A mechanistic empirical method to predict permanent deformation on tropical soils on pavements

Antonio Carlos Rodrigues Guimarães
Department of Civil Engineering - Militar Institute of Engineering (IME), Rio de Janeiro, Brazil
Laura Maria Goretti da Motta
Department of Civil Engineering – Federal University of Rio de Janeiro, (COPPE/UFRJ) Rio de Janeiro, Brazil
Henry Guillermo Córdova Valdiviezo
Department of Civil Engineering – Militar Institute of Engineering (IME), Rio de Janeiro, Brazil

ABSTRACT
This paper presents several permanent deformation tests of compacted tropical soils used for road pavements in Brazil. It is proposed a mathematical model to predict permanent deformation based on stress conditions and number of load applications. There were developed a lot of triaxial tests with repeated load, up to 150,000 cycles in 8 materials samples: 2 laterite gravels, 2 fine lateritic soils, 2 non-lateritic fine sands, 1 kaolinitic soil, and one crushed stone. There were studied permanent deformation and plastic shakedown, main factors of the materials tested under repeated loading, through permanent deformation increasing rate analysis at each cycle. The purpose is to check any possible strengthening of soils due to load repetition. There is a strong evidence that plastic shakedown occurs frequently in compacted tropical soils used for pavements in Brazil.

RÉSUMÉ
Cet article présente les résultats des essais de déformation permanente des sols compactés tropicaux utilisés dans les chaussées au Brésil. Il est proposé un modèle mathématique pour prédire la déformation permanente en fonction de l'état des contraintes et le nombre d'applications de charge. Plusieurs essais triaxiaux cycliques jusqu'à 150.000 cycles, ont été effectués dans 8 échantillons de différents matériaux: 2 graviers de latérite, 2 sols latéritiques fins, 2 non-latéritiques sables fins, 1 sols kaolinitiques, et une pierre concassée. Il a été étudié les principaux facteurs de déformation permanente et “shakedown” plastique des matériaux testés sous chargement cyclique, à travers l'analyse du taux d'augmentation de déformation permanente à chaque cycle. Le but de l’étude était d'analyser la possibilité du gain de la résistance des sols due aux cycles de charge, car il ya des preuves solides que Le “shakedown” plastique se produit fréquemment dans les sols compactés tropicaux utilisés dans les chaussées au Brésil.

1 INTRODUCTION

In countries located in the intertropical zone such as Brazil, the tropical soils constitute highly leached, broad, and thick soil packages, which are rich in iron and aluminum oxide hydroxide and clay minerals, part of the group of kaolinite. For this reason, it is common the use of these minerals in base layers, sub-base layers, and pavement reinforcement.

There are at least two sets of tropical soils that differ from each other for their soil gradational composition: laterites and thin lateritic soil. The peculiarities of geotechnical behavior of those soils have conditioned the development of their own classification methodology, mechanistic behavior evaluation, and performance prediction of geotechnical works.

Longer than two centuries ago, more precisely in 1807, the Englishman Buchanam suggested the term *Laterite*, related to the Latin term *Later*, which means brick, to name a reddish material that is appropriate for construction, and exploited in the mountains of Malabar, India (Bigarella, 2007).

Since the pioneering works of Buchanam, the term *laterite* has been used to describe very distinctive materials, found in hardened and non-hardened natural deposits or fields.

The ISSMFE (International Society for Soil Mechanics and Foundation Engineering) definition for lateritic boulder is: *A natural material, typical in humid tropical areas that contains a great percentage of grains in boulder fraction in the shape of concretions, nodules, pisolites or resembling shapes, all of them essentially constituted with hydrated iron or aluminum oxide. Also it may contain other grains in boulder fraction such as quartz, but in a small amount.”*

From the pedological perspective, laterites, according to Lepsch (2002), are regarded as part of the plinthosol group in the current Brazilian classification; concretionary lateritic soils and hydromorphic laterites, based on the old Brazilian classification; and plinthosol, according to WRB

(World Reference Base). The main feature of this group of soils is the abundance of plinthite (more than 15%), equivalent to immature or soft laterite, or petroplinthite, or mature or hard laterite, or laterite hardpan.

The term *plinthite* also refers to brick as well as the term laterite, however, its origin is from the Greek Language (*plinthos* = *brick*), and was introduced because the term *latosol* often refers to all developed soils in humid tropics.

In the Brazilian road engineering, the term *laterite*, strictly speaking, refers to lateritic boulders, known as gravel or lateritic, as well as other terms. The lateritic boulders are part of materials, widely used for paving in Brazil since 1950. Numerous authors described aspect of the mechanistic lateritic behavior, as in Cardoso (1987), Grace (1991), Indraratna (1991), Mahalinga-Iyer e Williams (1996), Seixas (1997), Santos (1998), Vertamatti (1998), Guimarães (2001), Omotosho (2004), Sunil et al (2006), Guimarães e Motta (2008a E 2008b). Most of it is consolidated in Norma DNIT 098/2007, specific for bouldery lateritic soils.

From the pedogenetic perspective, not always the tropical soils are formed by lateritic bouldery concretions, and they may contain concretions with dimensions correspondent to the fractions thin sand and silt. In this case, the soils are thin lateritic ones which may be sandy, whose behavior peculiarities are described in the pioneering work of Nogami and Villibor (1995), and consolidated in the practical experience in the State of São Paulo, where it has been registered that, by the present date, more than 6.000km of low-cost pavements have been built using this type of material in base and sub-base layers.

The analysis of tropical soils mechanistic behavior for the employment in pavement layers has been made since 1977, through the pioneering works of Professor Jacques de Medina of COPPE/UFRJ, mainly in term of obtaining the resilient module through repeated load triaxial test.

Over the years the studies for permanent deformation evaluation of Brazilian tropical soils, in order to predict deepening of wheel tracks, have been in second scope, mainly because the principal problem, historically observed in the Brazilian pavement, has been the fatigue cracking.

Nevertheless, this reality has been changed considerably due to the increase in the Brazilian roads' traffic, in consequence of the national new economic scenario.

This work allows the evaluation of the behavior of diverse origins and geotechnical characteristics of Brazilian tropical soils, when submitted to repeated load triaxial tests for the evaluation of permanent deformation and occurrence research of shakedown, based on a mathematical model proposed for the materials behavior prediction according to obtained results. The entire research can be seen in Guimarães (2009).

2 MATERIALS

Materials selection for the present work has considered the need for soils studies from several regions of the country and that they have been employed effectively in pavement layers.

The studied soils were divided into two groups according to the soil gradational composition. The bouldery materials illustrated (table 1), include laterites from Acre and from Porto Velho, in Brazilian Amazon, a sort of non-lateritic gravel arising from the southeast region, and a basaltic grit from the south of the country, and used as a reference.

The thin soils are presented in table 2 and are part of a lateritic clay from Ribeirão Preto, SP, a loamy lateritic sand from Espírito Santo, a non-lateritic silt from Rio de Janeiro (Papucaia), and a thin non-lateritic sand from the southeast of the country (Campo Azul, MG).

Table 1. Characteristics of gravel soils tested.

Characteristics	Acre's laterite	Porto Velho's laterite	Corumbaíba's gravel	Chapecó's graduated grit
Optimum water content (%)	10,5	12,6	10,8	4,5
Liquid limit (%)	34,5	-	55	-
Plastic limit (%)	20,9	-	34	-
Sand (%)	30	10	14	27
Silt (%)	11	5	10	5,0
Clay (%)	19	12	18	1,2

Observation: Acre's laterite, Porto Velho's laterite and compressed Corumbaíba's gravel with Proctor intermediate energy, Chapecós graduated grit with Proctor modified energy.

Table 2. Characteristics of fine graded soils tested.

Characteristics	Ribeirão Preto's clay	ES's lateritic sand-clay	Papucaia's soil	Campo Azul/MG's thin sand
MCT Classification	LG'	LG'	NS'	NA
Optimum water content (%)	24	18	13	9,4
Liquid limit (%)	43,7	60,3	37,2	-
Plastic limit (%)	27,1	22,5	23,5	-
Sand (%)	38	45	64	81
Silt (%)	25	15	18	10
Clay (%)	37	38	15	9

Observation: Ribeirão Preto's Lateritic clay, ES's lateritic sand-clay and Papucaia's soil compressed with Proctor normal energy, Campo Azul's fine grained sand compressed with intermediate Proctor energy.

In Brazil, an intermediate level of energy between the normal and modified proctor has been historically used, because in tropical soils this level was sufficient just when a satisfactory density is reached.

The MCT classification (Miniature Compacted Tropical) corresponds to the Brazilian classification for fine soils employed in road engineering, with the first letter indicating if the soil has or not lateritic behavior (*L* for lateritic and *N* for non-lateritic).

3 METHODOLOGY

The basic concept of the methodology used in the present work is schematized in Figure 1, in which we can distinguish a phase of selection of material on the field and execution of long duration repeated load triaxial tests, above 100,000 application cycles of loads, followed by the evaluation phase of results through two distinct parts. The first part comprises the total permanent deformation analysis, in which the prediction model itself was developed; the second part consists of *shakedown* occurrence research based on the methodology developed in the University of Nottingham, where the material behavior is classified and the *shakedown* limit is studied.

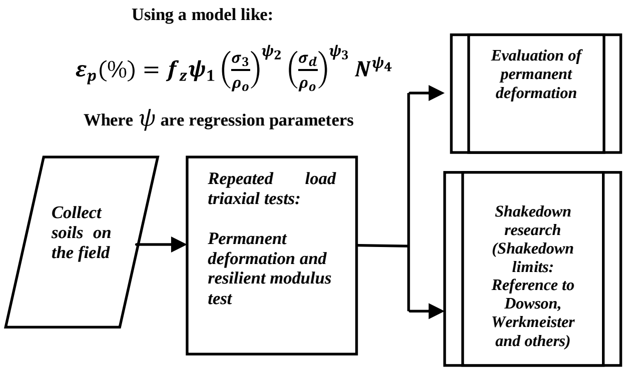

Figure 1. Methodology adopted on present study (Guimarães, 2009).

The long duration repeated load tests were executed with different stresses in a way that a similar stress to the one verified in the field of Brazilian pavement could be reproduced in laboratory. The tests were numbered from 1 to 9, and three levels of confining stress σ_3: 40, 80, and 120 kPa, and variable ratio σ_d / σ_3 : 1, 2 and 3. Thus, for instance, test 9 was executed with σ_3 = 120 kPa and σ_d = 360 kPa, and the highest pair of stress was used in the methodology.

From the tests results, a permanent deformation prediction model was obtained, whose mathematical expression is equation 1, used for calculating the multiple non-linear regression, from the parameters to the technique applied with the software *"Statistica 8.0."*

Those ψ_i parameters will be henceforth called permanent deformability parameters.

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

Where:

$\varepsilon_p(\%)$: Specific Permanent Deformation;

ψ_1, ψ_2, ψ_3: Regression Parameters;

σ_3: kPa Confining Stress;

σ_d: kPa Deviation Stress;

ρ_0: Reference Stress (Atmospheric Pressure considered: 100 kPa);

N: Number of Load Application Cycles.

The *shakedown* research followed the methodology created by Dawson and Wellner (1999), Apud Werkmeister et al. (2001) and Werkmeister (2003), in which the accumulated vertical permanent deformation is represented (meters) in the horizontal axis, demonstrated by the test body throughout the repeated load tests; and in the vertical axis of the chart, the increase rate of vertical permanent deformation for each cycle.

According to the material response, it will be classified as behavior type A, which corresponds to shakedown, in other terms, when an accumulated permanent deformation becomes constant; behavior type B, in which it is always observable a non-null permanent deformation increase rate; and behavior type C, in which the material tends to a breakdown.

For the preparation of the test samples, it was used 10cm height x 10cm diameter width cylindrical molds compressed with an amount of energy equivalent to the intermediate proctor when the soil is bouldery, (with the exception of Chapecó's graduated grit), and energy equivalent to normal proctor test when the soil is thin. The samples of soils were damped down to optimal point, and homogenized and kept for at least 24 hours in a humid chamber.

The reading of the first load cycle was discarded, because it was regarded as a stroke adjustment.

4 RESULTS

4.1 Permanent Deformation Results

A typical permanent deformation test result for the granular materials studied is presented in Figures 2 and 3, where it can be observed a fast increase of the accumulated permanent deformation in the tests' early phase, followed by a certain accommodation of these deformations as the load cycles application (N) number increased.

This same pattern was observed in the other cases of permanent deformation that differed from each other because the final accumulated permanent deformation level. However, for the studied bouldery materials, the observed final amount of permanent deformation was very low, below 2.0mm.

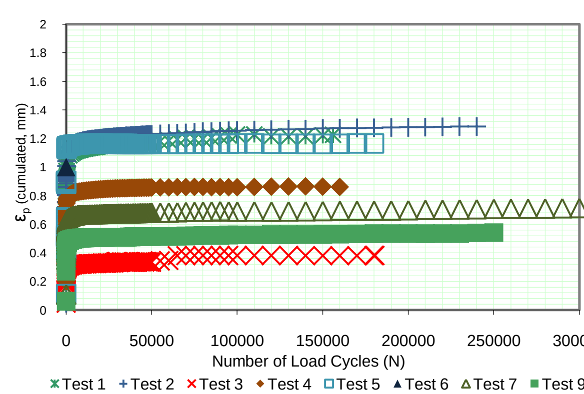

Figure 2. Porto Velho's Laterite Accumulated Permanent Deformation.

Concerning to Corumbaíba's gravel, shown in Figure 3, the same response pattern was observed, but the accumulated permanent deformation observed was slightly higher.

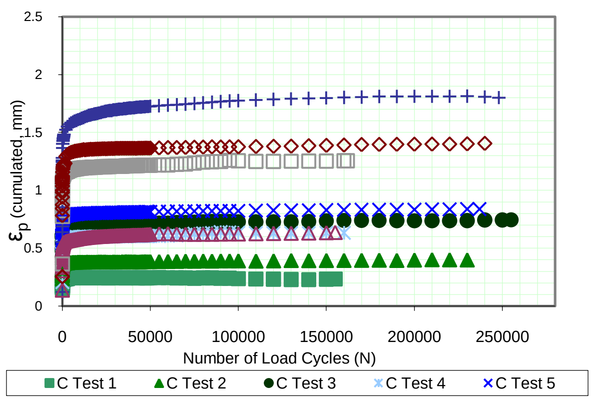

Figure 3. Accumulated Permanent Deformation of Corumbaíba's gravel.

The accumulated permanent deformation curve shape was similar in the behavior presented by the studied thin soils. Nevertheless, the final amounts are much higher and these results turn the soil worrying in terms of usage for pavement engineering works. In Figure 4 it is shown the result for clay from Ribeirão Preto, and in Figure 5, the result for loamy sand from Espírito Santo (ES).

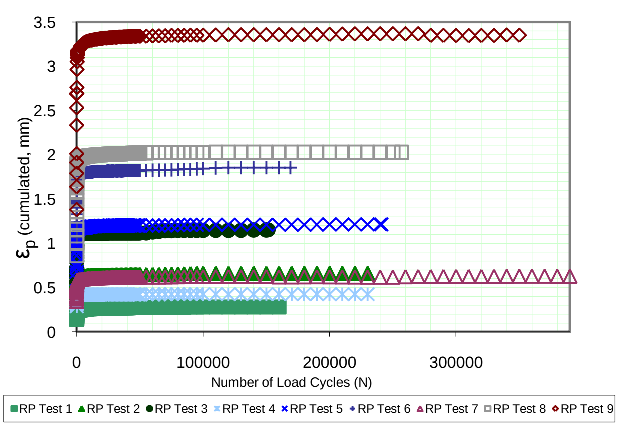

Figure 4. Accumulated Permanent Deformation of Ribeirão Preto's clay.

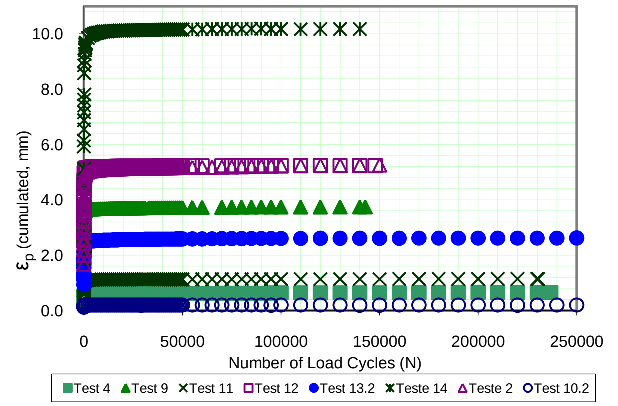

Figure 5: Accumulated Permanent Deformation of the ES's sand-clay soil.

It is presented in table 2 the amounts of total permanent deformation for three different tests, both for the clay from Ribeirão Preto and the loamy sand from Espírito Santo (ES).

Both soils have geotechnical classification LG, in other words, they are part of loamy soils of lateritic behavior. However, they differ from each other because of the laterization degree, higher in Ribeirão Preto's clay and mineralogical composition.

Ribeirão Preto's clay is richer in Fe and Al oxide-hydroxides which are natural cements. For this condition, perhaps the highest permanent deformation amounts were lower than those from sand-clay from Espírito Santo, as we can see it in table 2.

Table 3. Permanent Deformation Values of Ribeirão Preto's clay and ES's sand-clay.

Material	**Test**	**σ_d kPa**	**σ_3 kPa**	**ε_p mm**	**N_{final}**
Ribeirão Preto's clay	1	40	40	0,281	160.000
	5	160	80	1,214	240.000
	9	360	120	3,351	340.000
ES's loamy sand	1	40	40	0,197	250.000
	5	140	70	3,750	142.800
	9	240	120	10,177	140.000

Figure 6 shows a comparative chart between the Ribeirão Preto's clay accumulated permanent deformation and the observed deformation for the graduated grit from Chapecó, where we can see that the deformations are similar with the lower tension levels. However, there is a tendency of more emphasized increase of the permanent deformation in Ribeirão Preto's clay, as the stress increases, and there may be a 42% total permanent deformation difference in the higher stress level.

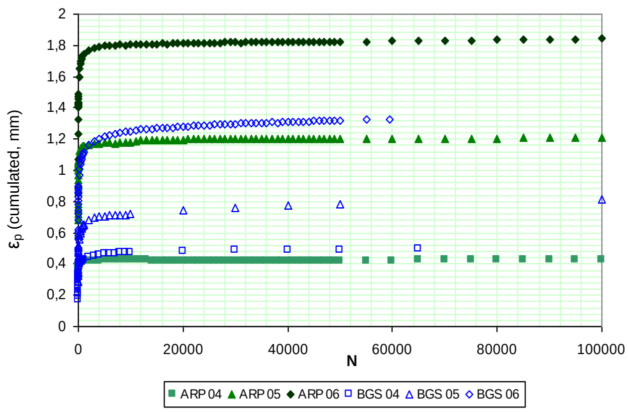

Figure 6. Comparison between total permanent deformation shown by clay from Ribeirão Preto, São Paulo, and graduated grit. 80 kPa confining stress and 10cm diameter x 20cm height samples' test.

4.2 Model Parameters

The proposed model in the present work, which parameters are presented in table 3, shows good accuracy for permanent deformation prediction, either for bouldery materials or thin soils, submitted to repeated loads action, both because of high correlation coefficients (above 0.9) and for the other pertinent factors analysis, such as the deviation normality condition verification. The mathematic tool itself describes satisfactorily the observed behavior of laboratory repeated loads in the tests.

The present research keeps the execution of tests with soils from other regions of the country, with the inclusion of this model in the performance monitoring of at least 60 distinct pavements spread across Brazil, which is in its implementation process, conducted by Petrobras,.

Thus, a broader tropical soils database from Brazil will be obtained, as well as field-laboratory factors.

Table 4. Soils Parameters of the Permanent Deformation Model

Material	$\varepsilon_p(\%) = \psi_1(\sigma_3)^{\psi_2}.(\sigma_d)^{\psi_3}.(N)^{\psi_4}$			
	ψ_1	ψ_2	ψ_3	ψ_4
Laterita Acre	0,105	0,839	-0,014	0,041
Chapecó`s Graduated Grit	0,079	-0,598	1,243	0,081
Corumbaíba's gravel	0,180	-0,212	0,840	0,443
Laterite from Porto Velho	0,180	0,470	0,336	0,047
Lateritic Clay from Ribeirão Preto	0,206	-0,24	1,34	0,038
Lateritic Sand-clay from ES	0,643	0,093	1,579	0,055
Papucaia`s soil	0,244	0,419	1,309	0,069
Fine Grained Sand from Campo Azul, MG	0,050	-1,579	1,875	0,064

4.3 Shakedown Research

In the methodology created by Werkmeister (2003), the data are analyzed in a graphical form, according to the model of Dawson and Wellner, which is illustrated in Figure 7. In the vertical axis, there is a permanent deformation increase rate and in the horizontal axis, the vertical permanent deformation.

Therefore, a trippingly decreasing curve, that is approximately parallel to the vertical axis, indicates that the permanent deformation increase rate tends to be zero, in other terms, the material begins to shakedown. This fact is favorable to the pavement project, because the tested material insignificantly contributes to the total deepening of the wheel tracks.

When the curve becomes approximately parallel to the horizontal axis, without reaching a value of the order of magnitude 10^{7} meters per load application cycle, the permanent deformation increase rate may be low, however, there will always be a deformation increase. In other terms, there will be successive contributions to the wheel track deepening. That is the case of plastic creep.

Concerning Campo Azul's thin sand, shown in Figure 7, it's observable that for the lowest stress levels occurred shakedown. Nevertheless, as the stress levels were elevated, the behavior changed for plastic creep. Similar results were observed for the soil of Papucaia, as shown in Figure 8.

For Acre laterite, Figure 9, it was observed that, even in tests with elevated stress levels, the predominant behavior was "shakedown", which indicates that this type of material is favorable to pavement usage, considering this aspect.

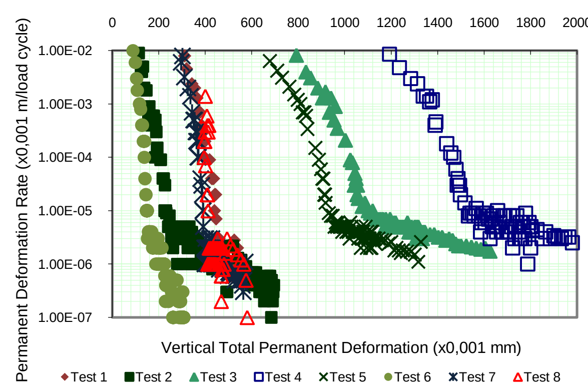

Figure 7. Shakedown Research Of the Fine Sand from Campo Azul Using the Dawson and Wellner Model. Each sample was of 10cm diameter and 20cm height.

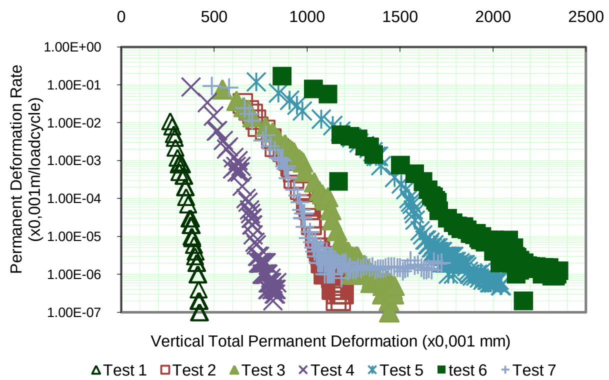

Figure 8. Shakedown Research of the Solo Papucaia (Papucaia Soil) Using the Dawson and Wellner Model. Each sample was of 10cm diameter and 20cm height.

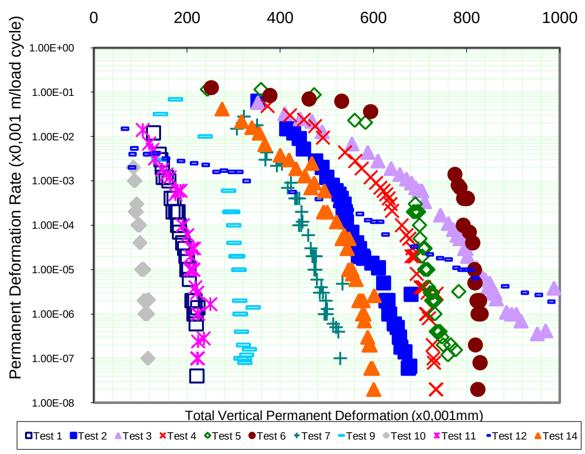

Figure 9. Shakedown Research of the Laterita Acre (Acre Laterite) Using the Dawson and Wellner Model. Each sample 10cm diameter and 20cm height.

Based on Figures 7, 8 and 9, it is not possible to mathematically distinguish which the limit between shakedown and plastic creep would be. For this reason, Werkmeister (2003) proposed an analysis in stresses σ_1 and σ_1/σ_3 space, as shown in Picture 10. In this space, the limit between the two behavior patterns is a function that approaches the top stress levels that they correspond. There were tests in which shakedown occurred. When stress is below that value, the soils present shakedown, and above this value there is plastic creep.

In Figure 9, the stresses used in the research with laterite from Porto Velho are compared to the shakedown limit for the granodiorite tested by Werkmeister (2003). It is concluded that the laterite from Porto Velho has slightly superior shakedown limit than the granodiorite. In other words, the laterite from Porto Velho can be required with stress a slighted elevated than the granodiorite and still there will be shakedown.

Concerning a pavement constituted with laterite from Porto Velho, in a way that the stresses (σ_1 and σ_1/σ_3) don't exceed the shakedown limit, this layer will not contribute significantly to the total deepening of the wheel track, and therefore, it is desirable in terms of structural project.

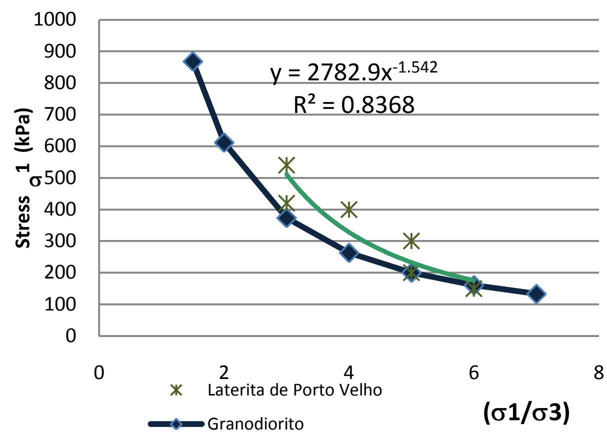

Figure 10. Comparison between shakedown limits of the granodiorite (Werkmeister, 2003) and Porto Velho Laterite gravel.

In the other tests observed with laterites, it can be noticed that the shakedown limit has the same magnitude as the one observed for the grits studied by Werkmeister.

5 CONCLUSION

The proposed model of permanent deformation is regarded as appropriate for the prediction of the researched materials contribution, especially in tropical soils, deepening of pavement wheel tracks. For granular tropical soils the permanent deformations magnitude was very low, in the other hand, for granular tropical soils the magnitude with elevated stress had high values.

The analysis model of behavior concerning permanent deformation of the materials proposed by Werkmeister (2003) and others, represented by the analysis of the permanent deformation increase rate, enables to distinguish three different response levels, labeled as behaviors types A, B and C. The model was successfully applied to the studied materials in the present work, being possible to see a similarity between the limits of shakedown.

6 REFERENCES

Ingold, T.S. and Miller, K.S. 1983. Drained Axisymmetric Loading of Reinforced Clay, *Journal of Geotechnical Engineering*, ASCE, 109(3): 883-898.

Ingold, T.S. and Miller, K.S. 1983. Drained Axisymmetric Loading of Reinforced Clay, *Journal of Geotechnical Engineering*, ASCE, 109(3): 883-898.

Bigarella, J. J., Becker, R. D. e Santos, G. F dos (2007). "Estrutura e Origem das Paisagens Tropicais e

Subtropicais, Volume 2". 2nd Edition – Florianópolis/SC, Edited by UFSC, 2007.
Cardoso, H., S. (1987) "Procedure for Flexible Airfield Pavement Design Based on Permanent Deformation". Tese PhD. University of Maryland. EUA.
COMMITTEE ON TROPICAL SOILS OF THE ISSMFE (1985). Peculiarities of Tropical Soils Used as Construction Materials. Topic 4.2: Roads. Progress Report 1981-1985. First International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils.
Costa, M. L da (1997). Lateritization as a Major Process of Ore Deposit Formation in the Amazon Region. Journal of Explor. Mining Geol.. Vol 6 n°1, PP. 79-104. Canadian Institute of Mining, Metallurgy and Petroleum. Published by Elsevier Science Ltd.
Guimarães, A. C. R (2001). "A Study about permanent deformation on soils and the Shakedown Theory Applied to Flexible Pavements". Master Thesis. Civil Engineering Department COPPE/UFRJ. Rio de Janeiro, 280 pages. In portuguese.
Guimarães, A. C. R. e Motta, L. M. G. da (2008a). "Um Estudo Sobre Deformação Permanente em Solos Lateríticos Concrecionados do Sudoeste da Amazônia Através de Ensaios Triaxiais de Cargas Repetidas". Summary of the IV Luso-Brazilian Geothecnical Congress, Coimbra, Portugal, April 2008.
Guimarães, A. C. R. e Motta, L. M. G. da (2008b). "Um Estudo Sobre a Deformabilidade de Uma Laterita do Acre Através de Ensaios Triaxiais de Cargas Repetidas". Summary of the 15th ABPv's Urban Paving Meeting, Salvador/BA, May 2008.
Guimarães, A. C. R. (2009). A Mechanistic-empirical Method to Predict Permanent Deformation on Tropical Soils on Pavements. PhD Thesis (in Portuguese).
Grace, H. (1991). Investigations in Kenya and Malawi Using As-Dug Laterite as Bases for Bituminous Surfaced Roads. Journal of Geotechnical and Geological Engineering, 1991, 9, 183 – 195.
Indraratna, B e Nutalaya, P(1991). Some Engineering Characteristics of a Compacted Lateritic Residual Soils. Journal of Geotechnical and Geological Engineering, 1991, 9, 125 – 137.
Lepsch. Igo F. (2002). Formação e Conservação dos Solos"". Edited by "Oficina de Textos", San Paulo.
Mahalinga-yer, U. e Williams, D. J. (1996). Properties and Performance of Lateritic Soil in Road Pavements. Journal of Engineering Geology 46 (1997) 71-80. Elsevier Science.
Medina, J. e Motta, L. M. G da (2005). "Mecânica dos Pavimentos" 2nd Edition. ISBN 85-905987-1-3. Rio de Janeiro 2006.
Nogami, J. S e Villibor, D. F. (1995). "Pavimentação de Baixo Custo com Solos Lateríticos". Editora Villibor, San Paulo, Brasil.
DNIT STANDARDS 098/2007 ES. "Pavimentação – Base Estabilizada Granulometricamente com Utilização de Solo Laterítico – Especificação de Serviço".
Omotosho, O. (2004). Influence of Gravelly Exclusion on Compaction of Lateritic Soils. Journal of Geotechnical and Geological Engineering 22: 351-359, 2004.
Santos, J. D. G. (1998). "Contribuição ao Estudo dos Solos Lateríticos Granulares Como Camada de Pavimento". Doctor Degree Thesis. Civil Engineering Program – COPPE/UFRJ. Rio de Janeiro.
Seixas, S. (1997). "Comportamento Dinâmico dos Materiais Constituintes do Pavimento da Pista de Pouso do Novo Aeroporto de Rio Branco".Magister DegreeThesis, Civil Engineering Program – COPPE/UFRJ. Rio de Janeiro.
Sunil, B. M., Nayak, S. e Shrihari, S. (2006). Effect of pH on the Geotechnical Properties of Laterite. Journal of Engineering Geology (85) pag 197 - 203. Elsevier.
Vertamatti, E. (1988). "Contribuição ao Conhecimento Geotécnico de Solos da Amazônia com Base na Investigação de Aeroportos e Metodologia MCT e Resiliente". Doctor Degree Thesis. Air transportation Area. ITA. San José dos Campos/SP.
Werkmeister, S., Dawson, A. R., Wellner, F. (2001). Permanent Deformation Behavior of Granular Materials and the Shakedown Concept. Transportation Research Record nº 01-0152, Washington, DC.
Werkmeister, S., Numrich, R., Dawson, A., Wellner, F. (2003). Design of Granular Pavement Layers Considering Climatic Conditions. Transportation Research Board, 82º Annual Meeting. January 12-16, 2003, Washington D.C.
Werkmeister, S. (2003). Permanent Deformation Behavior of Unbound Granular Materials in Pavement Constructions. Doctor Degree Thesis. Thecnical University of Dresden, 189 pg.
Werkmeister, S., DAWSON, A. R., WELLNER, F. (2004). Pavement Design for Unbound Granular Materials. Journal of Transportation Engineering ©ASCE/September/October.