Research Article

Study of the Permanent Deformation of Soil Used in Flexible Pavement Design

Wendel S. Cabral, Suelly H. A. Barroso, and Samuel A. Torquato

1Department of Transport Engineering, Federal University of Ceará, Campus do Pici-Block 703-60455-760, Fortaleza, CE, Brazil
2Department of Geotechnics, University of Brasília, Brasília, DF, Brazil

Correspondence should be addressed to Wendel S. Cabral; wendel.cabral@ufersa.edu.br

Received 10 February 2020; Revised 20 August 2020; Accepted 1 October 2020; Published 21 October 2020

Copyright © 2020 Wendel S. Cabral et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The decreasing supply of soils with geotechnical parameters suitable for pavement designs is a visible problem in our environment. In order to establish more efficient designs and adequate construction criteria, it is essential to understand the performance of materials. This is a study of the permanent deformation (PD) of soil used in pavement layers, obtaining prediction models through the technique of artificial neural networks, in addition to the design of pavement structures using mechanistic-empirical and empirical methods. The multistage repeated load triaxial (RLT) test, as well as numerical analyses of stresses and displacements using the CAP3D program, was used. The results showed that both the test procedure and the prediction models performed satisfactorily in obtaining PD behavior. Moreover, designs using the methods adopted resulted in distinct structures, that is, thickness different from the granular pavement layers. It was concluded that the model and test procedure exhibit significant potential for characterizing and modeling the PD of granular materials.

1. Introduction

Increased socioeconomic development, the need for investments in highway infrastructure, and declining supply of appropriate raw materials are visible problems in our environment. As a result, there is a need for careful mechanical assessment of the subgrade of highways, in addition to granular layers that may exhibit nonlinear behavior that is often simplified in linear analyses of design processes, causing changes that compromise their performance.

In this regard, the structural assessment of pavements is a complex problem, requiring more careful analyses of how different parameters perform, such as stress-deformation relationships that occur in the pavement. Deformation occurs in two parts: recoverable (resilient) and plastic (permanent). Recoverable deformation is used in some mechanistic-empirical design models, where the modulus of resilience (MR) is obtained using the test specified by the National Department of Transport Infrastructure [1].

The main mathematical models that express the MR as a function of the stresses applied to the materials, especially deviator ($\sigma_d$) and confining stress ($\sigma_3$), are those developed by Macêdo [2], known as the compound model, the combined or mixed model, proposed by Aranovich [3], and the Witczak and Uzan [4] model, which is recommended for calculating the MR in the guide for the design of pavement structures [5], in addition to the Guimarães [6] model.

Permanent deformation (PD) is one of the most relevant phenomena in the study of the structural behavior of pavement, whose accumulation in the layers significantly favors the wheel track rutting (WTR) defect, one of the main flexible pavement deterioration processes. According to Salour et al. [7], subgrade soil in low-volume roads may contribute with more than 40% of total WTR on the pavement surface.

The accumulation of deformation depends on many variables with different degrees of importance. The main influencing factors are the state of stress, number of load cycles, reorientation of primary stresses, moisture content, grain size and distribution, and degree of compaction; Lekarp et al. [8].

Permanent deformation is generally characterized by extensive laboratory studies with repeated load triaxial tests.
In these tests, cyclic loads within ranges that are frequently experienced by field materials are applied to samples under certain confinement pressures and moisture content. The test data are, then, used to develop and calibrate constitutive models that can estimate the PD behavior of the materials.

The common practice for obtaining PD is to use the single stage test with long cycles (minimum 150,000), applying constant amplitude cyclic loading to the sample. This technique is time consuming and requires significant energy resources. A test developed and approved in Brazil [9] established new demands in analyses and mechanical assessments in future pavement designs.

However, in recent years, a number of studies have been carried out with the multistage tests. In these tests, a cyclic load with different magnitudes is applied to a single sample. This approach may considerably reduce the time and effort needed to characterize the material under different stress conditions and explain the effect of stress history on its behavior.

Erlingsson and Rahman [10] proposed a complex and reasonable approach for continuous modeling of the PD accumulation behavior of granular layers based on multistage repeated load triaxial (RLT) tests. In a study by Rahman and Erlingsson [11], three permanent deformation models were adapted to multistage RLT test data for several coarse granular materials, and the concept showed satisfactory results.

Analysis of the literature demonstrates the difficulty in properly modeling the PD of soils, since a number of different mathematical formulations are presented, including a set of variables, not always the same in each case. Concern about perfectly modeling the behavior obtained in the tests does not guarantee the practical implementation of the model developed if these formulations cannot be associated with the design methods.

In this respect, the Guimarães [6] model stands out because it satisfactorily describes the PD obtained using the repeated load triaxial test. The study was a reference in developing the Brazilian guideline for PD tests and the model used as a mathematical function of mechanistic-empirical design programs and nonlinear analysis of the mechanical behavior of pavement.

Artificial Neural Networks (ANNs) are presented as an efficient computational tool for obtaining solutions to complex nonlinear problems, with various applications in practically all areas of knowledge. Basically, these are Artificial Intelligence (AI) techniques that have the essential property of being able to learn a function from processes that simulate biological nervous systems. Currently, one of the main uses are applications that work with data simulation [12].

Although guidelines on PD tests are already in place, in Brazil pavement is still empirically designed [13], considering soil layer information obtained in static load tests, that is, based on your CBR (California Bearing Ratio) data. Pavement performance is quite variable for both acting loads and the speed at which vehicles travel, as well as the uncertainties of soil properties.

To allow more appropriate analyses of the mechanical behavior of soils compared to traditional CBR-based analyses, resilient modulus and permanent deformation tests using RLT test equipment are performed [14]. Thus, the implementation of mechanistic-empirical methodologies that introduce more complex tests with more significant parameters is important in order to predict global pavement behavior.

Pavement structure and its mechanical analysis were obtained using the CAP3D (Computational Analysis of Pavements—3D) computational program. The program was developed by Holanda et al. [15] for numerical analysis based on the FEM (Finite Element Method) using object-oriented programming (OOP), which makes it possible to more easily expand the system. Using this application to calculate stresses, deformations, and displacements saves time and is more versatile, making it easier to assess nonlinear elasticity, which is important for materials that exhibit this behavior.

According to Araújo et al. [16], CAP3D is able to analyze flat, asymmetric, and three-dimensional models, using elements with different shapes and orders of interpolation (linear and quadratic). The system can also consider different constitutive models and perform linear and nonlinear static or dynamic analyses, using different algorithms. The program also determines the damage to asphalt pavements, improving the correlation between the field and the laboratory and facilitating the behavior prediction of asphalt materials in real pavements.

In light of those mentioned above, this study proposes to help understand the mechanical behavior of the soils assessed, generating PD estimation models using the nonlinear regression technique and MR to determine the model that most satisfactorily represents the materials used. This information can be used in designs and to compare the traditional empirical and mechanistic-empirical method, contributing to pavement designs with better performance optimizing available resources.

2. Materials and Methods

2.1. Materials. The study area was the microregion of Mossoro, located in Rio Grande do Norte (RN) state in Northeastern Brazil. Soil deposits, in addition to the gravel used to stabilize the base layer, are found in the municipalities of Mossoro and Areia Branca, located at 5°15′53″S and 37°38′69″W and 4°96′69″S and 37°03′74″W, respectively (Figure 1). They exhibit the properties of haplic cambisol (M1) and dystrophic yellow latosol (AB) soils, with a calcarenite and clayey-sandy geological profile, and occurring widely throughout the country.

Cambisol exhibits a microstructure composed of moderately developed granules and subangular blocks (stones in the soil mass), strong to partially accommodated, with porosity composed of nonoriented cracks. The latosols found are cohesive and hard when dry, becoming brittle when wet, and exhibit a homogeneous color, with little difference between the horizons or layers and medium or fine texture with the significant presence of clay.

According to a survey of local highway construction projects, cambisol is present in the subgrades of state highways RN014 and RN015 and federal highways BR 437,
part of BR 405, and the widening of BR 304. According to the projects surveyed, the class of soil, as defined by the American Association of State Highway and Transportation Officials [17], belongs to group A-2-6. Latosol is present in approximately 48% of the subgrade of highways that cross the study area, especially part of BR 304, nearly all of BR 110, in addition to RN 011, 013, and 016. This soil belongs to group A-2-4.

Simple graduated gravel (SGG), of granite origin, used to stabilize the soil in base layers in this study, was also used in different highway projects in the study region. This material was collected at the Coelho de Brito Commercial quarry on highway RN 233, in the municipality of Caraúbas, 75 km from Mossoró.

2.2. Methods

2.2.1. Sample Preparation and Conventional Mechanical Tests. In the laboratory, the soils were submitted to initial handling procedures for conducting tests, in line with the National Department of Highways and Roads [18]. In the next stage, Particle Size Distribution tests were conducted according to Brazilian standard NBR 7181 [19], specific gravity [20], liquid limits [21], and plastic limits [22], in addition to conventional mechanical tests, such as compaction tests [23], California Bearing Ratio (CBR) and expansion [24], test to evaluate the subgrade strength of roads and pavements, and soil expandability index, respectively, using the intermediate compaction energy in the making of the specimens.

2.2.2. Tests with Dynamic Loading

(1) Modulus of Resilience. Soil resilience was assessed in order to understand the elastic behavior of the granular layers of the pavements in the region and create a mechanistic-empirical design of a pavement structure. The MR values were obtained using a repeated load triaxial test, according to DNIT standard [1]. The experimental data were analyzed using the nonlinear regression technique.

The LAB Fit program was used for calculations and to determine the model that most satisfactorily represented the soil tests. This can be observed in the correlation coefficients adjusted ($R^2$) of the models with respect to the real elastic deformation data obtained in the tests.

(2) Permanent Deformation. The multistage repeated load triaxial (RLT) test method adopted by the European CEN [25] standard was used. This technique can be applied for a rapid assessment of the PDs produced by varying magnitudes of cyclic loading, conducted in a single test specimen. The entire soil sample preparation procedure, as well as the
specimen molding techniques and test equipment preparation, was the same as those used in the MR test method.

After soil sample compaction in the tripartite cylinder (10 x 20 cm), the test specimens were placed in the triaxial equipment and submitted to testing to determine deformability parameters. In the RLT tests, the cyclic loads within the ranges often observed for the material in the field are applied in samples under certain confinement pressures and moisture content (M1, AB, and the mixture exhibited an optimal moisture content of 12.5, 6.0, and 6.5%, respectively).

The confinement pressures or confining stress, as well as the deviator stress used in the tests, are illustrated in Table 1 at a loading frequency of 1 Hz (0.1 second pulse followed by a rest period of 0.9 seconds or 60 cycles per minute) submitted to a programmed number of load cycles (N).

According to Table 1, σd/σ3 ratios of 1, 2, 3, and 4, respectively, were adopted, totaling 12 tests. This procedure aimed at using different load simulations in these materials, in order to assess soil behavior and its real structural capacity.

Once all the operational processes were concluded, the LVDT (Linear Variable Transformer Variable) test was automatically initiated, recording the readings at a previously established interval and characterizing the accumulation of deformations throughout the trial. Figure 2 presents the main test stages, showing demolding of the test specimen, LVDT installation, triaxial equipment, and the test control program, respectively.

Triaxial tests were carried out sequentially, consisting of four stress stages in the same test specimen of each sample, using established combinations of different deviator (σd) and constant confining (σ3) stresses, but maintaining the other conditions unchanged. In each stage, 10,000 cycles were applied, totaling 40,000 loadings in the experiment, in order to simulate different load profiles (vehicles) by increasing vertical energy intensity on the resurfaced roadway.

The Guimarães [6] model (\(\varepsilon_p = K_1 \cdot \sigma_3^{k1} \cdot \sigma_d^{k2} \cdot N^{k3}\)) was used to obtain preliminary deformability parameters (K) to predict the total PD (\(\delta_p\)) of each material studied, applying the correlation between confining stress (σ3), deviator stress (σd), and traffic (N), using the nonlinear regression technique.

For this purpose, the Artificial Neural Networks (ANN) technique was used as a tool for developing and obtaining models. In order to predict the magnitude of the specific DP occurring in the materials used in the pavement of the highways in that location, tests were carried out in different topologies in search of the highest possible level of confidence, that is, a model with the least error.

2.2.3. Designing Pavement Structures. In this stage, empirical design was performed according to the [13] guideline and mechanistic-empirical design of the theoretical structure of pavement for comparison purposes, with different traffic volumes (N), in addition to the CBR, MR, and PD of the soils investigated. Both mechanistic-empirical design, using prediction and rupture criteria of the affected structure, and numerical analysis were conducted using the Computational Analysis of Pavements—3D (CAP3D) program. The CAP3D is applied for numerical analysis based on the Finite Element Method (FEM) and uses stress and deformation as input data.

The soils adopted for all the layers exhibited plastic and resilient behavior at optimal moisture content, using the model that best represented the material. In the base layer, a mixture composed of 50% soil (A-2-4) was used and more than 50% simple graduated gravel (SGG) in the sub-base. Different resurfacing materials were used in certain structures, as well as layer thicknesses, in the two methods, as a function of “N” demand levels.

3. Results and Discussion

3.1. Classification, Characterization, and Conventional Mechanical Tests of the Materials. The granulometric composition of the soils and mixture under study and the results of the characterization test are summarized in Tables 2 and 3, respectively.

M1 and AB soils exhibited liquid limits of 24.2% and 20.2% and plastic limits of 15.61% and 12.31%, as well as a plasticity index of 8.55% and 7.85%, respectively. The SGG used in the mixture showed a Los Angeles abrasion of 36.67% and shape index of 0.91, using the pachymeter, in addition to satisfactory adhesiveness (without DOPE).

3.2. Dynamic Load Tests

3.2.1. Modulus of Resilience. The resilient behavior of the material showed a significant variation in the first load application cycles and accommodation in the final cycles. This performance reflects a near-real situation when the pavement layers are submitted to loads, showing that during use, the structure absorbs these stresses until a certain time, undergoing resilient stabilization until reaching stiffness during the paving period.

After the modulus of resilience test, the MR variation estimation models were generated as a function of stress state (σd and σ3). The compound (MR = K1 · σ3 \(\sigma_3^{k1} \cdot σ_d^{k2} \cdot N^{k3}\)), Guimarães [6] (MR = \(k_1 \cdot σ_3^{k1} \cdot σ_d^{k2} \cdot N^{k3}\)), combined

| Tests | Stress (kPa) | N  |
|-------|-------------|----|
| 1     | 40          |    |
| 2     | 80          |    |
| 3     | 120         | 40 |
| 4     | 160         | 10,000 |
| 5     | 80          |    |
| 6     | 120         |    |
| 7     | 240         | 80 |
| 8     | 320         |    |
| 9     | 120         |    |
| 10    | 240         |    |
| 11    | 360         | 120 |
| 12    | 480         |    |

Table 1: Relation of the stress used in triaxial repeated load tests.
(MR = \[k_1 + k_2 \cdot (k_3 - \sigma d^{k_2})\sigma d^{k_3}\]), and AASHTO
(MR = K_1 \cdot \theta^{k_2} \cdot \tau_{oct}^{k_3}) models were tested, the last including
the first stress invariant (\(\theta\)) and octahedral shear stress (\(\tau_{oct}\)), values that occurred in any element of the soil
in the pavement layer.

After simulations, the compound model exhibited better performance in the resilient behavior of the material, indicating the highest correlation coefficient (\(R^2\)) and making it possible to obtain the most representative MR model of the materials. According to the equations shown in Table 4, these models enable analysis of hardening during the traffic load in M1 and AB soils and the mixture under study.

### Table 2: Summary of the granulometric composition (%) of the study materials.

| Soils  | Clay + silty | Fine | Medium | Coarse | Boulder |
|--------|--------------|------|--------|--------|---------|
| M1     | 29           | 43   | 23     | 3      | 2       |
| AB     | 19           | 33   | 27     | 10     | 11      |
| Mixture| 2.9          | 3.2  | 13.3   | 15.8   | 64.9    |

### Table 3: Results of the characterization tests of the collected materials.

| Materials | CBR (%) | Expansion (%) | DSG (g/cm³) | Hot (%) | AASTHO |
|-----------|---------|---------------|-------------|---------|--------|
| M1        | 11.3    | 0.070         | 1.89        | 12.5    | A-2-6  |
| AB        | 41.9    | —             | 1.97        | 6.0     | A-2-4  |
| Mixture   | 66.3    | —             | 2.122       | 6.5     | —      |

### Table 4: Evaluated models of the tested materials.

| Materials | Models | Equation | \(R^2\) |
|-----------|--------|----------|---------|
| M1        | Compound | \(RM = 141.79\sigma 0.0197\sigma d^{0.5567}\) | 0.836 |
| AB        | Compound | \(RM = 590.77\sigma 0.2169\sigma d^{1.1431}\) | 0.844 |
| Mixture   | Compound | \(RM = 935.81\sigma 0.3268\sigma d^{0.0168}\) | 0.877 |

3.2.2. Permanent Deformation. All the valid results of permanent deformation tests conducted with the materials selected are presented and assessed in order to understand this parameter in the pavement structure. According to the guideline used here, a single sample of M1, AB, and the mixture of soils represented the progressive buckling of granular layers of a pavement.

Figures 3–5 show the occurrence, development, and consequences at different loading levels, thereby justifying the use of the materials in certain types of highway structures. The deformation values presented demonstrate that the materials tested tended to stabilize in all the loading sequences used before the total cycle concluded, revealing good resistance.

These figures show total PD values in the three sequences of load stresses determined in the tests, from the first applied load to the 40,000 cycles for the materials under study. Given that the admissible value for total WTR is up to 12.5 mm, the index typically used in highway construction, the materials tested exhibit little deformation, tending to rapid accommodation in the structure when submitted to loads, providing
good resistance since they do not experience excessive buckling.

Iterative analyses of optimization and sensitivity were conducted to calibrate the model parameters for the two soils and the mixture (SGG). During each iteration, the accumulated PD calculated by the model with an assumed set of parameters was compared with the PD measured in the triaxial tests. The square error (difference between the calculated and measured PD) was calculated for each set of data. The model parameters were optimized in order to minimize the error sum of squares ($R^2$) with the solver function in Microsoft Excel.

Table 5 presents the deformability parameters ($K$) of the models to predict the PD of the materials studied. In general, satisfactory goodness of fit was observed for the materials tested. The stresses (confining or deviation) that most influence the occurrence of PD can be identified by the signal of their respective parameters present in the mathematical models of deformation prediction. This behavior is probably explained by the biophysical diversity of the microregion, that is, the pedological, geological, vegetation, morphological, and hydrological differences existing in the study area, with the need for further study for this understanding.

We opted to use the MSE tool (Mean of Squared Error or Average Square of Errors) to measure the performance of the tested topology, in addition to the correlation coefficient ($R^2$), considering the training, validation, and test sets. The results of the topology performance of the developed neural model, for this dataset, are presented in Table 6.

3.3 Designing the Pavement Structure. The three typical pavement structures were designed using the material collected and the respective data obtained. The three analyses were carried out in resurfaced pavements in double surface treatment (DST) and hot mix bituminous concrete (HMBC). The empirical method [13] and numerical analysis in the elastic-linear regime were used to assess the behavior of the structure by applying the CAP3D mechanistic-empirical prediction tool.

The traditional method was used to determine layer thickness according to the number $N$ (traffic) and the CBR value of the subgrade. The demand levels ($N$) for the structure with DST of $1 \times 10^6$, $5 \times 10^6$, and $1 \times 10^7$ for highways in HMBC, growth rate (2%), construction time (10 years), abaci, tables, and coefficients were considered to obtain the layer thicknesses of the structures assessed. The same subgrade and materials as those applied in the sub-base and base of the pavement were used.

The same structural conditions of the pavement, materials, and traffic profile were adopted, and the structure obtained by CAP3D also included the regression coefficients of the permanent deformation models and the modulus of resilience obtained for the material studied, as well as Poisson’s coefficient ($\nu$) extracted from Bastos [26]. Figure 6 shows the thicknesses obtained in the structures of the three pavements under study, using the two design methods.

The designs created using the empirical and mechanistic-empirical methods resulted in distinct structures, as shown in Figure 6. In the pavement that represents a low traffic volume highway, with $N$ of $1 \times 10^6$ and a 2.5 cm surfacing layer, the thickness of the base obtained in CAP3D was 15% less than that calculated by the DNIT method.

Figure 6 also shows lower pavement layer thicknesses, with an $N$ of $5 \times 10^6$ and $1 \times 10^7$. In the DNIT procedure, the base layer of these structures requires 3 m higher thickness in order to resemble the behavior of pavements analyzed with CAP3D. With respect to the sub-base, the thickness was 33.3
and 37.5% lower using the mechanistic-empirical method with surfacing layers of 5.0 and 7.5 cm, respectively.

Table 7 presents the total values obtained for the three pavements designed from the occurrence of permanent deformation, a phenomenon that caused wheel track rutting and surfacing layer fatigue in the form of a cracked area.

The vertical compressive stresses acting on the subgrade are used to analyze the PD on the central vertical loading axis, where the maximum admissible values were obtained applying the method proposed by Motta [27] and used by Benevides et al. [28]. The fatigue of the structures was also determined by the deflection (displacement) on the pavement surface. The maximum admissible deflections were calculated using the equations recommended by Preussler [29].

The spreading of vertical stresses (compression) and deflection at the top of the pavement (vertical displacement) in the structures designed after loading can be seen in the images processed by the N1Pos program of the CAP3D. Figures 7 and 8 show these occurrences in the pavement with HMBC surfacing layers ($N = 1 \times 10^7$). The vertical and deflection (vertical displacement) stresses caused by loading did not compromise the pavement, since they did not produce buckling levels that are uncomfortable or hazardous to drivers.
4. Conclusions

A series of multistage RLT tests were conducted with two soils and a mixture of both, and the model proposed by Guimarães [6] demonstrated a good performance in predicting the relationship between the number of load applications, stress level, and response to PD. As such, this equation satisfactorily predicts the behavior of the materials studied.

Multistage repeated load trial tests (applications of 10,000 cycles per stage) displayed satisfactory behavior in obtaining the PD values of the materials investigated here. Compared to long load cycle methodologies, this technique proved to be superior in terms of resource optimization, producing reliable and coherent results for analyses and assessments.

The PD values obtained are admissible, that is, the materials tested can be used in paving projects. Moreover, obtaining the prediction models made it possible to use the parameters ($K$) in the mechanistic-empirical design programs for highway pavement. The computational application CAP3D predicted the performance of the pavement structure throughout its life cycle, both from a structural standpoint and in terms of the economic viability of different periods of the project, optimizing the use of materials, methods, and construction timelines.

Mechanical analysis of the pavement loads made it possible to visualize the occurrence of stresses and deflections in the structure and understand their effects, as well as the likely soil behavior after load application. Both vertical compressive stresses acting on the subgrade and deflection on the top of the pavement (vertical displacement) are lower than the maximum admissible values, revealing that the number of repetitions adopted will not cause PD rupture in the structure, that is, the pavement will perform satisfactorily throughout construction.

After several attempts and analyses to obtain the best explanatory topology of the neural model and being aware that there are other possible combinations to reach the most satisfactory network, it was not possible to perform them, and the development of the available ANN was able to generate model parameters prediction of PD for the studied soils.

In the present study, the model and test procedure were assessed using only two subgrade materials and a mixture (SGG). There is an apparent need to conduct additional tests in order to establish a database for the parameters of the material, study the influence of different soil moisture contents and degrees of compaction in these parameters, and, if possible, consider the uncertainties of the soil properties in the test and design procedures. Additional validation of model predictions with field data is recommended and would be of significant interest.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors thank the Foundation for the Support of Scientific and Technological Development of the state of Ceará (FUNCAP) for financing this research and for the scholarship awarded to the doctoral student involved in this investigation.

References

[1] National Department of Transport Infrastructure—DNIT, Paving: Soils: Determination of the Resilience Module: Test Method, National Department of Transport Infrastructure—DNIT, Rio de Janeiro, Brazil, 2010.
[2] J. A. G. Macêdo, "Interpretation of deflectometric tests for structural evaluation of flexible pavements—the experience

![Figure 8: Deflection at the top of the pavement.](image-url)
with FWD in Brazil,” Master’s thesis, COPPE/UFRJ, Rio de Janeiro, Brazil, 1996.

[3] L. A. S. Aranovich, “Performance of low cost pavements in the state of Paraná,” Master’s thesis, COPPE/UFRJ, Rio de Janeiro, Brazil, 1985.

[4] M. W. Witzczak and J. Uzan, “The universal airport pavement design system,” Report 1 of 4, granular material characterization, University of Maryland, College Park, MD, USA, 1988.

[5] American Association of State Highway and Transportation Officials—AASHTO, Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials—AASHTO, Washington, DC, USA, 1993.

[6] A. C. R. Guimarães, “A mechanistic-empirical method for the prediction of permanent deformation in tropical soils constituent of pavements,” Master’s thesis, Civil Engineering Program of COPPE/UFRJ, Rio de Janeiro, Brazil, 2009.

[7] F. Salour, M. S. Rahman, and S. Erlingsson, “Characterizing permanent deformation of silty Sand subgrades by using a model based on multistage repeated-load triaxial testing,” Transportation Research Record: Journal of the Transportation Research Board, vol. 2578, no. 1, pp. 47–57, 2016.

[8] F. Lekarp, U. Isacsson, and A. Dawson, “State of the art. II: permanent strain response of unbound aggregates,” Journal of Transportation Engineering, vol. 126, no. 1, pp. 76–83, 2000.

[9] National Department of Transport Infrastructure—DNER, Paving: Soils: Determination of Permanent Deformation: Test Instruction, National Department of Transport Infrastructure—DNER, 179 IE, Rio de Janeiro, Brazil, 2018.

[10] S. Erlingsson and M. S. Rahman, “Evaluation of permanent deformation characteristics of unbound granular materials by means of multistage repeated-load triaxial tests,” Transportation Research Record: Journal of the Transportation Research Board, vol. 2369, no. 1, pp. 11–19, 2013.

[11] M. S. Rahman and S. Erlingsson, “Predicting permanent deformation behaviour of unbound granular materials,” International Journal of Pavement Engineering, vol. 16, no. 7, pp. 587–601, 2015.

[12] A. J. A. Ribeiro, “A prediction model for the soil resilience module in the state of Ceará for paving purposes,” Doctoral thesis in transport engineering, Doctoral thesis, Federal University, do Ceará, Fortaleza, Brazil, 2016.

[13] National Department of Transport Infrastructure—DNER, Manual of Paving, Institute for Road Research, Rio de Janeiro, Brazil, 3rd edition, 2006.

[14] C. Lima, L. Motta, F. T. S. Aragão, and A. C. R. Guimarães, “Mechanical characterization of fine-grained lateritic soils for mechanistic-empirical flexible pavement design,” Journal of Testing and Evaluation, vol. 48, no. 1, pp. 1–17, 2020.

[15] A. Holanda, E. Parente Jr., T. D. P. Araújo, L. T. B. Melo, F. Evangelista Jr., and J. B. Soares, “Finite element modeling of flexible pavements,” in Proceedings of the XXVII Iberian Latin-American Congress on Computational Methods in Engineering (CILAMCE), Belém, Brazil, September 2006.

[16] P. C. Araújo Jr., J. B. Soares, A. Holanda, E. Parente Jr., and F. Evangelista Jr., “Dynamic viscoelastic analysis of asphalt pavements using finite element formulation,” Road Materials and Pavement Design, vol. 11, no. 2, pp. 409–433, 2010.

[17] American Association of State Highway and Transportation Officials—AASHTO, Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes, American Association of State Highway and Transportation Officials—AASHTO, Washington, DC, USA, 1973.

[18] National Department of Highways and Roads—DNER, Soils—Preparation of Soil Samples for Characterization Tests, National Department of Road Roads—DNER, ME 041, Rio de Janeiro, Brazil, 1994.

[19] Brazilian Association of Technical Standards—ABNT, Soil: Granulometric Analysis, Brazilian Association of Technical Standards—ABNT, NBR 7181, Rio de Janeiro, Brazil, 1984.

[20] Brazilian Association of Technical Standards—ABNT, Soil: Determination of the Liquidity Limit, Brazilian Association of Technical Standards—ABNT, NBR 6508, Rio de Janeiro, Brazil, 1984.

[21] Brazilian Association of Technical Standards—ABNT, Soil: Determination of the Plasticity Limit, Brazilian Association of Technical Standards—ABNT, NBR 7180, Rio de Janeiro, Brazil, 1984.

[22] Brazilian Association of Technical Standards—ABNT, Soil: Determination of the California Support Index Using Unprocessed Samples, National Department of Road Roads—DNER, ME 049, Rio de Janeiro, Brazil, 1994.

[23] European Committee for Standardization—CEN, Cyclic Load Triaxial Test for Unbound Mixtures, pp. 13286-13287, European Standard, EN, Brussels, Belgium, 2004.

[24] J. B. S. Bastos, “Influence of moisture variation on the pavement behavior of the metropolitan region of Fortaleza,” Master’s dissertation, Federal University of Ceará, Fortaleza, Brazil, 2013.

[25] L. M. G. Motta, “Method of dimensioning flexible pavements; reliability criteria and repeated load tests,” Master’s thesis, COPPE/UFRJ, Rio de Janeiro, Brazil, 1991.

[26] S. A. S. Benevides, L. M. G. Motta, and J. B. Soares, “Design of asphalt pavements using the empirical methods of DNER and the resilience of COPPE/UFRJ on highways in Ceará,” in Proceedings of the XIV ANPET—Transport Research and Teaching Congress, vol. 1, pp. 591–602, Gramado, Brazil, 2000.

[27] E. S. Preussler, “Study of flexible formatting of flexible pavements and application to the design of reinforcement layers,” Master’s thesis, Federal University of Rio de Janeiro, COPPE/UFRJ, Rio de Janeiro, Brazil, 1983.