Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

Influence of the addition of carbon nanotube on the physical behavior of a lateritic soil from the southwest Amazon

Marcelo Victor de Assis Morais[1#], Marcelo Ramon da Silva Nunes[2], Carlos Drumond do Nascimento Morais[3], Ricardo Ribeiro do Nascimento[1], Anselmo Fortunato Ruiz Rodriguez[1]

Article

Keywords
Lateritic soil
Carbon nanotubes
Soil improvement
Nanotechnology

Abstract

In this work we evaluate the physical-mechanical behavior of lateritic soil with addition of carbon nanotubes. The soil was collected in a commercial deposit located in Rio Branco – AC and later characterized through particle size tests, X-Ray Diffraction, X-Ray Dispersion Spectroscopy and Tropical Compressed Miniature essay. The dispersion of nanotubes in solution was carried out and the size of the nanoparticles was verified using Dynamic Light Spreading - DLS, Zeta Potential and *PDI*. Three percentages of additions (0.05%, 0.1% and 0.2%) of carbon nanotubes were evaluated and compared with the control group according to the parameters of Atterberg limits, real density, dry density maximum and optimum humidity. The results indicate that the soil has a clayey behavior with a medium texture, with the presence of clay mineral kaolinite in its composition and silicon and iron oxides. The dispersion of carbon nanotubes reached particles with an average hydrodynamic diameter of 68.9 nm and Zeta Potential of -24.87 mV and *PDI* of 0.231, characterizing a solution as moderately dispersed and kinetically stable. The results of the liquidity limit and plasticity tests showed a reduction of 10 and 13%, respectively, with the addition of carbon nanotubes, while for the parameters of plasticity index, real specific mass, maximum dry density and optimal moisture, they did not show significant variation. Carbon nanotubes interact with soils with lateritic behavior, and further studies are essential to better understand the mechanisms behind this interaction.

1. Introduction

One of the biggest challenges in carrying out infrastructure or paving works is related to finding soil deposits with low quality geotechnical properties, such as low resistance and high deformability, requiring geotechnical engineering to apply soil improvement techniques that minimize the problems of settlement and stability that are typical of these soils (Silva et al., 2020).

Among the fine soils widely used in bases and subbases of pavements, soils that present lateritic behavior stand out, where despite their natural state presenting low support capacity, when compacted they acquire high resistance, a factor that, together with its abundance in Brazilian territory, justifies its use in urban paving works (Arruda, 2020).

However, despite its properties enabling its use in the construction of traffic routes, soils with lateritic behavior may require the use of improvement techniques to increase resistance due to the most varied loads that the highway must withstand (Silva & Castro, 2020). Located in the extreme southwest of the Brazilian Amazon, the state of Acre is geologically characterized by a sedimentary basin with a thick horizon of fine material, occupying almost the entire surface of the state, where about 70% of the soil in the region is composed of clayey soils, which has low support capacity and high expansion in the presence of water (Acre, 2010). According to the AcreBioClima Environmental Studies and Services Group (Acre, 2010), the state has monthly rainfall indices above 200 mm, factors that make it difficult to build roads with the minimum resistance indices adopted by conventional methods, such as the *CBR*.

[#]Corresponding author. E-mail address: marcelo.morais@ufac.br
[1]Universidade Federal do Acre, Rio Branco, AC, Brasil.
[2]Instituto Federal do Acre, Sena Madureira, AC, Brasil.
[3]Instituto Federal de Rondônia, Porto Velho, RO, Brasil.

Submitted on June 21, 2023; Final Acceptance on February 27, 2024; Discussion open until February 28, 2025.

https://doi.org/10.28927/SR.2024.007523

Soil chemical stabilization is the improvement of soil geotechnical properties, notably strength, durability and deformability, and usually occurs through the addition of cementitious materials to the soil in situ (Corrêa-Silva et al., 2020). Among the main types of stabilizing agents, lime, Portland cement, asphalt, emulsions and acrylic polymers can be mentioned (Machado et al., 2017). However, the significant environmental impacts associated with the production of these elements bring a global concern (Eyo et al., 2020). With this, nanotechnology has been proving to be a promising area, since the use of nanomaterials, in addition to being feasible from a technical point of view, is also proving to be an economical alternative, due to the very low amount of nanomaterials needed in the soil to achieve improvement in the geotechnical parameters (Karumanchi et al., 2020).

Among nanomaterials, carbon nanotubes (CNT) are considered one of the most promising in the construction industry. CNT's have excellent properties, such as high tensile strength, high modulus of elasticity and excellent electricity conductor (Taha et al., 2018). In addition, these nanomaterials are already widely available on the market, with good quality products and relatively low prices, which favors their use for research (Taha & Alsharef, 2018). Compared to other types of cementitious materials used for soil stabilization, CNTs have proven to be an ecological alternative, highlighting their high potential for absorbing biological contaminants or those associated with bodies of water, due to their high specific surface area (Alobaid et al., 2022).

Despite this scenario, there is still little research related to the use of nanomaterials in soils to verify improvements in geotechnical properties, and even less for the investigation of these materials in soils with lateritic behavior, making this research a pioneer in this area of knowledge. The objective of this work is to verify the influence of the addition of carbon nanotubes in a lateritic soil of the southwest region of the Amazon, aiming at improvements in the physical properties.

2. Materials and Methods

2.1 Description of study place

The State of Acre is in the extreme southwest of the Brazilian Amazon, between latitudes 07°07'S and 11°08'S and longitudes 66°30'W and 74°WGr. Its territorial surface is 164221.36 km^2, corresponding to 4% of the Brazilian Amazon area and 1.9% of the national territory (Acre, 2010).

Among the geological units, the Solimões Formation occupies about 85% of the territory of Acre, and this formation originated from sediments coming from rivers from the Cretaceous period (Acre, 2010). Dystrophic Red-Yellow Argisols and Latosols dominate the eastern tablelands of the State, with deep, well-drained, leached soils, low natural fertility and the occurrence of lateritic crusts. Such characteristics result from the fact that the mineralogical composition of the Solimões Formation consist of clays with a high expansion content due to moisture variations (Shinzato et al., 2012).

2.2 Collection of samples

The lateritic soil samples come from a commercial deposit located on BR 317, km 15, coordinates 10° 06' 29.37" S and 67° 38' 39.66" W, Rio Branco – AC, Brazil, as shown in Figure 1.

After collection, the materials were stored, homogenized and sealed at room temperature at the Soil Laboratory of the Federal University of Acre (UFAC).

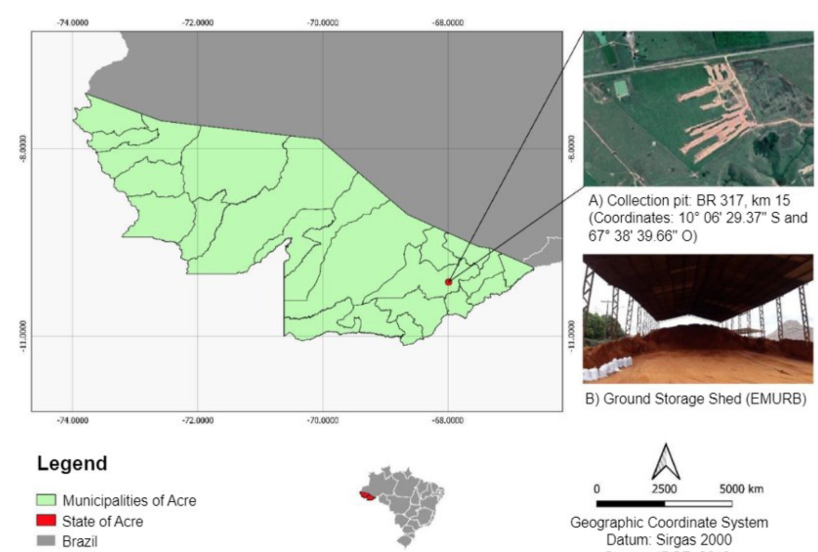

Figure 1. Location of the lateritic soil removal deposit.

2.3 Soil characterization

2.3.1 Granulometric analysis

To determine the dimensions of the lateritic soil particles, as well as their percentages, the granulometry test was carried out using sieves and sedimentation in accordance with NBR 7181/16 (ABNT, 2016). The granulometric analysis by sieves was carried out at the UFAC Soil Laboratory, while the granulometric analysis by sedimentation was carried out at the Technology Foundation of the State of Acre (FUNTAC).

2.3.2 MCT test

To verify the lateritic behavior of the soil, the MCT test was carried out, according to the DNER ME-258/94 and DNER ME-256/94 (DNER, 1994d, 1994e) standards, which are the Mini-MCV and mass loss by immersion tests, respectively. The MCT methodology is used to distinguish the behavior of soils from tropical regions, especially those soils with considerable particle sizes smaller than 2 mm (Lima et al., 2020). The following coefficients are calculated: *c'* (grading parameter that differentiates sandy and clayey materials), *d'* (parameter of the compaction curve that is directly related to the maximum density) and *Pi* (parameter that quantifies the degree of soil laterization). These parameters are necessary to calculate *e',* which is the parameter that classifies the soil as being lateritic or non-lateritic. All steps were carried out at the FUNTAC Soil Laboratory.

2.3.3 Chemical analysis

The chemical composition of the lateritic soil sample was carried out using an energy dispersive X-ray system (EDX), in the forensic laboratory of the Civil Police of the State of Acre. The equipment used was a Shimadzu EDX 720. EDX is an essential accessory in the study of microscopic characterization of materials, as it allows immediate identification of the chemical composition (Araújo, 2022). When the electron beam falls on a mineral, the outermost electrons of the atoms and the constituent ions are excited, changing energy levels. When they return to their initial position, they release the acquired energy, which is emitted at wavelengths in the X-ray spectrum. A detector installed in the vacuum chamber measures the energy associated with this electron. As the electrons of a given atom have different energies, it is possible, at the point of incidence of the beam, to determine which chemical elements are present in that location and thus instantly identify which mineral is being observed.

2.3.4 Mineralogical analysis

To carry out the mineralogical analysis of the existing clay fraction in the lateritic soil studied (fraction less than 0.002 mm), the X-ray diffraction technique was used, using the X-Ray Diffractometer equipment. The test was carried out at the Department of Geoscience of the University Federal of Amazonas, with equipment model Shimadzu XRD 6000®, using X-ray tube with Cu Kα radiation, wavelength of 0.15418 nm. The configuration used was a monochromator with slits (1, 1, 0.30), at 40kV and a current of 30 mA and a speed of 2000 deg/min. The identification of clay minerals present in the soil was performed using the Match! software. When characterizing clay minerals, the use of the X-ray diffraction technique becomes even more indicated, since the high quartz content of the sample and its ease of orientation result in well-defined peaks of great intensity in this crystalline phase, which helps in the identification of phases (Albers et al., 2002).

2.4 Preparation and characterization of carbon nanotubes

2.4.1 Obtaining carbon nanotubes

The CNTs used in the research are of the multiple wall type (MWCNT), and were commercially obtained from the company CNTCompany, located in South Korea, and the product in question is called CTube120.

2.4.2 Dispersion of carbon nanotubes

Carbon nanotubes are very small particles with a very large specific surface, which makes them tend to attract and agglomerate (Cwirzen et al., 2008). To take real benefits from its potential, it is necessary to make a good dispersion of the particles. The methodology used in this work was adapted from Taha et al. (2018) and Rafael (2017).

First, a 0.15% Tween 80 surfactant solution was prepared to promote better solubilization of the nanotubes in the aqueous medium. The use of the surfactant is justified because it has the property of reducing the interfacial tension between two components of different affinities (Leite, 2020), in the example water and nanotubes, forming a homogeneous mixture. The solution was placed on a magnetic stirrer for 2 h, and then the carbon nanotubes were added at a concentration of 0.01% in relation to the solution, as shown in Figure 2.

However, just inserting the nanotubes into the solution is not enough, as the nanotubes tend to agglomerate in the dispersion. Therefore, an ultrasonic homogenizer brand Sonoplus Bandelin, model UW 2070, equipped with a titanium rod was used. Rafael (2017) verified that the increase in temperature produces negative effects on the dispersion of MWCNT, and with that, the solution was stored in a container containing crushed ice, to control the temperature during the test. Ultrasound was used with a frequency of 20 kHz and power of 500 W for 10 minutes, as shown in Figure 3.

After the process of dispersing the nanotubes through the ultrasonic homogenizer, the amount of soil necessary for

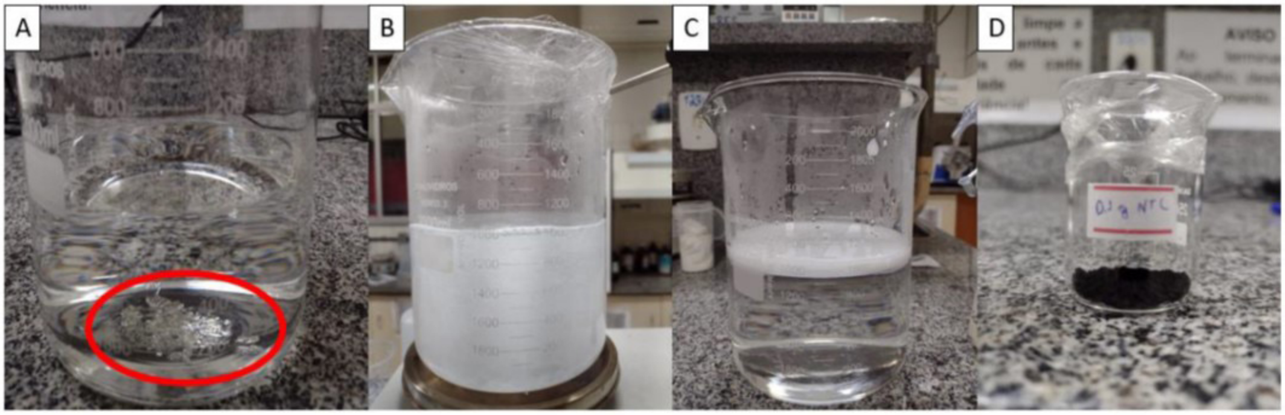

Figure 2. Solution for carbon nanotubes dispersion. (A) Solution with Tween 80 surfactant (before the shaker); (B) Solution during magnetic stirrer; (C) Solution after 2 h period on shaker; (D) Nanotubes used in the solution.

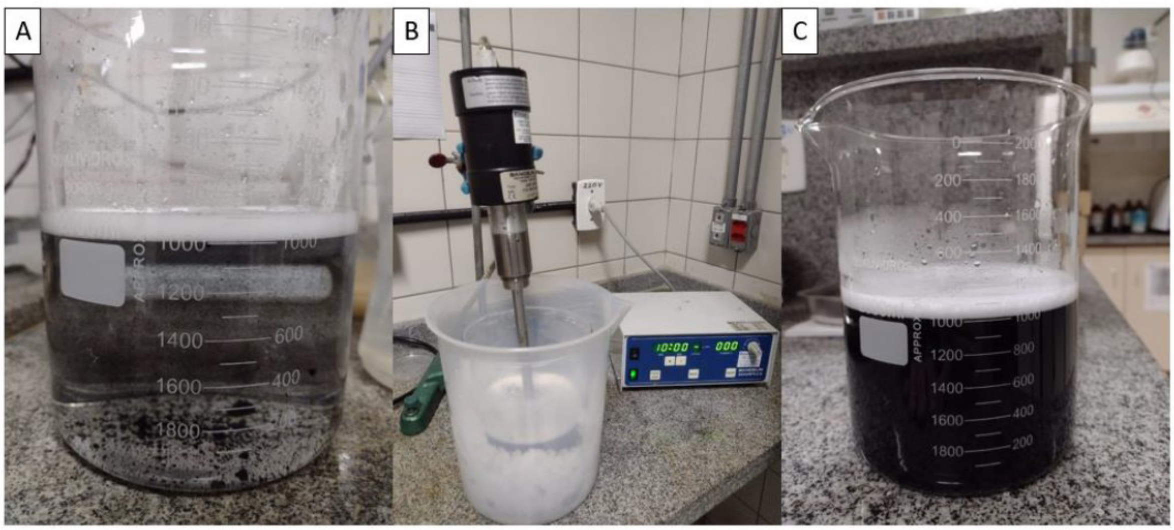

Figure 3. Dispersion process of carbon nanotubes. (A) Addition of the nanotubes to the solution before the ultrasound; (B) Solution in a temperature-controlled container for use in ultrasound; (C) Solution after 10 minutes in the ultrasonic homogenizer.

carrying out each test was added inside the container with the solution, the magnetic stirrer was used for 15 minutes and then the material was taken to an oven at 100 °C, for complete drying of the water. Finally, the dry material was slightly crumbled in a mortar with the aid of a mortar hand and separated into identified flasks referring to the test to be carried out with the appropriate percentages of carbon nanotubes for this research, as shown in Figure 4.

2.4.3 Average size, Polydispersity Index (*PDI*) and Zeta Potential

The particle size after the carbon nanotube dispersion process, the polydispersity index and the Zeta Potential were determined with Zetasizer Nano ZS 90 equipment (Malvern Instruments; Malvern, UK), performed using the Dynamic Light Scattering (EDL) technique. This technique is widely used for evaluating the dimensions of particles in suspension, because when the particle is illuminated by a light source, it will scatter light in all directions, and this technique consists of analyzing the intensity fluctuations of the scattered light at a certain angle, which provides information about the particle movement and, consequently, its mean hydrodynamic diameter (Nomura et al., 2014).

In addition, through the *PDI* and the Zeta Potential, it is possible to evaluate the quality and stability of the solutions. In an Eppendorf tube, a solution was prepared with 100 μL of each sample together with 2 mL of ultrapure water, and the solution was stirred for approximately 2 min. 900 μL of each solution were removed for analysis of particle size, *PDI* and Zeta potential. The analyzes were made from 10 runs with 3 reading cycles and a scattering angle of 173º and a temperature of 25 °C. The average particle diameter and the *PDI* were calculated from the particle size distribution and the Zeta Potential values were determined by measuring the electrophoretic mobility, expressed in mV.

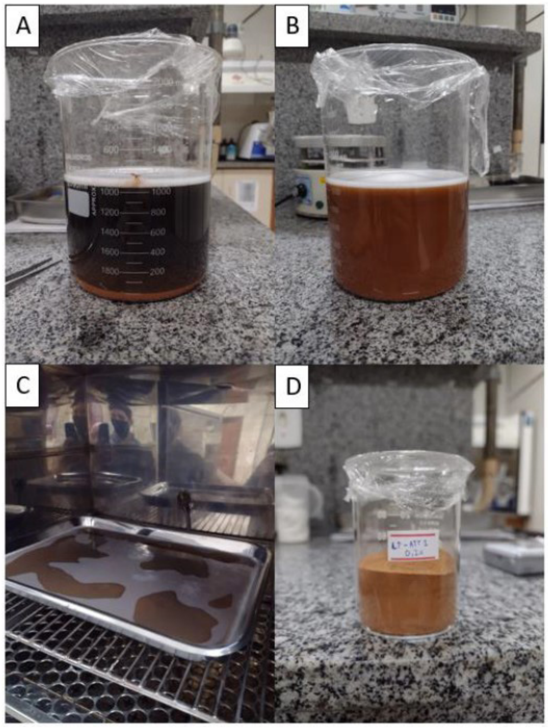

Figure 4. Process of preparation of samples used for physical and mechanical tests. (A) Addition of soil to the solution, before the agitator; (B) Soil solution + nanotubes after the shaker; (C) drying the solution in an oven; (D) Sample to be used in physical.

2.5 Statistical and experimental design

Different percentages of carbon nanotubes (0, 0.05, 0.1 and 0.2%) were added to the soil samples, as proposed by Alsharef et al. (2016), and subsequently evaluated and compared the physical properties of the soil with the addition of carbon nanotubes compared to the original soil.

For these tests, a factorial experiment installed in a completely randomized design, in triplicate, was used, and the data obtained in the mechanical tests were statistically analyzed according to the normality of the errors and the homogeneity of the variances of the data, and if assumptions were met, it was carried out an analysis of variance (ANOVA) and Tukey's test with 5% probability for comparison between means, as shown in Table 1. The homogeneity of variances was performed using the Prophet® software, while the normality of errors and ANOVA were performed using the Sisvar® program.

Table 1. Statistical and experimental design of the research.

Treatments	Repetitions		
	I	II	III
Group 01 (0% of MWCNT)	G1.1	G1.2	G1.3
Group 02 (0.05% of MWCNT)	G2.1	G2.2	G2.3
Group 03 (0.1% of MWCNT)	G3.1	G3.2	G3.3
Group 04 (0.2% of MWCNT)	G4.1	G4.2	G4.3

2.6 Physical and mechanical soil tests

To carry out the liquidity limit test, the recommendations of the DNER ME 122/94 (DNER, 1994b) standard were followed. As for the plasticity limit test, it was performed according to the DNER ME 082/94 standard (DNER, 1994c). To determine the plasticity index, the averages of the liquidity limits were subtracted from those of the plasticity limits. The Atterberg limits tests were performed with the samples from the control group and the samples with the addition of carbon nanotubes. For the determination of the Atterberg limits, approximately 200 g of material (air-dried) passing through the #40 sieve (0.42 mm) was separated. Atterberg limits define the consistency and behavior of cohesive soil at different water contents. These limits are important as they are related to the parameters of contraction, expansion and settlement of the soil (Rehman et al., 2020).

To determine the maximum dry density and optimal moisture, the recommendations of the DNIT 164/2013 (DNIT, 2013) standard were followed, which provides for compaction using unworked samples, using normal compression energy. To determine the real specific mass of the lateritic soil before and after the addition of different percentages of carbon nanotubes, the recommendations of the DNER ME 093/94 (DNER, 1994a) standard were followed.

3. Results and discussions

3.1 Soil characterization

3.1.1 Granulometry

Through the granulometry test, it was possible to obtain the granulometric curve of the soil, as shown in Figure 5.

Through Figure 5, it is possible to see that this is a soil with more than 50% of its composition consisting of fine particles (silt and clay), being composed mainly of clay. From the percentages of each soil component, it is possible to classify the soil as a medium texture soil (Santos et al., 2018). Texture is one of the main indicators of soil quality, since it influences the dynamics of adhesion and cohesion between soil particles, as well as the dynamics of water in the soil (Centeno et al., 2017).

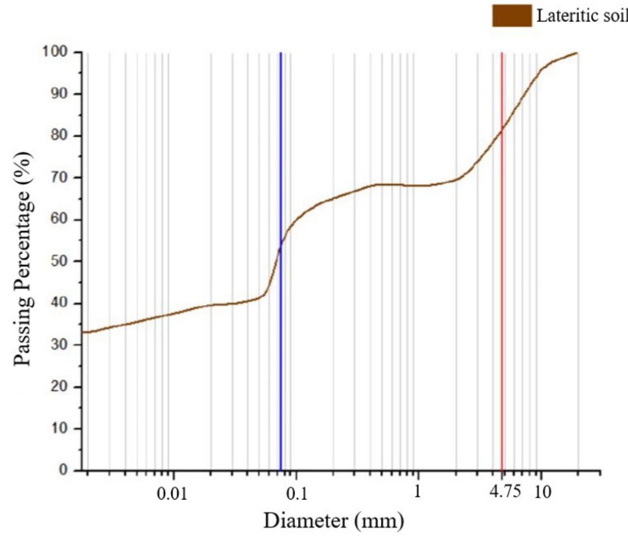

Figure 5. Graph of soil granulometry.

3.1.2 MCT test

Through the MCT test, it was possible to determine whether the soil in question has a lateritic behavior or not. Thus, according to Figure 6 and after the tests performed, the soil was classified as sandy lateritic.

According to the Unified Soil Classification System (USCS), the soil used in the research was determined to be between clay or silt of low compressibility, which corroborates the statement that the soil is lateritic, with non-plastic behavior and non-expansive, according to Figure 7.

In the HRB classification system, the soil was classified as a clayey soil of the A-7-5 group, presenting general behavior as a weak to poor subgrade. However, it is important to point out that the use of techniques considered traditional for soil classification is not suitable for tropical soils, given the peculiarities inherent to this type of soil (Nogami & Villibor, 1991).

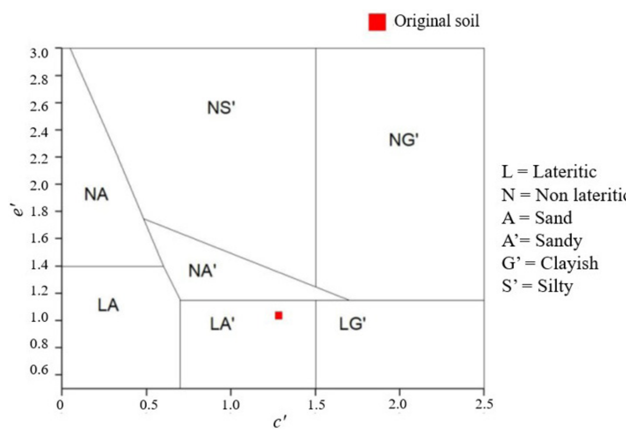

Figure 6. MCT classification abacus with soil results used in research.

3.1.3 Chemical analysis (EDX)

Figure 8 shows the chemical composition of the soil, obtained through the EDX technique. The main constituents of the soil are the minerals silicon, iron and titanium, which are present in the form of oxides. The elements Si and Fe are considered the most important chemical elements of lateritic soils (Borba, 1981). This collaborates, together with the results obtained in the DRX, that the analyzed material has the characteristics of a lateritic soil.

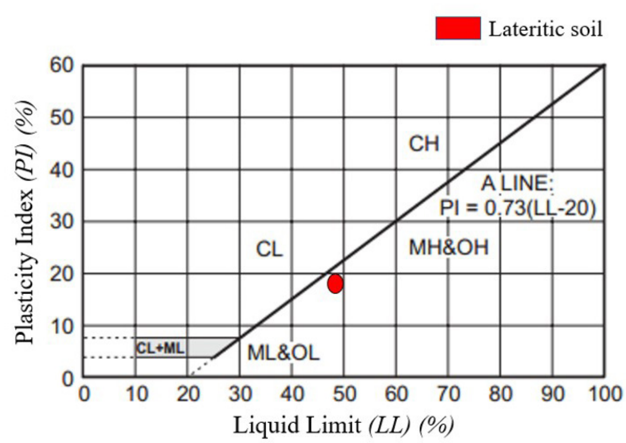

Figure 7. Plasticity chart with soil classification.

3.1.4. Mineralogical analysis (DRX)

The X-ray diffractogram of the soil used in the research is shown in Figure 9. Although there are well-defined peaks at 2θ = 26.66° and 2θ = 20.86°, these peaks correspond to the quartz minerals present in the sample (Hazen et al., 1989). The peaks of 2θ = 50.12°, 22.15° and others correspond to the kaolinite clay mineral (Gruner, 1932). Kaolinite has a lamellar structure formed by the regular stacking of layers 1:1, in which each layer consists of a sheet of silicon and oxygen tetrahedrons and a sheet of alumina octahedrons with basal spacing of approximately 0.7 nm and of chemical

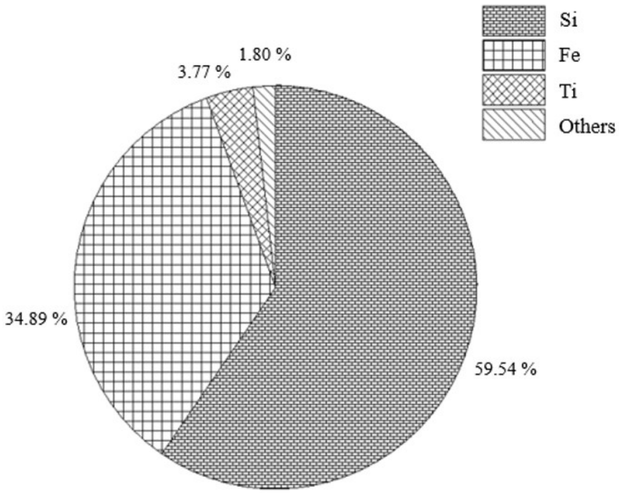

Figure 8. Soil Chemical Composition.

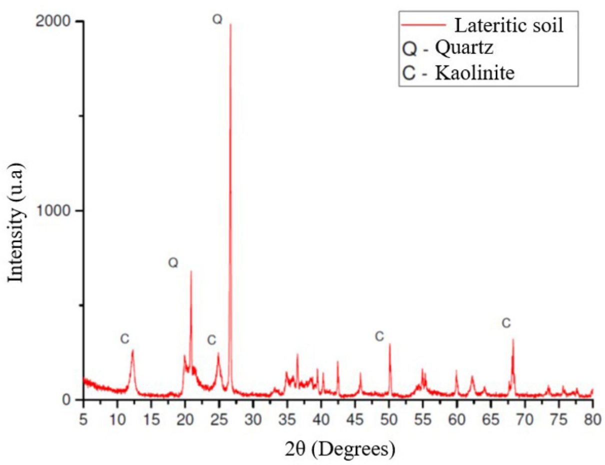

Figure 9. Lateritic soil X-ray diffractogram.

composition $Al_2O_32SiO_22H_2O$ (Scorzelli et al., 2008). This mineral clay, due to its low expansion potential, is indicated for use in impermeable barriers, in addition to having less water dispersion (Borba et al., 2019).

3.2 Carbon nanotubes

3.2.1 Characterization of nanotubes

The properties of the nanotubes are shown in Table 2.

Images of carbon nanotubes through scanning electron microscopy are shown in Figure 10.

3.2.2 Dispersion of carbon nanotubes (average size, *PDI* and Zeta Potential)

Through the DLS, it was possible to analyze the average hydrodynamic diameter of the nanoparticles dispersed in the solutions. The result is shown in Figure 11, where particles with an average hydrodynamic diameter of 68.9 nm were

Table 2. Properties of carbon nanotubes (CTube 120).

Property	CTube 120
Appearance	Black Powder
Carbon Purity (%)	≥ 97
Average diameter (nm)	20
Length (μm)	1-25
Metal oxide (%)	≤ 3
Apparent density (g/cm^3)	0.030-0.050
Specific surface (m^2/g)	150-250

obtained, satisfactorily meeting the requirement that the particles remain in the nanometer scale after dispersion. The results show better results than research done with other types of surfactants, as shown in Table 3.

It is possible to notice that the solution becomes more homogeneous with low levels of surfactants, followed by a relative trend of stability as the concentration increases. This variation can be divided into two states: one where the surfactant is limited and another where there is an excess. At low concentrations, there is not enough surfactant to protect all particles present in the solution. Consequently, small oil droplets collide with each other, which increases the particle size. The dimensions of the particles, in this state, are defined by the type and concentration of surfactant present in the solution (Yang et al., 2013; Zhu et al., 2019). The surfactant used in the research, Tween 80, is highly recommended to obtain homogeneous solutions and highly ordered nanoparticles, due to its hydrophilic character (Hamza et al., 2020).

Figure 12 shows the graph of the Zeta Potential of the solution. The average Zeta potential obtained in all experimental runs was around -24.87 mV and the *PDI* obtained was around 0.231. In general, $PDI < 0.1$, 0.1 – 0.4 and > 0.4 represent highly dispersed, moderately dispersed and colloidal solutions, respectively (Zaib et al., 2020). The closer to 0 mV the Zeta Potential value, the greater the tendency for the solution to agglomerate, while values close to -40 mV represent solutions with good stability (Salopek et al., 1992; Clogston & Patri, 2011). These results indicate that the solution appears as moderately dispersed, and the Zeta Potential far from 0 mV indicates that the particles present in the solution present enough repulsion to keep it stable.

3.3 Physical tests

3.3.1 Atterberg limits

The results of the Atterberg limits tests are shown in Figure 13. First, the homogeneity of the data variances was calculated using the Bartlett test and the normality of the errors using the Shapiro-Wilk test, where the hypothesis of difference in variances and abnormality in errors was rejected. With that, we proceeded with the ANOVA.

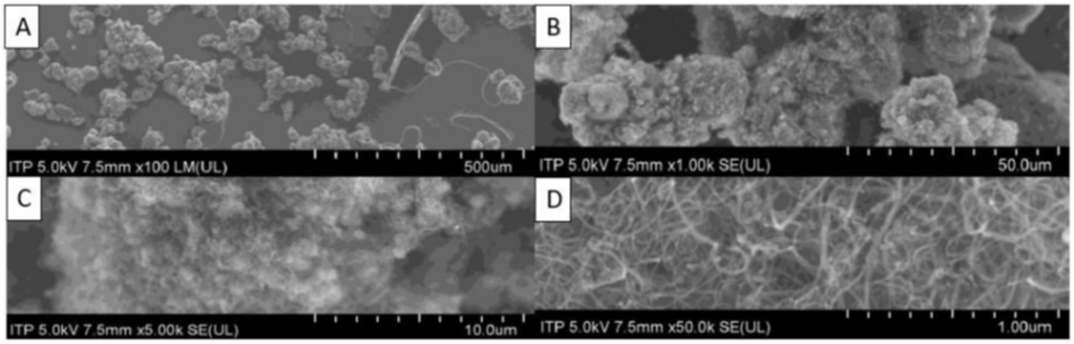

Figure 10. Scanning Electron Microscope (SEM) image of carbon nanotubes. (A) 20x magnification; (B) 200x magnification; (C) 1000x magnification; (D) 10.000x magnification.

Table 3. Mean hydrodynamic diameter obtained from MWCNT in solutions with different surfactants, with 0.01% MWCNT.

Author	Surfactants	Average diameter (nm)
Figueiredo et al. (2015)	Glycerox 0.5%	197.2
	Glycerox 1%	167.6
	Glycerox 3%	175.2
	Amber 4001 0.5%	521.45
	Amber 4001 1%	322.85
	Amber 4001 3%	316.8
Rafael (2017)	Pluronic F-127 0.03%	198.4
	Policarboxilato 0.05%	221.1
	SDBS 0.03%	206.9
	SDOCO 0.03%	207.1
	Triton X-100 0.1%	174.0
	SDBS 0.015% + Pluronic F-127 0.015%	191.3
	SDBS 0.015% + Policarboxilato 0.25%	200.2
	SDBS 0.015% + *SDOCO* 0.015%	205.1
	SDBS 0.015% +Triton X-100 0.05%	188.0
	SDOCO 0.015% + Pluronic F-127 0.015%	191.0
Moura (2015)	Amber 2006 0.1%	354.9
	Amber 2006 0.5%	431.1
	Amber 2006 1%	514.9
	Amber 2006 2%	816.0
	Amber 2002 0.1%	424.0
	Amber 2002 0.5%	304.1
	Amber 2002 1%	399.9
	Amber 2002 2%	623.9
	Amber 2001 0.1%	550.0
	Amber 2001 0.5%	548.0
	Amber 2001 1%	871.6
	Amber 2001 2%	985.0

From the results obtained, the addition of CNTs to the soil showed a significant difference in the parameters of liquidity limit and plasticity limit, while for the plasticity index there was no significant difference. The percentage of addition that proved to be the most efficient was 0.2%, presenting a reduction according to the percentage variation in relation to the initial value of about 10% in the *LL* and 13% in the *PL*, followed by the percentages of 0.1%, which showed a reduction of 15% in the *PL* and 0.05% with similar values for *LL* and *PL*.

Atterberg limits play an important role in soil identification and classification. These parameters may indicate some possible geotechnical problems that may arise in the soil, such as potential for expansion and workability (Alsharef et al., 2016). Reductions in the Atterberg limits are indicators of soil improvement (Majeed & Taha, 2012).

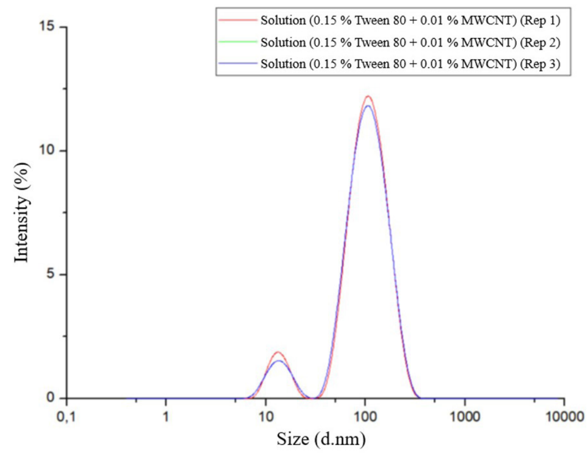

Figure 11. DLS with the dispersion solution with 0.15% Tween 80 and 0.01% MWCNT.

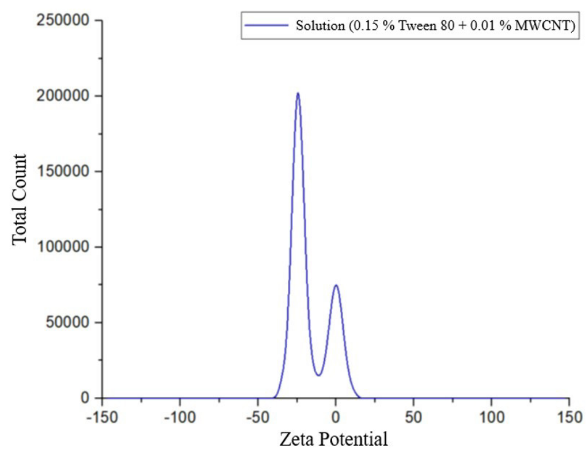

Figure 12. Graph of the Zeta Potential of the solution with 0.15% Tween 80 and 0.01% MWCNT.

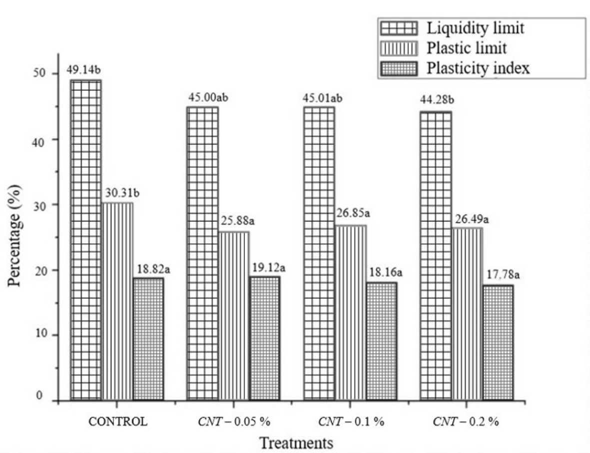

Figure 13. Averages of the Atterberg limits for the samples (control groups and with different additions of CNTs). Obs: Groups with the same letter do not differ significantly in relation to their means, according to the Tukey Test (α = 5%).

A possible explanation for the reduction of these indices is that the carbon nanotubes form a coating layer around the clay lamellae, which causes a suppression of its reactivity, reducing the possible absorption of water from the soil (Krishnan & Shukla, 2019).

The result of soil classification according to the Unified Soil Classification System is shown in Figure 14. It is possible to see that, even after changes to the Atterberg limits, the soil maintained its non-plastic and non-expansive behavior characteristics. This behavior is advantageous, as an increase in Atterberg limits is related to a greater potential for soil expansibility (Mearek et al., 2022).

3.3.2 Real specific mass

The results of the real specific mass tests are shown in Figure 15. First, the homogeneity of the data variances was calculated using the Bartlett test and the normality of the errors using the Shapiro-Wilk test, where the hypothesis of difference in variances and abnormality in errors was rejected. With that, we proceeded with the ANOVA.

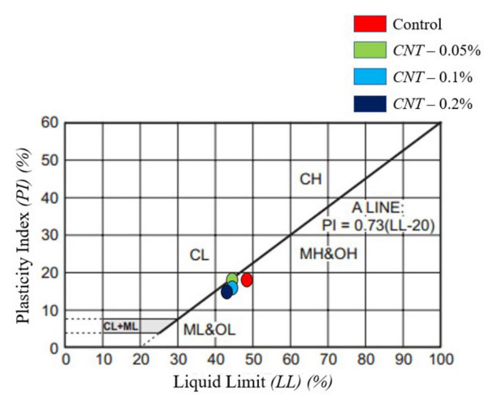

Figure 14. Sample results with CNTs according to USCS.

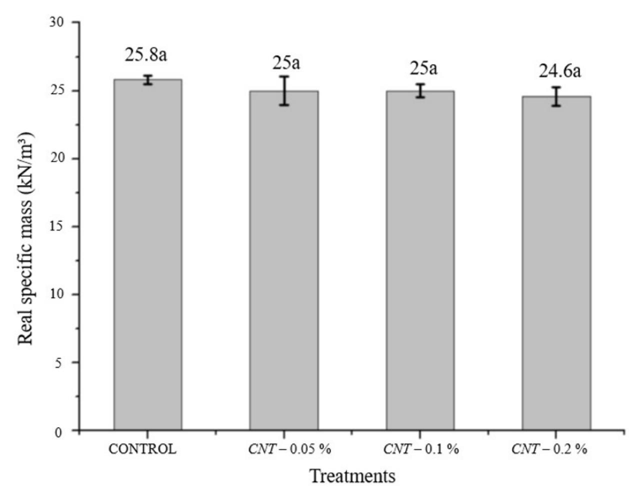

Figure 15. Averages of the real specific mass of the samples of the control groups and with different additions of CNTs. Obs: Groups with the same letter do not differ significantly in relation to their means, according to the Tukey Test (α = 5%).

Although there was a reduction in the mean real specific mass as the percentage of CNTs in the samples increased, this reduction was not significant. This reduction is expected, due to the low density of CNTs, in addition to meeting the results obtained by Taha & Alsharef (2018). However, due to the non-significant result, it is possible that higher percentages of addition of carbon nanotubes in the soil could lead to relevant results, due to the tendency of reduction as the percentage of CNTs increases, observed in Figure 15.

3.3.3 Maximum dry density and optimum moisture

The homogeneity of data variances was calculated using the Bartlett test and the normality of errors using the Shapiro-Wilk test, where the hypothesis of difference in variances and abnormality in errors was rejected. With that, we proceeded with the ANOVA. The results of the mean maximum dry density and optimal moisture of the samples from the control group and with different additions of CNTs are shown in Figure 16.

The values of maximum dry density showed an increase in the percentages of addition of 0.05% and 0.1% of CNTs, while there was a reduction in the values of optimal moisture in the observed treatments. However, there was no significant variation in both maximum dry density values and optimal moisture values. The increase and decrease in the values of maximum dry density and optimal moisture, respectively, are in line with those obtained by Alsharef et al. (2016), which also showed a small variation in these values of 2% and 6%.

The increase in density can be caused by the rearrangement and consolidation of soil particles promoted by filling the nanoparticles in the voids present in the specimen (Krishnan & Shukla, 2019). The reduction in the optimal moisture content can be explained by the formation of nanocomposites that fill the voids in the soil, occupying the water space, where the ion exchange mechanism is the main phenomenon that maintains the connection between clay minerals and carbon nanotubes (Azzam, 2014). However, despite these mechanisms, the results obtained here do not demonstrate that there was a significant change in these parameters, so performing treatments with different percentages can lead to values with a significant difference.

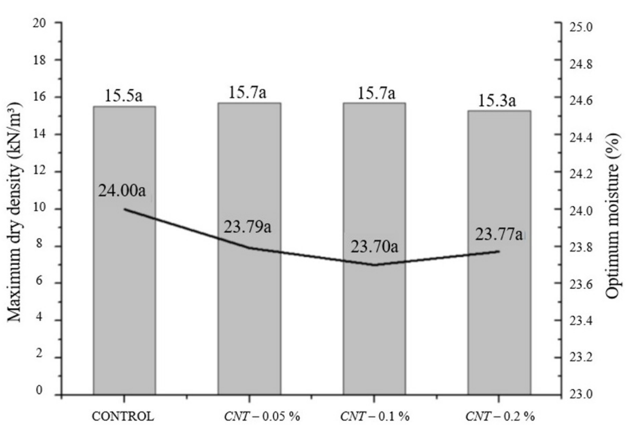

Figure 16. Means of maximum dry densities and optimal moisture of soil samples (control groups and with different additions of CNTs). Obs: Groups with the same letter do not differ significantly in relation to their means, according to the Tukey Test (α = 5%).

4. Conclusions

The granulometry test revealed that the soil has more than 50% of its weight passing through the #200 sieve, being predominantly composed of silt with 24.76% and clay with 33.05%, being able to classify the soil as being a clayey soil of texture average. The MCT methodology allowed classifying the soil as a lateritic sandy type. Through the granulometry results and the Atterberg Limits, the soil was classified as low compressibility clay/silt in the USCS soil classification system and A-7-5 in the HRB system, classifying it as a clayey soil with weak behavior as subgrade. The X-Ray Diffraction analysis allowed us to identify the clay minerals present in the soil, where kaolinite was the main component of the soil, and together with the chemical test through EDX it allowed us to identify the main chemical compounds present in the soil, with predominance for silicon and iron. The results obtained from these tests corroborate the statement that the soil used in the research was a soil with lateritic behavior.

The Dynamic Light Scattering measurements showed that solutions with the dispersion of carbon nanotubes resulted in an average hydrodynamic diameter of the particles of 68.9 nm, a result considered to be of better quality compared to other studies, and the Zeta Potential was -24.87 mV and *PDI* of 0.231. These results confirm that the dispersion was carried out properly and that the solution is considered moderately dispersed, with a good tendency towards kinetic stability, where it was possible to reach the nanometric scale of carbon nanotubes in the solution. These factors collaborate so that the results of the mechanical and physical tests are reliable.

According to the physical tests, the addition of different percentages of carbon nanotubes showed a reduction of 10 and 13%, respectively, in the parameters of liquidity limit and plasticity limit, and these results indicate a tendency for improvement in the soil, since as the liquidity limit decreases, so does soil compressibility, among other variables. However, despite the variation in the mean values of real specific mass, maximum dry density and optimal soil moisture, it was not possible to observe a significant difference in the results of these parameters after the addition of different percentages of carbon nanotubes in comparison with the samples. control group soil. Running these tests with different percentages of nanotubes can lead to results with significant variation, so further studies are needed to investigate these variations.

Advances in MWCNT synthesis methods have resulted in a substantial decrease in their cost, which opens several possibilities for their use in different fields. In the present study, the percentage that proved to be most advantageous was 0.2% of carbon nanotubes, which represents a very small amount in relation to the soil, which leads to low implementation costs. However, special attention must be paid to the techniques for dispersing carbon nanotubes before mixing, as it plays a fundamental role in the correct incorporation of nanomaterials into the soil.

Through this work, it is possible to state that carbon nanotubes interact with soils with lateritic behavior, and that further studies are essential to better understand the mechanisms behind this interaction. During the research, it was not possible to find in the scientific literature works that use carbon nanotubes in the region of Acre or even in the North of Brazil, so that this work constitutes a pioneer in the investigation related to the addition of nanomaterials in soils of the region, establishing it as a scientific basis for further research with the use of nanoparticles in soils in the region to have a scientific-technical basis.

Acknowledgements

The authors are appreciative of the funding support provided by Higher Education Personnel Improvement Coordination (CAPES), Federal University of Acre (UFAC).

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Marcelo Victor de Assis Morais: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft. Marcelo Ramon da Silva Nunes: methodology, resources, validation, writing - reviewing and editing. Carlos Drumond do Nascimento Morais: methodology, investigation, visualization, writing - reviewing and editing. Ricardo Ribeiro do Nascimento: conceptualization, formal analysis, methodology, project administration, investigation, supervision, validation, writing – review & editing. Anselmo Fortunato Ruiz Rodriguez: conceptualization, funding acquisition, methodology, project administration, resources, supervision, validation, writing - reviewing and editing.

Data availability

All the data and models that support the findings of this study are available from the corresponding author upon request.

List of symbols and abbreviations

c'	Parameter that differentiates sandy and clayey materials
d'	Parameter of the compaction curve that is directly related to the maximum density
e'	Parameter that classifies the soil as being lateritic or non-lateritic
ANOVA	Analysis of Variance
CBR	California Bear Rating
CH	Highly plasticity inorganic clays
CL	Low plasticity inorganic clays
CNT	Carbon Nanotubes
DLS	Dynamic Light Scattering
DNER	National Department of Highways
DNIT	National Department of Transport Infrastructure
DRX	X-Ray Diffractometer
EDS	Energy Dispersive Spectroscopy
EDX	Energy Dispersive X-ray System
EMURB	Municipal Urbanization Company of Rio Branco
FUNTAC	Technology Foundation of the State of Acre
HRB	Highway Research Board
LA	Lateritic Sand
LA'	Lateritic Sandy
LG'	Lateritic Clayish
LL	Liquid Limit
PL	Plastic limit
MCT	Tropical Compressed Miniature
MCV	Moisture Condition Value
MH	High plasticity silt
ML	Low plasticity silt
MWCNT	Multi Wall Carbon Nanotubes
NA	Non lateritic Sand
NA'	Non lateritic Sandy
NG'	Non lateritic Clayish
NS'	Non lateritic Silty
OH	High plasticity organic clay
OL	Low plasticity organic clay
PDI	Polidispersivity Index
Pi	Parameter that quantifies the degree of soil laterization
PI	Plasticity Index
SDBS	Sodium Dodecyl Benzene Sulfonate
SDOCO	Sodium Deoxy Cholate
SDS	Sodium Dodecyl Sulfate
USCS	Unified Soil Classification System
UFAC	Federal University of Acre

References

ABNT NBR 7181. (2016). *Solo: análise granulométrica.* ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

Acre. Secretaria de Estado de Meio Ambiente. Programa Estadual de Zoneamento Ecológico -Econômico do Acre. (2010). *Livro temático: recursos naturais: geologia, geomorfologia e solos do Acre* (Coleção Temática do ZEE, Vol. 2). Rio Branco.

Albers, A.P.F., Melchiades, F.G., Machado, R., Baldo, J.B., & Boschi, A.O. (2002). A simple method of characterizing clay minerals by X-ray diffraction. *Cerâmica*, 48(305), 34-37. http://dx.doi.org/10.1590/S0366-69132002000100008.

Alobaid, A., Rehman, K.U., Andleeb, S., Erinle, K.O., & Mahmood, A. (2022). Capacity assessment of carbon-based nanoparticles in stabilizing degraded soils. *Journal of King Saud University. Science*, 34(1), 101716. http://dx.doi.org/10.1016/j.jksus.2021.101716.

Alsharef, J.M.A., Taha, M.R., Firoozi, A.A., & Govindasamy, P. (2016). Potential of using nanocarbons to stabilize weak soils. *Applied and Environmental Soil Science*, 2016, 1-9. http://dx.doi.org/10.1155/2016/5060531.

Araújo, H.A.O. (2022). *Study on the validation of a methodology for classifying laterite soils with a view to creating road pavement layers* [Master's dissertation]. Universidade Federal de Campina Grande.

Arruda, M.S.Z.J. (2020). *Characterization of material from construction material processing plants to analyze its influence on lateritic soil stabilization* [Master's dissertation]. Universidade Estadual Paulista.

Azzam, W.R. (2014). Behavior of modified clay microstructure using polymer nanocomposites technique. *Alexandria Engineering Journal*, 53(1), 143-150. http://dx.doi.org/10.1016/j.aej.2013.11.010.

Borba, S.M.C. (1981). *Study of the chemical and mineralogical properties of tropical red soils in north and northeast Brazil* [Master's dissertation]. Universidade Federal do Rio Grande do Sul, Porto Alegre.

Borba, W.F., Silva, J.L.S., Kemerich, P.D.C., Fernandes, G.D., Terra, L.G., Lobler, C.A., Trombeta, H.W., & Souza, E.E.B. (2019). Identificação de argilominerais em solo de aterro sanitário na região noroeste no estado do Rio Grande do Sul, Brasil. *Anuário do Instituto de Geociências*, 42(2), 178-183. http://dx.doi.org/10.11137/2019_2_178_183.

Centeno, L.N., Guevara, M.D.F., Cecconello, S.T., Sousa, R.O., & Timm, L.C. (2017). Textura do solo: conceitos e aplicações em solos arenosos. *Revista Brasileira de Engenharia e Sustentabilidade*, 4(1), 31-37. http://dx.doi.org/10.15210/rbes.v4i1.11576.

Clogston, J.D., & Patri, A.K. (2011). Zeta potential measurement. In S.E. McNeil (Ed.), *Characterization of nanoparticles intended for drug delivery* (pp. 63-70). Totowa, NJ: Humana Press Inc. http://dx.doi.org/10.1007/978-1-60327-198-1_6.

Corrêa-Silva, M., Miranda, T., Rouainia, M., Araújo, N., Glendinning, S., & Cristelo, N. (2020). Geomechanical behavior of a soft soil stabilized with alkali-activated blast-furnace slags. *Journal of Cleaner Production*, 267, 122-127. http://dx.doi.org/10.1016/j.jclepro.2020.122017.

Cwirzen, A., Habermehl-Cwirzen, K., & Penttala, V. (2008). Surface decoration of carbon nanotubes and mechanical properties of cement/carbon nanotube composites. *Advances in Cement Research*, 20(2), 65-73. http://dx.doi.org/10.1680/adcr.2008.20.2.65.

DNER ME 093/94. (1994a). *Solos: determinação da densidade real: método de ensaio.* DNER - Departamento Nacional de Estradas de Rodagem, Rio de Janeiro, RJ (in Portuguese).

DNER ME 122/94. (1994b). *Solos: determinação do limite de liquidez: método de referência e método expedito: método de ensaio.* DNER - Departamento Nacional de Estradas de Rodagem, Rio de Janeiro, RJ (in Portuguese).

DNER ME 082/94. (1994c). *Solos: determinação do limite de plasticidade: método de ensaio.* DNER - Departamento Nacional de Estradas de Rodagem, Rio de Janeiro, RJ (in Portuguese).

DNER ME 258/94. (1994d). *Solos compactados em equipamentos Mini-MCV em miniatura: método de ensaio.* DNER - Departamento Nacional de Estradas de Rodagem, Rio de Janeiro, RJ (in Portuguese).

DNER ME 256/94. (1994e). *Solos compactados em equipamento miniatura: determinação da perda de massa por imersão: especificação de serviço.* DNER - Departamento Nacional de Estradas de Rodagem, Rio de Janeiro, RJ (in Portuguese).

DNIT 164/2013. (2013). *Solos: compactação utilizando amostras não trabalhadas: método de ensaio.* DNIT - Departamento Nacional de Infraestrutura de Transportes, Rio de Janeiro, RJ (in Portuguese).

Eyo, E.U., Ng'ambi, S., & Abbey, S.J. (2020). Incorporation of a nanotechnology-based additive in cementitious products for clay stabilization. *Journal of Rock Mechanics and Geotechnical Engineering*, 12(5), 1056-1069. http://dx.doi.org/10.1016/j.jrmge.2019.12.018.

Figueiredo, D.T.R., Correia, A.A.S., Hunkeler, D., & Rasteiro, M.G.B.V. (2015). Surfactants for dispersion of carbon nanotubes applied in soil stabilization. *Colloids and Surfaces. A, Physicochemical and Engineering Aspects*, 480, 405-412. http://dx.doi.org/10.1016/j.colsurfa.2014.12.027.

Gruner, J.W. (1932). The crystal structure of kaolinite. *Zeitschrift für Kristallographie. Crystalline Materials*, 83(6), 75-88. http://dx.doi.org/10.1524/zkri.1932.83.1.75.

Hamza, M.A., Abou-Gamra, Z.M., Ahmed, M.A., & Medien, H.A.A. (2020). The critical role of Tween 80 as a 'green' template on the physical properties and photocatalytic performance of TiO 2 nanoparticles for Rhodamine B photodegradation. *Journal of Materials Science Materials in Electronics*, 31(6), 4650-4661. http://dx.doi.org/10.1007/s10854-020-03017-2.

Hazen, R.M., Finger, L.W., Hemley, R.J., & Mao, H.K. (1989). High-pressure crystal chemistry and amorphization of α-quartz. *Solid State Communications*, 72(5), 507-511. http://dx.doi.org/10.1016/0038-1098(89)90607-8.

Karumanchi, M., Avula, G., Pangi, R., & Sirigiri, S. (2020). Improvement of consistency limits, specific gravities, and permeability characteristics of soft soil with nanomaterial: nanoclay. *Materials Today: Proceedings*, 33(1), 232-238. http://dx.doi.org/10.1016/j.matpr.2020.03.832.

Krishnan, J., & Shukla, S. (2019). The behaviour of soil stabilised with nanoparticles: an extensive review of the present status and its applications. *Arabian Journal of Geosciences*, 12(14), 1-25. http://dx.doi.org/10.1007/s12517-019-4595-6.

Leite, J.P.C. (2020). *Obtenção de regiões em diagramas ternários utilizando óleos de coco e milho*. Federal Rural University of the Semiarid (In Portuguese).

Lima, C.D.A., Motta, L.M.G., Aragão, F.T.S., & Guimarães, A.C.R. (2020). Mechanical characterization of fine-grained lateritic soils for mechanistic-empirical flexible pavement design. *Journal of Testing and Evaluation*, 48(1), 1-17. http://dx.doi.org/10.1520/JTE20180890.

Machado, L.F.M., Cavalcante, E.H., Albuquerque, F.S., & Sales, A.T.C. (2017). Adição de uma associação polimérica a um solo arenoso-argiloso com vista à estabilização química de materiais de pavimentação. *Matéria*, 22(3), 1-13. http://dx.doi.org/10.1590/s1517-707620170003.0204.

Majeed, Z.H., & Taha, M.R. (2012). Effect of nanomaterial treatment on geotechnical properties of a Penang soft soil. *Journal of Asian Scientific Research*, 2(11), 587-592.

Mearek, S.M., Shadhar, A.K., & Abbood, H.H. (2022). Relation between swelling pressure and potential expansion soil with Atterberg limits. *Wasit Journal of Engineering Sciences*, 10(2), 12-19. http://dx.doi.org/10.31185/ejuow.Vol10.Iss2.333.

Moura, M.S.M.R. (2015). *Improvement of carbon nanotube dispersions for application in soil chemical stabilization* [Master's thesis]. University of Coimbra (in Portuguese).

Nogami, J.S., & Villibor, D.F. (1991). Use of lateritic fine-grained soils in road pavement base courses. *Geotechnical and Geological Engineering*, 9(3), 167-182. http://dx.doi.org/10.1007/BF00881739.

Nomura, D. A., Enoki, T. A., Goldman, C., & Lamy, M. T. (2014). *Espalhamento dinâmico de luz*. São Paulo: Universidade de São Paulo (in Portuguese).

Rafael, N.F. (2017). *Chemical stabilization of soils using nanoparticles* [Doctoral thesis]. University of Coimbra (in Portuguese).

Rehman, H.U., Pouladi, N., Pulido-Moncada, M., & Arthur, E. (2020). Repeatability and agreement between methods for determining the Atterberg limits of fine-grained soils. *Soil Science Society of America Journal*, 84(1), 21-30. http://dx.doi.org/10.1002/saj2.20001.

Salopek, B., Krasic, D., & Filipovic, S. (1992). Measurement and application of zeta-potential. *Rudarsko-Geolosko-Naftni Zbornik*, 4(1), 147-151.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araujo Filho, J.C., Oliveira, J.B., & Cunha, T.J.F. (2018). *Sistema brasileiro de classificação de solos*. Brasília: Embrapa.

Scorzelli, R.B., Bertolino, L.C., Luz, A.B., Duttine, M., Silva, F.A.N.G., & Munayco, P. (2008). Spectroscopy studies of kaolin from different Brazilian regions. *Clay Minerals*, 43(1), 129-135. http://dx.doi.org/10.1180/claymin.2008.043.1.10.

Shinzato, E., Adamy, A., Dantas, M. E., Oliveira Filho, I. B., Teixeira, W. G., & Lumbreras, J. F. (2012). Análise morfopedológica: um instrumento para elaboração de um mapa de geodiversidade do estado do Acre. In *Anais do 46º Congresso Brasileiro de Geologia* (pp. 455-482), Santos (in Portuguese).

Silva, J.S., & Castro, R.M. (2020). Análise da influência do comprimento e do teor de fibras adicionadas na armadura de solo laterítico. *Revista Uniaraguaia*, 15(2), 76-84 (in Portuguese).

Silva, R.R.C., Tavares, M.S., Nascimento, A.M.A., Ferraudo, B.C., & Rodrigues, R.L. (2020). Avaliação dos parâmetros mecânicos e físicos de solos moles através da injeção de colunas de argamassa associada a geodrenos verticais. *Brazilian Journal of Development*, 6(12), 490-506. http://dx.doi.org/10.34117/bjdv6n12-740.

Taha, M.R., & Alsharef, J.M.A. (2018). Performance of soil stabilized with carbon nanomaterials. *Chemical Engineering Transactions*, 63, 757-762. http://dx.doi.org/10.3303/CET1863127.

Taha, M.R., Alsharef, J.M.A., Al-Mansob, R.A., & Khan, T.A. (2018). Effects of nano-carbon reinforcement on the swelling and shrinkage behavior of soil. *Sains Malaysiana*, 47(1), 195-205. http://dx.doi.org/10.17576/jsm-2018-4701-23.

Yang, Y., Leser, M.E., Sher, A.A., & McClements, D.J. (2013). Formation and stability of emulsions using a natural small molecule surfactant: Quillaja saponin (Q-Naturale®). *Food Hydrocolloids*, 30(2), 589-596. http://dx.doi.org/10.1016/j.foodhyd.2012.08.008.

Zaib, Q., Adeyemi, I., Warsinger, D.M., & AlNashef, I.M. (2020). Deep eutectic solvent assisted dispersion of carbon nanotubes in water. *Frontiers in Chemistry*, 8, 808. http://dx.doi.org/10.3389/fchem.2020.00808.

Zhu, Z., Wen, Y., Yi, J., Cao, Y., Liu, F., & McClements, D.J. (2019). Comparison of natural and synthetic surfactants at forming and stabilizing nanoemulsions: Tea saponin, Quillaja saponin, and Tween 80. *Journal of Colloid and Interface Science*, 536, 80-87. http://dx.doi.org/10.1016/j.jcis.2018.10.024.