the deviator stress. For instance, the stress ratio $\sigma_d/\sigma_3 = 3$ caused a total plastic displacement more than 300% larger than the $\sigma_d/\sigma_3 = 1$ at $N = 100{,}000$. This indicates a non-linear relationship between the deviator stress and the resistance to permanent displacements and infers that the materials are more susceptible to plastic responses for larger deviator stresses. This type of behavior has already been observed by other authors for fine lateritic materials (e.g., Guimarães et al., 2019; Lima et al., 2019).

In addition, a shakedown analysis was performed for the Acre laterite gravel. As shown in Figure 8, most of the behaviors were of type A, which indicates that the *PD* of this laterite tends to accommodate after a certain number of load applications. This, in turn, infers that this material could be potentially adopted in the composition of pavement layers in the field, as it quickly accommodates and does not exhibit considerable initial deformations, even without stabilization to improve its load bearing capacity.

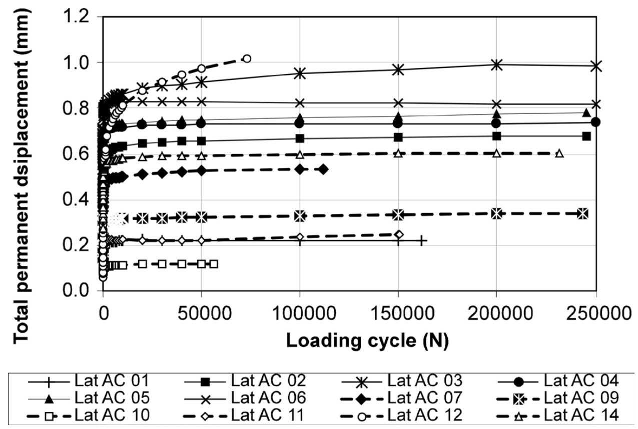

Figure 7. Total permanent displacements for the Acre laterite of this study subjected to various stress states.

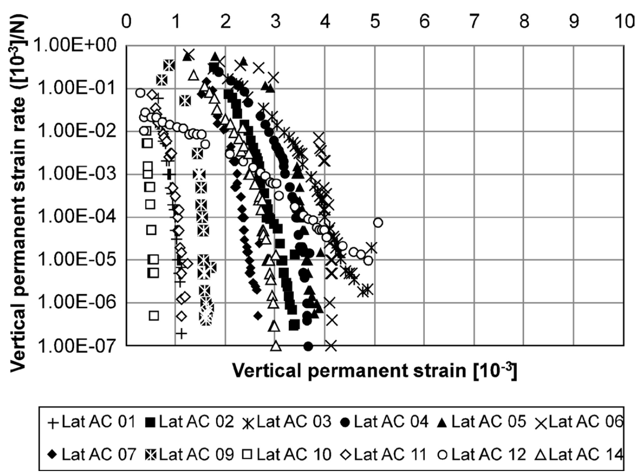

Figure 8. Vertical permanent strain rate *versus* vertical permanent strains of the Acre laterite of this study.

Table 5. Permanent displacement (mm) results for the four tests submitted to the confining pressure of 105 kPa.

Test	σ_d (kPa)	σ_d/σ_3	$\varepsilon_p^{initial}$	$\varepsilon_p^{10.000}$	$\varepsilon_p^{100.000}$
1	105.0	1	0.128	0.220	0.223
14	157.5	1.5	0.275	0.581	0.598
2	210.0	2	0.352	0.635	0.668
3	315.0	3	0.352	0.864	0.952

Table 6. Deformability parameters of the *RM* predictive model with respect to the confining stress for different laterites used in the city of Rio de Janeiro (Ramos & Motta, 2004).

Material	Resilient modulus $RM = k_1 \times (\sigma_3)^{k_2}$	*RM* (MPa)
Quartz monzonite	$RM = 782.9\ (\sigma_3)^{0.37}$	334
Trachyte	$RM = 1{,}018.1\ (\sigma_3)^{0.42}$	387
Granite	$RM = 731.5\ (\sigma_3)^{0.37}$	312
Quartz diorite	$RM = 896.8\ (\sigma_3)^{0.41}$	349
Acre laterite gravel of this study	$RM = 207.7\ (\sigma_3)^{-0.34}$	763

3.2 Elastic behavior

Figure 9 shows the *RM* results for the Acre laterite gravel, plotted in a log-log space in separated graphics to better illustrate the relationship with the deviator and confining stresses. Two replicates were tested and their *RM*s were 585 MPa and 566 MPa. A significantly stronger linear relationship with the deviator stress was observed, although this laterite is a granular material. This trend has been identified elsewhere in the literature for fine soils (Guimarães et al., 2019; Lima et al., 2019). This fact may be a consequence of good cohesion provided by the clay of this laterite, unlike other coarse materials that often present more sand and/or silt in their composition.

One way to evaluate the stiffness of the material is by comparison with other material results. Therefore, *RM* values obtained by Ramos & Motta (2004) for unbound granular materials from different quarries of Rio de Janeiro were compared to the ones obtained for the material evaluated in this study.

For the sake of comparison, Table 6 shows the *RM* for a confining stress of 100 kPa of the Acre laterite gravel and of other laterites used in Rio de Janeiro in Ramos & Motta (2004). The confining stress was selected to model the *RM* results because it was the most significant parameter for the granular materials analyzed by Ramos & Motta (2004). This is also often the case for materials with coarser aggregates.

As shown, the Acre laterite gravel presented *RM* value around twice the *RM* of the other laterites and this indicates that the material may be efficient to prevent the deformability of the pavement layer in which it is applied in the field.

3.3 Simulations and field considerations

With the results of the *PD* and *RM* tests, a non-linear multiple regression analysis was performed to identify the parameters used as inputs by the *PD* predictive model implemented in MeDiNa. Figure 10 shows the results of a parametric analysis performed to evaluate the rutting potential of the pavement layers, except for the asphalt surface layer, for which no *PD* was considered. In this analysis, the structures and traffic levels shown in Figure 10 were simulated.

As shown, the Acre laterite presented rutting of less than 0.2 mm, which is a low value, even considering measurement uncertainty that might be associated with the *PD* test (Santos et al., 2022). Therefore, the simulation indicates that it is a material with good deformability characteristics and can be a good option for the application in different structural layers and for distinct traffic levels, including considerably high volumes.

The comparison between sections S3 and S4 also shows that the use of the material in the subbase (S4) rather than in the base (S3) resulted in a significantly higher stress level to the materials of the other layers, as well as in more severe rutting in the base layer and, consequently, in the whole pavement structure. A considerable number of cracks in the asphalt surface layer was also predicted for the S4 structure.

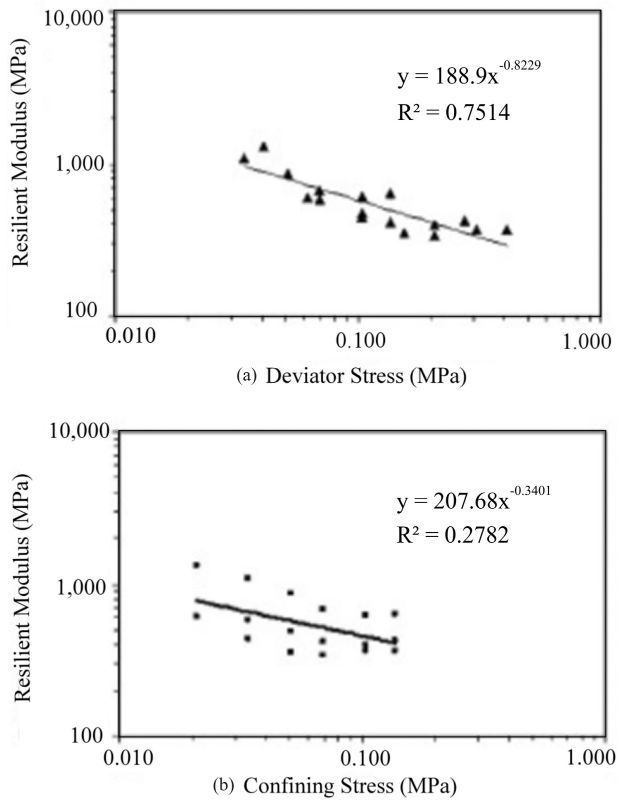

Figure 9. Relationship between the *RM* results for the Acre laterite gravel evaluated in this study and the (a) deviator stress and (b) confining stress.

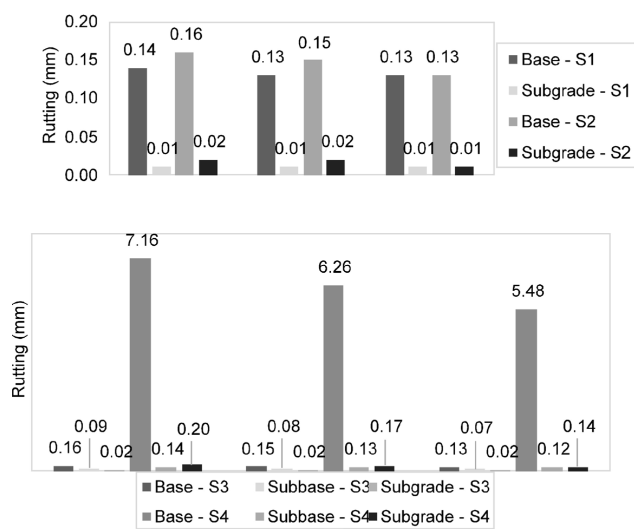

Figure 10. Rutting predicted from MeDiNa simulations for different traffic levels and pavement structures using the Acre laterite gravel in the composition of the base or subbase layers.

In addition to illustrating the good load bearing capacity of the laterite evaluated in this study, these simulations also highlight the importance of structural analyses based on the mechanical behavior of the materials to improve the material selection and the design of the pavement structure.

It is worth mentioning that acceptance *PD* criteria for the pavement layers vary in the literature. In various studies such as Guimarães (2001, 2009), a limit of 12.5 mm has been adopted for the accumulated rutting of the whole pavement structure submitted to high traffic volumes. In Brazil, the MeDiNa pavement design method specifies limits that vary between 10 and 20 mm, according to the type of track. Limits of up to 16 mm can also be found in the literature (Verstraeten, 1989). Thus, the deformability of the Acre laterite gravel resulted in overall pavement rutting significantly smaller than the typical tolerances for all the 12 cases evaluated in the simulations, which demonstrates the potential of the material to be used in the composition of pavement layers.

4. Conclusion

Laterites are commonly discarded because they do not meet certain traditional criteria. However, field experience and some literature works have already shown that these materials may present good load bearing capacity. In that sense, the Acre laterite gravel, a material of widespread occurrence in the northern region of Brazil was evaluated in this paper. For that, traditional characterizations and mechanical tests were performed to evaluate the resilient modulus (*RM*) and the resistance to permanent deformation (*PD*) of the material.

The characterization based on traditional parameters indicated that the Acre laterite gravel did not meet three criteria: its gradation curve could not be placed within the limits of the existing specifications, the plasticity index of the material was high, and its *CBR* value was low. Additionally, a high absorption was identified for the laterite and this may affect the optimum moisture content to be adopted during the construction of pavement structures.

In the mechanical characterization, the *RM* of the Acre laterite gravel was more sensitive to the variation of the deviator stress than to that of the confining stress. In addition, the material exhibited a significantly higher *RM* than other laterites, which turns it into a good candidate to be successfully adopted in the composition of base or sub-base layers. A good performance was also observed as the *PD* of the material was classified as type A based on the Shakedown theory and accommodated during the tests. In addition, low *PD* values were observed after 150,000 loading cycles.

A structural analysis using the MeDiNa program was also performed for 12 structures by varying the position of the pavement layer composed by the Acre laterite gravel and the traffic level. The results indicated that this laterite can be potentially adopted in the composition of the pavement layers as it presents good resistance to *PD*. It was also observed that the performance of the pavement structure was improved when the laterite was used in the base layer rather than in the sub-base. This highlighted the importance of performing structural analyses considering the mechanical behavior of materials to improve the material selection and design of pavement structures.

In summary, this paper demonstrated that the Acre laterite gravel evaluated can be potentially adopted in the composition of base or sub-base layers, although the material is considered inadequate by traditional criteria. Thus, it may be a good strategy to conduct a more comprehensive analysis of the material characteristics before rejecting them. As in this research, this could reveal a good mechanical performance of such materials and result in significant savings to the pavement construction process, as local materials can be selected and avoid expenditures with the transportation of others from distant locations.

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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

Antonio Carlos Rodrigues Guimarães: conceptualization, formal analysis, investigation, methodology and writing – original draft. Caroline Dias Amancio de Lima: formal analysis and writing – original draft. Francisco Thiago Sacramento Aragão: formal analysis and writing – original draft. Laura Maria Goretti da Motta: formal analysis and writing – original draft. Juliana Tanabe Assad dos Santos: writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

CBR	California Bearing Ratio
FEM	Finite Element Methods
LL	Liquid Limit
M-E	Mechanistic empirical
OMC	Optimum moisture content
PD	Permanent deformation
PI	Platicity index
RLT	Repeated load triaxial

RM	Resilient Modulus
ε_p	Permanent displacement
σ_d	Deviatoric stress
σ_c	Confining pressure

References

AASHTO T 307. (2003). *Determining the resilient modulus of soils and aggregate materials.* AASHTO – American Association of State Highway and Transportation Officials, Washington, DC.

ABNT NBR 7181/2016. (2016). *Soil - Grain size distribution*. ABNT -Associação Brasileira de Normas Técnica, São Paulo, SP (in Portuguese).

AG PT/T053. (2006). D*etermination of permanent deformation and resilient modulus characteristics of unbound granular materials under drained conditions*. Austroads – Association of Australian and New Zealand Road Transport and Traffic Authorities*,* Sidney.

ASTM STP1437. (2003). *Resilient modulus testing for pavement components.* ASTM International, West Conshohocken, PA. http://dx.doi.org/10.1520/STP1437-EB.

Barbosa, V.H.R., Marques, M.E.S., & Guimarães, A.C.R. (2018). Mineralogical characterization of a soil in acre for the production of artificial calcined clay aggregates. *Matéria*, 23, e-12181. http://dx.doi.org/10.1590/s1517-707620180003.0515.

Bona, A.C.D., & Guimarães, A.C.R. (2021). Evaluation of the permanent and resilient deformation of an alternative laterite used in road pavement. *Transportes*, 29(3), 1-13. http://dx.doi.org/10.14295/transportes.v29i3.2404.

Cardoso, H.S. (1987). *Procedure for flexible airfield pavement design based on permanent deformation* [Ph.D. dissertation]. University of Maryland’s repository.

Carvalho, J.C., Rezende, L.R., Cardoso, F.B.F., Lucena, L.C.F.L., Guimarães, R.C., & Valencia, Y.G. (2015). Tropical soils for highways construction: peculiarities and considerations. *Transportation Geotechnics*, 5, 3-19. http://dx.doi.org/10.1016/j.trgeo.2015.10.004.

CEN EN 13286-7. (2004). *Unbound and hydraulically bound mixtures. Part 7: cyclic load triaxial tests for unbound mixtures.* CEN – European Committee for Standardization, Brussels.

Costa, M.L. (1985). Contribuição à geologia das lateritas do Acre e sua importância para construção civil. In *Anais do II Simpósio de Geologia da Amazônia* (Vol. 2, pp. 297-311), Pará. Belém: SBG/NNo (in Portuguese).

Costa, M.L. (1991). Aspectos geológicos dos lateritos da Amazônia. *Revista Brasileira de Geociencias*, 21(2), 146-160. http://dx.doi.org/10.25249/0375-7536.1991146160.

Dalla Roza, A.E. (2018). *Contribution to mechanistic-empirical project of asphalt pavements in the northern region of the State of Mato Grosso* [Master’s dissertation, Universidade Federal do Rio de Janeiro]. Universidade Federal do Rio de Janeiro’s repository (in Portuguese). Retrieved in October 12, 2022, from http://hdl.handle.net/11422/13410

DNIT 098. (2007). *Pavimentação - base estabilizada granulometricamente com utilização de solo laterítico - especificação de serviço.* DNIT – Departamento Nacional de Infraestrutura de Transportes, Rio de Janeiro, RJ (in Portuguese).

DNIT 134. (2018a). *Pavimentação - solos - determinação do módulo de resiliência - método de ensaio.* DNIT – Departamento Nacional de Infraestrutura de Transportes, Rio de Janeiro, RJ (in Portuguese).

DNIT 179. (2018b). *Pavimentação - solos - determinação da deformação permanente - instrução de ensaio.* DNIT – Departamento Nacional de Infraestrutura de Transportes, Rio de Janeiro, RJ (in Portuguese).

Freitas, J.B., Rezende, L.R., & Gitirana Junior, G.F.G. (2020). Prediction of the resilient modulus of two tropical subgrade soils considering unsaturated conditions. *Engineering Geology*, 270, 105580. http://dx.doi.org/10.1016/j.enggeo.2020.105580.

Gidigasu, M.D. (1976). *Laterite soil engineering: pedogenesis and engineering principles*. Amsterdam: Elsevier.

Guimarães, A.C.R. (2001). *A study about permanent deformation in soils and the shakedown theory applied to flexible pavements* [Master’s dissertation]. Universidade Federal do Rio de Janeiro’s repository (in Portuguese).

Guimarães, A.C.R., & Motta, L.M.G. (2008). Um estudo sobre deformação permanente em solos lateríticos concrecionados do sudoeste da Amazônia através de ensaios triaxiais de cargas repetidas. In *Anais do IV Congresso Luso-Brasileiro de Geotecnia*, Coimbra. ABMS/SPG (in Portuguese).

Guimarães, A.C.R. (2009). *A mechanistic-empirical method for predicting permanent deformation in tropical pavement constituents* [Doctoral thesis]. Universidade Federal do Rio de Janeiro’s repository (in Portuguese).

Guimarães, A.C.R., Motta, L.M.G., & Castro, C.D. (2018). Permanent deformation parameters of fine - grained tropical soils. *Road Materials and Pavement Design*, 20(7), 1-18. http://dx.doi.org/10.1080/14680629.2018.1473283.

Guimarães, A.C.R., Motta, L.M.G., & Castro, C.D. (2019). Permanent deformation parameters of fine - grained tropical soils. *Road Materials and Pavement Design*, 20(7), 1664-1681. http://dx.doi.org/10.1080/14680629.2018.1473283.

Guimarães, A.C.R., Silva Filho, J.C., & Castro, C.D. (2021). Contribution to the use of alternative material in sub-ballast layer of heavy haul railroad. *Transportation Geotechnics*, 30, 100524. http://dx.doi.org/10.1016/j.trgeo.2021.100524.

Grace, H. (1991). Investigations in Kenya and Malawi using as-dug laterite as bases for betuminous surfaced roads. *Geotechnical and Geological Engineering*, 9(3-4), 183-195. http://dx.doi.org/10.1007/BF00881740.

Indraratna, B., & Nutalaya, P. (1991). Some engineering characteristics of a compacted lateritic residual soils. *Geotechnical and Geological Engineering*, 9(2), 125-137. http://dx.doi.org/10.1007/BF00881254.

Lima, C.D.A., Motta, L.M.G., & Aragão, F.T.S. (2019). Effects of compaction moisture content on permanent deformation of soils subjected to repeated triaxial load tests. *Transportation Research Record: Journal of the Transportation Research Board*, 2673(2), 466-476. http://dx.doi.org/10.1177/0361198118825124.

Lima, C.D.A., Motta, L.M.G., & Aragão, F.T.S. (2021a). A permanent deformation predictive model for fine tropical soils considering the effects of the compaction moisture content on material selection. *Transportation Geotechnics*, 28, 100534. http://dx.doi.org/10.1016/j.trgeo.2021.100534.

Lima, C.D.A., Motta, L.M.G., Aragão, F.T.S., & Guimarães, A.C.R. (2021b). Mechanical characterization of fine-grained lateritic soils for mechanistic-empirical flexible pavement design. *Journal of Testing and Evaluation*, 48(1), 1-17. http://dx.doi.org/10.1520/JTE20180890.

Mahalinga-Iyer, U., & Williams, D.J. (1997). Properties and performance of lateritic soil in road pavements. *Engineering Geology*, 46(2), 71-80. http://dx.doi.org/10.1016/S0013-7952(96)00096-8.

Melfi, A.J., & Carvalho, A. (1983). Lateritisation processes. In *Proceedings of the International Seminar on Lateritisation Processes.* São Paulo: IAG/USP.

Menezes, L.C.A., Guimarães, A.C.R., & Castro, C.D. (2021). Study of the influence of the rail platform profile submitted to rainwater on its structural behavior. *Brazilian Journal of Development*, 7(1), 4918-4930. http://dx.doi.org/10.34117/bjdv7n1-334.

Morin, W.J., & Todor, P.C. (1975). *Laterite and lateritic soils and other problem soils of the tropics*. Washington, D.C.: Agency for International Development.

NCHRP 01-28A. (2004a). *Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design.* Transportation Research Board, Washington, DC.

NCHRP RD 285. (2004b). *Laboratory determination of resilient modulus for flexible pavement design.* Transportation Research Board, Washington, DC.

Netterberg, F. (2014). *Review of specifications for the use of laterites in road pavement.* South Africa: Crown Agents, AFCAP and UKaid.

Omotosho, O. (2004). Influence of gravelly exclusion on compaction of lateritic soils. *Geotechnical and Geological Engineering*, 22(3), 351-359. http://dx.doi.org/10.1023/B:GEGE.0000025036.13997.df.

Paige-Green, P., Pinard, M., & Netterberg, F. (2015). A review of specifications for lateritic materials for low volume roads. *Transportation Geotechnics*, 5, 86-98. http://dx.doi.org/10.1016/j.trgeo.2015.10.002.

Qian, J., Chen, K., Tian, Y., Zeng, F., & Wang, L. (2019). Performance evaluation of flexible pavements with a lateritic gravel base using accelerated pavement testing. *Construction & Building Materials*, 228, 116790. http://dx.doi.org/10.1016/j.conbuildmat.2019.116790.

Ramos, C.R., & Motta, L.M.G. (2004). Estudo do comportamento resiliente de diversos solos e materiais britados do município do Rio de Janeiro. In *Anais da 35ª Reunião Anual de Pavimentação* (Vol. 1). Rio de Janeiro: ABPv.

Samb, F., Berthaud, Y., Ba, M., Fall, M., & Benboudjema, F. (2018). Nonlinear mechanical behavior analysis of flexible lateritic pavements of Senegal (West Africa) by FEM for M.-E. Pavement Design. *Geotechnical and Geological Engineering*, 36(5), 2939-2956. http://dx.doi.org/10.1007/s10706-018-0514-y.

Santos, J.D.G. (1998). *Contribution for study of granular soil lateritic soils in pavement* [Doctoral thesis]. Universidade Federal do Rio de Janeiro's repository (in Portuguese).

Santos, J.T.A., Silva, P.A.L., & Guimarães, A.C.R. (2022). Evaluation of measurement uncertainty in permanente deformation tests of lateritic soils. *Transportes*, 30(2), 1-15. http://dx.doi.org/10.14295/transportes.v25i2.1174.

Santos, G.P.P., Guimarães, A.C.R., & Motta, L.M.G. (2012). Mechanical behavior of materials used for paving in the Southwest of the Brazilian Amazon. *Procedia: Social and Behavioral Sciences*, 48, 3348-3360. http://dx.doi.org/10.1016/j.sbspro.2012.06.1300.

Seixas, S. (1997). *Dynamic behavior of the runway pavement materials of the new airport of Rio Branco* [Master's dissertation]. Universidade Federal do Rio de Janeiro's repository (in Portuguese).

Silva, M.F., Ribeiro, M.M.P., Furlan, A.P., & Fabbri, G.T.P. (2021). Effect of compaction water content and stress ratio on permanent deformation of a subgrade lateritic soil. *Transportation Geotechnics*, 26, 100443. http://dx.doi.org/10.1016/j.trgeo.2020.100443.

Sousa, M.A.S., Guimarães, A.C.R., & Castro, C.D. (2021). Geotechnical and resilient characteristics of taludes soils along of the Carajás railway for purposes of use in transport infrastructure. *Geosul*, 36(80), 119-132. http://dx.doi.org/10.5007/2177-5230.2021.e76654.

Sunil, B.M., Nayak, S., & Shrihari, S. (2006). Effect of pH on the geotechnical properties of Laterite. *Engineering Geology*, 85(1-2), 197-203. http://dx.doi.org/10.1016/j.enggeo.2005.09.039.

Verstraeten, J. (1989). Design and strengthening methods for bituminous pavements. In *Anais do 2º Simpósio Internacional de Avaliação de Pavimentos e Projetos de Reforço* (Vol. 2). Rio de Janeiro: ABPv.

Vertamatti, E. (1998). *Contribuição ao conhecimento geotécnico de solos da Amazônia com base na investigação de aeroportos e metodologias MCT e resiliente* [Doctoral thesis]. Instituto Tecnológico de Aeronáutica's repository (in Portuguese).

Werkmeister, S. (2003). *Permanent deformation behaviour of unbound granular materials in pavement constructions* [Doctoral thesis]. Technische Universität Dresden's repository.