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Georeferenced Geotechnical Database of Subgrades of Federal Roads Located in the State of Ceará/Brasil

Banco de dados geotécnico georreferenciado dos subleitos de rodovias federais localizadas no Estado do Ceará/Brazil

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Abstract: This article presents an analysis of the subgrade data provided in printed report format by the National Department of Transport Infrastructure (DNIT). The information was digitized and inserted into an electronic spreadsheet to create a georeferenced geotechnical database, using Microsoft Excel and QGIS Desktop in order to enableverification of results and corrections of soil classification errors. It began with the construction of a digital platform for prior knowledge of the geotechnical characteristics of certain regions of the state of Ceará, as well as the generation of models and thematic maps. The analyzed spreadsheet contains geotechnical study identification, road name, station, UTM coordinates, drilling depth, optimum water content, maximum dry density, California Bearing Ratio (CBR), expansion, liquidity limit, plasticity index, sieve analysis, group index, and AASHTO classification. The analysis of the results was carried out with the generation of dynamic tables and graphs, where it was possible to identify, based on the CBR, that the materials analyzed have adequate mechanical behavior to be used in highway subgrades, and that the AASHTO classification can predict the mechanical behavior of soils in the State of Ceará.

Keywords: Database; Subgrade soils; Federal highways.

Resumo: Este artigo apresenta uma análise de dados de subleitos que foram fornecidos pelo Departamento Nacional de Infraestrutura de Transportes (DNIT), em formato de relatórios analógicos. As informações foram digitalizadas e transformadas em um banco de dados geotécnicos georreferenciados, através do Microsoft Excel e QGIS Desktop 3.28.9, possibilitando verificações dos resultados e correções de erros de classificação dos solos, dando início à construção de uma plataforma digital para o conhecimento prévio das características geotécnicas de determinadas regiões do Estado, bem como, a geração de modelos e mapas temáticos. A planilha analisada contém: identificação de estudo geotécnico, rodovia, estaca, coordenadas UTM, profundidade de coleta, umidade ótima, massa específica seca máxima, California Bearing Ratio (CBR), expansão, limite de liquidez, índice de plasticidade, granulometria, observações relativas às peculiaridades dos solos analisados, índice de grupo e classificação da American Association of State Highway and Transportation Officials (AASHTO). A análise dos resultados foi feita com a geração de tabelas e gráficos dinâmicos, constatando-se que, de acordo com o CBR, os materiais analisados têm comportamento mecânico adequado para serem utilizados em subleitos de rodovias, e que a classificação da AASHTO consegue prever adequadamente o comportamento mecânico dos solos do Estado do Ceará.

Palavras-chave: Banco de dados; Solos de subleitos; Rodovias federais.

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1. Introduction

Geotechnical databases gather information that aids in decision-making, such as selecting the best construction site, determining the type of foundation, identifying applicable soil treatment methodologies, and estimating geotechnical parameters (BARBOSA, 2018). The combined use of geographic information systems and databases allows for the collection and observation of geotechnical parameters based on their spatial location, facilitating a quicker and more efficient understanding of specific areas (VALENTE, 2000).

The conception of geotechnical database systems is feasible due to the agility in applying calculations and processing data at lower costs (RENGERS et al., 2002; SOARES, 2011). The use combination of databases and maps is important for understanding occurrences, predictions, simulations, and strategic planning by combining traditional operations with the ability to select and research information while enabling data visualization and analysis (OLIVEIRA, 2015). In geotechnical terms, the subgrade is the foundation soil on which pavement structures, typically composed of sub-base, base, and surface layers, are built, as shown in Figure 1 (MEDINA; MOTTA, 2015; ZHANG; YI; FENG, 2020).

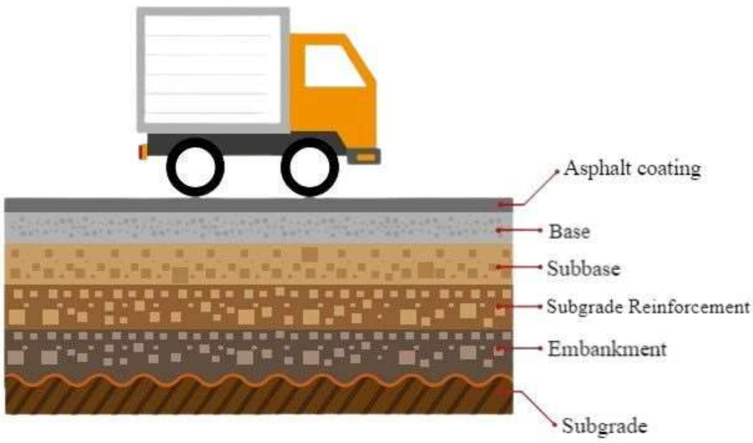

Figure 1 – Typical pavement structure.
Source: CNT (2017, p. 16).

A thorough investigation of the subgrade enables the correct acquisition of parameters used in pavement design, ensuring a longer life cycle of the structure (OLIVEIRA, 2019). Soil analyses allow recognizing, identifying, and characterizing the physical and mechanical properties of the materials composing the subgrade, as well as understanding the processes through which the pavement deteriorates (BALBO, 2007; RIBEIRO, 2013).

Since the 1970s, there has been a growing application of mechanistic-empirical pavement design methods, aiming to reconcile the load behavior with the stiffness of materials. (MEDINA; MOTTA, 2015; WANG *et al.*, 2024). To solve the structural problems of pavements, it is important to define the issues, load and deformation conditions, and material properties (BERNUCCI *et al.*, 2008).

Currently, Brazil's official method adopted for designing flexible pavements is based on the geotechnical parameter known as the California Bearing Ratio (CBR). This empirical method, developed in 1966 by the now-defunct National Department of Highways (DNER), currently known as DNIT, is used to determine the thicknesses of the layers in road pavements (SANTOS *et al.,* 2020).

Regardless of the pavement design method, mapping pre-existing data used in paving can improve the quality of preliminary road projects. The absence of this information makes it difficult to identify materials in the initial stages, often resulting in a greater demand for natural resources, longer execution times, and higher project costs (RIBEIRO; SILVA; BARROSO, 2018).

For the execution of road projects, collecting existing data and subsequently complementing it with new data collection is a way to ensure the correct implementation of the pavement (ROCHA *et al.,* 2022). By utilizing the information previously contained in database systems or provided by their users, it is possible to analyze and compare the results of the available parameters (SILVA *et al.,* 2014).

According to DNIT (2006), the basic data to compose a geotechnical road database are the results of soil characterization tests, such as grain size distribution, Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), optimum moisture content, maximum dry density, CBR, expansion, and AASHTO classification.

The Proctor compaction test determines the optimum moisture content and maximum dry density, where pressure, impact, or vibration increase the apparent specific mass of the soil and other materials. This process enhances contact among particles, reducing the void ratio by decreasing the amount of air in the soil structure. Reducing air voids makes it possible to lower the tendency for moisture variation in the pavement materials during service life (DNIT, 2006). This test is standardized by methods DNER-ME 129/94 and DNER-ME 162/94.

The CBR test involves obtaining the ratio between soils and a standardized graded crushed stone. Through empirical equations, the value of this ratio allows for calculating the thickness of the layers in flexible pavements based on traffic (BERNUCCI *et al.,* 2008). The procedure for determining the CBR and the expansion value in soils can follow the DNER-ME 049/94 specifications.

The determination of the Liquid Limit (LL) is standardized by the test specification DNER-ME 122/94, corresponding to the moisture content at the boundary between the liquid and plastic states of soil. The Plasticity Index (PI) is the numerical difference between the LL and the Plastic Limit (PL). The higher the PI, the more plastic the soil. The PL can be obtained following the specifications of the test method DNER-ME 082/94

The grain size analysis of soils is performed by determining the mass percentages of the different soil grains. The test is conducted by passing a soil sample through sieves of various standardized sizes. The amount of mass retained on each sieve is weighed, and the percentage passing through each sieve is calculated (EMBRAPA, 2017). The grain size test for pavement is standardized by DNER-ME 051/94 and DNER-ME 080/94.

Finally, AASHTO classification determines if the soil sample is granular (generally considered excellent to good for subgrades) or silty/clayey (generally considered regular to poor for subgrades). AASHTO classifies soils and soil-aggregate mixtures based on the particle size distribution, liquid limit, and plasticity index of the material. Soils are classified into seven groups (A-1 to A-7), with sub-groups (AASHTO, 1993).

The construction of this database was carried out within the scope of the "Subproject Integrated Platform for Data Structuring and Analysis Using Artificial Intelligence" under the "Research, Training, and Technical Support Project for National Asphalt Road Pavements" supported by DNIT. The construction of this database is legitimate to the need for a digitized information database, encompassing the results of geotechnical studies conducted by the federal road agency on federal highways in Ceará. Thus, its objective is to promote the dissemination of practices for digitizing and georeferencing data from existing projects.

2. Methodology

2.1. Data Acquisition

The information on the geotechnical parameters of the subgrades of the federal highways BR-020, BR-116, BR-222, BR-226, BR-304, BR-402, and BR-403 located in the State of Ceará (Figure 2) is sourced from summary tables of subgrade test results from a total of 44 studies provided by DNIT. The results from 19 engineering projects, 15 restoration projects, 1 revision, 2 rehabilitation projects, 1 capacity adaptation, 1 improvement, 5 restoration and improvement projects, 1 implementation and paving, and 1 improvement and paving project, which were acquired in physical format and executed between 1973 and 2009 by DNER/DNIT.

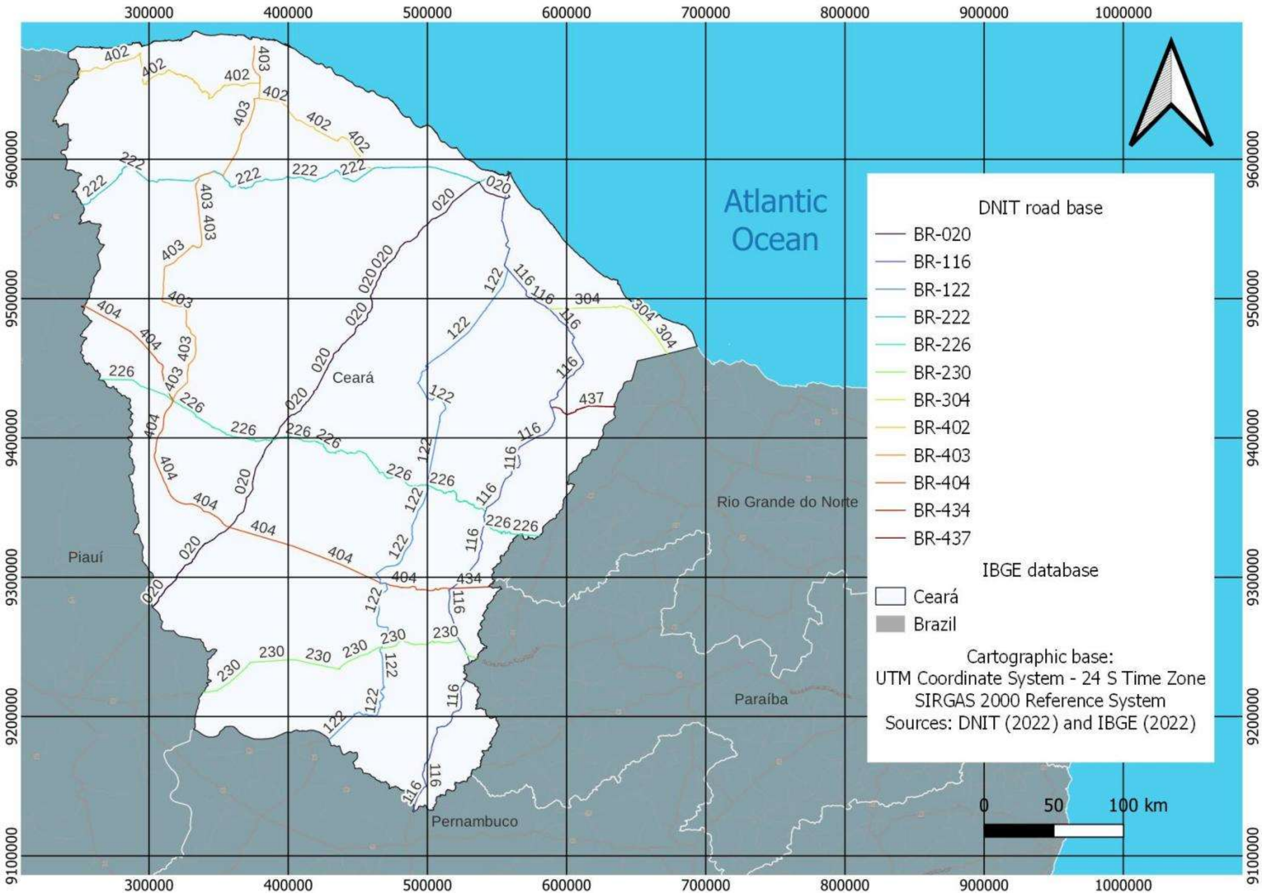

Figure 2 – Map of federal highways located in the State of Ceará.
Source: Authors (2024).

2.2. Data Digitization

The georeferenced geotechnical database has 7139 rows and 22 columns containing the identifications of the geotechnical studies, highways, stations, soil probing depth, UTM coordinates (X and Y), optimum moisture (%), maximum dry density (g/cm³), CBR (%), expansion (%), LL (%), IP (%), percentages passing through the sieves 50.8 mm (#2”), 25.4 mm (#1”), 9.5 mm (#3/8”), 4.76 mm (#4), 2 mm (#10), 0.42 mm (#40), and 0.074 mm (#200), observations related to the peculiarities of each analyzed soil, Group Indices (GI), and AASHTO classifications.

2.3. Data Analysis

For the execution of this work, the rows in the georeferenced geotechnical database that did not present all the considered parameter results were rejected. Thus, 5038 rows corresponding to 37 in 44 highway projects have been considered. The analysis of the results was performed by generating tables and dynamic graphs using Microsoft Excel, enabling the verification of each parameter's occurrence as well as obtaining dispersion and central tendency measures through descriptive statistics to obtain the mean, median, mode, standard deviation, and variance values.

2.4. Data Georeferencing

For geo-referencing the sample collection points for geotechnical analyses, the methodology of Ribeiro Silva and Barroso (2016) was used by locating the points of the subgrade information relative to the staking of the road axis. This procedure allowed the extraction of the coordinates of the sampled locations through QGIS Desktop 3.28.9 using DNIT's (SNV) road cartographic base, UTM coordinate system - zone 24 South, and SIRGAS 2000 reference system.

After extracting the UTM coordinates, it became possible to relate the sampled points' coordinates in the highway projects with other information and layers of the terrestrial physical environment as represented in Figure 3, aiding in the acquisition of variables for generating models and thematic maps of interest to highway agencies.

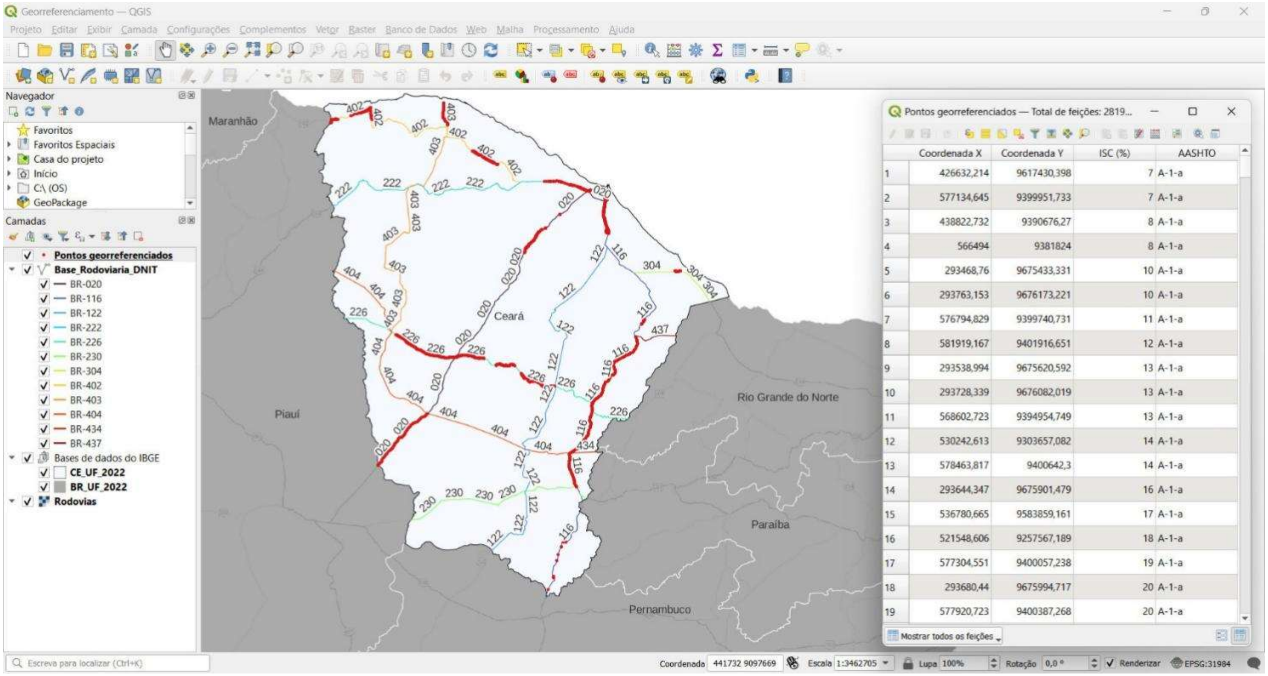

Figure 3 – Data manipulation in QGIS Desktop 3.28.9.
Source: Authors (2024).

3. Results and discussion

The information from the subgrade layers of the geotechnical studies of federal highways in the state of Ceará is composed of the following parameters: optimum moisture content (%), maximum dry density (g/cm³), CBR (%), expansion (%), liquid limit (%), plasticity index (%), particle size distribution (%), group index, and AASHTO classification. Tables 1 and 2 present these variables' most frequently occurring values (mode).

Table 1 – Most frequent occurrences of geotechnical parameter results

Optimum moisture (%)	9
Maximum dry density (g/cm³)	1,90
***CBR* (%)**	10
Expansion (%)	0
LL (%)	NP*
IP (%)	NP*
Sieve size 50.8 mm (%)	100
Sieve size 25.4 mm (%)	100
Sieve size 9.5 mm (%)	100

Sieve size 4.76 mm (%)	100
Sieve size 2 mm (%)	100
Sieve size 0.42 mm (%)	60
Sieve size 0.074 mm (%)	30
Group Index	0
AASHTO classification	A-2-4

**NP indicates "Not Present" or "Non-Plastic"*

Source: Authors (2024).

Table 2 – Most frequent occurrences of geotechnical parameter results by highway

Road	BR-020	BR-116	BR-222	BR-226	BR-304	BR-402	BR-403
Optimum moisture (%)	7.6 e 7.8	8.6	9	8.8	9.6	10.3	9.9
Maximum dry density (g/cm³)	2.15	1.90	2.00	1.90	1.96	1.83	1.90
***CBR* (%)**	12	8	10 e 14	10	19	10	8 e 9
Expansion (%)	0,1	0	0,1	0	0	0	0
LL (%)	NP	NP	NP	NP	NP	NP	NP
IP (%)	NP	NP	NP	NP	NP	NP	NP
Sieve size 50.8 mm (%)	100	100	100	100	100	100	100
Sieve size 25.4 mm (%)	100	100	100	100	100	100	100
Sieve size 9.5 mm (%)	100	100	100	100	100	100	100
Sieve size 4.76 mm (%)	100	100	100	100	100	100	100
Sieve size 2 mm (%)	74	100	60	82	100	100	55, 61 e 65
Sieve size 0.42 mm (%)	36	86	56	60	83 e 87	60	38
Sieve size 0.074 mm (%)	15 e 22	17	19	30	26	30	17, 19 e 20
Group Index	0	0	0	0	0	0	0
AASHTO classification	A-1-b	A-2-4	A-2-4	A-2-4	A-2-4	A-2-4	A-1-b

Source: Authors (2024).

The quantity of data for each geotechnical parameter by highway is represented in Figure 4. Statistical analysis of the CBR values showed that most occurrences in the soil database were above 2%. According to DNIT (2006), values above 2% indicate adequate behavior as subgrade, while for CBR values below 2%, replacing the material with another with a higher value is recommended.

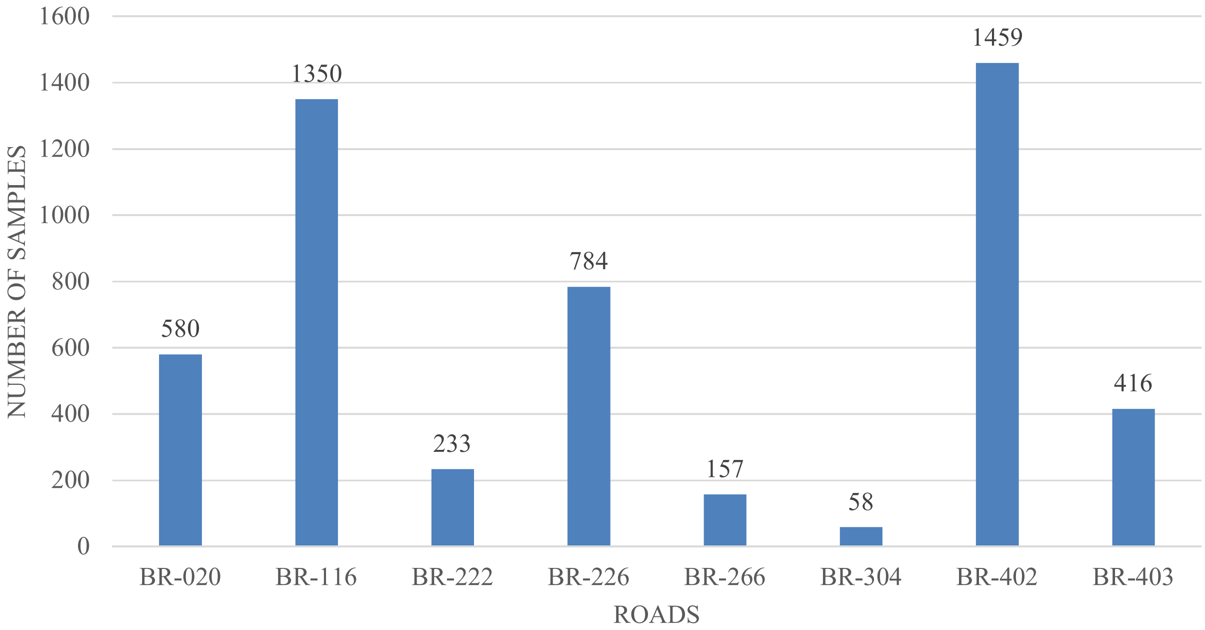

Figure 4 – Chart of the information obtained from geotechnical parameters by highway.
Source: Authors (2024).

By verifying the CBR occurrences by AASHTO classification as shown in Table 3, it is noticeable that soils exhibiting fair to poor subgrade behavior (A-4, A-5, A-6, A-7-5, and A-7-6) have a lower average CBR value, while soils showing excellent to good subgrade behavior (A-1-a, A-1-b, A-2-4, A-2-5, A-2-6, A-2-7, and A-3) have a higher average CBR value. This indicates that the AASHTO classification can predict the mechanical behavior of soils in Ceará, confirming the conclusions of Chaves (2000) and Barroso (2002) for the Metropolitan Region of Fortaleza.It is possible to say that there is a significant difference in their ranges when comparing the CBR values from the geotechnical studies to correlation values between CBR and AASHTO Classification from Senço (2007).

Table 3 – Statistical verification of cbr (%) values by AASHTO classification.

AASHTO Classification	***CBR (%)***	**Number of samples**	**Mean**	**Median**	**Mode**	**Std Deviation**	**Variance**
A-1-a	7 - 117	165	52	59	64	30	876
A-1-b	0 - 129	962	33	21	13	26	651
A-2-4	0 - 146	2394	17	13	10	12	153
A-2-5	9	1	9	9	-	-	-
A-2-6	1 - 78	261	15	12	13	11	120
A-2-7	5 - 12	2	8,5	8,5	-	5	25
A-3	3 - 39	144	17	16	10	7	46
A-4	0 - 91	852	11	10	10	6	32
A-5	0 - 6	5	3	4	-	2	6
A-6	1 - 34	225	10	10	10	5	26
A-7-5	0 - 13	11	4	3	0	4	18
A-7-6	0 - 10	15	4	3	2	3	11

Source: Authors (2024).

The statistical verifications of the data for optimum moisture content (%), maximum dry density (g/cm³), and expansion (%) by AASHTO classification are represented in Tables 4, 5, and 6, respectively.

Table 4 – Statistical verification of optimum moisture (%) values by AASHTO classification.

AASHTO Classification	**Optimum moisture (%)**	**Number of samples**	**Mean**	**Median**	**Mode**	**Std Deviation**	**Variance**
A-1-a	4.5 - 15	165	8.1	7.8	6.9	2.0	3.9
A-1-b	1.7 - 15.2	962	8.9	8.7	8.8	1.9	3.5
A-2-4	0.4 - 35	2394	9.9	9.7	9	2.1	4.6
A-2-5	19.5	1	19.5	19.5	-	-	-
A-2-6	5.7 - 17.3	261	10.9	10.5	9.7	1.9	3.7
A-2-7	9 - 15.2	2	12.1	12.1	-	4.4	19.2
A-3	4.4 - 12.7	144	9	8.8	8.2	1.7	2.8
A-4	1.3 - 51	852	11.4	11.1	10.1	2.7	7.1
A-5	18.3 - 21.6	5	19.7	19	-	1.5	2.1
A-6	6 - 19.8	225	12.6	12.3	10.1	2.4	5.8
A-7-5	11 - 20.4	11	14.8	14.9	11	3.5	12
A-7-6	9.5 - 17.6	15	14.6	14.4	13.1	2	3.9

Source: Authors (2024).

Table 5 – Statistical verification of maximum dry density (g/cm³) values by AASHTO classification.

AASHTO Classification	**Maximum dry density (g/cm³)**	**Number of samples**	**Mean**	**Median**	**Mode**	**Std Deviation**	**Variance**
A-1-a	1.7 - 2.24	165	2.058	2.098	2.13	0.118	0.014
A-1-b	1.15 - 13.5	962	2.014	2.002	1.9	0.391	0.153
A-2-4	0.175 - 14.5	2394	1.932	1.905	1.9	0.501	0.251
A-2-5	1.68	1	1.68	1.68	-	-	-
A-2-6	1.6 - 2.18	261	1.907	1.91	1.89	0.118	0.014
A-2-7	1.85 - 1.87	2	1.86	1.86	-	0.014	0
A-3	1.682 - 2.14	144	1.841	1.795	1.78	0.122	0.015
A-4	1 - 2.15	852	1.829	1.83	1.8	0.099	0.01
A-5	1.61 - 1.674	5	1.641	1.633	-	0.03	0.001
A-6	0.745 - 2.05	225	1.793	1.8	1.79	0.12	0.014
A-7-5	1.61 - 1.9	11	1.789	1.82	1.789	0.102	0.01
A-7-6	1.63 - 1.87	15	1.753	1.732	1.63	0.079	0.006

Source: Authors (2024).

Table 6 – Statistical verification of expansion (%) values by AASHTO classification.

AASHTO Classification	**Expansion (%)**	**Number of samples**	**Mean**	**Median**	**Mode**	**Std Deviation**	**Variance**
A-1-a	0 - 0.7	165	0.1	0	0	0.1	0
A-1-b	0 - 1.5	962	0.1	0	0	0.2	0
A-2-4	0 - 9.3	962	0.1	0.1	0	0.4	0.1
A-2-5	0.8	1	0.8	0.8	-	-	-
A-2-6	0 - 3	261	0.2	0.1	0	0.4	0.2
A-2-7	0.2 - 0.3	2	0.3	0.3	-	0.1	0
A-3	0 - 0.3	144	0	0	0	0.1	0
A-4	0 - 2.2	852	0.2	0.1	0.1	0.3	0.1
A-5	0.5 - 3.5	5	1.9	1.8	-	1.2	1.5
A-6	0 - 3.8	225	0.5	0.2	0.1	0.6	0.4
A-7-5	0 - 3.8	11	1.4	0.4	0	1.7	2.9
A-7-6	0 - 2.6	15	0.7	0.3	0	0.9	0.8

Source: Authors (2024).

Analyzing the number of AASHTO classifications occurrences, it was found that the majority of samples was Classified as A-2-4 (2394), followed by A-1-b (962), A-4 (852), A-2-6 (261), A-6 (225), A-1-a (165), and A-3 (144). The lowest occurrences were A-2-5 (1), A-2-7 (2), A-5 (5), A-7-5 (11) and A-7-6 (15). Therefore, the general behavior as a subgrade of the analyzed soils is considered excellent to good.

The soil classifications from the geotechnical studies were checked and corrected. Among the 5037 samples, 64 AASHTO classifications were missing (1.27%), and 261 soils with erroneous AASHTO classifications were identified (5.18%). All errors found in the AASHTO classifications were automatically corrected in Microsoft Excel.

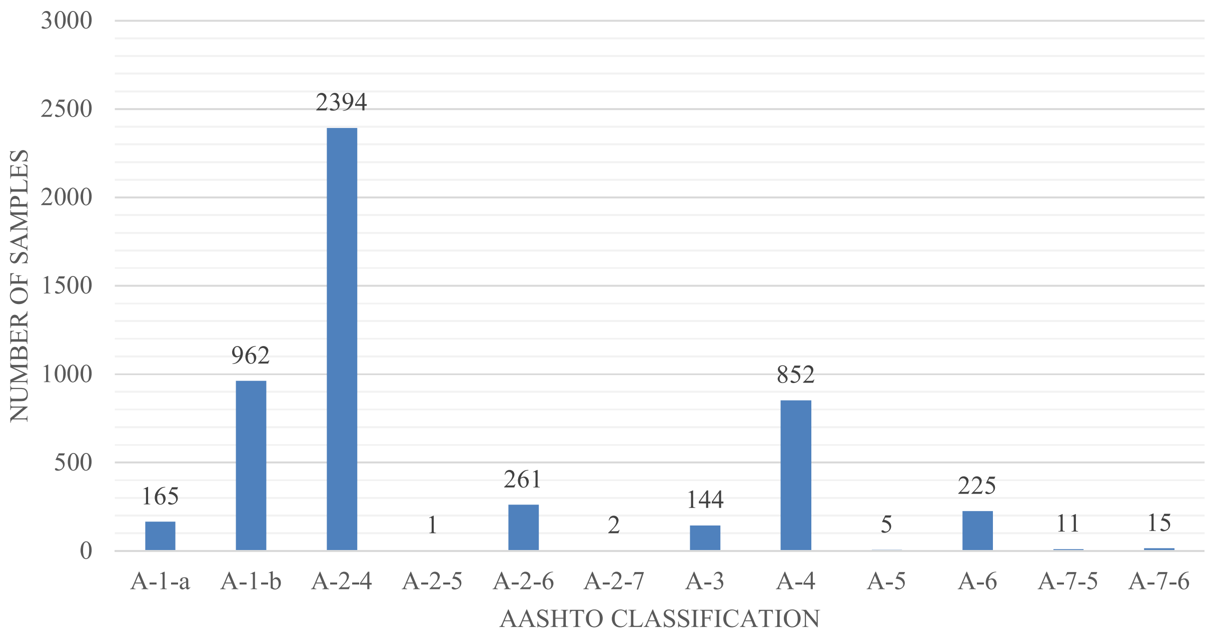

Figure 5 – Chart of AASHTO classification occurrences.
Source: Authors (2024).

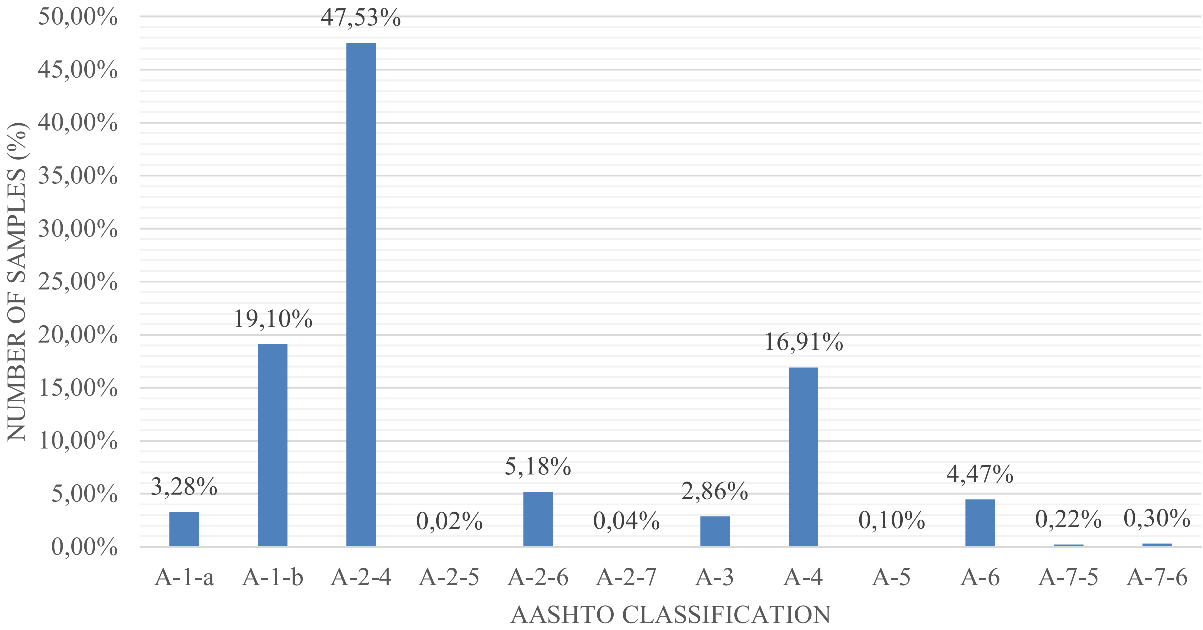

Figure 6 – Chart of AASHTO classification occurrence percentages.
Source: Authors (2024).

Table 7 presents information on the georeferenced data. However, it was not possible to georeference all stations due to the lack of more precise location information, as some geotechnical studies did not provide the necessary pieces of information.

Table 7 – Georeferenced points

Road	Number of samples	Number of samples georreferenced	(%) of samples georreferenced
BR-020	580	318	54.83%
BR-116	1350	995	73.70%
BR-222	233	125	53.65%
BR-226	941	698	74.18%
BR-304	58	56	96.55%
BR-402	1459	535	36.67%
BR-403	416	92	22.12%
Total	5037	2819	55.97%

Source: Authors (2024).

Figure 7 shows the map of georeferenced points on each categorized highway described in Table 7 according to the UTM coordinates in the database. Figures 8 and 9 present the maps of points with graded CBR and categorized AASHTO classifications, respectively. The georeferencing of the points demonstrated the viability of integrating existing geotechnical data and maps, enabling prior knowledge of the soil materials in certain locations. This information can be useful for reducing resource use, execution time, and costs in projects for duplication, recovery, and restoration of georeferenced highways, as well as in basic projects and feasibility analyses of new roads near the located points.

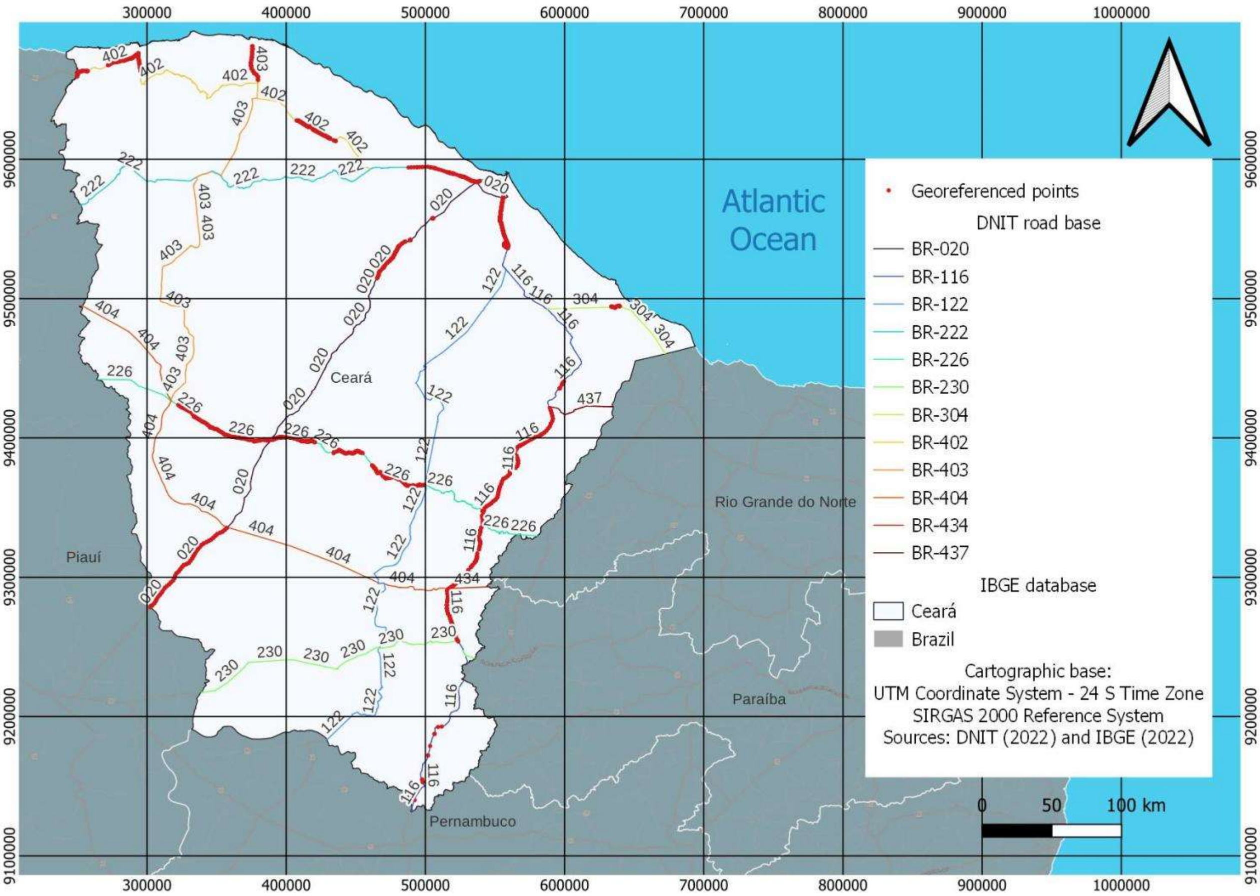

Figure 7 – Map of georeferenced points.
Source: Authors (2024).

The occurrences of CBR in the georeferenced points are represented in Table 8 and Figure 8. The occurrences of AASHTO classifications in the georeferenced points are shown in Table 9 and Figure 9.

Table 8 – CBR (%) occurrences at georeferenced points.

***CBR* (%)**	0 - 11	11 -19	19 - 30	30 - 45	45 - 62	62 - 82	82 - 146
Number of samples	1071	949	490	221	128	129	71

Source: Authors (2024).

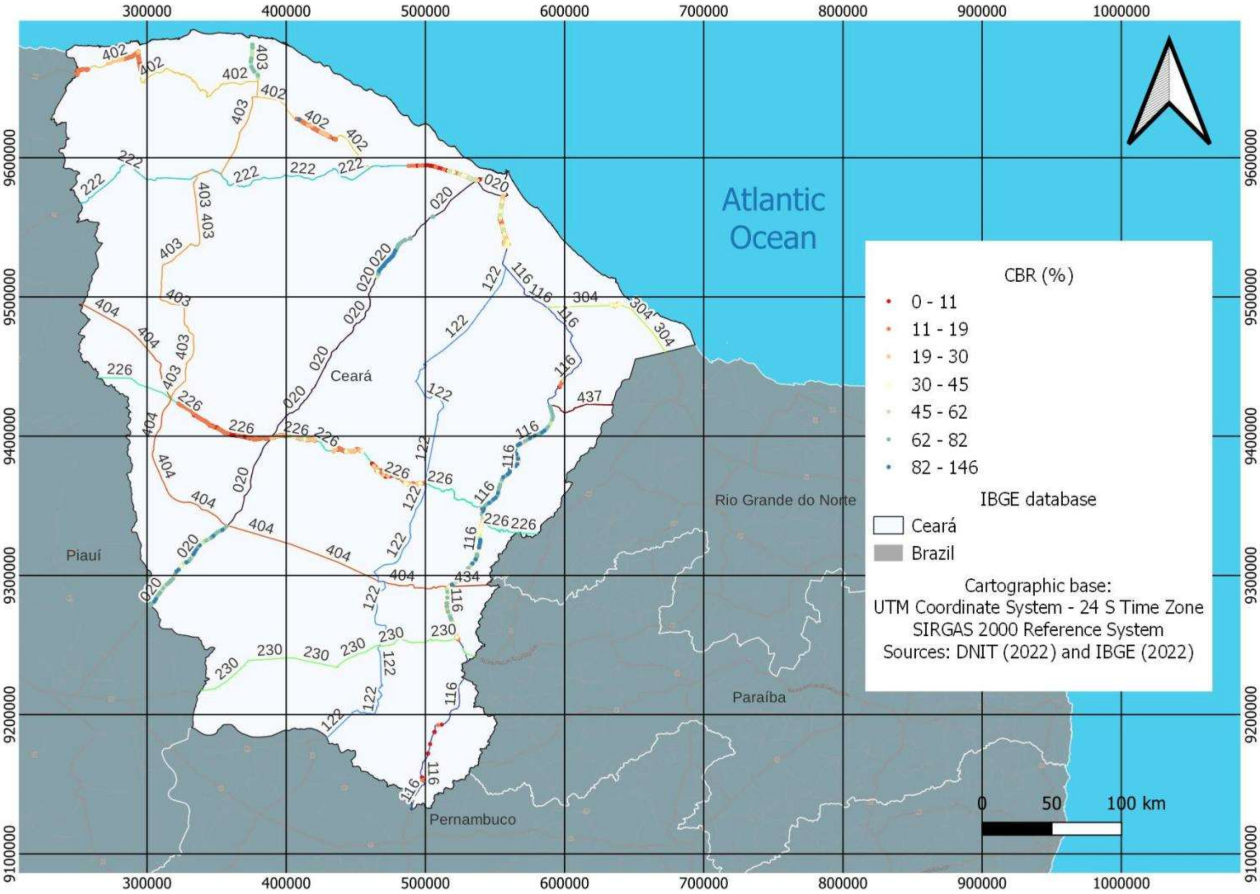

Figure 8 – Map of georeferenced points graduated by CBR (%).
Source: Authors (2024).

Table 9 – AASHTO classification occurrences at georeferenced points.

AASHTO Classification	A-1-a	A-1-b	A-2-4	A-2-6	A-3	A-4	A-6	A-7-5	A-7-6
Number of samples	118	580	1345	106	124	422	109	5	10

Source: Authors (2024).

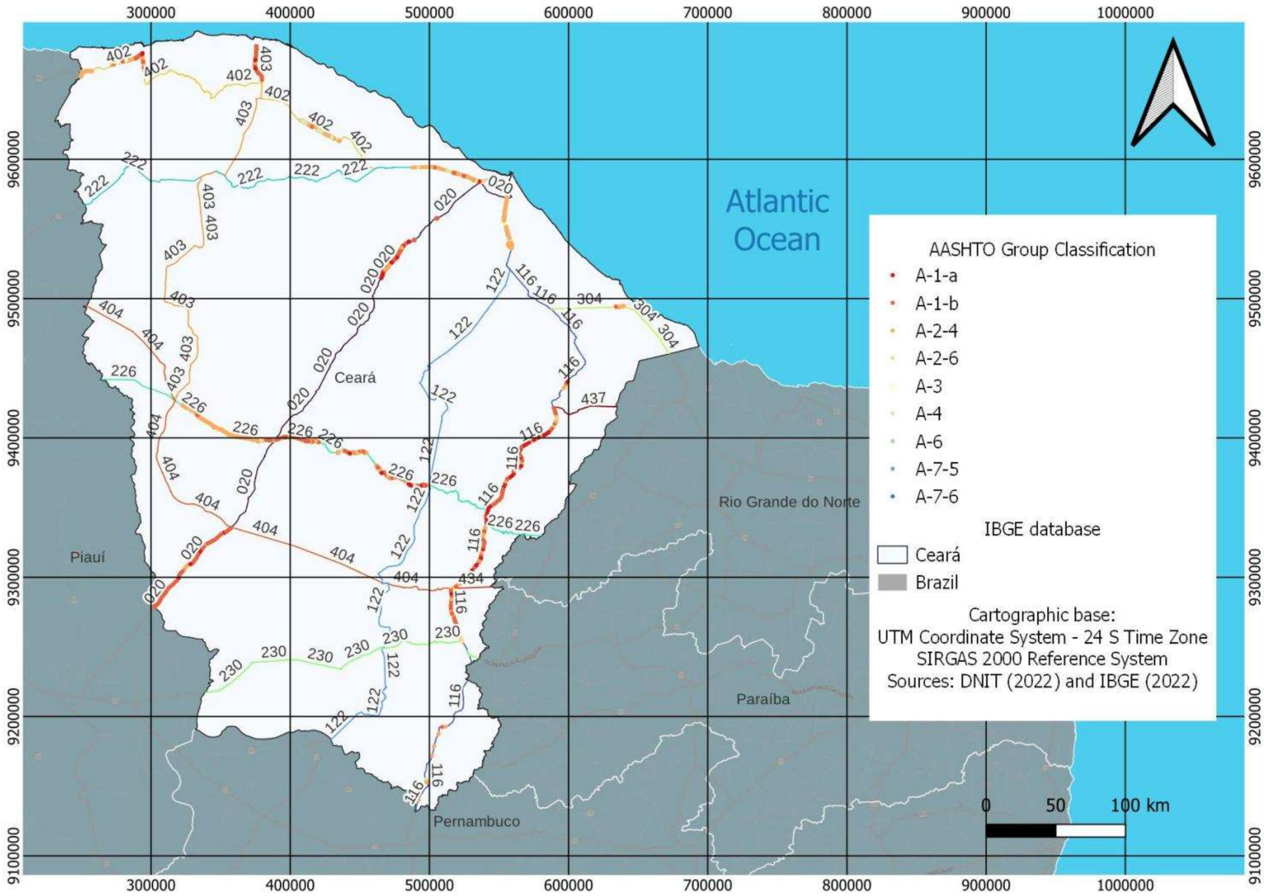

Figure 9 – Map of georeferenced points categorized by AASHTO group classification.
Source: Authors (2024).

4. Conclusions

The results show that generally, the values of CBR of the analyzed soils are greater than 2%, indicating no need for a subgrade reinforcement layer for lower traffic. This evidence shows that the AASHTO classification can predict the mechanical behavior of soils in the state of Ceará. The general rating of the subgrade behavior of soils from the BR-020, BR-116, BR-222, BR-226, BR-304, BR-402, and BR-403 highways is excellent to good.

The digitization and georeferencing of the geotechnical subgrade data related to this article enabled the analysis of results, correction of soil classification errors, and initiated the construction of a digital platform for generating models and thematic maps of interest to road agencies, contributing to the optimization in providing information of the subgrade soils properties necessary for the road project.

Finally, it is suggested that the execution of this work inspires future studies, such as the construction of predictive models of geotechnical soil information and the expansion of the georeferenced geotechnical database to the sub-base and base layers, which also integrate the pavement structure.

Knowlegments

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