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PERMANENT DEFORMATION ANALYSIS OF THREE TROPICAL SOILS AT DIFFERENT HUMIDITIES USING MULTISTAGE LOADING

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Abstract: This experimental research aims to analyze the permanent deformation of three tropical soils, in a triaxial apparatus of cyclic loading, using increasing loads in multistage. For this test, three soils from the BR-040 right-of-way were used (Km 06: A-7-5, Km 26: A-1-b and Km 824: A-2-4). After classifying the material, two specimens were molded at normal compaction energy (at optimal and optimal humidity +2%), totaling six specimens. The permanent deformation test was carried out according to the multistage loading technique, which considerably reduced laboratory time and the amount of material used. The results indicate that the soil at Km 26 reached the highest values of permanent deformation, and, in addition, the specimen tested at optimum humidity + 2%, reached the maximum DP possible to be recorded by the LVDT of the equipment, in the second cycle of charging (5% SD). The soil at Km 824 deformed less, taking into account the last loading stage and both moisture and density conditions. Therefore, it is concluded that this technique for evaluating the behavior of the soil contributed greatly to the research, since, in a simplified way, it is possible to obtain more information on the mechanical performance of the soil.
Keywords: Multistage; Permanent deformation; Triaxial; optimal humidity.

INTRODUCTION

Based on triaxial laboratory tests, in several stages or multistage, of granular soils, Gidel et al., (2001) developed a method to calculate permanent deformation using a single specimen (CP), recording the effects of loads to different load cycles and voltage levels applied. The objective was, through this optimization, to predict the rupture (collapse) of the soil in a shorter period. Without this, to validate this model, if the single-stage loading technique were used, different specimens must have been molded for each pair of tension used. In order to reduce the time and quantity of materials, a different approach was tested, which consisted of requesting the same specimen with different and increasing levels of axial and confining stresses, referred to as deviation and hydrostatic stresses (p and q). in the aforementioned study.

In Brazil, the permanent deformation (DP) test is regulated by the DNIT 179/2018 – IE standard (DNIT, 2018). In that standard, 9 voltage pairs are defined for the test, which occurs with cycles from 1 to 5 Hz, with a frequency of 2 Hz being the most recommended, provided that the pulse duration is 0.1 second. Said standard determines a minimum number of 6 (six) tasting glasses to obtain the constants of the non-linear regression model. Using the recommended frequency of 2 Hz and 150,000 load cycles, each complete test would take, on average, 20 hours and fifty minutes for each voltage pair chosen per specimen. Using the same frequency, it is possible to evaluate the behavior of the soil for 4 different voltage pairs in just 6 hours in multistage loading.

Using the premises pointed out by Gidel et al., (2001) and aiming to optimize laboratory time and validate the contribution of this multistage loading technique, the objective of this study is to analyze the influence of moisture on the mechanical behavior of three tropical soils subjected to to a cyclic load, in triaxial equipment, using distinct and increasing pairs of deviation and confining voltages.

As a delimitation, this article carried out a comparative analysis of the mechanical behavior of soils without the objective of dimensioning the pavement. The soils used in this research came from the BR-040 right of way and were tested in the laboratory, following the guidelines of the norms that regulate this experiment. Each CP was requested in 4 loads of 10,000 cycles, totaling 40,000 cycles.

It was observed, at the end of the study, that the use of the multistage loading technique provided a greater amount of information on the mechanical behavior of the soil in less time and using a smaller amount of material. Therefore, an important procedure to evaluate the responses of materials to cyclic requests of axial loading.

LITERATURE REVIEW

Permanent deformation has been a very important tool for the analysis and selection of materials, validating their safe use in pavement layers. This test is carried out on the repeated load triaxial device, which can be influenced by several factors, such as: the applied stresses, the number of loads (N), the duration and frequency of the request, the type of material, gradation and shape of the particle, the moisture content and the density of the material, (Medina and Motta, 2015).

Lately, new studies using multistage loading in the DP test are being researched in the scientific community. This technique is also found in the European standard EN 13826-7 (2004), which standardizes the test and aims to evaluate, more expeditiously, the response of the material to different requests. With this, it is easier to determine the maximum stress levels supported by the material and which must not be exceeded.

The EN 13826-7 standard recommends the application of 10,000 charge cycles, in four charging stages, with different and increasing values of deviation voltage, keeping the confining voltage fixed, adopting 0.5% of DP as a stop criterion, if it occurs. Among some studies in the literature that used this technique, the following stand out: Arulrajah et al., (2021); Bilodeau and Perez Gonzalez, (2021); Cabral et al., (2020); Khasawneh, (2020); Bilodeau et al., (2013); Gidel et al., (2001), as seen in Table 1.

Gidel et al., (2001) claimed that the single-stage loading to determine the DP of a material and to know its mechanical behavior, uses only a single pair of stresses, making the study more time consuming. Therefore, they tested a different approach, requesting the same sample with successive and increasing pairs of voltages. Thus, it is possible to reduce the number of tests to be carried out (time and material savings) and decreasing the experimental dispersion, since the same sample is used to obtain information on several stress levels.

The research carried out by Bilodeau et al., (2013) with soils containing RAP (Recycled Asphaltic Coating), in five different gradations of mixtures, also used the multistage loading technique, with a frequency of 2 Hz. The authors concluded that there was a good synergy between the mechanical behavior of the soil with the RAP and the parameters used in the test. This way, it was possible to establish a layer thickness capable of containing the deformations in the pavement.

Ribeiro *et al*., (2014) studied the behavior of an LA' soil (A-3 equivalent), varying stresses and moisture content. The Wot and ρWot found were, respectively, 11.8% and 2.035 g/cm³. The MR at Wot = 164.09 MPa and Wot + 1.5% = 142.10 Mpa, considering σ_3 = 180 KPa and σ_d = 71 KPa. The voltages used in the tests can be seen in Table 2.

This way, the authors obtained the following results: increasing the deviation tension by 4 times, the DP doubled, and, a 3% increase in the humidity between the tensions T3 and T4, there was an increase of 20% in the DP, considering single-stage loading. The authors also concluded that the material's resilient modulus was more influenced by moisture variation, but permanent deformation was less sensitive to this variation. The addition of the deviation voltage had a greater influence than the humidity on the DP variation.

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Author (Year)	Stages	p (kPa)	q (kPa)	q/p	Cycles
Arulrajah *et al.*, (2021)	4	67/93/120/147	80/160/240/320	1,2/1,7/2/2,1	10.000
Bilodeau e Perez Gonzalez, (2021)	6	1ª - 23/24/27/29/31/33 2ª - 52/55/58/62/65/68 3ª - 79/83/87/93/97/101	1ª - 9/12/20/27/32/40 2ª - 20/30/40/50/60/70 3ª - 27/40/52/68/80/92	1ª - 0,3/0,5/0,7/0,9/1,0/1,2 2ª - 0,3/0,5/0,7/0,8/0,9/1 3ª - 0,3/0,5/0,6/0,7/0,8/0,9	10.000
Cabral *et al.*, (2020)	4	1ª - 53/67/80/93 2ª - 107/120/160/187 3ª - 160/200/240/280	1ª - 40/80/120/160 2ª - 80/120/240/320 3ª - 120/240/360/480	1ª - 0,75/1,2/1,5/1,7 2ª - 0,75/1/1,5/1,7 3ª - 0,75/1,2/1,5/1,7	10.000
Khasawneh, (2020)	4	1ª - 27,5/41,3/62/82,7; 2ª - 13,7/27,5/34,4/48,2	1ª - 16,5/24,8/37,2/49,2 2ª - 13,7/27,5/34,4/48,2	1ª - 0,5 2ª - 1	10.000
Bilodeau *et al.*, (2013)	3	37/53/70	50/100/150	1,3/1,8/2,1	10.000
Gidel *et al.*, (2001)	4	1ª - 60/120/180/240; 2ª - 75/150/225/ 300; 3ª - 100/200/300/400; 4ª - 100/200/300/450; 5ª - 100/200/300/450;	1ª - 150/300/450/600 2ª - 150/300/450/600 3ª - 150/300/450/600 4ª - 100/200/300/450 5ª - 50/100/150/225	1ª - 2,5 2ª - 2 3ª - 1,5 4ª - 1 5ª - 0,5	10.000

Table 1 - Multistage procedure in PD

Source: Authors (2022)

Tensions	σd	σ3	σd/ σ3
T1	35	70	0,5
T2	70	70	1
T3	105	70	1,5
T4	140	70	2

Table 2 - Voltage pairs

Source: Adaptado de Ribeiro et al., (2014)

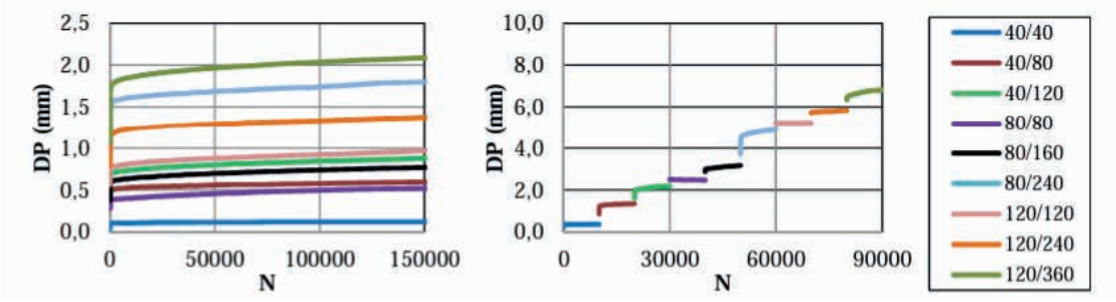

Figure 1 - Resulting curves for soils tested in single and multistage

Source: Adapted from Barros et al., (2019) In the studies by Barros et al., (2019), both the loading protocols of the multistage and single-stage tests were compared, as can be seen in Figure 1. It is possible to observe that the permanent deformation achieved, using this multistage loading technique, greatly surpassed the DP value achieved by single-stage loading. In this test, for each multistage loading cycle, the soil did not follow a linear pattern of DP variation.

Khasawneh (2020) applied the multistage loading technique to determine the DP of two soils classified as A-4a and A-6a. In addition to varying the moisture of these soils (Wot and Wot +2%), the sample was also requested at four different values of confining stresses and deviation, using 10,000 cycles for each stage and keeping constant the ratio between stresses (q/p). The author concluded that this procedure can be performed at different stress levels and load cycles, thus obtaining a greater amount of material information. To facilitate understanding, Figure 2 shows the DP for p/q = 0.5 and 1, of a silty clay at optimum moisture content and at optimum moisture content + 2%. As it can be seen, the DP varied both by the influence of humidity and by the variation of tensions.

The Brazilian authors, in the article written by Cabral et al. (2020), obtained the permanent deformation (DP) of the materials tested using the multistage loading technique. They proposed prediction models using the technique of artificial neural networks and numerical analysis of stresses and displacements using the CAP3D program. The results showed that both the test procedure and the prediction models performed satisfactorily in obtaining the DP behavior. Therefore, it was concluded that the model and test procedure have significant potential to characterize and model the PD of granular materials.

In another study carried out by Arulrajah et al., (2021), the authors used construction and demolition samples, such as crushed bricks (CB) and recycled concrete aggregates (RCA), in different stress combinations. The multistage technique was applied at a frequency of 5 Hz for a total of 40,000 cycles. The authors claimed that the higher the voltage deviation number, the higher the DP in the two types of materials tested.

METHODOLOGY

The exploratory and quantitative research, briefly, as follows: after the characterization of the material – granulometry; classification according to SUCS and Hrb methodology; compaction curve to determine optimum moisture content and Atterberg limits to determine soil liquidity and plasticity limits – the soil was subjected to cyclic stresses, using triaxial equipment, with the aim of better understanding its mechanical behavior. These tests were carried out in the laboratory of LESFER/COPPE/UFRJ.

Complementarily, it is possible to visualize in Table 3 the tests carried out and the norms that were used to guide the experiments of this research.

TRIAXIAL OF REPEATED LOADS

When performing the permanent deformation test on different specimens, using the same material and the same stresses, experimental dispersion occurs, as elucidated by Gidel et al., (2001). This dispersion is caused because it is impossible to mold identical test specimens, for example, with the same number of voids, same arrangement of grains, in short, stating that all the independent variables that influence the mechanical behavior of the soil, are the same in all CPs.

For the methodology of this study, the procedure indicated in the article by Gidel et al., (2001) was used, applying 10,000 intermediate cycles of multistage loading with

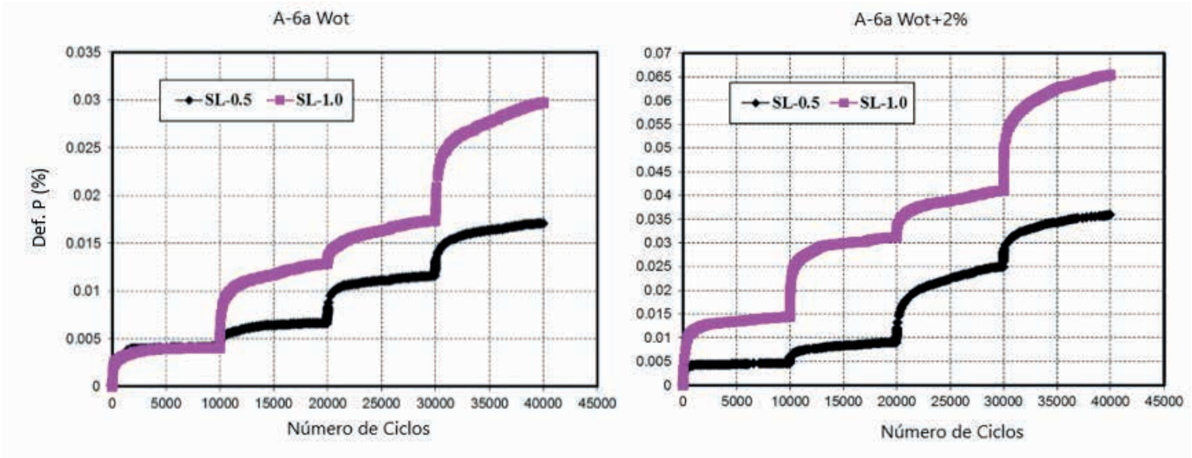

Figura 2 - DP para carregamento multiestágio

Fonte: Adaptado de Khasawneh (2020)

Rehearsal	Standard name	Standard number
Mini-MCV	Compacted soils in miniature equipment – Mini-MCV	DNER-ME 258/94
Granulometry	Particle size analysis by sieving	DNER-ME 080/94
Sedimentation	Particle size analysis	DNER-ME 051/94
LL	Determination of the Liquidity Limit	DNER-ME 122/94
LP	Determination of Plasticity Limit	DNER-ME 082/94
compaction	Compaction using unworked samples	DNIT 164/2013 - ME
Humidity	Soils - Determination of moisture content	DNER-ME 213/94

Table 3 - Tests performed

Source: Authors (2022)

Internship	σ1	σ3	σd	σ1/ σ3	p = (σ1 + 2σ3)/3 < 300 KPa	q = (σ1 - σ3) < 600 Kpa	q/p <=3
1	50	20	30	2,5	30	30	1
2	75	30	45	2,5	45	45	1
3	100	40	60	2,5	60	60	1
4	125	50	75	2,5	75	75	1

Table 4 - Relationship between input voltages and p and q

Source: Authors (2022)

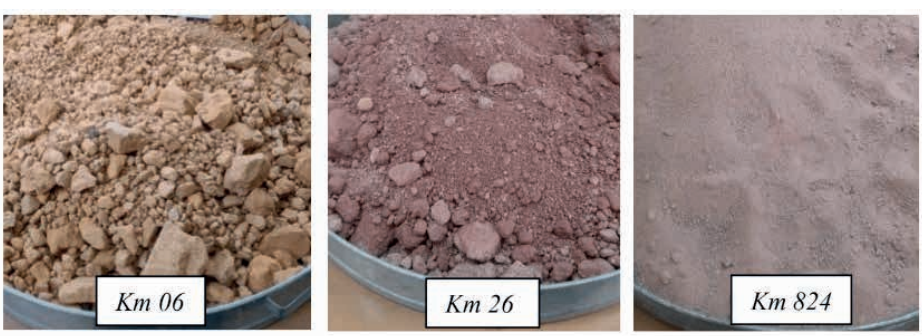

Figure 3 - Soils selected for carrying out the tests

Source: Authors (2022)

4 increasing pairs of stresses p and q, with their constant ratios. The tests were carried out at optimum humidity and at optimum humidity +2%, the latter being of the drained type, totaling 40,000 cycles of load application and a frequency of 2 Hz (with 0.1 s of load application and 0.4 s rest). Using 100 x 200 mm cylindrical molds with samples passing through the 25.4 mm (1 in.) sieve.

The stresses p and q are the mean stresses and deviation. Equations 1 and 2 explain this relationship with the voltage *inputs* used in the triaxial equipment:

$$p = \frac{(\sigma_1 + 2\sigma_3)}{3} \quad (1)$$

Being:

σ_1 = axial tension

σ_3 = confining tension

$$q = (\sigma_1 - \sigma_3) = \sigma_d \quad (2)$$

Being:

$q = \sigma_d$ = voltage bypass

Table 4 lists the voltages used in this work and their relationships, as explained in equations 1 and 2.

Step loading consists of requesting the same specimen with a constant q/p ratio, for $p<300$ kPa and $q < 600$ kPa.

Because these are soils that possibly have a low capacity to resist stress, because although two of them are lateritic, they are close to the border of non-lateritic soils, with the presence of fines, it was decided, therefore, to use a p ratio /q = 1, using smaller values of deviation and confining stress, aiming to complete the 4 charging cycles.

In addition to this caveat, normal compaction energy was used, as these are soils found in the road subgrade, where they originated. As the loads applying to the stress bulb are more attenuated in the subgrade, it was decided, therefore, to investigate the behavior of these soils with the mentioned compaction energy, thinking about a possible reinforcement of the subgrade with the available material.

RESULTS AND DISCUSSION

Using the methodology explained in item 3, the tests mentioned were carried out.

SOIL CHARACTERIZATION

For this work, three soils in the BR-040 right of way were selected, which were named according to the location of extraction of the deformed samples: km 06, km 26 and km 824, whose visual aspects are recorded in Figure 3.

Figure4showstheresultsofthegranulometry tests by sieving and sedimentation for each type of soil tested. It is noteworthy that, in order to analyze the mechanical behavior of soils, it is imperative to test them in the laboratory. The physical classification of the material does not standardize its mechanical performance, other variables can influence the result of its performance, such as, for example, the presence of iron and aluminum ions, salts and silica, among other chemical elements, as well as the combination of these with the other physical characteristics of the soil, such as the irregularity of the grains, which makes the soil more or less sensitive to the presence of moisture, etc.

Figure 5 shows the curves generated by the compaction test at normal Proctor energy for each of the soils in this work.

In Table 5 it is possible to visualize the results of the tests used to classify the soils used in this article.

It was chosen to work in the wet branch, because above the optimum humidity, air particles are occluded and there is a greater loss of mechanical resistance of the soil. In addition, there is a decrease in the mechanical interlocking of soil particles, due to the decrease in friction due to the increase in moisture, Braja and Sobhan (2019). So, it becomes more interesting to understand and evaluate the mechanical behavior of the soil

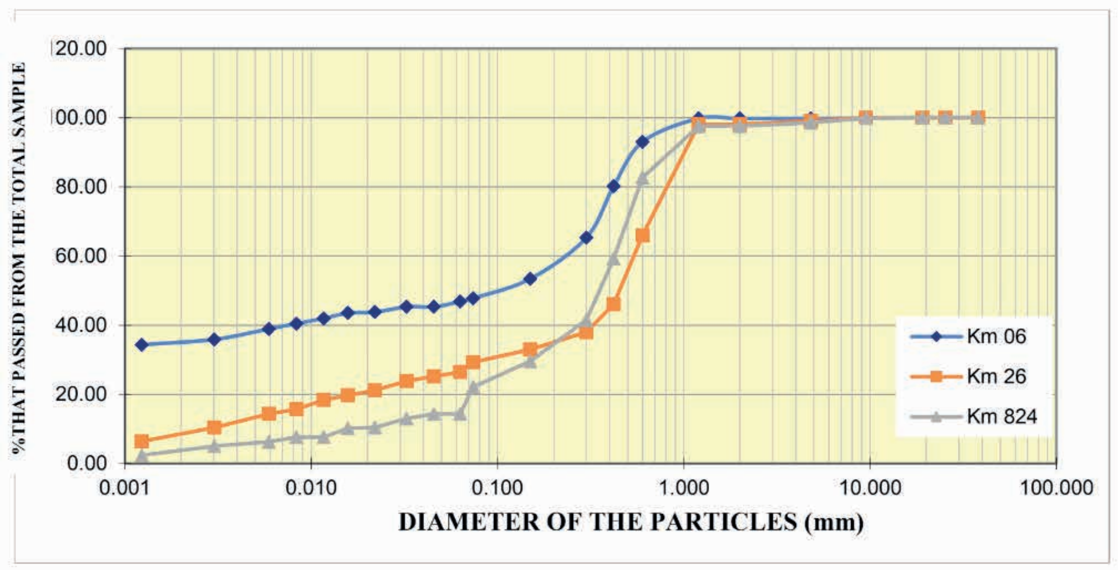

Figura 4 - Granulometria dos solos

Source: Authors (2022)

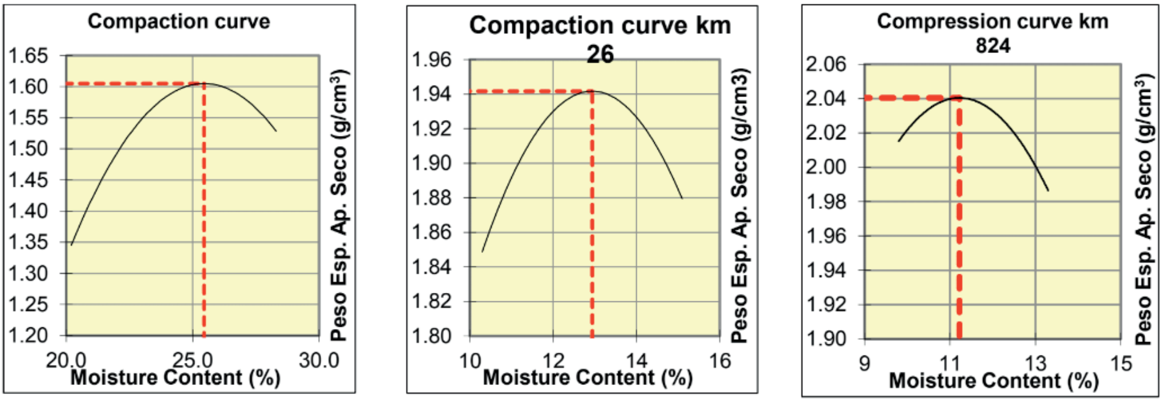

Figure 5 - Compaction curves

Soils	Classification Sucs/Hrb	W hygroscopic	[1] W Great	LL	LP	IP	[2] ρWot (g/cm³)	[3] ρWot + 2% (g/cm³)
Km 06	SC/A-7-5	12,30%	25,45%	67,04%	47,64%	19,40%	2,066	1,917
Km 26	SM/A-1-b	0,65%	12,94%	36,99%	33,14%	3,85%	2,160	2,132
Km 824	SM/A-2-4	6,65%	11,22%	18,06%	17,08%	0,98%	2,046	2,018

[1] Optimal moisture obtained from soil dried in an oven at 105 °C.

[2] Dry specific weight for CP compacted at optimum moisture.

[3] Dry specific weight for compacted CP at optimum humidity + 2%.

Table 5 - Soil classification

Source: Authors (2022)

under these conditions.

Mainly, because during the execution of the project in the field, without the same controls for these variables, water spraying can lead to a compaction failure, which may occur in the wet branch. Therefore, understanding the behavior of the soil under these conditions is very important to predict possible pathologies that may occur on the pavement, such as the sinking of wheel tracks, a defect in the pavement caused by the addition of permanent deformation. In terms of constructive practice, the flow control and the displacement speed of the water spreading truck, for example, may not occur correctly, which greatly justifies the referred study and the humidity conditions tested in this experimental research.

MECHANICAL PERFORMANCE

After the performed analyses, it was observed that due to a greater permanent deformation at Wot +2%, the analyzes below refer mainly to this condition of density and humidity.

The soil at Km 06 (A-7-5) showed an increase in the MR value in both conditions. Between the first and last stage for wot this increase was 92.48 Mpa while for wot+2 the increase was only 21.98 Mpa. This can be explained, because in the wet branch the soil particles in the presence of excess water become more hydrated, the voids are filled with water, with a decrease in the interlocking of the particles and an increase in the volume of the soil, which favors the drop in its mechanical resistance capacity.

In relation to the total accumulated DP, the soil in wot presented a value of 0.4% in contrast to the wot+2 soil presented a total accumulated DP of 1%, in this case, for each loading stage the DP was about 0.3 %. Results that corroborate the performance in the MR test, as it was observed that the amount of water in the soil influenced the mechanical performance of the material, both in terms of elastic and plastic behavior.

The soil at Km 824 (A-2-4) showed an increase in the MR value in both conditions. Between the first and last stage for wot this increase was 80.78 Mpa, while for wot+2 the increase was only 39.44 Mpa. In the same way that occurred in the soil at Km 06, the increase in MR in the soil with wot+2 was more discreet, that is, despite the increase in tensions maintaining the soil density at levels that provide an increase in MR, this does not means that it is the best soil performance.

When evaluating the first 10,000 loading cycles, it was observed that the soil at Km 824 had lower DP values for the compacted soil at wot + 2%, distinguishing it from the other soils. As it presents a greater presence of fines in its granulometry, humidity may have influenced the reduction of DP for the requesting voltage pairs in the wet branch. Condition that was not perpetuated in subsequent loads, as the soil starts to behave similarly to the others.

The soil at Km 824 (A-2-4) obtained the lowest DP values, both in optimum moisture and in optimum moisture +2%. It is evident that other variables influence the mechanical behavior of the soils, such as: its mineralogy, grain disposition, chemical composition of attached particles, its specific surface, its interaction with humidity and others. It is extremely important to always evaluate the mechanical behavior of the materials in the laboratory, considering all the boundary conditions, before using them in paving, ensuring a better use of these materials.

In relation to the total accumulated DP, the soil in the wot presented a value of 0.38% in contrast to the wot+2 soil presented a total accumulated DP of 0.67%. Once again, the performance of the soil MR is confirmed, as previously explained, even with a slight increase in the MR value, the plastic deformation increases when the soil is in a

Cycle	Def. P (%) Wot	Def. P (%) Wot+2%	Δ Def. *P* (%)
ε^{10000}	0,044	0,067	0,023
ε^{20000}	0,180	0,350	0,170
ε^{30000}	0,307	0,677	0,370
ε^{40000}	0,428	0,996	0,568

Table 6 - Def. P(%) of Km 06

Source: Authors (2022)

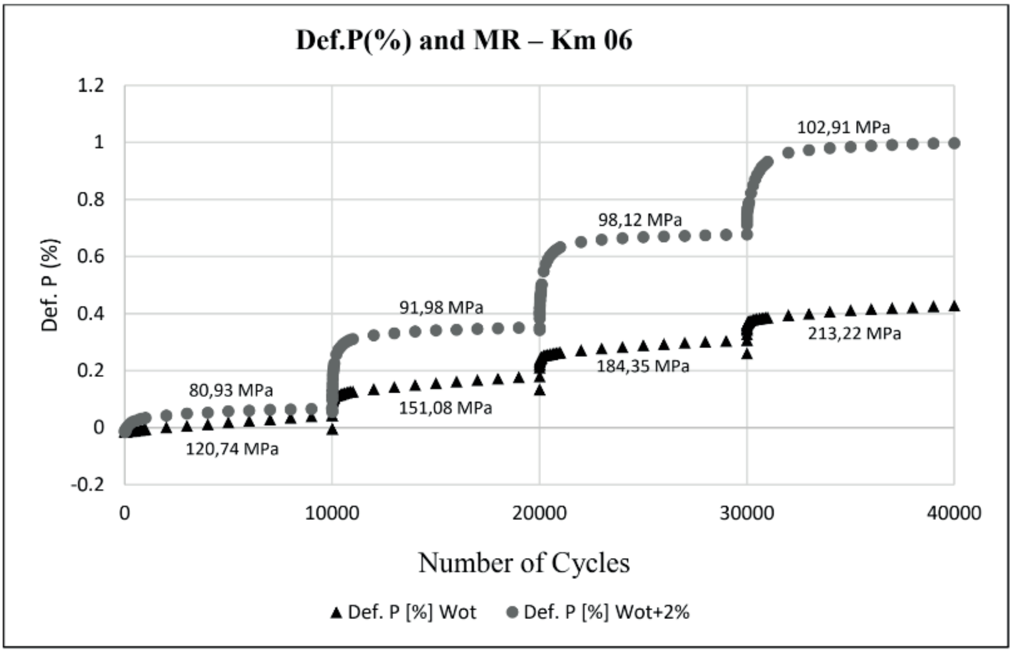

Figure 6 - Information about DP and MR (MPa) in the Km 06 multistage loading

Source: Authors (2022)

humid condition.

In the soil at Km 26 (A-1-b) the sample collapsed in the wet condition (wot+2) and it was not possible to determine its MR beyond the first stage (18.36 Mpa). Between the first and last stage for wot this increase was 64.05 Mpa. In this case, for a soil classified as LG', the excess of the clay fraction in the presence of water above the maximum density may have influenced its elastic behavior, which weakens in the face of changes/increases in load.

In relation to the total accumulated DP, the soil in the wot presented a value of 1.4%. Among the constituent soils of this research, the soil with the highest percentage of permanent deformation for the mentioned condition. Also, the smallest increase in the difference of the MR value between the first and last stage.

The multistage test made it possible to monitor the performance of the soils in terms of accumulated loading at different stresses, a procedure that approximates the real conditions of traffic demand on highways. In addition, the possibility of changing the stress value allows checking the behavior of the soil under different load conditions, for its application in different pavement layers.

In Figure 9, the performance of the three soils in Wot can be observed. For a 250% increase in axial and confining stresses, between the first and last stage, the DP of Km 06 varied 872.7% considering the same interval, reaching 0.428% of DP in the last stage. Following the same logic, the soil at km 824 had an increase of 132.7%, reaching 0.398% and finally, the soil at km 26 had a variation of 154.1%, reaching 1.484% of DP.

This means that the material from km 06 showed a marked variation in DP between stages, as there was less deformation in the first loading cycle. Which may indicate that its mechanical performance is less sensitive to low stresses.

Figure 10 similarly displays the comparative performance of the three soils at Wot + 2%. Observing the first loading stage, it is verified that the soil of km 26 is sensitive to humidity, due to the increase of deformations in relation to the other samples. Considering the addition of axial and confining stresses of 250%, the non-recoverable deformations of km 06 increased by 1486.6%, reaching a DP of 0.996%. At km 824, the DP increased by 238.6%, reaching 0.622% of plastic deformation.

Here, under these moisture conditions, in the first loading stage, the soil at km 06 and 824 showed a DP of 0.067% and 0.063% respectively. This mechanical behavior was similar to what happened at Km 06 at optimal humidity.

The increase in the voltage pair is not percentage constant. Between the second and first stages, the axial and confining stresses had an increase of 150%. Between the third and second stages, it was 133.3% and, finally, between the fourth and penultimate stage, 125%.

Despite the occurrence of a non-linear increase in stresses, the DP did not always increase or decrease for the same loading conditions between soils and moisture conditions tested. The soil at Km 26, for example, even with the highest absolute values of deformation, in each loading stage, its DP decreased in the optimal humidity for each stage (0.584%, 0.371%, 0.267% and 0.262%). The same pattern of behavior did not occur in the other soils, highlighting the soil at Km 06, at Wot + 2%, which increased the DP in all stages (0.067%, 0.350%, 0.677%, 0.996%).

Weighing the results obtained in this experiment and in the study carried out by Ribeiro et al., (2014), it is evident that it is possible to obtain the same conclusions in less time and with fewer resources when comparing with the single-stage test, without the problem of dispersion experimental, since

Cycle	Def. P (%) Wot	Def. P (%) Wot+2%	Δ Def. *P* (%)
ε^{10000}	0,171	0,063	-0,108
ε^{20000}	0,254	0,255	0,001
ε^{30000}	0,324	0,444	0,120
ε^{40000}	0,398	0,622	0,224

Table 7: Def. P (%) of Km 824

Source: Authors (2022)

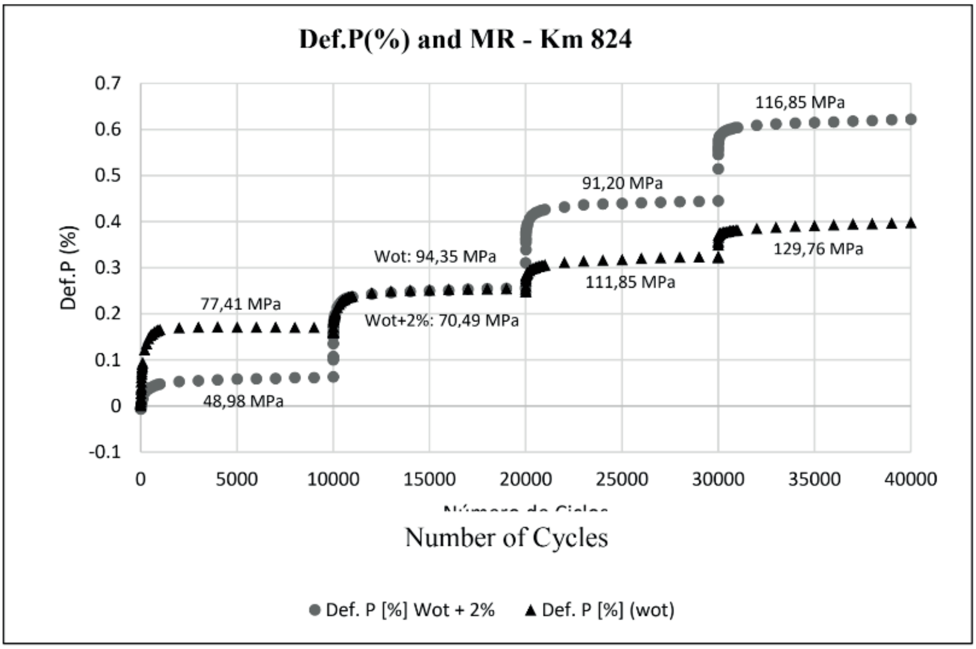

Figure 7 - Information about DP and MR (MPa) in the Km 824 multistage loading

Source: Authors (2022)

Cycle	Def. P (%) Wot	Def. P (%) Wot+2%	Δ Def. *P* (%)
ε^{10000}	0,584	1,936	1,352
ε^{20000}	0,955	x*	x*
ε^{30000}	1,222	x*	x*
ε^{40000}	1,484	x*	x*

* There was no possibility to continue the test due to the excessive deformation of the CP.

Table 8 - Def. P(%) of km 26

Source: Authors (2022)

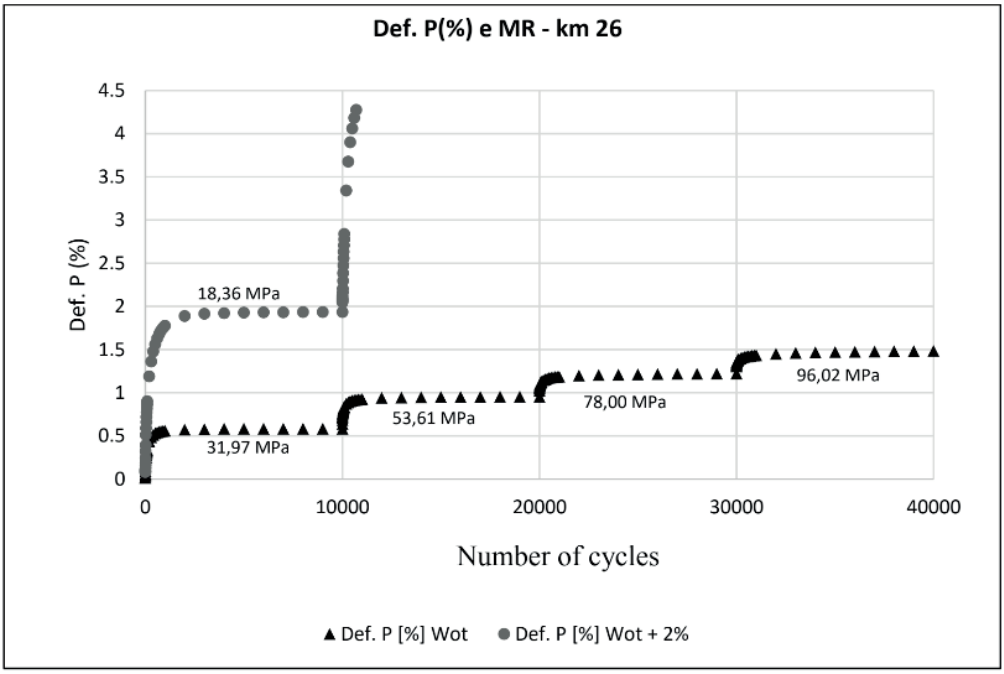

Figure 8 - Information about DP and MR (MPa) in the Km 26 multistage loading

Source: Authors (2022)

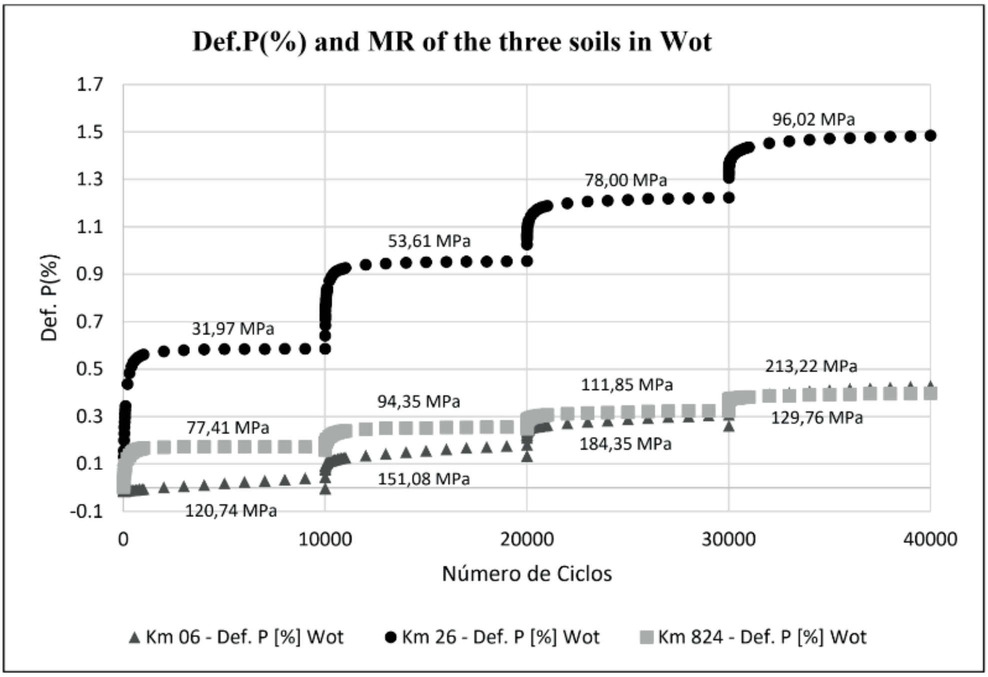

Figure 9 - DP and MR (MPa) of the three soils in Wot

Source: Authors (2022)

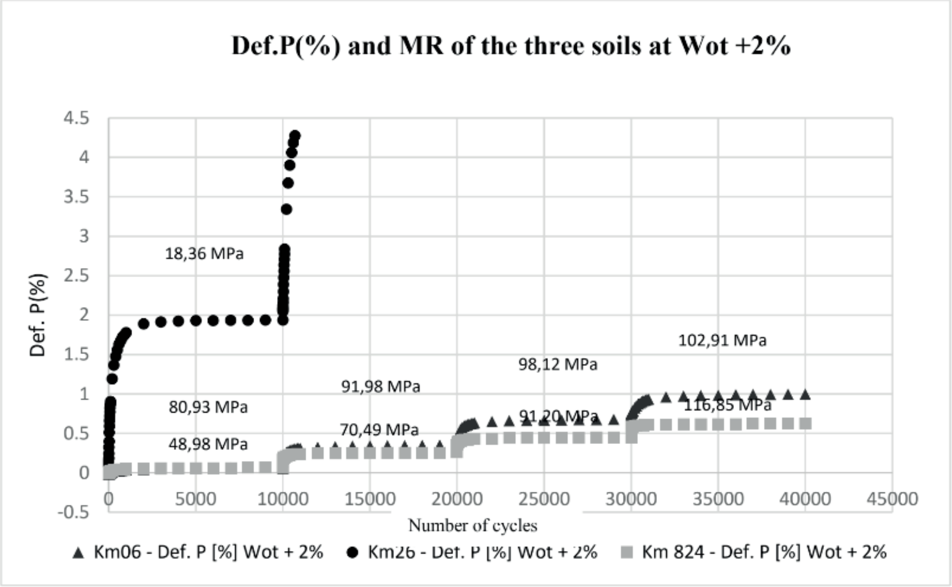

Figure 10 - DP and MR (MPa) of the three soils at Wot + 2%

Source: Authors (2022)

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in multistage loading the test is performed using a single CP for different voltage pairs.

Considering the tests carried out by Khasawneh (2020) and the results achieved by this research, it is observed that humidity has a considerable influence on the DP increment of these soils, whether it is a tropical or temperate soil. Taking into account the execution of soil compaction in the field, where humidity control is more tenuous, a small increase of 2% can lead the soil to work in the wet branch, causing the early appearance of pathologies that will influence the reduction of pavement service life.

CONCLUSION

This study sought to evaluate the possibility of using multistage loading in the laboratory, optimizing time and resources to get the best out of the tests. This technique is a good option for studying the mechanical behavior of soils, comparing the performance of these materials with each other and their relationship with the applied stresses.

With multistage loading, other loading configurations can be explored, seeking the borderline conditions of material resistance to cyclic requests. For soils contained in the pavement layers, the same sample is requested numerous times by cyclic axial loads, varying in intensity. Which means that the multistage test is close to what happened in the field, since the same sample is being requested with different loads.

In order to better understand the behavior of the material, it is suggested to use the multistage technique to find the boundary stresses of the material, thus determining the test stresses. It is possible to vary the confining and deviation voltages in a ratio of 1 to 4 or 5, starting at 20 KPa for the confining voltage, going up to the 150 KPa limit of the last loading sequence recommended in the EN 13826-7 (2004) standard, with a frequency of 5 Hz. The analysis of the mechanical behavior will occur in the sequence subsequent to the one in which the CP is compromised by excess accumulation of PD. Furthermore, it is advisable to carry out the MR test on the same specimen where the stress tracking test will be carried out, in order to obtain a more complete analysis of the mechanical behavior of the soil or material. This analysis would take, on average, two and a half hours to be performed, and the MR curve, obtained by non-linear regression, could be used for the other voltage pairs used.

As the deviation and confining stresses increase, the soil can decrease or increase its DP. In the case of behavior change, that tension pair becomes of interest and must be analyzed more deeply. This occurs because there may be a greater influence of confining or axial stress, depending on the type of soil. Which could indicate, for example, that it would not go into *shakedown.*

Exemplifying the contribution of the multistage test, there is the possibility of analyzing, in the same specimen, the increase in axial stresses, as it happens with the pavement layers in the field. Let's say that an unexpected increase in the number N occurs on a highway, caused by the unexpected diversion of traffic from a nearby highway. The multi-stage test allows understanding the performance of the soil against the increase in these requests.

More research needs to be developed and encouraged to build a better understanding of the relationship between loading cycles, confining stresses and deviation of the multistage test and the mechanical behavior of soils, exploring more possibilities and configurations of *inputs* to build prediction models for the different types of soils and materials used in road paving.

Therefore, this study contributes greatly to the state of the art of understanding the mechanical behavior of soils more expeditiously

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