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Environmental Alternative for the Stabilization of Amazonic Soils

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Abstract

The typical superficial soils of Amazonas present, in general, low technical quality for use in paving, being necessary to adapt them to the geotechnical requirements. As one of the alternatives, there is chemical stabilization, which minimizes the participation, as a rule, of natural materials. In this way, the compositions of two soils (red and white) characteristic of the Petroleum Base Pedro Geólogo de Moura (Coari-AM) were analyzed, in the presence of chemical additives, Portland cement and Roadcem. Soils were characterized in terms of chemical and mineralogical aspects, additives and compositions according to X-ray diffraction mineralogy (XRD). The mechanical behavior of the formulations was also determined. The results of the chemical analysis showed very acid soils with a low organic matter content, and according to mineralogy, kaolinite and ilite clay minerals were identified. As for the additive, Portland cement, the presence of the main constituents of the product (CP II E-32), dicalcium silicate (C_2S), tricalcium silicate (C_3S), tricalcium aluminate (C_3A) and ferro-aluminate (C_4AF), in addition to gypsum and calcite, was evident. Regarding Roadcem®, the presence of the minerals halite (NaCl) and silvite (KCl) was observed. The results of the Portland-Roadcem® cement and Portland-Roadcem® cement-soil compositions showed the presence of halite and silvite. It should also be noted that the chemical additive Roadcem® developed a crystalline structure, when added to the natural soil, in the studied formulations. In mechanical performance, according to indirect tensile strength test and four-point bending test, an increase in soil resistance was observed when additives participated.

Keywords: chemical stabilization; Portland cement; Roadcem®; indirect tensile strength; four-point bending test (4PB).

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1. Introduction

The physiographic and geotechnical characteristics of the Amazon, as a rule, present difficult conditions for the construction of pavements. Specific to the State of Amazonas, we have, as an example, the Operations Base Geologist Pedro de Moura (OBGPM), located in Urucu in the Municipality of Coari-AM / BR. The construction and maintenance of the road system of this Petrobras oil base attests to problems, such as: rainy season with high rainfall and for eight months a year, surface soils with fine granulometry (clay and silt), lack of rocky raw material for obtaining stony aggregates, and environmental restrictions. Such conditions, combined with the low navigability of the rivers during the summer, precarious logistics for driving people and cargo, long transportation times by river, long distances for displacement, and the pressing needs of a social and economic order, have provided, until this moment, technical solutions at a high cost in the construction of pavements in the Amazon rainforest. In Civil Engineering, among the techniques for building pavements, chemical stabilization stands out. It is based on a reaction process, that is, the soil is treated with chemical additives, which generate changes in its behavior, for example, regarding the gain of resistance and stability. In this context, there is Roadcem, a product manufactured by PowerCem Technologies, which mentions economic and environmental advantages, both in the reduction of the construction cost and in the environmental impacts [1]. It is as a by-product additive based on nanotechnology, which contains synthetic zeolites and alkaline earth metals in its composition [2]. Through chemical reactions with the soil, it modifies its mineralogy, resulting in a strong, durable and fibrous crystalline structure. Additionally, it changes the dynamics and chemistry of cement hydration, improving the crystallization process and the formation of crystalline structures with longer "needles" [3]. This crystalline framework reinforces and increases the resistance and flexibility of the stabilized layers of a floor, as well as improves the overall performance of cement in paving [1]. In another context, there is the determination of the mechanical behavior of stabilized soils, through tests. Specific to the indirect tensile strength test (diametrical compression), there are works in the literature related to soils with coal residue [4], coconut fiber [5], Tylac® 4190 [6] and fly ash [7]. Regarding the four-point bending test, it is only mentioned in the study by Wu [8], whose approach is allusive to the dynamic modulus under similar conditions to the one researched in the work in question, due to the lack of investigations on this theme. Therefore, in the present work, the chemical stabilization of soils from Urucu added with Roadcem® and Portland cement was investigated, in order to minimize the use of natural resources and present a technical alternative in the rational use of representative soils in the Amazon region.

2. Materials and Methods

The materials participating in the research correspond to two typical soils of the Operational Base Geologist Pedro de Moura (OBGPM), located about 650 km southwest of Manaus (AM), and in the coordinates 5 ° South Latitude and 65 ° West Longitude (Figure 1). Two chemical additives are also present in the study, the traditional Portland cement, widely used in chemical stabilization processes, and the Roadcem® additive, patented by the Dutch company PowerCem Technologies, developed to be used mainly in the construction of roads, together with Portland cement for soil stabilization in situ.

Figure 1: BOGPM location (Google Earth, 2017)

2.1. Soils, Additives and Compositions

The soils under study, a white and a red one, were collected by deformed sampling. Both materials were subjected to prior preparation procedures, that is, drying, breaking and sifting, for further analysis. Such procedures were carried out at the Soil Laboratory of the Geotechnical Group (GEOTEC) of the Federal University of Amazonas (UFAM). The Portland cement additive used, type CP II-E, has a specification equal to 94% to 56% of clinker + plaster and 6% to 34% of slag, with or without the addition of carbonate material up to a maximum limit of 10% in mass (NBR 11578). Also participating was the additive Roadcem®, a fine powder, consisting, in mass, of alkali metals and alkaline earth metals (60-80%), zeolites and synthetic oxides (5-10%), and activators in the range of 5-10% [9]. The aforementioned materials integrated the compositions Portland-Roadcem® cement, white-cement Portland-Roadcem® soil, and red-cement Portland-Roadcem® soil.

2.2. Experimental Program

2.2.1. Chemical and Mineralogical Characterization

Soils were chemically analyzed for aspects of Active Acidity (pH), Organic Matter (OM), Total Cation Exchange Capacity (CTC-T), Effective Cation Exchange Capacity (CTC-t), Base Saturation (V), Aluminum Saturation (m), Cation Content of Calcium (Ca), Potassium (K), Magnesium (Mg), Aluminum (Al), as well as granulometry. These tests were carried out at the Soil Analysis and Fertility Laboratory, of the Faculty of Agricultural Sciences (FAS/UFAM), according to the guidelines of the Brazilian Agricultural Research Corporation (EMBRAPA). As for mineralogics, soils, additives and compositions were investigated using the X-ray diffractometer, Shimadzu, model XRD-6000, according to CuKα radiation emission ($\lambda = 1.5418$ Å), voltage and current equal to 40Kv and 30m, respectively. The readings of the samples occurred with an initial 2-theta equal to 5°, a final 2-theta corresponding to 60°, with a step width of 0.02° and counting time of 0.60 seconds. Such an experiment, using the Powder Method, was carried out in the Laboratory of Mineralogical Techniques, of the Department of Geosciences (DEGEO / UFAM).

2.2.2. Mechanical Characterization

The red soil was chosen to represent the natural materials that form the surface layer of the Urucu geotechnical profile, aiming to study the mechanical behavior when mixed with additives. Thus, for natural soil and red cement-Portland soil, and red cement-Portland soil Roadcem compositions, specimens were molded in accordance with the determined compaction parameters. They followed a healing process that sought to simulate execution in the field. Therefore, the samples were exposed to the environment, and every day water was sprinkled, so that the cement could correctly perform the curing procedure. This methodology was carried out during the period of 3 days, considering that it is the time that was waited in the field for the execution of the other phases of the experimental stretch built in Urucu. In particular to the indirect tensile strength test (ITS), cylindrical specimens were molded and following the guidelines of the ASTM D6931 standard, the test was performed using an IPTM Global UTM14. Specifically, to the four-point bending test, prismatic samples were made, and the experiment was carried out on a Pneumatic Standalone 4 Point Bending from IPC Global. Following the standard EN 12697-26, for the application of a sinusoidal load on the specimen, the frequency series of 1 Hz, 3 Hz, 10 Hz and 1 Hz were used. The repetition of the first value checks if the specimen was damaged during the test. For each frequency, 100 repetitions were considered. As for loading, a controlled deformation mode was chosen, setting the maximum deformation amplitude at 50µm / m, a value that, according to the standard, does not cause damage to the samples.

3. Results

3.1. Soils

According to data in Table 1, the pH of both soils (red and white) showed low values, being classified as very acid.

Table 1: Chemical analysis of Urucu soils

Test	White Soil	Red Soil	Classification	Parameter
Ph	3,7	3,8	Low	pH < 5
M.O $_{\text{dag/Kg-1}}$	0,9	1,1	Low	< 1,5
CTC -T $_{\text{cmolc/dm-3}}$	31,9	21,2	High	> 15
CTC – t $_{\text{cmolc/dm-3}}$	8,7	4,4	High, Low	>4,0/ < 5,0
V $_{\%}$	2,0	3,4	low saturation	< 50
m $_{\%}$	92,5	83,5	High	> 50
Ca $_{\text{cmolc/dm-3}}$	0,5	0,6	Low	< 1,6
Mg $_{\text{cmolc/dm-3}}$	0,1	0,1	Low	< 0,4
K $_{\text{mg/dm-3}}$	20	12	Low	< 30
Al $_{\text{cmolc/dm-3}}$	8,1	3,7	High	> 1,0

It is observed that, in general, tropical regions have such characteristics, resulting from the action of intense weathering arising from high rainfall and high temperatures [10]. There are low levels indicating organic matter. It is noteworthy that this parameter and the type of mineral clay influence the Total CTC (T), which showed high values for both soils. Alluding to effective CTC (t), it was noted that due to the high aluminum content present in white soil, this indicated a higher value (8.7) relative to red soil (4.4). Therefore, they were classified as high and low effective CTC, respectively. Depending on base saturation (V%), both soils are of low saturation. Concerning the aluminum saturation index (m), the group of soils showed high levels (>50). It is emphasized that a low value of the V index means that there is a small amount of cations (Ca^{2+}, Mg^{2+} and K^+) saturating the negative colloidal charges, and that most of them are being neutralized by H^+ and Al_3^+. Generally acidic soils demonstrate: insignificant V values; low levels of calcium, magnesium and potassium; and, still, high levels of aluminum [10]. Therefore, it generally appears that the soils showed similar chemical characteristics. However, it is worth mentioning that there was an important difference between them due to the higher aluminum content in the white soil, which resulted in a higher value of the effective CTC. Specifically, to the texture, analyzed by the granulometry test by sedimentation, the percentages exposed in Table 2 were determined. Based on these data, the red soil was classified as sand-silty clay, while the white soil as clay silto-sandy [11]. Although these results show differences, both soils showed greater participation of fines (silt and clay), that is, 71.65% and 93.6% for red and white soil, respectively. This result is typical of soils in the Amazon Region, which, due to this granulometry, are normally highly influenced by humidity, causing great variations in their plastic properties [12].

Table 2: Granulometric composition of Urucu soils

Soil	**Clay (%)**	**Silt (%)**	**Sand (%)**
Red	56,36	15,29	28,35
White	51,40	42,20	6,40

The mineralogical identification of the soils expressed similar diffractograms (Figure 2), in which the presence of the primary mineral quartz (Q) was observed, with well-defined and high intensity peaks, in addition to characteristic peaks of ilite (I) and kaolinite (C). It is emphasized that in the Amazon Region there is a predominance of lateritic soils, these arising from transformations of the upper part of the subsoil due to weathering, especially through the process called laterization. They are essentially constituted by the clay mineral of the kaolinite group, also presenting hydrated iron and / or aluminum oxides [13,14].

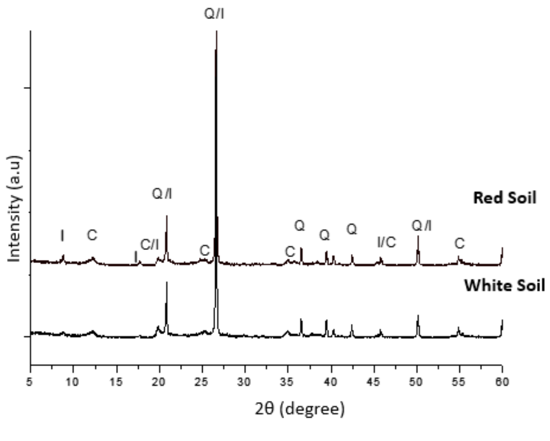

Figure 2: Diffractograms of Urucu soils

In summary, the characterization by XRD showed similarity of soils (white and red) in terms of mineralogy, although with different granulometries. It is also noticed that both natural materials from Urucu have quartz (primary mineral) in their composition; kaolinite of structure 1:1, connected by hydrogen bonds and with a basal spacing of 7A°, being a non-expansive clay; in addition to the 2: 1 structure illite, non-expansive clay, with a fixed basal spacing of 10A°, with the presence of characteristic potassium ions K^+, allowing the structure to be rigid.

3.2. Additions

The diffractometry of the Portland cement additive, CP II E-32, identified its main and usual constituents, namely: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and iron-aluminate (C_4AF), in addition calcite and gypsum (Figure 3). The Portland cement mineralogy, regardless of the product typology, presents the aforementioned minerals [15].

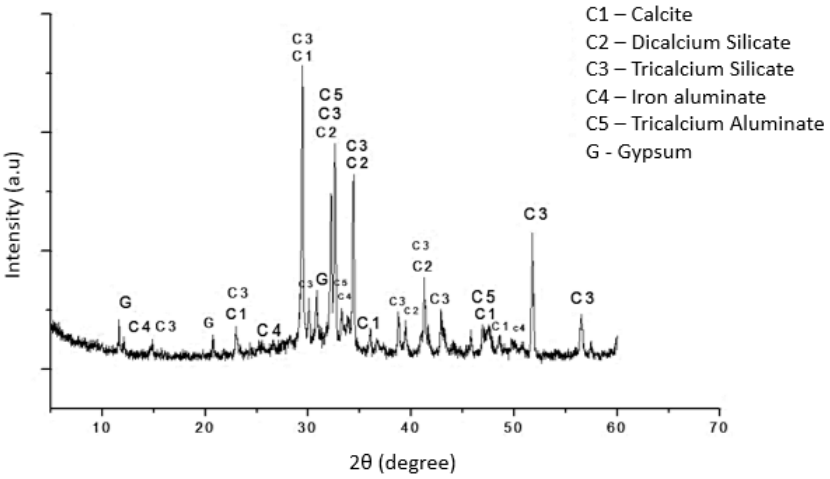

Figure 3: Portland cement diffractogram (CP II E 32)

Concerning the Roadcem® additive, it can be emphasized that there are still few available studies in the literature. Such product, according to La Roij [9], comprises groups of compounds, in a combination, in general, of chlorides, as well as of magnesium oxide, magnesium hydrogen phosphate, magnesium sulfate, sodium and silica carbonate and / or zeolite and / or apatite. The relevant information to the handling of the mentioned additive by PowerCem Technologies, emphasizes that the curing of the compositions with its participation, must meet specific conditions of humidity and the sufficient presence of oxygen, in order to provide the development of a dense crystalline matrix [1]. In order to verify this behavior, Roadcem® was isolated, which presented stages of hydration. Within three months, the presence of small crystals was identified, and, at six months, crystalline plates were macroscopically visualized. The mineralogy of these phases, here called hydrated, anhydrous and crystalline, was analyzed. The diffractograms of the representative samples of these steps (Figure 4), showed the presence of characteristic and well-defined peaks of the minerals halite and silvite, sodium chloride (NaCl) and potassium chloride (KCl) respectively. Thus, through the XRD results, the major compounds of the product were recognized, that is, sodium and potassium chloride [9].

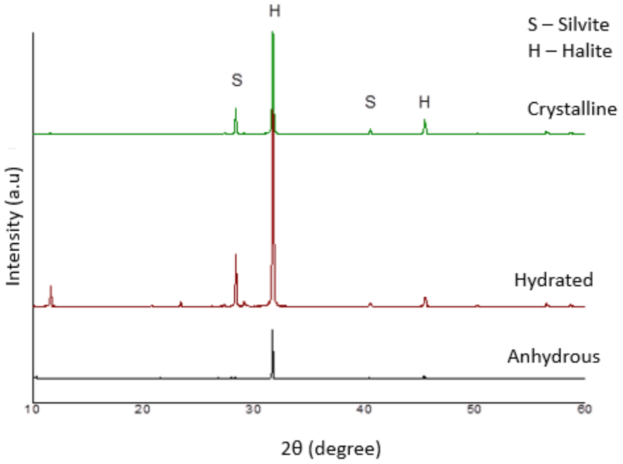

Figure 4: Roadcem® diffractograms in the different phases

3.3. Additives and compositions

3.3.1. Mineraalogical analysis

The Roadcem® product was produced as an additive to cement. Thus, in order to analyze the chemical interaction between them, diffractometry of the hydrated Portland-Roadcem® cement composition was performed, in addition to the cement paste, for comparison purposes. After a period of six months, the said formulation showed the presence of the crystalline matrix of Roadcem®, as well as a more rigid material relative to cement paste (Figure 5). Concerning the mineralogy, there was a similarity between the diffractograms of the composition and the cement paste, confirming the presence of the main components of the cement (Figure 6), in addition to specific and well-defined peaks of halite and silvite.

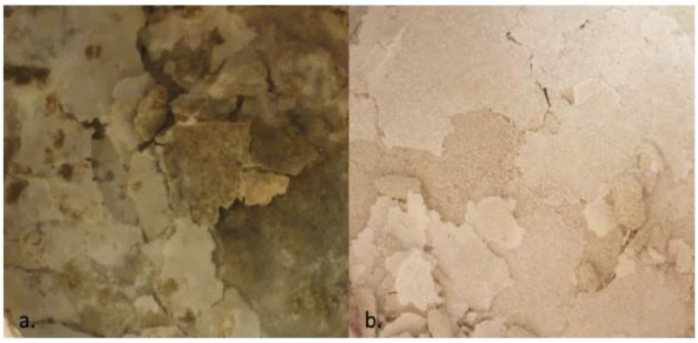

Figure 5: a) Cement- Roadcem® composition; b) Cement paste

Regarding the compositions Portland-Roadcem® cement, white-cement Portland-Roadcem® soil, and red-cement Portland-Roadcem® soil, after six months, crystalline matrices were distinguished, which can be seen in Figure 7. Diffractometry (Figure 8) allusive to these formulations mainly shows the peaks of the main members of Roadcem®, halite and silvite, and the quartz in the mixture with the white soil.

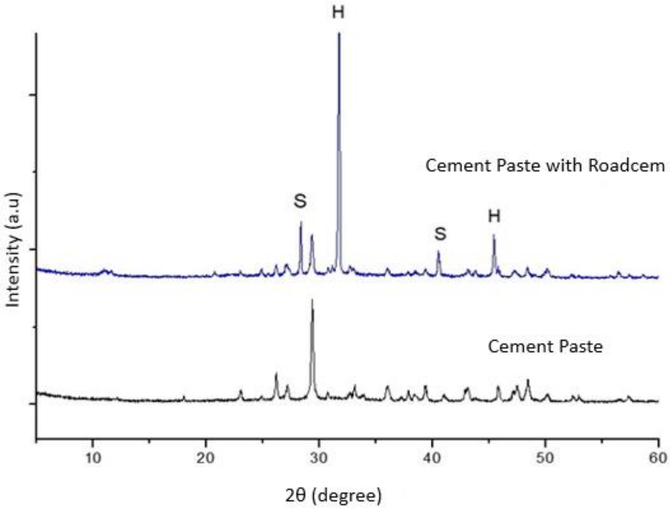

Figure 6: Diffractograms of the cement-Roadcem® composition and the cement paste

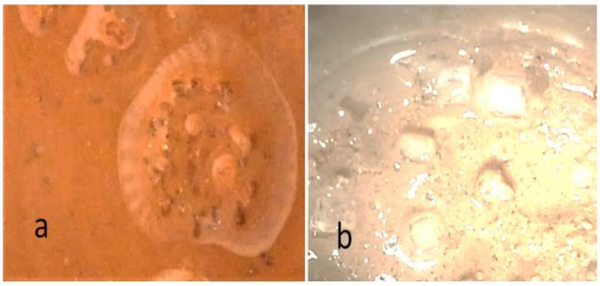

Figure 7: Compositions after six months: a) red cement-Portland-Roadcem® soil and b) white cement-Portland-Roadcem® soil

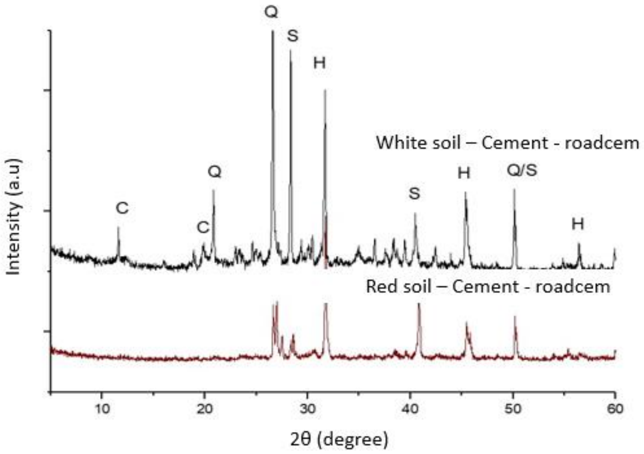

Figure 8: Diffractograms of soil compositions with Portland-Roadcem® cement (6 months)

According to the Dutch company PowerCem Technologies, the effectiveness of Roadcem® for road construction is due to the development of a crystalline matrix formed by the product, which fills the voids present in the soil and provides resistance to the stabilization process [1]. In the present study, the formation of this crystalline matrix in the Portland-Roadcem® cement mixture is highlighted, emphasizing the presence of high intensity peaks of the main constituents of Roadcem® (halite and silvite), as shown by diffractometry. Such matrix was found in both typical soils of Urucu (Coari-AM), with well-ordered crystals standing out in the white soil. It is also indicated that the development of these matrices did not occur in an immediate process. Initially at three months, there was intense hydration of the compositions promoted by the additive Roadcem®. At six months, the white-cement Portland-Roadcem® and red-cement Portland-Roadcem soil formulations presented crystalline matrices of Roadcem®, which were observed macroscopically. It should be noted that the aforementioned crystalline matrices were obtained under specific conditions of humidity and sufficient presence of oxygen. Therefore, through these results, it was found that the aforementioned additive developed the crystalline matrix, as mentioned by the product supplier, PowerCem Technologies. Wu [8] analyzed two soils, one clayey and the other sandy with Roadcem®, according to different dosages of the additive, in a total period of 90 days. The morphological results by scanning electron microscopy (SEM) showed dense microstructure. According to this study, the interaction of soils with Roadcem®, involves a complex chemical reaction, which needs further investigation.

3.3.2. Mechanical Behavior

The average values determined in the tensile strength test by diametrical compression (σt) are shown in Table 3. An increase of more than 100% of this parameter is observed for the compositions, in relation to the natural soil. The biggest increase for the Portland soil-cement mixture stands out, with a high value equal to 383%, indicative of natural soil. The Portland-Roadcem soil-cement composition, in turn, showed an increase of around 244%. WU [8] researching the Portland-Roadcem clay-cement mixture indicates an average value (1.59MPa), similar to that exposed in the mentioned table (1.54MPa), related to the tensile strength for 7 days of curing. The percentage difference, between the two numerical values, is 2.53%. Allied to this, WU [8] also attests that the addition of Roadcem to the compositions, in the studied humidities, did not significantly change the mentioned parameter (σt).

Table 3: Indirect Tensile Strength Result

Composition	**σt (MPa)**
Natural Soil	0,73
Soil + Cement	2,30
Soil + Cement + Roadcem	1,54

The literature cites other publications on stabilized soils. Table 4 describes some results of these studies for the dosage of 9% Portland cement, 0.9% Roadcem, with a seven-day curing period. Although some test conditions were different, in particular, the curing time and percentage of cement and stabilizing additive were compared to the values of the present study. Thus, in terms of percentage increases, the chemical stabilizer Roadcem showed higher values than all compared formulations, specifically: coal residue (94.94%); Tylac® 4190 (61.04%); fine fly ash (92.86%); heavy fly ash (90.91%); granulated blast furnace slag (88.96%); coconut fiber (98.38%).

Table 4: Literature work on the Tensile Strength of stabilized soils

Additions	**Curing period (days)**	**Portland Cement (%)**	**Stabilizing Additive (%)**	**ITS (MPa)**
Coal waste	14	6	5	0,078
Tylac® 4190	7	4	5	0,6
Gray flywheel small	7	-	6	0,11
Gray flywheel	7	-	6	0,14
Granulated blast furnace slag	7	-	3	0,17
Coconut fiber	7	5	1	0,025

In turn, the samples made to perform the four-point flexion test were compacted until the pre-established measurements were reached, whose height ranged from 50.0mm to 50.9mm. Figure 9 shows an example of the beam (specimen) after the test, under the template used as a guide for its construction. From the data generated during the test, the dynamic stiffness module was calculated. In Figure 10, the increase of this parameter, as the frequency was increased, can be seen, for all the formulations studied, diverging from Wu [8], in which the mentioned parameter remained basically constant compared to the different frequencies in the range of 0,4 to 20Hz. The significant addition of the complex module in the additive compositions in relation to the natural soil should also be noted. In particular, the formulations at the frequency of 10Hz, indicative of the “in natura” material (742 MPa), showed values of 3758 MPa (soil-cement) and 3250 MPa (soil-cement-Roadcem).

Figure 9: Beams positioned below the standard meter

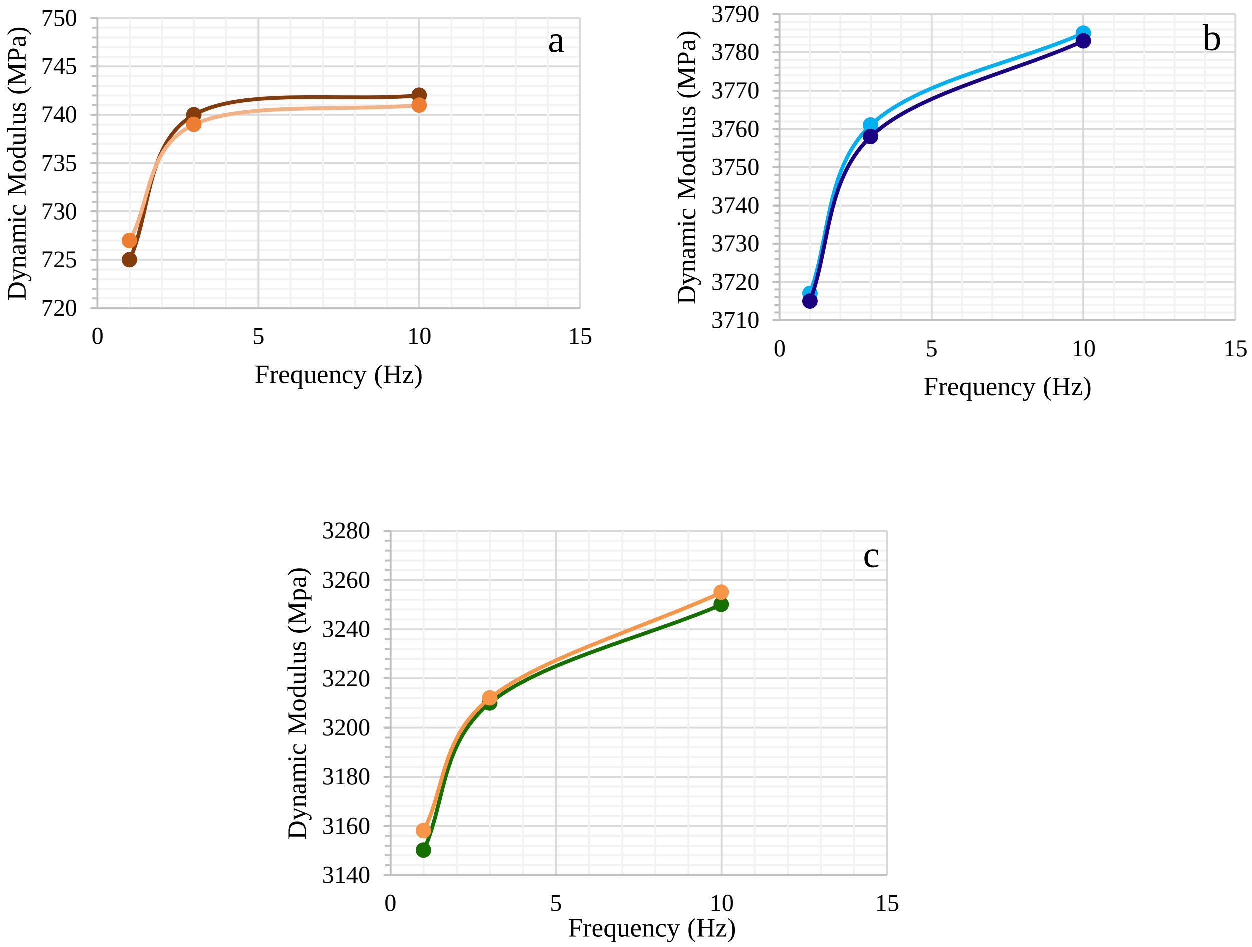

Figure 10: a) Dynamic modulus of natural soil; b) soil + 9% cement; c) soil + 9% cement + 0,9% Roadcem

4. Conclusion

The results obtained made it possible to understand the behavior of the chemical additive Roadcem® when mixed with two soils characteristic of the Urucu region (Coari-AM) and in the presence of Portland cement. In view of the analyzes carried out, it was concluded:

a) The soils presented similar chemical profiles and predominant granulometry of fines (clay + silt), that is, 93.6% and 68.5%, for white and red soil, respectively;
b) The additive Roadcem® hydrates in contact with oxygen and forms crystals, which grow generating an intense crystalline matrix, having sodium chloride and potassium chloride in its constitution.
c) The presence of oxygen and moisture is essential for the development of the crystalline matrix;
d) Roadcem® analyzed in isolation, in the composition Roadcem®-Portland cement, as well as in the formulations white soil-Portland-Roadcem® and red soil-Portland-Roadcem®, showed the formation of the crystalline matrix, with typical and high peaks intensity of the main constituents of the said additive;
e) Roadcem® crystals can be viewed at a macroscopic level, but not immediately, requiring a reaction

period of six months for such observation;

f) The behavior of the mixtures, when submitted to the tensile strength test, showed better results alluding to the natural soil. It is worth mentioning the Portland soil-cement composition, which reached a value of 2.3 MPa, that is, an increase of more than 300% in relation to the “in natura” material;

g) The stiffness module of the compositions increased with respect to the natural soil. It is noteworthy, in terms of average values and for the frequency of 10 Hz, a value equal to 3785 MPa for the Portland soil-cement mixture, and 3250 MPa for the Portland-Roadcem soil-cement formulation.

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