Study of soils used with subgrade and sub-ballast in Brazilian railways

http://dx.doi.org/10.1590/0370-44672021750023

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Abstract

Brazil has an extremely limited railroad network compared to other developed and developing countries. There are projects to expand this mesh. Knowing that the cost of implementing a railroad is high, research for solutions that allow cost reduction is of great importance. But the parameters of the materials used in the subgrade and sub-ballast layers are from other countries, which can cause the cost to increase to meet these parameters. Through strength parameters and mineralogical analysis, it is possible to use or not fine tropical soils as a layer of railway pavement. A critical analysis of the standards that are used to scale and/or verify whether a particular soil can be used in these layers was undertaken. For this, the following tests were performed: Granulometry, Atterberg Limits, Compaction, California Support Index (CBR or ISC), Expansion, MCT Classification Test (Miniature, Compacted, Tropical), Dynamic Triaxial and X-Ray Diffraction. From the results, it could be seen that although one of the soils is thin, it presented satisfactory results in relation to the use in layers of the railway pavement. It was verified that it is necessary to use more modern tests, focusing on mechanistic dimensioning for dimensioning pavement layers.

Keywords: subgrade, sub-ballast, tropical soils.

1. Introduction

Brina (1988) divided the railway pavement into infrastructure and superstructure. According to the author, the infrastructure consists of earthworks and the services to be defined that are below the earthworks. The superstructure consists of the sub-ballast, ballast, sleepers, rails and fastening elements. According to Spada (2003), the subgrade layer is the foundation of a railway, whose main function is to guarantee a stable layer for the structure of a railway line, making it difficult to weaken the entire structure by reducing the capacity of cargo or even significant settlements.

According to Brina (1988), the sub-ballast is the layer of the superstructure of a railway that is causally linked to the infrastructure. It has the following functions:

- Increase the support capacity of the platform, allowing to increase the rate of work on the ground, when the loads are transmitted through the ballast, causing its layer to have a lesser thickness;
- Prevent the ballast from penetrating the platform, protecting the subgrade layer;
- Increase the resistance of the bed (finished surface of the railway platform) to erosion, water penetration, thus improving the drainage of the track;
- Allow elasticity to the ballast support, making sure that the track is not rigid.

According to Spada (2003), the subgrade layer is the foundation of a railway, whose main function is to guarantee a stable layer for the structure of a railway line, making it difficult to weaken the entire structure by reducing the capacity of load or even significant settlement.

Between the end of the 60s and the beginning of the 70s, the São Paulo State

Department of Highways (DER/SP) built experimental tracks using fine sandy soils as bases, which until then had not been used in these layers. But it was found that the good performance of these fine materials, even using criteria used were flawed in relation to the characterization and classification of soils used in pavement layers in Brazil, showed good durability resistance (Oliveira, 2018).

Nogami and Villibor (1981) found it exceedingly difficult to apply systems usually used to classify soils in tropical regions, and then proposed another classification, which was called the MCT Methodology (Miniature, Compacted, Tropical). According to Villibor and Alves (2017), this methodology was developed to study thin tropical, lateritic and saprolitic soils. It was based on tests that provided analysis of the mechanical and water properties, using specimens with smaller dimensions, compacted from materials passing through the 2.0 mm sieve.

According to Nogami and Villibor (1995), this showed the need to develop more appropriate criteria, not so related to traditional index properties, but more linked to the mechanical and hydraulic properties of compacted soils.

Two distinct soils of different granulometry were used (a granular and a fine soil). The objective is to evaluate the behavior of both and show that tropical soil (fine) can be used in the layers of a railway pavement. Another objective is to show that we need tests that aim to characterize Brazilian soils.

The parameters recommended for the use of materials in layers of subgrade and sub-ballast in Brazil are printed from other countries and use tests that do not consider the specificity of Brazilian soils, in this case, tropical soils. The test that checks soil resistance as a parameter of use is the California Baring Ratio (CBR), which is a test that has existed for almost 1 (one) century. The load applied in this type of test is punctual, and not cyclical. Cyclic loading is characteristic of application on a floor.

2. Materials and methods

The materials used in the research were collected in a stretch of the North-South Railway, located in the north of the State of Goiás. These materials were sent to the Railways and Asphalt Laboratory (UFOP) where all tests were carried out.

In the samples of sub-ballast and subgrade material, the following tests and the respective standards were carried out: DNER ME 093/94 (Soils - Granulometric Analysis); DNER ME 122/94 (Consistency Limits – LL); DNER ME 082/94 (Consistency Limits – PL); DNIT 164/2013 ME (Soils – Compaction using unworked samples – Test Method); DNIT 172/2016 ME (Soils – Determination of the California Support Index using unworked samples – Test Method); DNIT 134/2018 ME (Flexible Floors – Soils – Determination of the Resilience Modulus – Test Method); DNER ME 228/94 (Compaction on Miniature Equipment); DNER ME 256/94 (Compacted Soils in Miniature Equipment - Determination of Mass Loss by Immersion). DNIT is the National Transport Infrastructure Department.

The X-Ray Diffraction Test was also carried out on the soil samples to identify, characterize and quantify the mineral phases that make up the soil. This test was carried out at Nanolab (Laboratory of the Metallurgical Engineering Department of the Universidade Federal de Ouro Preto).

3. Results and analysis

3.1 Results of tests on subgrade material

Figure 1 shows the granulometry result of the subgrade material.

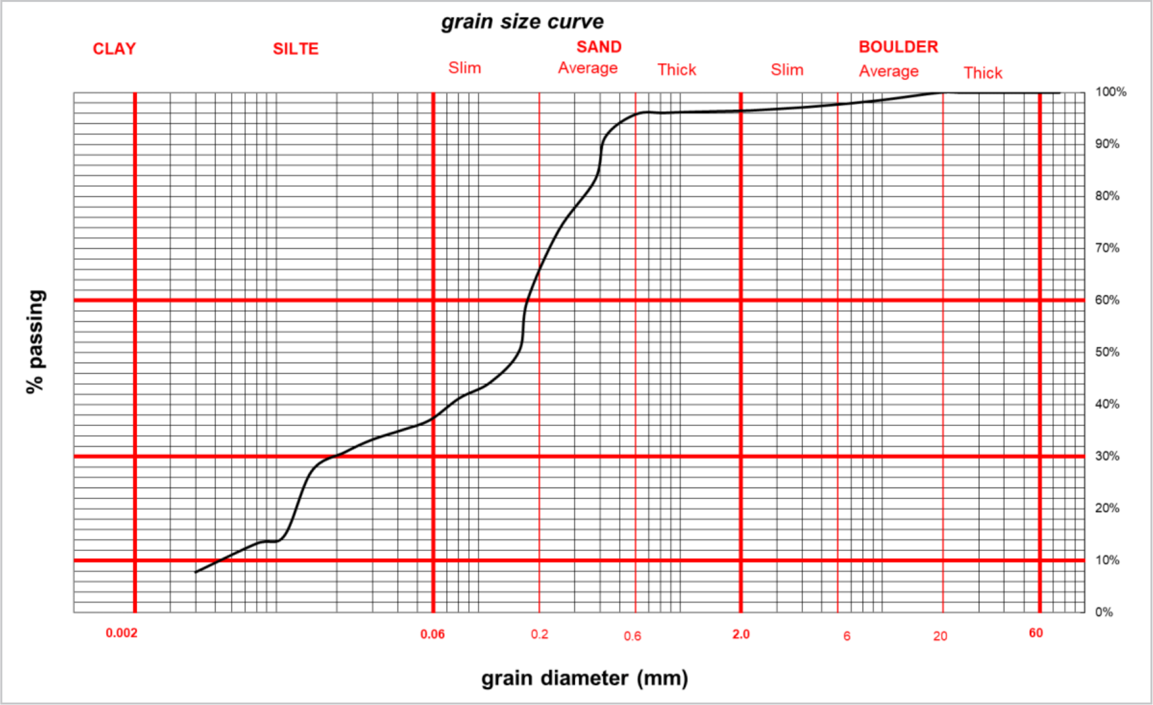

Figure 1 - Granulometric curve of the subgrade material.

By the granulometry test, we have some parameters such as D10, D30, D50, D60, which are respectively: 0.006, 0.02, 0.151 and 0.18. From these parameters, we have the result of CNU (Coefficient of Non-Uniformity) and C_c (Coefficient of Curvature), which are presented below in Table 1 (Hilário and Fernandes, 2021).

Table 1 - Result of CNU and C_c.

Layer	CNU	C_c
Subgrade	31	0.42

Through the granulometric curve, the material has a greater amount in the sand fraction. The soil can be well graded or poorly graded. Since this soil is well graded, the grains present different grain sizes, which induces a better behavior because the embryosation of its particles indicates a better understanding for its use in paving works. This better wrapping of the grains offers a lower compressibility, and consequently, a greater resistance of the layer.

According to the values found for CNU and C_c, the subgrade material has a non-uniform granulometric curve and the material is poorly graded.

For the value of CNU, the soil that has a granulometric distribution that allows a good use in engineering works, as it presents grains in different sizes.

Regarding the values of Atterberg Limits in the subgrade material we have (Hilário and Fernandes, 2021):

- LL (Liquidity Limit) = 23.4 %;
- PL (Plasticity Limit) = 19.0 %;
- PI (Plasticity Index) = 4.4 %.

The Liquidity Limit Value is the lowest moisture content with which a soil may be able to flow. The Plasticity Limit, on the other hand, is the moisture content at which the soil, being in the plastic state, in case it loses moisture, changes to the semi-solid state. The Plasticity Index is a measure of the degree of plasticity of the fines and can indirectly indicate the amount and type of plastic fines. The values recommended by DNIT (2006), to be used in pavement layers, are (these values are designated for temperate soils, not covering lateritic soils):

- LL ≤ 25;
- PI ≤ 6.

Regarding the results of LL and PI, the values were below the lower limit of the recommended by the norm for the subgrade layer.

Pinto (2006) presented values, from the Atterberg Indices, of some Brazilian soils, among them, a clayey sand, whose LL value varied from 20 to 40, and the IP value varied from 5 to 15. The value of the LL of the subgrade material under study, when compared to the materials analyzed by Pinto (2006), fit. The IP value, although it did not fit in comparison to the analyzed soils, had awfully close values.

The low PI value (4.4%) is because the material has a significant percentage in the sand fraction. Although the subgrade material has a predominance of the sand fraction, which can cause the material to have no plasticity (the sand has no cohesion), an IP value was found.

After analyzing the particle size and LL and PL, it is possible to determine the TRB (Transportation Research Board) classification of the material. According to this classification, the material is classified as A-2-4, which is a rocky material or silty or clayey sands. According to this classification, the material is characterized as "excellent to good" to be used as a subgrade. These classifications do not fit tropical soils. Knowing that the TRB classification is an A-2-4 soil, the (Unified Soil Classification System) USCS classification of the subgrade material fits into the GM-SM group, Where (Hilário and Fernandes, 2021):

- GM - Silty gravel with sand;
- SM - Silty sand, mixture of sand and silt or silt.

The results of the tests for maximum dry density, optimum moisture content, CBR and expansion are shown below (Hilário and Fernandes, 2021):

- Maximum dry density ($\rho_{máx}$) – 1.90 g/cm³;
- Optimum moisture content (Wót) – 14.4%;
- California Baring Ratio (CBR) – 17.5%;
- Expansion – 0%.

Pinto (2006) shows that fine lateritic clay sands, even poorly graded, present an optimal humidity variation of 12 to 14%. In relation to the maximum dry density, this material has a value of up to 1.9 g/cm³. The subgrade material used in the study results in an optimum humidity of 14.4% and its maximum dry density of 1.90 g/cm³.

Santos (2017) studied sandy soils, whose CBR values ranged from 8 to 20%.

Zica (2010), in his dissertation, studied a soil for which the TRB classification was A-2-4. Using normal compaction energy, the CBR values ranged from 13 to 15, awfully close to the values found in the study.

In the same study, the expansion of the material ranged from 0.03 to 0.1%. Values close to those of this study. This low value of expansion was due to the characteristic of the soil and its granulometry, with predominance in the sandy fraction. Zica (2010) studied soils to be used in paving layers, as well as the studies done in this thesis.

The results met the Railway Service Instruction - ISF-207 (2017) and the Infrastructure Services Specification - Landfill (VALEC, 2017) for the landfill body.

For the last 60 cm of the landfill, these same bodies recommend that the expansion value must be less than 2% and its CBR must be equal to or greater than 8%. Based on the results presented, the material is suitable for use as a subgrade layer.

The coefficients of the subgrade's MCT methodology (c ', d', e' and Pi), obtained by means of Mini-MCV (Moisture Condition Value) compaction and by immersion mass loss, are shown in Table 2 and the classification appears in Figure 2.

Table 2 - Parameters of the MCT methodology.

Layer	Mini-MCV Compression Parameters			
	d'	c'	e'	Pi (%)
Subgrade	50.0	0.98	0.77	5.00

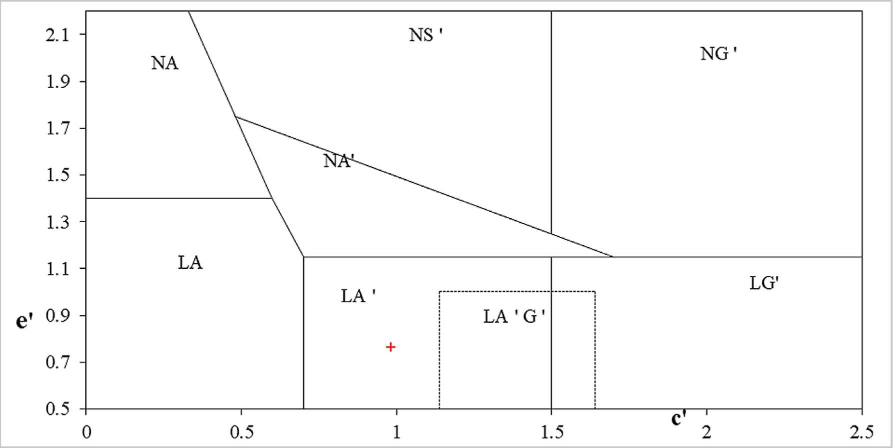

Figure 2 - Subgrade's MCT classification.

Analyzing the data obtained in Table 2 and Figure 2, it was concluded that the material under study falls under the *LA'* classification (Sandy Lateritic). According to Nogami and Villibor (1995), *LA'* soils have a good support capacity, high Resilience Module, low expandability, being allowed to be used in pavement layers.

The authors understand that *d'* values greater than 20 are characteristic of lateritic clays. The *d'* coefficient is the slope of the straight line corresponding to the dry branch of the compaction curve, for a total of 12 strokes, in the vicinity of the point of maximum specific dry mass.

The coefficient *c'* is the slope of the deformability curve corresponding to Mini-MCV equal to 10, being obtained, in general, by graphical interpolation procedures. This coefficient corresponds to the ratio of the variation of the sinking to the variation of the Mini-MCV of the rectilinear part of the deformability curve.

Nogami and Villibor (1995) argue that values of *c'* less than 1, are characteristic of non-plastic sands and silts or with little cohesion. Analyzing the Mass Loss by Immersion, it can be concluded that the subgrade material, in study, presented a low loss of mass, showing that the soil has a good cohesion.

Regarding the results of the Resilience Module (MR), Figure 3 presents the graph of the composite model. The result of the linear regression of this model is shown in Table 3.

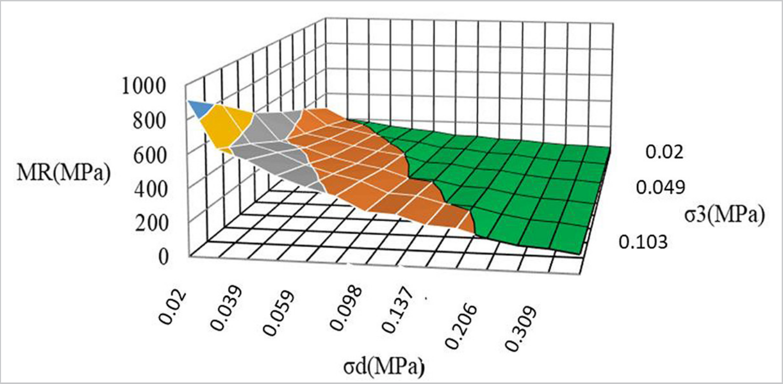

Figure 3 - Composite model chart.

Table 3 - Result of the Composite Model.

Layer	$MR = k1 * \sigma_3^{k2} * \sigma_d^{k3}$			
	k1	k2	k3	R²
Subgrade	205	0.6147	-0.6955	0.947

The average value of the Resilience Module found was 187.99. The R² presented a value awfully close to one.

Rangel *et al.* (2015) presented recommended or typical Brazilian values of 60 MPa, 80 MPa and 120 MPa for the Subgrade Resilience Module.

Table 4 presents the results of the X-Ray Diffraction test of the subgrade sample.

Table 4 - X-Ray diffraction result.

	Gibbsite (%)	Quartz (%)	Hematite (%)	Kaolinite (%)
Sample 1	2.4	64.5	5.5	27.6
Sample 2	1.6	75.4	4.4	18.6
Sample 3	2.8	62.0	5.7	29.5

In the X-ray Diffraction test of the subgrade sample, a larger amount of Quartz was found, followed by Kaolinite. Hematite and Gibbisite were also found, but in smaller quantities.

The predominance of Quartz and Kaolinite has a direct influence on the results of expansion and resistance of the subgrade soil. These are minerals that have good strength and low expandability. This shows that thin soils can be used in layers of subgrade, in many cases. Due to the MCT characterization, the presence of lateritic soils was evident, the result of the Resilience Module presented an applicable value, and the presence of the clay minerals found in the X-Ray Diffraction tests was evident.

3.2 Analysis regarding subgrade material

According to the results presented, it is concluded that the material studied in the syudy can be used as a subgrade layer of a railway, as it fits all the values required by the parameters of Brazilian standards.

Making a more careful analysis, it is possible to be more critical to the reference values and the tests used. This is because the parameters used by Brazilian standards come from values recommended by other countries; that is, for soils that do not have the characteristics of Brazilian soils.

An example is the CBR value found for the subgrade layer. According to values recommended by DNIT and VALEC, the material could not be used as a sub-ballast layer for railways and a sub-base for highways. It is known that the CBR test has its origins in the 1920s of the last century, from the State of California, in the United States. Although the soil used in the research for the subgrade layer is thinner, it has good load capacity because it is a lateritic soil.

For tropical soils, in the case of Brazil, we have the MCT test, which showed that the subgrade material under study has a good load capacity, is not very expansive, and has low deformability, which enables it to be used in several layers of the pavement, whether by road or rail. This is evident when we compare the values of the Material Resilience Module test with the values of other studies.

The dynamic triaxial test, which provides the MR, should be used more for the characterization of materials used in paving because it provides a better characteristic when applied to the sample of dynamic loads, different from the CBR test, which is a point load, presenting soil resistance to penetration.

Rangel *et al.*, (2015) used material for subgrade with RM values between 60 and 120 MPa. The MR value found in the present study was 187.99 MPa.

It is possible that there will be losses of excellent quality materials, when the TRB classification is performed on Brazilian soils, as the classifications and parameters for Brazilian soils are not made.

In some cases, to meet the values recommended today, either this material is discarded, or stabilization (chemical or granulometric) is carried out, which makes the cost of the work unnecessarily higher.

3.3 Results of tests on the sub-ballast material

Figure 4 shows the granulometry result of the sub-ballast material.

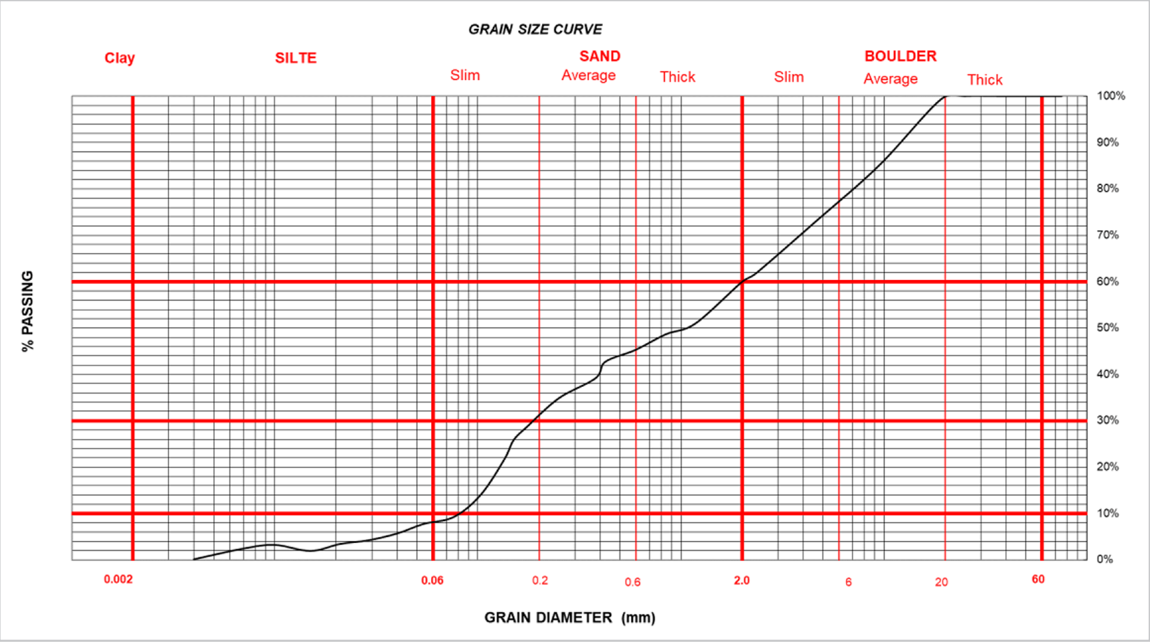

Figure 4 - Granulometric curve of the sub-ballast material.

By the granulometry test, some parameters are obtained, such as D10, D30, D50, D60, which are respectively: 0.08, 0.19, 1.20 and 2.005. From these parameters, we obtain the result of the CNU (Non-Uniformity Coefficient) and the C_c (Curvature Coefficient), which are, respectively, 25 and 0.22. (Hilário and Fernandes, 2021).

By the granulometry of the material, the strip that best fits the DNIT is obtained. The track with the best fit was track D.

The granulometry also fits the specifications of the Railway Service Instruction - Permanent Track Superstructure Project - Ballast and Sub-ballast (ISF-212/2015) and the Infrastructure Services Specification – Sub-ballast 2017, from VALEC.

In relation to the Atterberg Limits, the sub-ballast material proved to be non-plastic.

As a result, the material fit the Railway Service Instruction - Permanent

Track Superstructure Project - Ballast and Sub-ballast (ISF-212/2015) and the Infrastructure Services Specification - 2017 Sub-ballast, from VALEC.

Analyzing the grain size curve and the values of LL and PL, the TRB classification of the sub-ballast material is A-1-b. This classification includes materials consisting mainly of coarse sand, with or without well-graded soil binder. According to the TRB classification, the material is characterized as "excellent to good" to be used in pavement layers. According to Brina (1979), the sub-ballast material must fall within the A-1 range of the TRB classification.

Knowing that, by the TRB classification, it is an A-1-b soil, the SUCS classification of the subgrade material that fits it in the GM group, where:

- GM - Silty gravel with sand.

The results of the compaction, expansion and CBR test parameters are shown in Table 5 (Hilário and Gilberto, 2021).

Table 5 - Compression, CBR and expansion.

Layer	Wót (%)	$\rho_{máx}$ (g/cm³)	Expansion (%)	CBR (%)
Sub-ballast	8.8	2.308	0.02	45.3

According to Pinto (2006), it shows that soils with the same granulometric framing as the sub-ballast material, present maximum dry specific masses in the order of 2.0 to 2.1 g / cm³ and optimum moisture content between 9% to 10%.

In his study, Santos (2017) found CBR values above 50%, for soils with the same graduation.

The expansion value was low due to the fact that the soil matrix is sandier, with gravel, with little material that presents expandability.

The sub-ballast material fit in the values specified in the Railway Service Instruction for Permanent Track Superstructure Project - Ballast and Sublastro (ISF-212/2015) and the VALEC Infrastructure Services Specification - Landfill (2017).

The MCT test was not carried out on the sub-ballast material, as the percentage passing through the 2.0 mm sieve was 59.97%. To perform the test, it should have at least 95% of through soil, according to Barroso (2002), that is, a test for the characterization of fine soils. The studied soil has a high percentage of gravel.

In relation to the results of the Resilience Module (RM) of the studied sub-ballast material, Figure 5 presents the graph of the composite model. The result of the linear regression of this model is shown in Table 6.

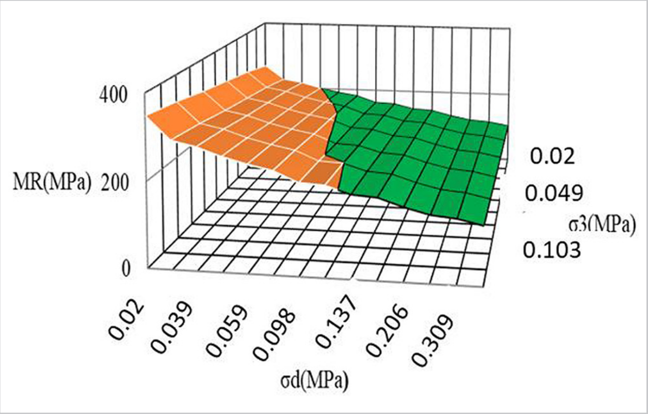

Figure 5 - Composite model chart.

Table 6 - Result of the composite model.

Layer	$MR = k1 * \sigma_3^{k2} * \sigma_d^{k3}$			
	k1	k2	k3	R²
Sub-ballast	136	0.1418	-0.3132	0.574

The value of the average MR found was 199.76 MPa. The Resilience Module value found in this study (199.76 MPa) was awfully close to that of Range *et al.*, (2015), where recommended values for the sub-ballast layer were presented. These values were 100 MPa and 200 MPa.

Table 7 presents the results of the X-Ray Diffraction test of the sub-ballast sample.

Table 7 - X-Ray diffraction result.

Sample 1	Anorthoclase (%)	Kaolinite (%)	Hematite (%)	Quartz (%)	Iron Oxide (%)
	31.3	13.0	6.7	49.0	-
Sample 2	49.2	0.9	0.2	38.4	11.3
Sample 3	39.0	0.0	0.2	43.5	17.3

In the X-ray Diffraction test of the sub-ballast sample, a greater amount of quartz and an ortoclase were found. Kaolin, iron oxide and hematite could also be observed, but in smaller amounts.

These values corroborate with the results of the expansion and resistance tests of the material. The value of the specific mass of the sub-ballast material was above the value established by Pinto (2006), occurred due to the ferric minerals present in the sample.

3.4 Analysis in relation to the sub-ballast material

According to the results presented, the material analyzed in the research can be used as a sub-ballast layer for a railway, fitting all the values required by the standards. As it is a sandy matrix, with gravel, the material has a low deformability, consequently, a low deflection, in addition to having little expansion.

Making a more careful analysis in relation to the results of the material used in the sub-ballast layer, it is noticed that, in the resistance criteria, in the CBR case, it fits to be used in the sub-ballast layer in railways, and as a sub-base material on highways. However, in the case of its use for the base of highways, following values recommended by Brazilian standards, this material would not fit.

The same criticism made about the subgrade, also applies in relation to the results of the sub-ballast. Since, in Brazil, parameters from other countries are used, there can be a lot of material loss in conditions to be used in pavement layers.

When the MR result is compared with the subgrade and sub-ballast value, they were awfully close. Even though the subgrade material is a thinner material, the MR value was close to the sub-ballast material, which is a more granular material, showing that the use of a finer granulometry in relation to the course one, did not have great interference when applying cyclic loads to the materials.

For fine materials, in Brazil, there is the MCT test, but for granular soil, there is no specific test for this soil, according to Brazilian standards. According to the MCT test, to make this analysis, the soil must have at least 95% passage through the 2.0 mm sieve.

There is still a lack of more judicious analyses that fit the Brazilian soil pattern.

4. Conclusions

Regarding the completion of materials that are usually used in layers of subgrade and sub-ballast, it is necessary to carry out tests to verify the true carrying capacity for tropical soils. These are tests and parameters that present coherent results for Brazilian soils, and not simply being parameters imported from other countries.

Mineralogical tests of materials are extremely important, as they are observed minerals / elements that provide better strength parameters, low deformability and low expandability, important characteristics for the materials are used in the subgrade and sub-ballast layers.

In addition, it is necessary to use the most modern tests (example: dynamic triaxial to obtain the Material Resilience Module) combined with parameters that characterize and assess the real resistance of tropical soils, focusing on the mechanistic design of the pavement, not empirical, such as is used today for dimensioning the layers of railway pavements. Therefore, it was evident, in the tests, that the uses of fine granular soils are suitable for railway pavement layers.

Acknowledgments

I would like to thank the Federal University of Ouro Preto and NUGEO (Núcleo de Geotecnia) for teaching quality and support since graduation to doctorate. To CAPES for the necessary and especially important funding to carry out the research.

References

BARROSO, S. H. A. ***Estudo dos solos da região metropolitana de Fortaleza para aplicação na engenharia rodoviária.*** 2002. Tese (Doutorado em Engenharia) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2002.

BRASIL. Ministério dos Transportes. Departamento Nacional de Estradas de Rodagem. ***DNER-ME 082/94***: Solos – determinação do limite de plasticidade. Rio de Janeiro: DNER, 1994.

BRASIL. Ministério dos Transportes. Departamento Nacional de Estradas de Rodagem. ***DNER-ME 093/94***: Solos – determinação da densidade real. Rio de Janeiro: DNER, 1994.

BRASIL. Ministério dos Transportes. Departamento Nacional de Estradas de Rodagem. ***DNER-ME 122/94***: Solos – determinação do limite de liquidez - método de referência. Rio de Janeiro: DNER, 1994.

BRASIL. Ministério dos Transportes. Departamento Nacional de Estradas de Rodagem. ***DNER-ME 228/94***: compactação em equipamento miniatura. Rio de Janeiro: DNER, 1994.

BRASIL. Ministério dos Transportes. Departamento Nacional de Estradas de Rodagem. ***DNER-ME 256/94***: Solos compactados em equipamento miniatura – determinação da perda de massa por imersão. Rio de Janeiro: DNER, 1994.

BRASIL. Ministério dos Transportes. Departamento Nacional de Infraestrutura de transportes. ***DNIT 134/2010 ME***: Pavimentos flexíveis – Solos – Determinação do módulo de resiliência – Método de ensaio. Rio de Janeiro: DNIT, 2010.

BRASIL. Ministério dos Transportes. Departamento Nacional de Infraestrutura de transportes. ***DNIT 164/2013 ME***: Solos – Compactação utilizando amostras não trabalhadas – Método de Ensaio. Rio de Janeiro: DNIT, 2013.

BRASIL. Ministério dos Transportes. Departamento Nacional de Infraestrutura de transportes. ***DNIT 172 ME***: Solos

– Determinação do Índice de Suporte Califórnia utilizando amostras não trabalhadas – Método de Ensaio. Rio de Janeiro: DNIT, 2016.

BRASIL. Ministério dos Transportes. Departamento Nacional de Infraestrutura de transportes. ***Manual de Pavimentação***. Rio de Janeiro: DNIT, 2005.

BRASIL. Ministério dos Transportes. Departamento Nacional de Infraestrutura de transportes. Instrução de Serviço Ferroviário. ***ISF-207***: estudos geotécnicos. Rio de Janeiro: DNIT, 2015.

BRASIL. Ministério dos Transportes. Departamento Nacional de Infraestrutura de transportes. Instrução de Serviço Ferroviário. ***ISF-212***: Projeto de superestrutura da via permanente: lastro e sublastro. Rio de Janeiro: DNIT, 2015.

BRINA, H. L. ***Estradas de ferro***. 2. ed. Belo Horizonte: Ed. UFMG, 1988. 2 v.

HILÁRIO, R. Q.; FERNANDES, G. Use of dynamic ballast testing equipment for analysis of rail aggregate breakdown. ***REM - International Engineering Journal***, Ouro Preto, v. 74, n.2, p. 155 -163, Apr./Jun. 2021.

NOGAMI, J. S.; VILLIBOR, D. F. Uma nova classificação de solos para finalidades rodoviárias. *In*: SIMPÓSIO BRASILEIRO DE SOLOS TROPICAIS EM ENGENHARIA, 1981, Rio de Janeiro. ***Anais* [...]**. Rio de Janeiro : COPPE/UFRJ, 1981.

NOGAMI, J. S.; VILLIBOR, D. F. Erosão na faixa marginal. *In*: NOGAMI, J. S.; VILLIBOR, D. F. ***Pavimentação de baixo custo com solos lateríticos***. São Paulo: Editora Villibor, 1995. Cap. 7, p. 169-196.

MUNIZ, L. F. M. ***Fundamentos teórico-experimentais da mecânica dos pavimentos ferroviários e esboço de um sistema de gerência aplicado à via permanente***. 2002. Tese (Doutorado em Engenharia Civil) - COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2002.

OLIVEIRA, F. G. ***Análise da aplicabilidade da classificação MCT na execução de bases rodoviárias com utilização de solos lateríticos estabilizados***. 2018. Dissertação (Mestrado em Geotecnia) - NUGEO, Escola de Minas, Universidade Federal de Ouro Preto, Ouro Preto, 2018.

PINTO, C. S. ***Curso básico de mecânica dos solos***: em 16 aulas. 3. ed. São Paulo: Oficina de Textos, 2016.

SANTOS, L. D. F. ***Estudo do comportamento do solo melhorado com cimento***. 2017. 55 f. Trabalho de Conclusão de Curso (Bacharelado em Engenharia Civil) – Escola de Engenharia, Universidade Federal Fluminense, Niterói, 2017.

SPADA, J. L. G. ***Uma abordagem de mecânica dos pavimentos aplicada ao entendimento do mecanismo de comportamento tensão–deformação da via férrea***. 2003. Tese (Doutorado em Engenharia Civil) - COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2003.

VALEC. ***Especificação de serviços de infraestrutura***: Aterro. Brasília: VALEC - Engenharia, Construções e Ferrovias, 2017. 15 p.

VALEC. ***Especificação de serviços de infraestrutura***: Sub-lastro. Brasília: VALEC - Engenharia, Construções e Ferrovias, 2017. 6 p.

VILLIBOR, D. F.; ALVES, D. M. L. Classificação de solos tropicais de granulação fina e grossa. ***Revista Pavimentação ABPv***, v. 43, p. 17 – 37, 2017.

ZICA, E. S. ***Estudo comparativo entre energias de compactação do subleito para subsidiar projetos de pavimentação***. 2010. Dissertação (Mestrado Profissional em Engenharia Geotécnica) - NUGEO, Escola de Minas, Universidade Federal de Ouro Preto, Ouro Preto, 2010.

Received: 27 April 2021 - Accepted: 8 February 2022.