Plastic deformation analysis of lateritic clay soils using multi-stage and single-stage methodology

Análise da deformação plástica de solo argiloso laterítico por meio da metodologia multiestágios e estágio único

Análisis de la deformación plástica de suelos arcillosos lateríticos mediante la metodología de etapas múltiples y de etapa única

DOI: 10.54033/cadpedv21n7-262

Originals received: 06/14/2024
Acceptance for publication: 07/05/2024

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ABSTRACT
This article verified the permanent deformation of lateritic clay soil used as a subgrade, and the results of different methodologies were compared. Plasticity characterization is pertinent as it is a material subject to large deformations when subjected to high stresses, justifying the need to investigate its plastic properties. In Brazil, this evaluation follows an extensive protocol involving various samples and stress conditions. However, other countries already use multistage tests to assess permanent deformation. Given the above, this article presents a comparison of the single-stage protocol with two multistage protocols adapted to two different conditions of application of load cycles, the first of which was carried out for six different pairs of stresses varying the confining and deviator stresses and the second with the confining stress fixed and only the deviator stress varying. It can be concluded that the accumulated permanent deformations grow as the applied stresses increase and show a tendency to settle. This result is firmly in line with what is identified by the so-called traditional methodology. The multistage methodology is promising for prior material characterization, making it possible to identify trends in behavior for various parameters with a shorter test time and a smaller quantity of material, and it could be used as a criterion for choosing between deposits. Further studies are needed to validate the protocol for a broader range of materials.

Keywords: Repeated Load Triaxial Tests. Deformability. Tropical Soil. Pavement.
fortemente alinhado com o identificado pela metodologia dita tradicional. A utilização da metodologia multiestágios é promissora para uma caracterização prévia do material, possibilitando identificar tendência de comportamentos para diversos parâmetros com um menor tempo de ensaio e uma menor quantidade de material, podendo vir a ser utilizada como critério de escolha entre jazidas. Ainda, são necessários mais estudos de forma a validar o protocolo para um conjunto maior de materiais.


**RESUMEN**
Este artículo verificó la deformación permanente del suelo arcilloso laterítico utilizado como subrasante, comparando los resultados de diferentes metodologías. La caracterización de la plasticidad es pertinente dado que se trata de un material sujeto a grandes deformaciones bajo altos esfuerzos, justificando la necesidad de investigar sus propiedades plásticas. En Brasil, esta evaluación sigue un extenso protocolo que involucra diversas muestras y condiciones de estrés. Sin embargo, en otros países ya se emplean pruebas multietapas para evaluar la deformación permanente. En este contexto, el artículo presenta una comparación del protocolo de una sola etapa con dos protocolos multietapas adaptados a dos condiciones diferentes de aplicación de ciclos de carga, el primero realizado para seis pares diferentes de esfuerzos variando los esfuerzos de confinamiento y desviador, y el segundo con el esfuerzo de confinamiento fijo y solo variando el esfuerzo desviador. Se concluye que las deformaciones permanentes acumuladas aumentan con el incremento de los esfuerzos aplicados y muestran una tendencia a estabilizarse. Este resultado concuerda con lo identificado por la metodología tradicional. La metodología multietapa muestra ser prometedora para la caracterización previa de materiales, permitiendo identificar tendencias de comportamiento para diversos parâmetros con un tiempo de prueba más corto y una menor cantidad de material, y podría ser utilizada como criterio para la selección entre depósitos. Se requieren más estudios para validar el protocolo en una gama más amplia de materiales.

**Palabras clave:** Ensayos Triaxiales de Cargas Repetidas. Deformabilidad. Suelos Tropicales. Pavimentación.

**1 INTRODUCTION**
Flexible pavements undergo deformation throughout their useful life, damaging the different layers that make up their structure. Excessive deformation can cause rutting, which, together with fatigue cracking, are the primary defects
of flexible pavement (Lekarp et al., 2000; Cerni et al., 2012; Medina; Motta, 2015).

Permanent deformation is, by definition, the result of the accumulation of non-recoverable deformations due to the action of loads since materials are not entirely elastic (Uzan, 2004). Plastic deformation can interfere with user safety and comfort, as it can saturate the underlying layers, accumulate water along the rutting, and make it difficult for the vehicle to move along the road (Bernucci et al., 2022). Rutting can be minimized by designing the pavement using the Método de Dimensionamento Nacional (MeDiNa), a Brazilian computational tool validated for this purpose. This method allows for the design of pavement based on the stresses to which it will be subjected, assessing the stiffness and damage of the layers to verify the behavior of permanent deformation in the granular and soil layers (DNIT, 2020).

Given this, based on adaptations to Brazilian regulations, this research aimed to evaluate two protocols for the permanent deformation test by applying multiple stages. Both conditions were proposed to evaluate the loads on clay soil with lateritic behavior. This procedure evaluated the possible reduction in time and amount of material required. The results of these evaluations are compared with the single-stage protocol carried out by Pascoal et al. (2023) for the same soil and compaction energy to validate the results/parameters obtained by the multi-stage protocol.

2 LITERATURE REVIEW

The permanent deformation test, carried out using repeated load triaxial equipment, aims to understand the behavior and determine plastic properties to be used in predicting the performance of materials in terms of this degradation mechanism, thus analyzing the structural response of the pavement. Therefore, in Brazil, the plastic properties of the material are characterized by applying at least 150,000 load cycles for each pair of confining and deflecting stresses following the DNIT 179 regulations (DNIT, 2018). The plastic characterization of a material is completed after at least six pairs of valid stresses have been carried out and can be carried out for nine pairs of stresses. This procedure requires
considerable time to prepare the samples since each sample is subjected to a pair and requires around 21 hours on the equipment mentioned, with tension applied at 2 Hz.

From the permanent deformation test, it is possible to distinguish types of material behavior in terms of resistance to plastic rupture, depending on the degree of stress applied. As indicated in the DNIT 179 (2018) standard, materials can exhibit four different types of behavior. Type I and II consider the material shakedown, indicating a tendency for the permanent deformation to stabilize with the number of loading cycles, differing from each other in terms of the high accumulated displacement value. Type III indicates that the material does not settle, while in Type IV, the material reaches rupture with low load cycle repetitions.

Following the precepts of Dawson; Wellner (1999) and Werkmeister et al., (2001), shakedown can be identified through analysis, and it is possible to find behavior A (occurrence of shakedown), behavior B (plastic creep) and C (incremental collapse). In addition, according to DNIT (2018), the material analyzed may exhibit AB behavior, encompassing materials with significant initial deformations followed by plastic creep. When carrying out these analyses, to check whether the material has reached shakedown, the increase in permanent deformations per load application cycle must be $10^{-7}$ to $10^{-3}$ m per load application cycle.

To obtain the plastic parameters, following the recommendation of the current regulations, the method described by Guimarães (2009) is used, according to equation 01, which is widely used in the national technical literature, and this model is included in the MeDiNa framework.

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

Where $\varepsilon_p(\%)$ represents the specific plastic deformation; $y_1, y_2, y_3, y_4$ são test regression parameters; $s_3$ is the confining stress; $s_d$ the deviator stress; $r_0$ is the reference pressure (atmospheric), and $N$ is the number of load application
cycles. An alternative for assessing the plastic behavior of materials is the multistage permanent deformation test, in which a single sample is subjected to different stress states. Several researchers have carried out multistage tests with variations of up to four stress states, generally with 10,000 cycles of stresses at each state, for various materials used in the subgrade, sub-base, or base of pavements (Cerni et al., 2012; Xiao et al., 2015; Nazzal et al., 2020a; Nazzal et al., 2020b). Tests with five or more stress variations have also been carried out in recent years, following international standards or adaptations made from these standards (Song; Ooi, 2010; Erlingsson; Rahman, 2013; Rahman; Erlingsson, 2015; Salour et al., 2016; Erlingsson et al., 2017; Delongui et al., 2018; Nguyen; Ahn, 2019; Naeini et al., 2021; Ben et al. 2022).

Because of this, comparisons were made between different protocols for permanent deformation testing with the application of multiple stages. The single stage was carried out as proposed by DNIT (2018) and applied to Pascoal et al. (2023), while conditions 1 and 2 (multistages) were carried out based on an adaptation of European standards (BSI, 2004), following protocols already widespread in the literature (Song; Ooi, 2010; Erlingsson; Rahman, 2013; Rahman; Erlingsson, 2015; Salour et al., 2016; Erlingsson et al., 2017; Delongui et al., 2018; Nguyen; Ahn, 2019; Naeini et al., 2021).

3 MATERIALS AND METHODS

The soil under study was extracted from the B pedological horizon of a quarry in the municipality of Cruz Alta, in the northwestern mesoregion of Rio Grande do Sul, Brazil, which was used to build a stretch of the RS-342 highway. The collection area has deep, dark red latosols with a medium clay texture (Lemos, 1973). Pascoal et al. (2021) characterized the soil used in this research. The physical and chemical characterization of the soil under study was conducted according to the following standards: granulometric analysis by sieving and sedimentation, with and without deflocculant (sodium hexametaphosphate), following the guidelines of NBR 7181 (ABNT, 2016); real specific mass of the grains, following the principles of NBR 6508 (ABNT, 2016); and Atterberg limits.
according to the standards of NBR 6459 (ABNT, 2016) and NBR 7180 (ABNT, 2016). Chemical analysis and X-ray fluorescence tests were also carried out. The results of these characterizations are shown in Table 1. It should be noted that the formation process of lateritic soils is the product of intense weathering that results in the leaching of less resistant minerals.

It should also be noted that this process reduces SiO2(Silicon Dioxide) and increases Fe2O3 (Iron Oxide) and Al2OH3 (Aluminum Oxide). As seen, there is a high concentration of iron and aluminum oxides. Therefore, the X-ray fluorescence characterization results corroborate the MCT classification (LG'-clay lateritic soil).

<table>
<thead>
<tr>
<th>Physical characterization</th>
<th>Chemical characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Coarse sand (0.6 - 2.0 mm)</td>
<td>0</td>
</tr>
<tr>
<td>% Medium sand (0.2 - 0.6mm)</td>
<td>8</td>
</tr>
<tr>
<td>% Fine sand (0.06 - 0.2mm)</td>
<td>25</td>
</tr>
<tr>
<td>% Silt (2µm - 0.6mm)</td>
<td>26</td>
</tr>
<tr>
<td>% Clay (%2µm)</td>
<td>41</td>
</tr>
<tr>
<td>Density (kN/m³)</td>
<td>27.8</td>
</tr>
<tr>
<td>Liquid limits (%)</td>
<td>55</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>44</td>
</tr>
<tr>
<td>Plasticity index (%)</td>
<td>11</td>
</tr>
<tr>
<td>Classification</td>
<td></td>
</tr>
<tr>
<td>AASHTO</td>
<td>A-7-6</td>
</tr>
<tr>
<td>SUCS</td>
<td>MH</td>
</tr>
<tr>
<td>MCT</td>
<td>LG’</td>
</tr>
</tbody>
</table>

Compaction - Intermediate Energy

| Optimal moisture (%) | 25.6 | Maximum dry density (kg/m³) | 1625 |

Resilient parameters - Composite model

| k1 | 739.2 | k2: 0.34 | k3: 0.00 | R²: 0.90 |

Source: Pascoal et al., 2021.

Since this material was used in RS-342 at standard energy for the body of the embankment and intermediate energy for the final layer of earthworks and because it performs well under stress in terms of resilient and permanent deformation, as found by Pascoal et al. (2023), it was decided to consider intermediate energy in this research. Therefore, compaction was carried out at this energy, using a tripartite cylinder with a diameter of 10 cm and a height of 20 cm in 10 layers, with 27 blows per layer, considering a drop height of 30.5 cm and a 2.5 kg hammer. DNIT (2018) allows a tolerance of ± 0.5% relative to the
optimum moisture content to validate the samples. As this standard does not indicate a criterion for varying the maximum dry density, a variation of ± 1% about the degree of compaction was adopted to validate the compaction of the test specimen.

The repeated load triaxial equipment is used to carry out the permanent deformation test. According to current regulations, the recommended load application frequency is 2 Hz. However, frequencies of 1 to 5 Hz can be used, and the duration of the load pulse for any frequency is 0.1 second. Throughout the test, the confining stress is kept constant (non-cyclic). Initially, conditioning cycles must be applied to adjust the piston and the cylinder head. Table 2 shows the nine pairs of confining stress and deviator recommended in the (DNIT, 2018). This standard allows six pairs of stresses to be tested if representative. Lima et al. (2019) investigated the best combination of pairs, shown in Table 2.

<table>
<thead>
<tr>
<th>Stress pair number</th>
<th>Confining stress σ₃ (kPa)</th>
<th>Desviator stress σ₆ (kPa)</th>
<th>Stress ratio σ₆ /σ₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>40</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>80</td>
<td>2</td>
</tr>
<tr>
<td>3*</td>
<td>120</td>
<td>120</td>
<td>3</td>
</tr>
<tr>
<td>4*</td>
<td>80</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>160</td>
<td>160</td>
<td>2</td>
</tr>
<tr>
<td>6*</td>
<td>240</td>
<td>240</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>8*</td>
<td>240</td>
<td>240</td>
<td>2</td>
</tr>
<tr>
<td>9*</td>
<td>360</td>
<td>360</td>
<td>3</td>
</tr>
</tbody>
</table>

Note: * Stress pairs selected for the Permanent Deformation test for single stage (Lima et al., 2019).

Source: Adapted DNIT, 2018 and Lima et al., 2019.

3.1 SINGLE STAGE PERMANENT DEFORMATION

To assess permanent deformation, Pascoal et al. (2023) conducted tests following the protocol of the DNIT (2018), applying a stress pair to each sample for at least 150,000 cycles at a frequency of 2 Hz. Each sample underwent the test for approximately 22 hours, resulting in a minimum of 9 days for complete characterization using the mentioned methodology. Figure 1 shows the accumulated deformation for the different stress pairs applied.
Among the results obtained, it is possible to identify patterns between the ratio of the stress pairs \(\frac{\sigma_d}{\sigma_3}\) and the observed deformation since the more significant the deviator stress to which the material is subjected, the greater the permanent deformations for the same confining stress. Among the behaviors identified, pairs with a ratio of 1 had the lowest accumulated deformations. Similarly, the pairs with the most considerable deformations were mainly those with a ratio of 3 between stresses, where an accumulated deformation of 1.22 mm was identified. Using multiple linear regression, Pascoal et al. (2023) obtained the parameters for the Guimarães (2009) model, considering \(\rho_0\) of 0.1 MPa for the calculation, obtaining the results shown in Table 3.

Table 3. Permanent Deformation parameters using the Guimarães (2009) model

<table>
<thead>
<tr>
<th>Soil – IE</th>
<th>(\psi_1)</th>
<th>(\psi_2)</th>
<th>(\psi_3)</th>
<th>(\psi_4)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Stage</td>
<td>0.083</td>
<td>0.699</td>
<td>0.517</td>
<td>0.103</td>
<td>0.93</td>
</tr>
</tbody>
</table>

\[ \varepsilon_p = 0.083 \left( \frac{\sigma_d}{\rho_0} \right)^{0.699} \left( \frac{\sigma_d}{\rho_0} \right)^{0.517} N^{0.103} \]

Source: Pascoal et al., 2023.

Figure 1 presents the results of the laboratory tests. Figure 1(a) shows the results of permanent deformation versus the number of load application cycles, considering the different pairs. Analysis of the material in terms of the pattern of its deformations revealed the occurrence of the shakedown phenomenon, as shown in Figure 1 (b). It should also be noted that all the samples tend to settle, showing A behavior, according to Dawson; Wellner (1999), and Type I behavior according to DNIT (2018). According to Guimarães (2009), the rate of change in permanent deformation can be zero with the increase in load cycles or tend to decrease considerably when the material is close to settling. Therefore, after a certain number of load application cycles, the deformations tended to become constant, showing minor variations.
Figure 1. Results of the tests (a) Accumulated Permanent Deformation; (b) Investigation of the occurrence of shakedown

Upon reaching 1,000 PD test cycles, there was a variation of 67% to 76% in the total accumulated deformation, except for the samples subjected to the lowest pair of stresses, which reached 51% of the total deformation at 1,000 cycles. At 10,000 cycles of repeated loading, the accumulated permanent deformation in the six samples subjected to different stress pairs was already close to 80%. At the end of 50,000 cycles, the samples showed between 90% and 99% of total deformation.
3.2 MULTI-STAGE PERMANENT DEFORMATION

The multistage methodology comes to the fore since the single-stage permanent deformation test, even when using the reduced protocol, ends up requiring an extended period, thus wearing out the mechanical part of the equipment, as well as requiring a more significant amount of material. Given this, Song; Ooi (2010), Delongui et al. (2018), Nguyen; Ahn (2019), applied the European standard EM 13286-7 (BSI, 2004) as a way of investigating the viability of the methodology applied to different materials used in paving.

The multistage methodology for characterizing the plastic properties of the material, this research proposes carrying out repeated load triaxial tests using two different multistage protocols. The objective is to analyze which of them is similar to the results found in the single-stage methodology. Therefore, it is proposed to vary the number of repetitions per load cycle, the deviator stresses, and the confining stresses according to the following conditions: the Condition 1 involves performing 10,000 cycles for each pair listed as 1, 3, 4, 6, 8, and 9 in Table 2, with the test carried out in triplicate, and the Condition 2 consists of conducting...
10,000 cycles for all the pairs in Table 2 on three different samples. In this condition, the confining stress is fixed, and the deviator stress is as follows:

- For a confining stress fixed at 40 kPa, the deviator stress varies at 40, 80, and 120 kPa;
- For a confining stress fixed at 80 kPa, the deviator stress varies at 80, 160, and 240 kPa;
- For a confining stress fixed at 120 kPa, the deviator stress varies at 120, 240, and 360 kPa.

The choice to carry out the tests with 10,000 repetition cycles is justified by the conclusions obtained when carrying out the procedure in a single stage. In addition, the BSI (2004) standards were taken as a basis. To analyze the results of the different methodologies, it was necessary to compare the behavior of permanent deformation and the occurrence of shakedown. In this way, a comparison can be made with the results obtained by Pascoal et al. (2023) applying the single-stage methodology to the same material, compared with the two multistage methodologies.

4 RESULTS AND ANALYSIS

4.1 MULTI-STAGE PERMANENT DEFORMATION – CONDITION 1

Table 4 shows the deformations obtained after the end of each application of a pair of stresses (10,000 stress cycles), where similarity can be seen between the three samples within all the pairs of stresses applied, with a range of between 3% and 17% in the coefficients of variation. It should be noted that the most significant variations occurred for the pair of stresses $\sigma_3$: 40 kPa and $\sigma_d$: 40 kPa and the most minor variations for pairs of $\sigma_3$: 120 kPa and $\sigma_d$: 360 kPa. For condition 1, in which six pairs were applied in sequence to the same sample, with the increasing stresses applied, there was an increase in the deformations identified. Figure 3 (a) shows that from the thousand cycles applied to each stress, the deformations become constant, with slight variations, except for the last pair. In the three samples subjected to the same protocol, the pair of stresses...
that caused accentuated deformations was $\sigma_3$: 120 kPa and $\sigma_d$: 360 kPa due to their magnitude and the ratio $\sigma_d/\sigma_3$ being 3.

When observing the accumulated permanent deformations of the three samples, similar behavior can be seen in all of them, in which it is possible to verify a tendency towards accommodation of the plastic deformations, classifying them as Type I or II, according to the DNIT (2018) and according to Dawson; Wellner (1999). To analyze the occurrence of shakedown, due to the similarity of the accumulated deformations at the end of the 10,000 cycles between the three samples, it was decided to calculate the average of these values. Thus, the average of the accumulated deformations of the samples was used to obtain the parameters using the Guimarães (2009) model. Figure 3 (b) shows the analysis of the occurrence of shakedown for the average value found.

Table 4. Analysis of deformations in samples subjected to condition 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_3$ (kPa)</th>
<th>$\sigma_d$ (kPa)</th>
<th>$\sigma_d/\sigma_3$</th>
<th>E 10,000 (mm)</th>
<th>Average (mm)</th>
<th>Standard deviation</th>
<th>Coefficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 01</td>
<td>40</td>
<td>120</td>
<td>3</td>
<td>0.061</td>
<td>0.062</td>
<td>0.008</td>
<td>12</td>
</tr>
<tr>
<td>S 02</td>
<td>40</td>
<td>120</td>
<td>3</td>
<td>0.061</td>
<td>0.062</td>
<td>0.008</td>
<td>12</td>
</tr>
<tr>
<td>S 03</td>
<td>40</td>
<td>120</td>
<td>3</td>
<td>0.061</td>
<td>0.062</td>
<td>0.008</td>
<td>12</td>
</tr>
<tr>
<td>S 01</td>
<td>70</td>
<td>240</td>
<td>3</td>
<td>0.116</td>
<td>0.133</td>
<td>0.017</td>
<td>12</td>
</tr>
<tr>
<td>S 02</td>
<td>70</td>
<td>240</td>
<td>3</td>
<td>0.116</td>
<td>0.133</td>
<td>0.017</td>
<td>12</td>
</tr>
<tr>
<td>S 03</td>
<td>70</td>
<td>240</td>
<td>3</td>
<td>0.116</td>
<td>0.133</td>
<td>0.017</td>
<td>12</td>
</tr>
<tr>
<td>S 01</td>
<td>100</td>
<td>360</td>
<td>3</td>
<td>0.308</td>
<td>0.306</td>
<td>0.011</td>
<td>3</td>
</tr>
<tr>
<td>S 02</td>
<td>100</td>
<td>360</td>
<td>3</td>
<td>0.308</td>
<td>0.306</td>
<td>0.011</td>
<td>3</td>
</tr>
<tr>
<td>S 03</td>
<td>100</td>
<td>360</td>
<td>3</td>
<td>0.308</td>
<td>0.306</td>
<td>0.011</td>
<td>3</td>
</tr>
</tbody>
</table>

Source: Authors.
Figure 3. (a) Multistage permanent deformation - condition 1; (b) Analysis of the occurrence of shakedown - condition 1.

In Table 5, the parameters of the Guimarães model (2009) can be observed. These parameters were varied for each of the six cycles to which the samples were subjected.
Table 5. Permanent deformation parameters using the Guimarães (2009) model for multistage condition 1

<table>
<thead>
<tr>
<th>Soil – IE</th>
<th>$\psi_1$</th>
<th>$\psi_2$</th>
<th>$\psi_3$</th>
<th>$\psi_4$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multistage Cond. 1 (1+2+3)</td>
<td>0.0005</td>
<td>-3.676</td>
<td>5.261</td>
<td>0.234</td>
<td>0.87</td>
</tr>
</tbody>
</table>

$\varepsilon_p = 0.0005 \left( \sigma_3 / \rho_0 \right)^{-3.676} \left( \sigma_d / \rho_0 \right)^{5.261} N^{0.234}$

Source: Authors.

4.2 MULTI-STAGE PERMANENT DEFORMATION – CONDITION 2

In the second multistage test protocol, the sample subjected to the 120 kPa confining stress suffered high deformations, so much so that data acquisition was impossible, and the test ended at the last pair of stresses, as shown in Figure 4. The other two samples, which had the confining stresses set at 40 and 80 kPa, suffered slight deformations compared to the 120 kPa confining stress.

![Figure 4 - Multistage permanent deformation - condition 2](image)

Table 6 summarizes the accumulated deformation in the following load repetition cycles: 50, 100, 500, 1,000, 5,000, and 10,000 for each stress pair applied, totaling 30,000 cycles, with 10,000 cycles for each of the three stress pairs applied in the standard.
Table 6. Deformation analysis of samples subjected to MS condition 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\sigma_3) (kPa)</th>
<th>(\sigma_d) (kPa)</th>
<th>(\sigma_d/\sigma_3)</th>
<th>Deformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E50</td>
</tr>
<tr>
<td>04</td>
<td>40</td>
<td>1</td>
<td></td>
<td>0.0136</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>2</td>
<td></td>
<td>0.0200</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>3</td>
<td></td>
<td>0.0140</td>
</tr>
<tr>
<td>05</td>
<td>80</td>
<td>1</td>
<td></td>
<td>0.0407</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>2</td>
<td></td>
<td>0.0433</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>3</td>
<td></td>
<td>0.0547</td>
</tr>
<tr>
<td>06</td>
<td>120</td>
<td>1</td>
<td></td>
<td>0.2780</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>2</td>
<td></td>
<td>0.1470</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>3</td>
<td></td>
<td>0.2150</td>
</tr>
</tbody>
</table>

Source: Authors.

For condition 2 of the multistage protocol, it was impossible to complete the analysis due to excessive deformations identified in sample 6 for the pair \(\sigma_3\): 120 kPa and \(\sigma_d\): 360 kPa. Due to the enormous magnitude of the deformation identified, the displacement transducer did not have enough travel to carry out data acquisition after 1000 cycles of load application for the third pair of stresses to which the sample was subjected, thus making it impossible to analyze the accumulated deformation and consequently investigate the occurrence of the shakedown phenomenon. In Table 7, the parameters of the Guimarães model (2009) can be observed, considering that the confining stress was fixed and the deviatoric stress varied.

Table 7. Permanent deformation parameters using the Guimarães (2009) model for multistage condition 2

<table>
<thead>
<tr>
<th>Soil – IE</th>
<th>(\psi_1)</th>
<th>(\psi_2)</th>
<th>(\psi_3)</th>
<th>(\psi_4)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multistage Cond. 2 (1+2+3)</td>
<td>0.399</td>
<td>2.730</td>
<td>-0.125</td>
<td>0.118</td>
<td>0.857</td>
</tr>
</tbody>
</table>

\[ \varepsilon_p = 0.399 (\sigma_3/\rho) + 2.730 (\sigma_d/\rho) - 0.125 N + 0.118 \]

Source: Authors.

4.3 COMPARISON BETWEEN SINGLE-STAGE METHODOLOGY AND MS PROTOCOLS

Protocol two was not completed due to high deformations in one of the samples because of a limitation in data acquisition. However, it has a promising procedure; the comparison between this protocol and the single stage will be limited to analyzing the behavior of the samples during the test, without considering
the occurrence of shakedown following the precepts of Dawson; Wellner (1999). The results obtained from the three samples in Condition 2 (2 m-e protocol) indicate that they have Type I or Type II behavior and tend to have plastic accommodation. In this case, this procedure could be used to characterize this soil’s behavior. In Condition 1 (1 m-e protocol), the samples are similar to each other and demonstrate Type I behavior for the five pairs of stresses to which they were subjected. Type II behavior was observed for the highest pair of stresses (σ₃: 120 kPa and σ_d: 360 kPa). Therefore, for the present analysis, this material tends to accommodate plastically, even with only 10,000 cycles of application of each pair of stresses, corroborating the conclusion by Pascoal et al. (2023).

The same occurs when analyzing the occurrence of shakedown for the samples in protocol 1, where type A behavior can be seen for all pairs of stresses, except for the pair σ₃: 120 and σ_d: 360 kPa, so when subjected to these stresses, when compacted under the ideal conditions at intermediate energy, this soil tends to show satisfactory behavior in terms of rutting. When subjected to higher stresses (σ₃: 120 and σ_d: 360 kPa), the behavior can be characterized as transitional between levels A and B, thus requiring a more rigorous analysis of the influence of these pairs on the material’s behavior. This same unique behavior, the results of which are shown in Figure 1.

5 CONCLUSIONS

Characterizing the materials used in the pavement subgrade is paramount, considering their influence on pathologies, especially rutting. Characterizing the material concerning its plastic deformation can provide answers as to its behavior and its tendency to settle and even predict its performance under stress. Because of this and to propose an alternative to reduce the test methodology, this study proposed an evaluation of the plastic behavior of a lateritic soil using a multistage permanent deformation test in two different conditions, compared to the results obtained by the conventional protocol of the current regulations. In the two conditions of the multistage methodology, the deformations stabilized, becoming practically constant with a few cycles of stress application. This behavior is
analogous to that identified by the test carried out using the conventional methodology. Another similarity between the different methodologies was the behavior when faced with pairs of ratios $\sigma_d/\sigma_3$: 3, with $\sigma_3$: 120 kPa and $\sigma_d$: 360 kPa, which caused deformations of high magnitudes.

When observing the behavior of the multistage methodologies about permanent deformations, there is a pattern among the samples analyzed, in which it is possible to see a tendency for plastic deformations to settle, classifying them as Type I or II, according to the DNIT (2018), corroborating the behavior identified for the conventional method. Therefore, applying the multistage methodology proved efficient for the material selection criterion since it is possible to identify behavior similar to the traditional methodology regarding the type of deformation and behavior in the face of different stress ratios. However, further research is required into the use of this protocol to determine permanent deformation parameters since it would be necessary to apply the concepts of time hardening (Erlingsson; Rahman, 2013), in which the accumulated permanent deformation established by the stress conditions and time are taken into account to calculate the equivalent number of load cycles required to achieve the same deformation in the case of a single stage. It is worth noting that the behavior observed through the proposed methodologies tends to differ for different materials, thus requiring an individual assessment for each case.

Therefore, this proposal is effective for better material utilization and reduced equipment usage time, presenting significant potential for agility and convenience in characterizing and classifying materials for road pavement layers.

Furthermore, when combined with the concepts of time hardening, applying multistage approaches holds significant potential to encourage the adoption and structuring of mechanistic analyses, such as those employed in MeDiNa. This contributes to incorporating these analyses into road pavement design, resulting in more resilient, durable, and economically viable pavements.

This advancement has a remarkable capacity to bring direct benefits to society by providing safer and higher quality highways and offering valuable insights for complementing national standards related to the determination of plastic deformation parameters of soils and granular layers. In future research, it
is recommended that the concepts of time hardening be applied to obtain permanent deformation parameters, thus ensuring a complete characterization of plastic properties using only the multistage methodology. Furthermore, the systematic approach presented in this study should be applied to different soils and granular materials to verify whether the behavioral trends between multistage and conventional analyses tend to converge, as observed for the investigated material.

ACKNOWLEDGMENTS

The authors thank FIEX, CAPES and the Federal University of Santa Maria (UFSM) for their research grants.
REFERENCES


