# Correlation study between CBR and DCP indexes of two tropical soils from the Brazilian Northeast as an instrument for in situ technological control

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**ABSTRACT:** To guarantee safety and functionality for any road construction project, technological control using in situ and laboratory tests is an essential tool. In this context, the use of the Dynamic Cone Penetrometer (DCP) has gained popularity to estimate soil parameters, such as the California Bearing Ratio (CBR), through correlation studies. Therefore, this paper is aimed to establish empirical relationships between CBR and DCP indexes of typical soils from Natal/RN, in the Brazilian Northeast. After an initial characterization, results were correlated from approximately 80 tests, performed on both soils at two different compaction energies and various moisture contents in-mold, subjected to distinct immersion conditions. According to the characterization tests, soil 1 was classified as a silty sand (SM), and soil two was classified as a well-graded silty sand (SM-SW). Additionally, both samples were considered as A-2-4 according to the highway classification. The obtainment of coefficients of determination ($R^2$) higher than 0.90 in 75% of the developed correlations, characterizes the applicability of DCP as a valid field-testing instrument for technological control of local paving works, as it is a simple, fast and low-cost test. The findings of this study represent an advancement in definition and standardization of a simple, efficient, and safe methodology to the estimate of empirical correlations between these two soil parameters.

**Keywords:** California Bearing Ratio; Dynamic Cone Penetrometer; Correlation Study; Technological Control; Field Testing.

## 1. Introduction

The need for technological control in paving is evident by the significant increase in traffic loads over the years [1]. To perform a proper soil analysis, it is highly recommended to conduct field and laboratory investigations to obtain strength and compressibility parameters that define the soil overall behavior.

Although investigation techniques such as the Standard Penetration Test (SPT), Cone Penetration Test (CPT) and California Bearing Ratio (CBR) are still indispensable for road design, other types of equipment can also be used to estimate soil strength at significantly lower costs. In this context, noninvasive and non-destructive methods have received significant attention [2] since they allow for soil analyses with little or no damage by ensuring minimal disturbance in situ. Therefore, the dynamic cone penetrometer (DCP) has been broadly utilized as an efficient complementary tool to evaluate soil strength in paving works due to its simplicity, and inexpensive cost [3].

Since CBR is still the most used method to evaluate soils before designing a pavement, the increasing need for in situ technological control has motivated researchers to conduct correlation studies between CBR and more straightforward tests to evaluate soil penetration resistance. Previous studies developed in different countries have obtained, with distinct soil types, equations able to estimate CBR from DCP results, demonstrating that there is a clear correlation between both parameters.

Even though determining empirical correlations simplifies the estimate of soil parameters, previous investigations highlight that the use of these equations should only be reliable if tests are performed at identical soil classification, and at the same location where the experimental research was conducted [4, 5]. Such necessity is evidenced, especially in Brazil, a country that presents a wide range of soil types and weather conditions between different regions.

Due to the lack of scientific evidence regarding correlation studies developed in the Brazilian Northeast, this paper aimed to perform correlation studies in two tropical soils from Natal, state of Rio Grande do Norte.

## 2. Background

### 2.1. Dynamic cone penetration test (DCP)

The dynamic cone penetration test is conducted by gradually penetrating a standardized, metallic cone tip in the soil by dropping an 8 kg hammer from a 575 mm height (Fig. 1). This procedure follows specifications of the American Society for Testing and Materials (ASTM), standard D-6951-2018 [6].

Determining the DCP index requires constant readings of the cummulative penetration depth reached by the tip of the equipment. Standard practice involves counting the number of blows necessary to penetrate a certain depth, usually considered to be 10 cm. However, for low-strength soils, readings are usually taken for each blow to get a better representation of the soil penetration resistance.

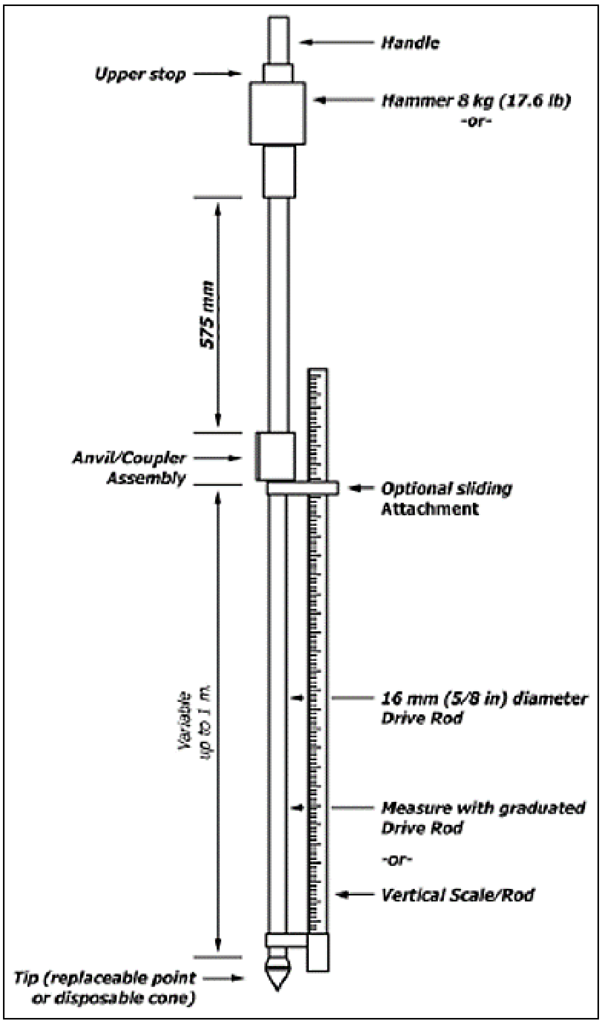


**Figure 1.** Dynamic cone penetrometer [6].

Although the DCP test cannot be used to replace laboratory testing completely, several authors point out the low-complexity operation at inexpensive costs as the main advantage of this equipment. Its procedure can provide a significant amount of testing in a short time interval, including in areas of difficult access for equipment to perform SPT, CPT or in-situ CBR testing [5, 7, 8].

Due to the reduced surface contact of the cone tip with the ground when the equipment is correctly positioned for the test, it is recommended that the reading corresponding to the first blow (zeroth blow) should be disregarded [4, 5, 9]. During the test, the number of blows and the penetration of the tip is recorded with the help of a ruler positioned next to the drive rod. The DCP index is then calculated using Eq. 1, where $Z_n$ and $Z_1$ are the offsets produced by the nth and first blows, where n is the number of blows. Additionally, soil layers of different strengths must be assigned different penetration rates.

$$I_{DCP} = \frac{Z_n - Z_1}{n-1} \quad (1)$$

DCP tests can be performed both in situ and in a the laboratory [3]. In these circumstances, soil specimens are molded in the large compaction cylinder (152 mm diameter, 178 mm height with a 63.5 mm high steel disc inside), and the test can be performed under compacted or undeformed sample conditions.

Due to its ease of reproduction and possible use in both field and laboratory, the DCP has a high potential for several purposes, such as soil compaction control, detection of collapsible porous soils, identification of structural deficiencies, and structural evaluation of pavements [2, 10 - 12].

In this context, results from the DCP test have often been used to estimate strength and deformability parameters obtainable by other test methods through the development of correlation studies. Thus, the dynamic cone penetrometer optimizes and facilitates technological control in the field during the paving process, as it can be related to parameters such as the CBR index itself, and other soil properties depending on the available equipment in situ.

## 2.2. Correlations between DCP and CBR

Correlation studies between DCP and CBR are developed when a structural pavement assessment is to be carried out [5] at low costs. The use of correlations may be justified by the difficulty of performing in situ CBR testing and the increasing need to optimize quality control in road infrastructure works [10].

In addition to requiring prior characterization of the evaluated sample, it is essential to mention that these studies should preferably be performed at soils under identical conditions of moisture content and compaction, either in situ or during laboratory molding. This precaution should be taken to ensure the reproductibility of results in soil samples that have the same classification and condition as the investigated soil.

In general, the correlations between the DCP and CBR indexes found in the relevant literature assume the power (Eq. 2) and logarithmic (Eq. 3) forms, as a function of two dimensionless parameters, A and B. These parameters depend on the soil properties and the boundary conditions to which it is subjected. The DCP index is given in millimeters per blow (mm/blow) and the CBR index is given as a percentage (%). In this paper, to ensure a consistent comparison, all logarithmic equations published by previous studies were converted to the format of Eq. 2, as parameters A and B are identical in both cases.

$$CBR = A \times DCP^B \quad (2)$$

$$Log(CBR) = Log(A) + B \times Log(DCP) \quad (3)$$

ASTM D6951:2018 recommends three correlations for estimating the California bearing ratio [13]. According to the standard, Eq. 4 applies to all soil types except for high compressibility (CH) and low compressibility (CL) clays with CBR less than 10%. On the other hand, Eqs. 5 and 6 are appropriate for CH and CL soils under these strength conditions, respectively. As in the previous equations, CBR is given as a percentage, and DCP is introduced in terms of mm/blow.

$$CBR = 292\, DCP^{-1.12} \tag{4}$$

$$CBR = \frac{1}{0.002871} DCP^{-1} \tag{5}$$

$$CBR = \frac{1}{0.017019} DCP^{-2} \tag{6}$$

The validity of the models presented in Eqs. 2 and 3 is also attested by a vast amount of studies that empirically relate these two types of tests (DCP and CBR) in one of these formats. The establishment of the correlation is based on a set of experimental points (DCP, CBR) that will define a trendline that will present an equation and its coefficient of determination ($R^2$). This coefficient is used as an indicator of the reliability of the equation obtained.

Thus, in addition to the correlations determined by ASTM, this literature review analyzed several correlation studies conducted in different countries. This analysis included the study areas, soil classifications, test conditions, equations, and their respective determination coefficients.

Therefore, Tables 1 through 3 present previous correlation studies between DCP and CBR performed in the laboratory over the last 23 years. The A and B equation parameters are also shown, as well as the obtained $R^2$. For each pair of tests, both CBR and DCP were performed under identical molding conditions of moisture content and compaction. It was observed that a significant amount of equations reached $R^2$ values above 0.90, and this attests to the statistical relationship between the two parameters.

For each study analyzed, a summary of the methodology followed in the laboratory was listed. In general, three study groups were identified: DCP and CBR tests performed immediately after specimen molding, at the moisture content of compaction (unsoaked condition, Table 1); DCP and CBR tests performed after immersion for 96 hours in the moisture content after submersion (soaked condition, Table 2); and DCP tests performed in unsoaked condition, related to CBR in soaked condition, after immersion for 96 hours (Table 3). This last type of correlation is called execution control and associates the DCP from field compaction conditions with the design CBR, which should be obtained after the sample is immersed in water for 4 days.

In addition to the three methods of correlation found, it was noted that the development of these equations in the laboratory does not follow a standardized methodology, as different authors adopted different boundary conditions. The most considerable discrepancy can be attributed to the conditions of the DCP test, which is usually performed on the same specimen immediately after the CBR test.

In addition to correlation studies developed in the laboratory, other authors have developed research to correlate CBR and DCP by performing in situ tests. Thus, previous studies that followed field methodologies [1, 19 - 24] were also included in this analysis. Of the seven studies analyzed, only two involved the field CBR test [19, 20], and this highlights the inherent difficulty to perform this procedure, as observed in other studies [10].

**Table 1.** Literature review for unsoaked correlation studies.

| Ref. | Country | Boundary Conditions | Equation Parameters | | |
|---|---|---|---|---|---|
| | | | A | B | $R^2$ |
| [9] | Saudi Arabia | CBR and DCP in different molds. | 355 | -1.31 | 0.96 |
| | | | 324 | -1.15 | 0.93 |
| | | | 501 | -1.35 | 0.87 |
| | | | 1445 | -1.36 | 0.81 |
| | | | 3715 | -1.86 | 0.83 |
| | | | 316 | -1.07 | 0.69 |
| [14] | Brazil | CBR and DCP in the same mold. DCP on the CBR orifice. | 321 | -1.07 | 0.98 |
| [15] | United States | CBR and DCP in the same mold, opposite sides. CBR orifice filled with soil. | 35.5 | -0.55 | 0.82 |
| [10] | Brazil | CBR and DCP in the same mold, opposite sides. Wooden disk inside CBR orifice. | 257 | -1.09 | 0.94 |
| | | | 925 | -1.34 | 0.96 |
| | | | 1062 | -1.40 | 0.92 |
| | | | 955 | -1.44 | 0.94 |
| | | | 644 | -1.40 | 0.86 |
| [4] | Brazil | CBR and DCP in the same mold. DCP on the CBR orifice. | 351 | -1.05 | 1.00 |
| | | | 955 | -1.27 | 0.82 |
| | | | 498 | -1.21 | 0.89 |
| | | | 248 | -1.06 | 0.82 |
| | | | 900 | -1.37 | 0.96 |
| | | | 364 | -1.10 | 0.83 |
| [16] | Brazil | CBR and DCP in the same mold, opposite sides. Wooden disk inside CBR orifice. | 741 | -1.12 | 0.98 |
| | | | 447 | -1.12 | 0.95 |
| | | | 214 | -0.83 | 0.96 |
| | | | 240 | -0.80 | 0.96 |
| | | | 347 | -0.96 | 0.90 |

**Table 2.** Literature review for soaked correlation studies.

| Ref. | Country | Boundary Conditions | Equation Parameters | | |
|---|---|---|---|---|---|
| | | | A | B | $R^2$ |
| [14] | Brazil | CBR and DCP in the same mold. DCP on the CBR orifice. | 276 | -1.02 | 0.93 |
| [3] | Brazil | CBR and DCP in the same mold, opposite sides. | 2053 | -1.65 | 0.78 |

**Table 3.** Literature review for execution control correlation studies.

| Ref. | Country | Boundary Conditions | Equation Parameters | | |
|---|---|---|---|---|---|
| | | | A | B | $R^2$ |
| [17] | Brazil | CBR and DCP in the same mold, opposite sides. | 457 | -1.36 | 1.00 |
| | | | 1075 | -1.74 | 0.99 |
| | | | 467 | -1.41 | 0.95 |
| [4] | Brazil | CBR and DCP in the same mold. DCP on the CBR orifice. | 149 | -1.01 | 0.71 |
| | | | 516 | -1.17 | 0.94 |
| | | | 127 | -0.94 | 0.72 |
| | | | 77.7 | -0.96 | 0.89 |
| | | | 107 | -0.93 | 0.76 |
| | | | 79.5 | -0.82 | 0.71 |
| [18] | Ecuador | CBR and DCP in different molds. | 242 | -1.24 | 0.80 |

In addition to the equations above, nine older correlation studies frequently cited in the relevant literature were also included in this analysis. It is important to restate that the methodologies of these studies and their respective test conditions were not analyzed in this article.

In this research, a total of 59 equations were analyzed, whose geographical distribution of the three mentioned categories is presented in Fig. 2. It is possible to observe the absence of scientific evidence of this type of study in Europe.

soil classification system (Highway Research Board, HRB).

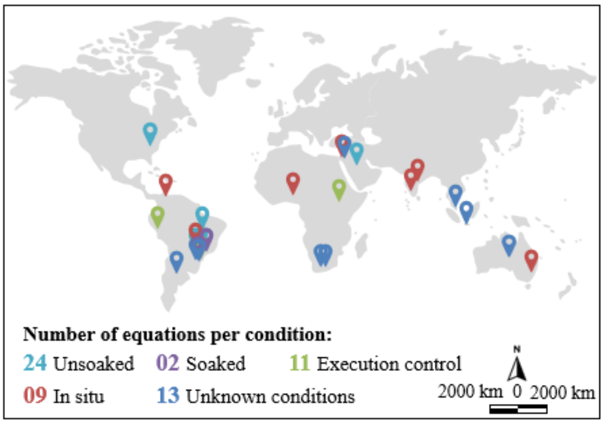


**Figure 2.** Geographic distribution of the literature review.

When applied in quality control of construction works, the field DCP test is performed after the pavement layer has been prepared, and the penetration index obtained is then applied to the desired correlation to estimate the CBR. Thus, the application of correlations under the unsoaked condition would be advisable to estimate in situ CBR (under the original layer compaction conditions), and design correlations would be recommended for obtaining the design CBR after soil submersion. Correspondingly, the correlations developed in the soaked condition would be applicable in exceptional cases of excessive rainfall.

However, it is important to emphasize that the use of empirical correlations with the DCP should be restricted to studies conducted on the same soil type [5], in order to avoid the indiscriminate use of correlations that may lead to misinterpretations and errors in strength prediction when applied to distinct soil samples [16].

## 3. Materials and methodology

### 3.1. Investigated sites

In this paper, two tropical soil samples from two areas of the city of Natal/RN (Fig. 3) were analyzed. Soil 1 (area 1, Fig. 4a) was collected in Northern Natal, and soil 2 (area 2, Fig. 4b) was obtained from Western Natal. About 200 kg of each material were collected in situ and stored in the soil mechanics laboratory of the Federal University of Rio Grande do Norte, where the experiments were conducted.

### 3.2. Soil characterization tests

After collecting the material and before performing the CBR and DCP tests, characterization tests were conducted and the soils were classified. Therefore, grain size distribution (sieve analysis and hydrometer test) [25], density of solids [26], Atterberg limits [27] and Proctor compaction (standard and modified efforts) [28, 29] tests were performed.

After the characterization tests were concluded, both soils were classified according to the Unified Soil Classification System (USCS) and AASHTO (Association of State Highway Transportation Officials)

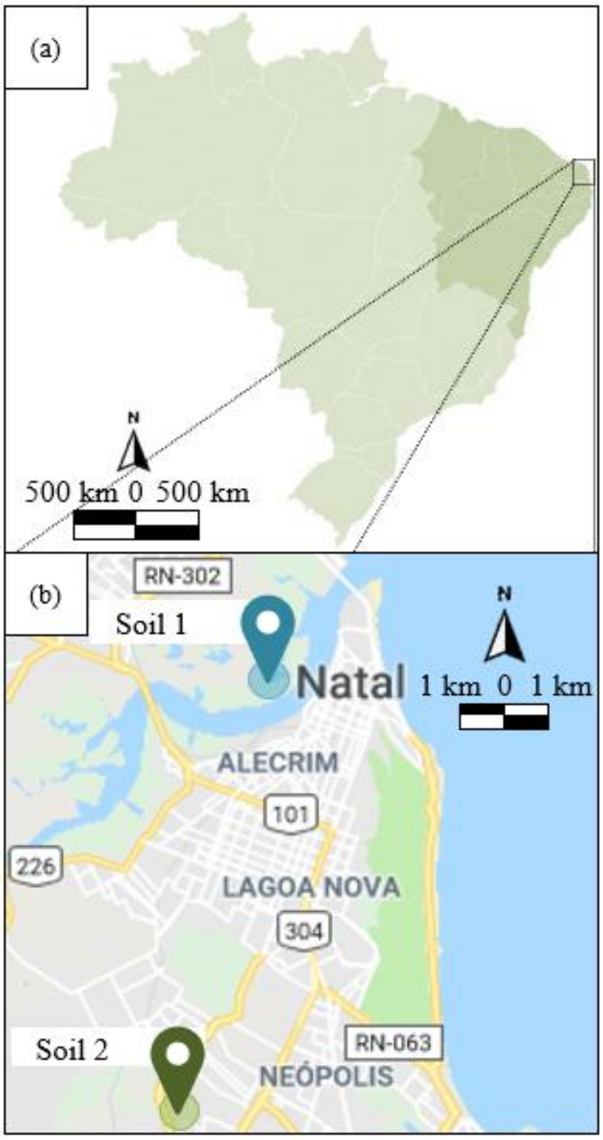


**Figure 3.** Location of study areas at (a) Brazilian northeast and (b) Natal/RN.

### 3.3. CBR and DCP tests

After the characterization and analysis of the compaction behavior of each material, the CBR [30] and DCP [6] tests were performed. The CBR tests were conducted on a hand-operated loading press, while the DCP tests were carried out with a penetrometer whose characteristics are identical to the equipment presented in Fig. 1. In order to reduce the risk of bias associated with the operation, the CBR and DCP tests of this study were preceded by preliminary tests to improve the researchers technique since the equipment used depended on manual operation. All specimens and all tests were prepared and performed by the same researchers, who developed the same functions throughout the experimental campaign.

The tests followed the methodologies of two previous researches [10, 16], in which the CBR and DCP tests were performed, in this sequence, in a single specimen for each moisture content of the compaction curve. It is relevant to note that these authors performed the

California bearing ratio and dynamic cone penetration tests only in the unsoaked condition; that is, no specimen had been immersed in water. Therefore, there is no previous soaked correlation data following this test methodology.

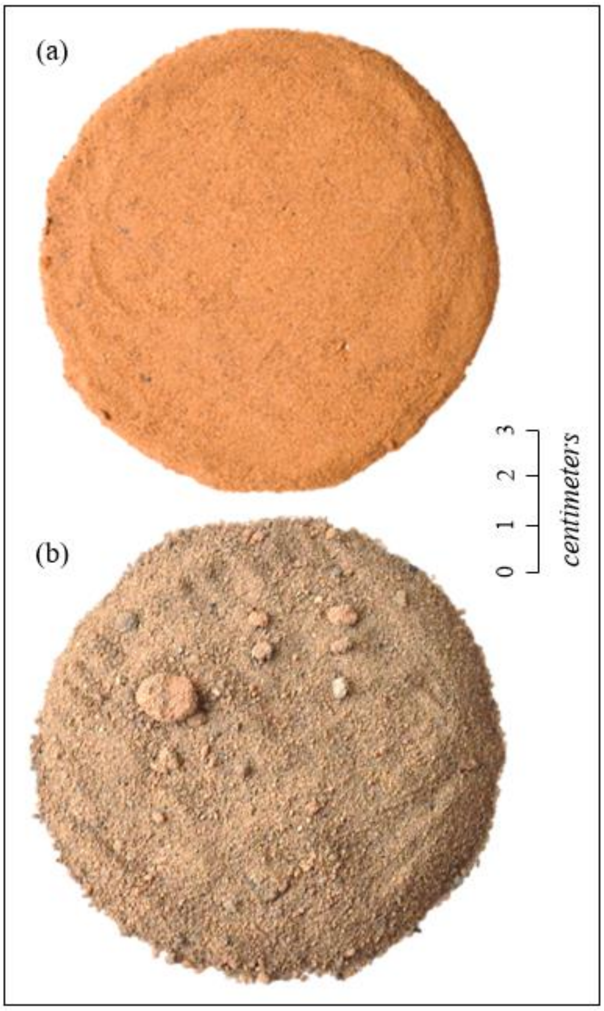


**Figure 4.** Samples of each soil examined.

In each molded specimen, the DCP test was performed shortly after the CBR test on the opposite face to the CBR orifice, which was filled with a wooden disc (Fig. 5) [10, 16]. The purpose of this methodology was to avoid material loss and prevent any impact between the cone tip and the steel disc at the bottom of the soil sample. Mold preparation for the DCP test is detailed in Fig. 6.


**Figure 5.** Wooden discs used to fill the CBR orifice.

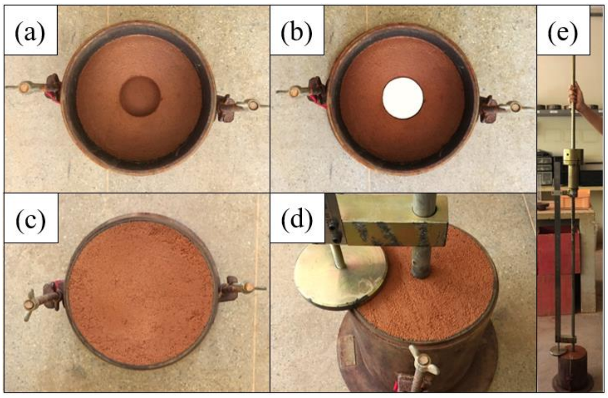


**Figure 6.** DCP test procedure: (a) orifice created by CBR piston; (b) placement of wooden disk; (c) insertion of steel disc at the bottom of the sample and invertion of soil specimen; (d) placement of the cone tip at the center of the mold; and (e) test execution.

In order to obtain all three types of correlation previously identified (unsoaked, soaked and execution control), both tests were performed with and without immersion. This way, for each moisture content of the compaction curve (optimum moisture content, two points in the dry branch and two in the wet branch), two samples were compacted. The first was submerged for 96 hours, and the second was ruptured shortly after molding. It was not an objective of this study to evaluate the expansion of soils in the specimens submitted to submersion.

Although it is usually recommended that the first blow of the DCP should be neglected [4, 5, 9], an alternative method was followed [16], in which the zeroth blow was not disregarded if the weight of the penetrometer was sufficient to fully penetrate the cone tip into the sample. This procedure was mainly followed due to the restrictive specimen height of approximately 100 mm, and the low penetration resistance shown by the specimens at high moisture contents.

Additionally, due to the contact with the wooden disc at the end of each test, all the final blows (depth of approximately 100 mm) were disregarded.

## 3.4. Data interpretation

After performing the tests, the analysis performed in this study consisted of establishing the correlations from the obtained results. Each test pair (DCP, CBR) corresponded to a point on the graph of interest. The experimental points for each soil in each test condition were then plotted, and a power trendline was inserted for each curve. The coefficient of determination ($R^2$) allowed evaluating the suitability of this methodology to the analyzed materials. The curves were not extrapolated, and only experimental results were considered.

# 4. Results and discussion

## 4.1. Soil characterization

The grain size distribution curves are a resultant from the sieve analysis and hydrometer test, shown in Fig. 7. While soil 1 was about 20% fine-grained (17.86% clay), soil 2 was approximately 10% fine-grained, with equal percentages of silt and clay. Both soils presented the sand fraction as predominant, reaching total percentages of 79.00% and 86.01%, respectively, for each soil.

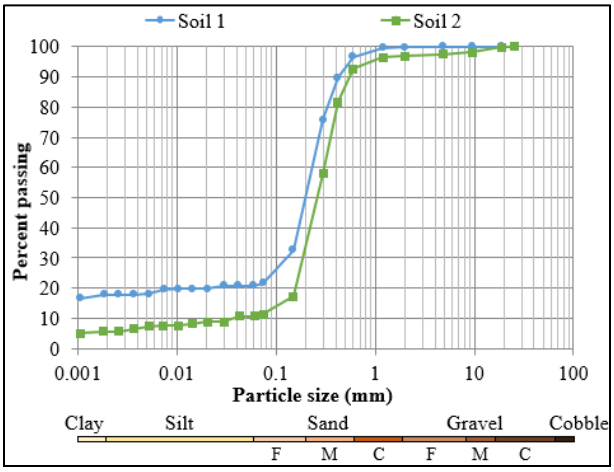


**Figure 7.** Grain size distribution curves.

Although soil 1 has a significant fraction of clay (17.86%), the liquid and plastic limit tests classified the material as not plastic. The same behavior was observed in soil 2, which has a lower clay fraction (5.75%).

Figs. 8 and 9 show photographs of the particle size distributions of each material retained after being washed in sieves #10 and #200, with subsequent drying, except for the fine-grained fractions (passing #200). The difference in color between the two samples is noticeable, in which red and orange tones predominate in soil 1 and brown and beige tones in soil 2. Additionally, as shown in Fig. 7, soil 2 presents fine to medium gravel.

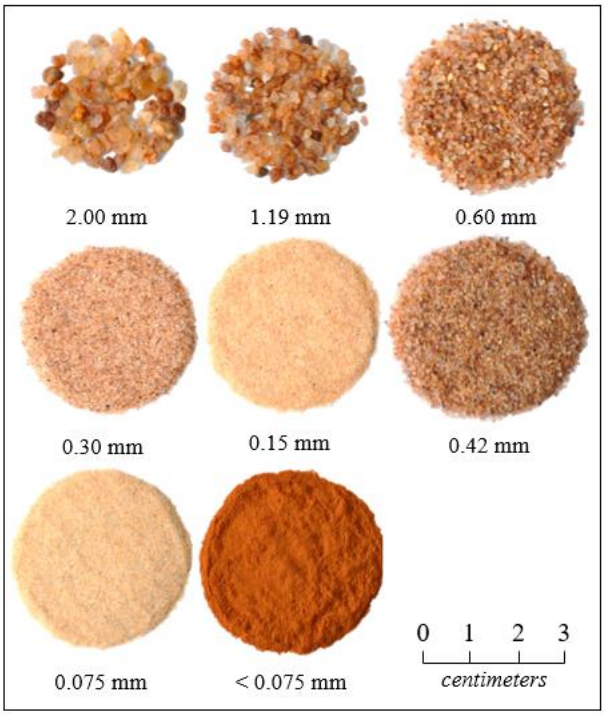


**Figure 8.** Grain size distribution for soil 1.

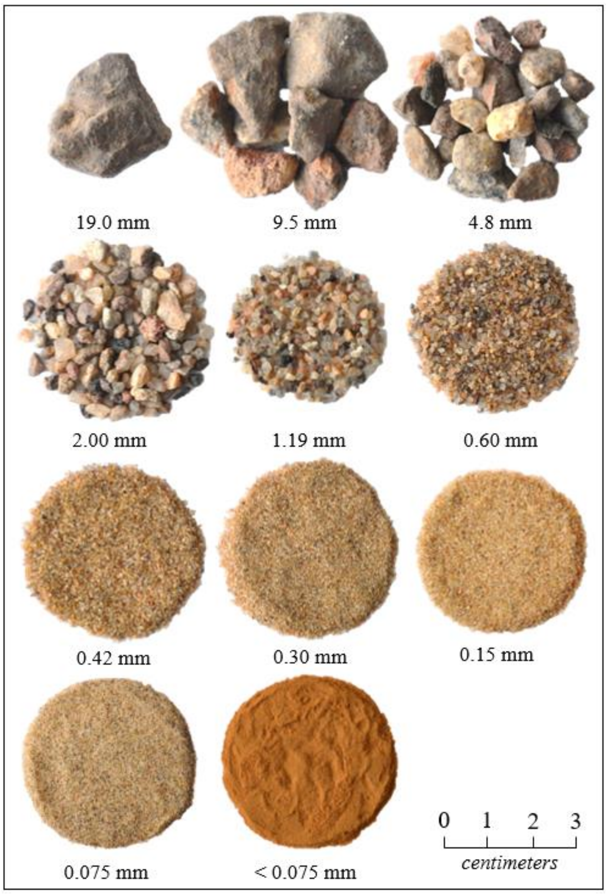


**Figure 9.** Grain size distribution for soil 2.

Table 4 shows the USCS and HRB classifications obtained from the characterization tests. The lack of plasticity of both samples classified them as silty sands according to the unified classification. Additionally, as the percentage of fine grains in soil 2 was between 5.0% and 12.0%, this soil received the additional classification of well-graded sand. As for the highway classification, both soils were classified as A-2 (silty or clayey sand) and A-2-4 (characteristics of silty soils, A-4) due to their lack of plasticity (PI ≤ 10.0).

**Table 4.** Soil classifications obtained.

| Sample | USCS | HRB |
|---|---|---|
| Soil 1 | Silty sand (SM) | A-2-4 |
| Soil 2 | Well-graded silty sand (SW-SM) | A-2-4 |

However, it is pertinent to point out that, considering only the grain size distribution of soil 1, the sample would be classified as a clayey sand (SC) due to the significant portion of clay in its composition. Nevertheless, the non-plastic behavior observed fits the soil into the silty sand category, although its silt fraction is not significant (3.01%). This highlights the limitations presented by conventional soil classification methodologies and suggests that this material be classified according to the MCT (Miniature, Compacted, Tropical) methodology, suitable for tropical soils.

The Proctor compaction curves obtained for both materials are shown in Figs. 10 and 11. Complementarily, the curves of 50% up to 100% saturation were plotted, determined from the density of solids tests performed (2.73 g/cm³ and 2.70g/cm³ for soils 1 and 2 respectively).

For both soils, it can be seen that the dry branches of the curves in standard and modified energies were parallel to each other, while the wet branches tend to converge. The parallel arrangement of wet branch points to saturation curves is also indicative of the appropriate fit of the experimental results. Even though all four curves are positioned in similar moisture content ranges (approximately 5.0% to 15.0%), the compaction curves of the two samples exhibit distinctly different behaviors: whereas soil 1 has a higher range of dry densities, soil 2 presents little expressive differences. Thus, for soil 1, the same increase in moisture content causes a greater increase or decrease in density when compared to the other sample. Both soils reached the optimum point at moisture content below 10% for both energies.

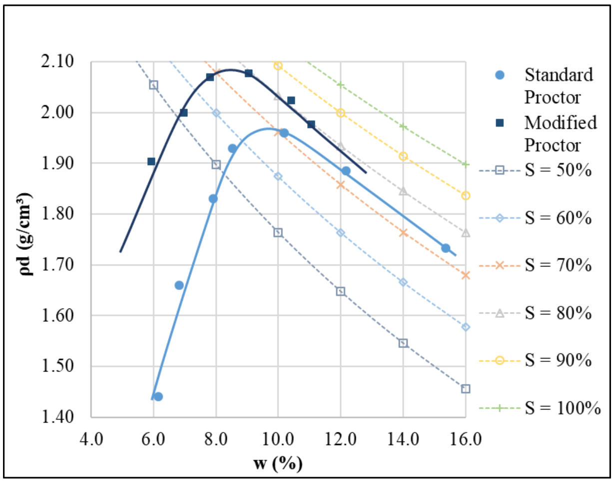


**Figure 10.** Proctor compaction curves for soil 1.

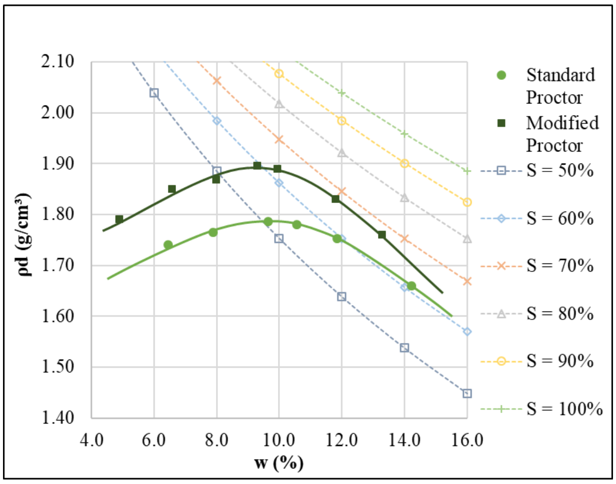


**Figure 11.** Proctor compaction curves for soil 2.

Therefore, it is, possible to compare the compaction curves obtained in this research with typically Brazilian soil compaction curves. The shape of the soil curve 1 is related to fine lateritic soil curves, which can reach significant maximum dry densities and present compaction curves with steep dry branches. Additionally, the shape described by soil 2 can be related to silty sand compaction curves, characterized by its rounded shape and low-density changes [31]. These similarities corroborate the conclusions inherent in the classification of each material.

Therefore, this research investigated two materials with identical HRB classification and very similar USCS classifications, but substantially different compaction behaviors. Such discrepancies are believed to affect the strength properties of each soil.

## 4.2. CBR and DCP tests

This section presents the CBR and DCP results of each soil and their respective correlations, as well as the soil physical indexes of all molded specimens. In addition to determining the moisture content (w) and dry density ($\rho_d$) of each sample, the wet density ($\rho$), porosity (n) and the degree of saturation (S) were also calculated.

For molds submerged for 96 (ninety-six) hours, the moisture content, wet density, and degree of saturation were also determined. It is important to enhance that the dry density and degree of porosity remain constant after immersion.

### 4.2.1. Soil 1

Based on compaction, it was presented in the previous section that soil 1 assumed the behavior of a fine, lateritic soil. In both energies, the highest strength occurred when the samples were molded in the dry branch of the curve and ruptured in the unsoaked condition.

However, after submersion, a considerable reduction in material strength was observed when it was compacted below the optimum moisture content. Given the steep slope of the dry branches of the two curves, such loss of strength can be attributed to high void ratios and porosities, implying in smaller dry densities. Thus, with immersion, water fills the volume of voids and increases the degree of saturation of the sample. This behavior leads to higher lubrication between particles and consequent reduction of friction [15, 32].

Due to the high position of the compaction curves concerning the iso-saturation lines, similar performance is presented by this material when compacted above the optimum moisture content.

Soil 1 presents a significant loss of strength regardless of whether the sample is submerged or not. Thus, in both DCP and CBR tests, the only condition in which there was no strength loss after submersion occurred when the soil was compacted at the optimum moisture content, at both compactive efforts. Certainly, the lower porosities and void ratios contributed to such material strength conservation. Therefore, in Tables 5 and 6, the physical indexes obtained for each sample with and without submersion are presented, as well as their respective strength results for both compaction energies.

It occurs a significant increase in the saturation degree of soaked samples when compacted below the optimal moisture content. Analyzing the optimum moisture contents at both compactive efforts, a low increase in moisture content after submersion is observed, due to the smaller porosities experienced.

**Table 5.** Results for soil 1 (standard Proctor).

| Unsoaked tests | | | | | | | Soaked tests | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| w (%) | $\rho$ (g/cm$^3$) | $\rho_d$ (g/cm$^3$) | n (%) | S (%) | CBR (%) | DCP (mm/blow) | w (%) | $\rho$ (g/cm$^3$) | $\rho_d$ (g/cm$^3$) | n (%) | S (%) | w96h (%) | $\rho_{96h}$ (g/cm$^3$) | S (%) | CBR (%) | DCP (mm/blow) |
| 6.7 | 1.779 | 1.668 | 38.8 | 28.6 | 17.1 | 10.3 | 6.8 | 1.778 | 1.664 | 38.9 | 29.2 | 16.1 | 1.931 | 68.6 | 0.4 | 97.0 |
| 9.0 | 2.066 | 1.896 | 30.4 | 56.0 | 25.8 | 15.2 | 8.5 | 2.094 | 1.929 | 29.2 | 56.3 | 10.5 | 2.132 | 69.4 | 26.3 | 15.2 |
| 10.7 | 2.132 | 1.926 | 29.3 | 70.4 | 7.5 | 32.7 | 11.6 | 2.163 | 1.938 | 28.9 | 77.8 | 13.1 | 2.192 | 88.0 | 4.5 | 46.5 |
| 13.0 | 2.141 | 1.895 | 30.4 | 80.7 | 2.5 | 89.0 | 12.2 | 2.115 | 1.885 | 30.8 | 74.4 | 13.2 | 2.133 | 80.5 | 2.8 | 47.5 |
| 15.4 | 1.999 | 1.733 | 36.4 | 73.1 | 0.0 | * | - | - | - | - | - | - | - | - | * | * |
| * This test was not performed due to the soil not presenting resistance to penetration during unsoaked testing. | | | | | | | | | | | | | | | | |

**Table 6.** Results for soil 1 (modified Proctor).

| Unsoaked tests | | | | | | | Soaked tests | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| w (%) | $\rho$ (g/cm$^3$) | $\rho_d$ (g/cm$^3$) | n (%) | S (%) | CBR (%) | DCP (mm/blow) | w (%) | $\rho$ (g/cm$^3$) | $\rho_d$ (kg/m$^3$) | n (%) | S (%) | $w_{96h}$ (%) | $\rho_{96h}$ (g/cm$^3$) | S (%) | CBR (%) | DCP (mm/blow) |
| 5.9 | 2.017 | 1.904 | 30.1 | 37.4 | 74.4 | 3.4 | 5.9 | 2.026 | 1.913 | 29.8 | 37.8 | 11.8 | 2.138 | 75.6 | 9.0 | 23.0 |
| 7.0 | 2.139 | 1.999 | 26.6 | 52.7 | 93.6 | 5.1 | 7.4 | 2.169 | 2.021 | 25.8 | 57.5 | 9.6 | 2.214 | 75.0 | 41.0 | 11.5 |
| 8.0 | 2.228 | 2.063 | 24.3 | 68.2 | 69.3 | 6.8 | 8.2 | 2.228 | 2.059 | 24.4 | 69.1 | 10.2 | 2.269 | 86.1 | 70.2 | 8.8 |
| 9.1 | 2.287 | 2.097 | 23.1 | 82.7 | 37.0 | 8.7 | 9.1 | 2.265 | 2.077 | 23.8 | 79.2 | 10.6 | 2.296 | 92.3 | 44.1 | 11.8 |
| 10.4 | 2.226 | 2.016 | 26.0 | 80.7 | 11.9 | 20.0 | 10.1 | 2.228 | 2.024 | 25.7 | 79.5 | 11.1 | 2.248 | 87.2 | 10.4 | 22.3 |
| 10.6 | 2.203 | 1.992 | 26.9 | 78.7 | 7.6 | 29.0 | 11.1 | 2.195 | 1.976 | 27.5 | 79.5 | 12.3 | 2.219 | 88.1 | 4.4 | 43.0 |
| * This test was not performed due to the soil not presenting resistance to penetration during unsoaked testing. | | | | | | | | | | | | | | | | |
| ** The DCP cone tip touched the wood disk in the first blow (test dismissed) | | | | | | | | | | | | | | | | |

The variations in bearing capacity between both energies before and after submersion demonstrate the significant loss of strength previously mentioned. It is noted, however, that the soaked CBR was superior to the unsoaked CBR in four test pairs, where three of them correspond to small increments of less than 1.0%. This occurred at the optimum moisture contents at both standard and modified proctor, and this implies that the strength before and after immersion is the same.

On the other hand, the CBR test at 9.06% moisture content in the modified effort after submersion showed an increase of approximately 7.0% in strength. Since the experimental approach of this research depends on manual operation, such behavioral discrepancy can be attributed to this limiting factor.

A similar before and after immersion comparison was made for dynamic cone penetration indexes, where higher penetrations indicate lower strengths. It was observed that all DCP indexes were higher after submersion, except for the tests performed at 13% moisture content in the standard Proctor. Such loss of strength after submersion was already expected.

The penetration indexes at the optimum moisture contents before and after immersion also did not present significant variations. The DCP index was kept constant in the standard Proctor and increased only 2.0 mm/blow in the modified Proctor. This behavior demonstrates that soil 1 strength does not change when compacted at the maximum dry density.

### 4.2.2. Soil 2

As previously presented, soil 2, from the western area of Natal/RN, was classified as a well-graded silty sand according to USCS and presented a compaction behavior compatible with this designation. The material reached low values of maximum dry density (about 1.80 g/cm$^3$ at the standard energy, and 1.90 g/cm$^3$ at the modified energy), and the compaction curves had little variability with the increase of moisture content.

After performing CBR and DCP tests on the samples molded at both compaction energies, the expected behavior was obtained: the soil reached low strengths, as the maximum CBR reached was only 38.54% (modified energy), when compacted at the optimum moisture content.

Tables 7 and 8 show the results obtained for soil 2 tests, including the soil indexes calculated after each molding and submersion. In addition to low CBR percentages in both energies, there were no DCP indexes lower than 29.30 mm/blow. This attests in advance to the absence of points in the steep branch of the correlation curve.

Analyzing the results of the physical indexes, it is observed that after submersion, similar saturation degrees were reached for each energy, from about 70% for the standard compaction energy and 80% for the modified, even though the initial saturations differed significantly. The same behavior was observed for the moisture contents after submersion in the standard compaction energy, where all specimens presented approximately 13.5% in moisture content.

**Table 7.** Results for soil 2 (standard Proctor).

| Unsoaked tests | | | | | | | Soaked tests | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| w (%) | ρ (g/cm³) | $\rho_d$ (g/cm³) | n (%) | S (%) | CBR (%) | DCP (mm/blow) | w (%) | ρ (g/cm³) | $\rho_d$ (kg/m³) | n (%) | S (%) | $w_{96h}$ (%) | $\rho_{96h}$ (g/cm³) | S (%) | CBR (%) | DCP (mm/blow) |
| 6.6 | 1.875 | 1.760 | 34.8 | 33.2 | 13.0 | 47.5 | 6.5 | 1.875 | 1.760 | 34.8 | 33.1 | 13.3 | 1.994 | 67.3 | 9.4 | 58.0 |
| 7.9 | 1.904 | 1.765 | 34.6 | 40.2 | 13.6 | 47.5 | 8.3 | 1.907 | 1.761 | 34.7 | 41.9 | 13.8 | 2.004 | 69.8 | 10.2 | 46.5 |
| 9.5 | 1.946 | 1.777 | 34.2 | 49.4 | 16.9 | 42.5 | 9.6 | 1.958 | 1.786 | 33.8 | 50.9 | 13.1 | 2.020 | 69.3 | 14.2 | 46.5 |
| 11.9 | 1.963 | 1.755 | 35.0 | 59.5 | 4.5 | 76.0 | 12.0 | 1.982 | 1.770 | 34.4 | 61.5 | 14.1 | 2.020 | 72.5 | 5.4 | 77.0 |
| 14.2 | 1.896 | 1.660 | 38.5 | 61.4 | 4.2 | ** | - | - | - | - | - | - | - | - | * | * |
| * This test was not performed due to the soil not presenting resistance to penetration during unsoaked testing. | | | | | | | | | | | | | | | | |

**Table 8.** Results for soil 2 (modified Proctor).

| Unsoaked tests | | | | | | | Soaked tests | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| w (%) | ρ (g/cm³) | $\rho_d$ (g/cm³) | n (%) | S (%) | CBR (%) | DCP (mm/blow) | w (%) | ρ (g/cm³) | $\rho_d$ (g/cm³) | n (%) | S (%) | $w_{96h}$ (%) | $\rho_{96h}$ (g/cm³) | S (%) | CBR (%) | DCP (mm/blow) |
| 5.0 | 1.878 | 1.789 | 33.7 | 26.4 | 22.8 | 44.0 | 5.0 | 1.854 | 1.765 | 34.6 | 25.7 | 16.4 | 2.055 | 83.6 | 16.1 | 38.0 |
| 6.4 | 2.000 | 1.880 | 30.3 | 39.5 | 35.8 | 29.3 | 6.6 | 1.972 | 1.850 | 31.5 | 38.7 | 14.6 | 2.120 | 85.8 | 23.5 | 31.7 |
| 9.3 | 2.071 | 1.895 | 29.8 | 59.2 | 38.5 | 31.3 | 9.4 | 2.065 | 1.887 | 30.1 | 58.9 | 13.1 | 2.135 | 82.3 | 22.9 | 37.0 |
| 11.1 | 2.039 | 1.834 | 32.0 | 63.8 | 16.8 | 48.0 | 10.7 | 2.039 | 1.842 | 31.8 | 62.0 | 12.6 | 2.074 | 73.2 | 6.5 | 64.0 |
| 13.1 | 1.945 | 1.720 | 36.3 | 61.9 | 2.2 | ** | - | - | - | - | - | - | - | - | * | * |
| * This test was not performed due to the soil not presenting resistance to penetration during unsoaked testing. | | | | | | | | | | | | | | | | |

It is possible to notice CBR variations with increasing moisture content for both compaction energies. While soil 1 suffered an abrupt drop in strength after submersion in the dry branches of the compaction curves, soil 2 demonstrated a less significant reduction. Except for the last data point at the standard energy, which showed a slight increase in strength at 12.0% moisture content, all soaked molds had lower CBR values than the unsoaked molds.

The highest strengths occurred at the optimum moisture contents, but unlike soil 1, CBR was not maintained after submersion. Additionally, the DCP variations were also analyzed, where the unsoaked resistance to penetration was higher than the resistance shown after submersion. However, the strength loss after immersion for soil 2 was lower than at soil 1.

## 4.3. DCP vs. CBR correlations

The correlations obtained in this research were compared to the standardized equations and literature review. Each analysis was separated by test condition: unsoaked, soaked, execution control, and all points (soaked and unsoaked). Thus, for the literature review studies, four ranges of results obtained under equivalent circumstances were shaded in the graphs.

### 4.3.1. Unsoaked tests

Fig. 12 gathers the results obtained in this study for the unsoaked tests performed in both soils, which were not subjected to immersion and occurred shortly after molding. The correlations obtained for each soil presented $R^2$ values that represent a satisfactory fit for the results in the power equation format.

For soil 2, the obtained correlation curve did not present points dispersed at less than 30 mm/blow DCP indexes. Due to such absence of experimental data for a significant portion to the left of the graph, it was decided not to extrapolate the results as their veracity could not be validated.

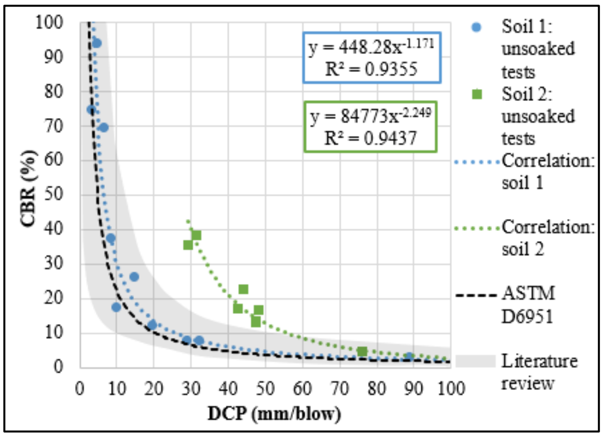


**Figure 12.** Correlations for unsoaked tests and comparison to literature review.

Fig. 12 also provides a comparison of correlations obtained with the ASTM correlation, which applies to all types of soil except those classified as CL (low compressibility clays) and CH (high compressibility clays). It is possible to observe a close proximity between the ASTM correlation and the correlation found in this paper for soil 1.

International correlations tend to be more conservative in relation to Brazilian soils [16]. This is observed in Fig. 12 where the standardized CBR values are slightly lower than the correlations obtained for the same penetration in soil 1. Such proximity between the curves attests that the methodology of this research was followed appropriately and that correlations developed for soil 1 may be applicable in the field.

Although the classification of soil 2 (SW-SM) is applicable for the plotted ASTM correlation, the distance between the black and green curves indicates that the standard estimate is not appropriate for this material, as the predicted CBR values are significantly lower than the actual results obtained experimentally.

Even though this soil has reached lower maximum strengths, it is possible to notice that the position of its curve is superior to soil 1 correlation at all points. Therefore, for higher penetrations, soil 2 has higher CBR values. Depending on the highway application, this can be considered as an advantage considering that soil 1 has superior CBR values only for DCPs up to 10.0 mm/blow. This attests observations pointed out by previous studies coarse-grained soils present higher CBR indexes than fine-grained soils for a same DCP index [4, 10, 16].

The gray area represents the range of results previously found in other studies, where it is possible to observe that the unsoaked correlation for soil 1 was fully contemplated by this range [4, 9, 10, 14 - 16]. Along with the proximity to the ASTM correlation, this fit also highlights the proper reproduction of both CBR and DCP test procedures [10, 16].

On the other hand, there was a significant disparity regarding the correlation curves obtained from previous studies and the experimental points obtained for soil 2 in this research. At lower strengths, both soils tend to converge with the obtained trend lines.

## 4.3.2. Soaked tests

Similarly, the tests performed in the soaked condition were also plotted (Fig. 13). Due to the significant loss of strength in soil 1 after submersion, especially when compacted out of the optimum moisture content, the displacement of the other points to lower positions in the curve is noticeable. It is also possible to identify that, for this soil, an almost perfect adjustment of the experimental points has occurred.

As in the unsoaked trials, the experimental points for soil 2 were also started at 30 mm/blow, and both soil samples presented lower CBR values when compared to Fig. 12. Even though the range of experimental points through the horizontal axis was reduced, high $R^2$ values were still obtained.

Among the analyzed studies, only two correlations were strictly developed under soaked conditions [3, 14], implying a smaller range of previous results. Even with a restricted range of previous studies, a similar positioning is observed for the soaked soil 1 correlation. Meanwhile, soil 2 demonstrated the same behavioral trend, in which it deviated from the range of results suggested by the bibliography.

Since using the soaked correlation requires DCP tests after atypical conditions of soil immersion, the lack of scientific evidence for this test condition may be justified. However, the evaluation of soaked correlations presents high relevance to analyze the displacement of the curves after submersion, and thus visualize the soil strength loss.

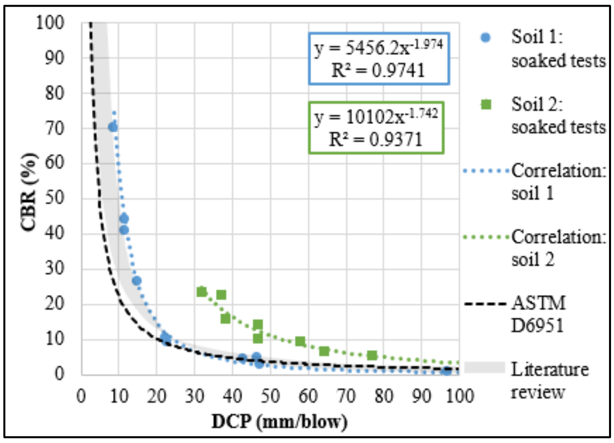


**Figure 13.** Correlations for soaked tests and comparison to literature review.

The correlation presented for soil 1 in Figure 13, however, suggests that after 20 mm/blow the soaked values tend to be higher than the unsoaked values. Such behavior can be credited to the mathematical adjustment of experimental points on the trendline. For this reason, it is recommended to use the correlation developed with all points presented in item 4.3.3., as it better represents the material behavior, regardless of whether it is subjected to drainage deficiencies or not.

## 4.3.3. Soaked and unsoaked tests

In order to obtain a representative correlation of the behavior described by both samples, all points with and without submersion were plotted on a single graph. As shown in Fig. 14, the $R^2$ values of the trendlines were still higher than 0.90. Such analysis is relevant once the soil cannot be expected to present unsoaked CBR values during excessive rainfall and unefficient drainage conditions.

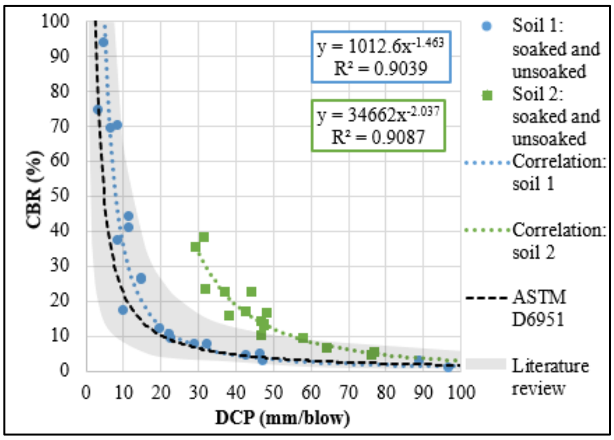


**Figure 14.** Correlations for soaked and unsoaked tests and comparison to literature review.

After assessing both soaked and unsoaked curves, it was observed that the behavior expectation was reached, as the unsoaked DCP indexes were lower than the soaked results. Additionally, and the unsoaked CBR values were higher than the soaked strength. The same strength behavior is observed in relation to the two previous comparisons, where soil 1 is within the range of previous studies and soil 2 has a significant discrepancy in strength.

The literature review correlation range presented in the figure is a combination of the unsoaked (Fig. 12) and soaked (Fig. 13) ranges, in addition to correlations developed by [2, 4, 16].

### 4.3.4. Execution control

According to the previous studies presented in the literature review, several authors also evaluate so-called "design" correlations for the estimate of the project CBR after immersion for 96 (ninety-six) hours, from unsoaked DCP indexes [4, 17, 18]. The $R^2$ values obtained by the authors ranged from 0.71 [4] to 1.00 [17], which indicates that there may be a close relationship between these two parameters when there is no abrupt loss in soil strength after immersion.

However, due to the potentially collapsible behavior presented by soil 1, unlike the previous studies, it was not possible to establish an adequate correlation between the unsoaked DCP and the soaked CBR for this material. Such inaccuracy to determine the project CBR can be concluded from the coefficient of determination presented in Fig. 15, which shows that the points obtained do not relate to each other.

Although the execution control correlation for soil 1 presented a corresponding $R^2$ value less than 0.20, it can be observed that the curve still fits the range of published execution control correlations [4, 17, 18, 34].

Opposed to soil 1, the small strength losses after immersion experienced by soil 2 allowed the estimate of an execution control correlation with a desirable fit. The lower CBR values predicted for soil 2 classify this correlation as conservative for road design.

Such behavior demonstrated by soil 1 shows that the comparison of the correlations obtained with previous studies should not be taken as absolute, as the fit of the experimental data must be analyzed first. Thus, while the correlations of soil 2 present satisfactory coefficients of determination ($R^2$) and deviate from the strength pattern expected by the literature, the correlation of execution control in soil 1 presents an insufficient data dependence that is suggested to be satisfactory by the range set by previous studies.

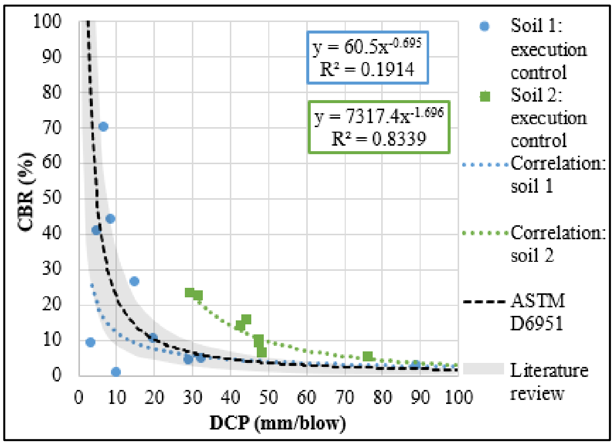


**Figure 15.** Correlations for execution control and comparison to literature review.

Except for the execution control correlation developed from soil 1 data (Fig. 15), all correlations determined in this research demonstrate that there is indeed a strong relationship between the two evaluated experimental parameters (CBR and DCP). This attests to the validity of the dynamic cone penetrometer as an efficient tool to evaluate soil strength [33].

The close similarity between existing correlations [13] and the equations developed for soil 1 characterizes that the ASTM correlation is representative for that material, although such correspondence did not occur for soil 2. The inadequacy of assuming a unique correlation between CBR and DCP for a wide range of soil types and classifications had already been pointed out by previous authors[10].

### 4.3.5. Final results

All correlations obtained in this experimental study, as well as their respective coefficients of determination ($R^2$), are presented in Table 9 below.

**Table 9.** Equation parameters for all correlations developed.

| Sample | Test condition | Equation parameters | | |
|---|---|---|---|---|
| | | A | B | $R^2$ |
| Soil 1 | Unsoaked | 448 | -1.17 | 0.94 |
| | Soaked | 5456 | -1.97 | 0.97 |
| | Soaked & unsoaked | 1013 | -1.46 | 0.90 |
| | Execution control | 60.5 | -0.70 | 0.19 |
| Soil 2 | Unsoaked | 84773 | -2.25 | 0.94 |
| | Soaked | 10102 | -1.74 | 0.94 |
| | Soaked & unsoaked | 34662 | -2.04 | 0.91 |
| | Execution control | 7317 | -1.70 | 0.83 |

In all comparisons developed, the same behavior was repeated for both samples, regardless of the test condition evaluated. While soil 1 presented high data correlation and fit into the reference ranges, soil 2 also presented high data correlation but did not fit into the results from 60 equations developed in previous studies. However, even though soil 2 presented a distinct behavior, the validity of the equations found can be attested by the high $R^2$ values obtained for each trendline established.

In all cases, soil 2 curves were positioned to the upper right, suggesting that the sample presents a higher strength. The position of these curves can be attributed to two main factors: the substantial geological and climate discrepancies from previous studies developed at four distinct continents; and the different methodologies to perform the DCP test, where small variations for all points are sufficient to significantly alter a correlation. A total of five different research methodologies were identified in this literature review.

Standardization of experimental procedures is of fundamental importance for the consistent and safe comparison of results for different soil types. The simplicity of the DCP test method, applied to the use of reliable correlations for an efficient CBR estimate, characterizes the dynamic cone penetrometer as a promising equipment to paving quality control in Brazil and worldwide.

The use of appropriate correlations to the study site and soil minimizes the occurrence of erroneous results due to possible differences in soil composition and conditions to which it is subjected.

## 5. Conclusions

The results obtained in the present study represent an advance in the definition and standardization of a simple methodology, which was proved to be efficient and safe for the estimate of empirical correlations between the California bearing ratio and the dynamic cone penetration index.

To do so, empirical correlations were established between the DCP and CBR indexes of two soils found in Natal, Rio Grande do Norte, Brazil. All tests were performed in the laboratory, and high coefficients of determination ($R^2$) were obtained, which reinforce the existing association between the two geotechnical parameters already pointed out by previous authors.

Soil 1 was classified as a silty sand (SM), and soil 2 was similarly classified as a well-graded silty sand (SM-SW). Due to the lack of plasticity of both soils, the A-2-4 highway classification was assigned. Although both soils presented almost identical classifications, it was found that the overall strength and compaction behaviors described by both samples were substantially different, suggesting that conventional geotechnical classifications are not best suited to tropical soils.

It was observed that, while soil 1 presented the highest CBR values and lowest DCP indexes, the molded specimens also experienced the largest loss of strength with the increase of moisture content. The range of results for this soil was significant, and varied from 0.43% to 93.63% for the CBR test, and from 3.44 mm/blow to 97.0 mm/blow for the DCP test. Meanwhile, soil 2 suffered less expressive CBR variations between 4.46% and 38.54%, and 29.3 mm/blow up to 77.0 mm/blow for the DCP index.

The literature review of previous studies served as a complementary tool to certify the validity of the equations found. However, due to discrepancies in the methods used by the previous authors, such validity could only be verified for soil 1. Therefore, the results obtained by this experimental research led to the conclusion that it is of pertinent interest to the geotechnical community, which is the creation of a database of related studies, preceded by a methodological standardization for the development of these equations.

This way, future studies should standardize the methodology for establishing empirical correlations from a comparison of the existing methods, and evaluate the most suitable procedure to perform the tests. Future field analysis should also include the boundary effect caused by the cylindrical molds, which certainly provides a higher lateral confinement in the tested samples. Such investigation would allow to understand in-depth how the test and boundary conditions affect the position of the correlation curves in the graphs, and how these factors interfere with the interpretation of soil strength.

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