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Evaluation of X-Ray Computed Tomography in an Erodible Soil Reinforced with Babassu Coconut Fibers and Construction Waste

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Abstract

To guarantee the maintenance of the environment, the civil construction sector has expanded its search for materials from renewable sources and, therefore, composite materials are being produced from the reuse of natural fibers and construction waste. This study analyzes the physical and mechanical behaviors of an erodible hillside soil reinforced with natural babassu coconut fibers and civil construction waste (CCW), class A. As methodological procedures, the Unidimensional Densification laboratory test was carried out for the soil, CCW, and composites, observing the void index versus log curves of the effective tension, the porosity content, and the compression index. The X-Ray Computed Tomography non-destructive test was also performed for comparative purposes of the porosity result. The results showed that the use of CCW and babassu coconut fibers in the reinforcement reduces voids present in the soil. This reduction points to better soil function in the face of erosion caused by the action of water. The composite with 50% soil + 49.5% residue + 0.5% fiber was the one with the lowest voids index, guaranteeing a 21% reduction in porosity. It was possible to verify that the tomography test provides results compatible with the one-dimensional densification test, regarding the determination of porosity, with variations of ± 3%.

Keywords: Composite materials; Non-destructive assay; Soil porosity.

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1. Introduction

Soil is an integral and fundamental part of civil engineering. In addition to being used as a building material, it supports the loads coming from the buildings to which it is subject. The soil has characteristics that vary between the different locations of the land. That is due to the processes that gave rise to it, the transport processes, and weathering. In general, soils have little resistance to mechanical stresses and, therefore, several improvement techniques have been investigated. The improvement is associated with soil treatments by chemical (addition of lime, cement), physical (granulometric stabilization), or mechanical (compaction) processes. The treatments can still be listed in three groups: (1) temporary - limited to the construction period; (2) permanent - without the addition of any materials; and (3) permanent - with the addition of materials to the natural soil [1,2,3]. Soil reinforcement is a technique to improve the physical characteristics and mechanical behavior through materials composed of desired properties [4]. According to [5], concerning the life cycle of a composite, it points to a lesser impact on human health, the environment, and natural resources throughout the cycle assessment. Improving soils with sustainable materials is one of the aspects that can generate positive impacts through the introduction of non-polluting materials and the reuse of residues [6]. In general, synthetic and natural fibers can be used to reinforce the soil. With the growing focus on maintaining the environment, it is advisable to use natural fibers with low biodegradation potential [7]. Thus, composites reinforced with natural fibers can have mechanical properties comparable to non-composites applied for the same purpose, maintaining the advantage with reduced energy consumption [8]. However, [9] warns that materials alone, which are being developed as environmentally friendly alternatives, won't capture the full extent of environmental liabilities. Natural fibers can be extracted from stems, leaves, seeds, fruits, wood, cereal straw, and other material waste [10]. Several studies are applying natural fibers in composites to improve the material properties [11]. Reference [12] realized that the original, unprocessed fibers have more favorable properties compared to recycled fibers. However, depending on their application, recycled fibers can replace new filaments. Natural fibers can also replace other materials, such as steel and polymers. In addition to natural fibers, civil construction waste (CCW) in aggregate form is also used for soil reinforcement. This application is configured as an environmentally correct destination for the CCW and can produce a new material (composite), more resistant, and which undergoes fewer deformations [13]. It is possible to analyze the chemical, physical, and mechanical properties of composite materials, mostly from tests that use non-recoverable specimens (CP's). Due to the technological control for molding the CP's and the sample size, non-destructive tests can be advantageous for scientific research as they reduce time and use of materials. The technique employed in X-ray Computed Tomography (CT) is one of the most modern non-destructive methods that allows images of the internal structure of materials to be obtained [14]. Non-Destructive Testing (END) techniques are alternatives for characterizing materials, which do not generate physical damage and do not affect mechanical properties [15]. The study of images from the soil tomography test allows defining their mechanical and physical properties, such as: locating defects and voids, porosity, the distribution of aggregates, soil density, the spatial distribution of water content, and water retention and movement on the ground [16,17,18]. According to [19], in the last 30 years, X-ray CT has provided a non-destructive means for visualizing and quantifying 3D soils, having been applied to cover the extensive characterization of the geometry of porous space and fractures within a soil sample. Thus, the visualization of 3D samples and the correlation of the results with complementary laboratory measurements, as in the density test, can help in understanding the processes of formation and development of pores over time. Thus, this study analyzed the physical and mechanical properties of a hillside erosive soil. It was reinforced with natural babassu coconut fibers and civil construction waste through the One-Dimension Density assay. For comparative purposes, the Computed Tomography test was performed to verify the effectiveness of geotechnical studies.

2. Materials and methods

The soil was removed from a slope in Bom Jesus, on the island of Itamaracá - PE. The civil construction waste (CCW) (class A) was collected from a recycling company located in Camaragibe, Metropolitan Region of Recife - PE. The babassu coconut shell was collected in a coconut breakers cooperative in Santa Inês - MA. To improve the fibers, cutting instruments were used. Repeated movements were applied in a scraping process. It was possible to detach residues, leaving the fibers visible. Then the fibers were shredded (Figure 1). Measuring fiber diameter (shredded) was performed with a caliper. Since the fibers are of natural origin, variations between 2mm to 4mm were found.

Figure 1: Process of processing babassu coconut fibers

The percentages of soil and CCW used in composites are following the best results obtained by [20], being: S50R50 (50% soil + 50% CCW) and S70R30 (70% soil + 30% CCW). To determine the content and length of babassu fibers, the works of [21, 22, 23, 24], were consulted. Thus, the incorporation levels were set at 0.5% and 1.0% and the length of 30 mm for the fibers. The nomenclature for composites is available in Table 1.

Table 1: An example of a table

Nomenclature	Composites
S50R49F1	Soil (50%) + CCW (49%) + babassu fibers (1%)
S50R49.5F0.5	Soil (50%) + CCW (49.5%) + babassu fibers (0.5%)
S70R29F1	Soil (70%) + CCW (29%) + babassu fibers (1%)
S70R29.5F0.5	Soil (70%) + CCW (29.5%) + babassu fibers (0.5%)
S99F1	Soil (99%) + babassu fibers (1%)
S99.5F0.5	Soil (99.5%) + babassu fibers (0.5%)

The physical and mechanical properties of the soil, CCW, and composites are shown in Table 2. Table 3 describes the physical and mechanical properties of babassu coconut fiber.

Table 2: Physical and mechanical properties of the soil, CCW, and composites

Physical						Mechanical	
Sample	Actual density (g/cm³)	LL (%)	PL (%)	PI (%)	Classification	Optimal humidity (%)	Maximun dry density (g/cm³)
Soil	2.73	53.28	21.75	31.53	Highly Plastic	28.2	1.53
CCW	2.61	NL	NP	-	Non plastic	12.7	1.89
S50R49.5F0.5	2.64	25.04	20.20	4.84	Little Plastic	17.1	1.73
S50R49F1	2.65	40.88	17.10	23.78	Highly Plastic	15.6	1.73
S70R29.5F0.5	2.66	27.31	18.40	8.90	Medium Plastic	21.4	1.65
S70R29F1	2.67	33.74	16.78	16.96	Highly Plastic	21.6	1.61
S99F1	2.63	39.54	17.15	22.39	Highly Plastic	20.8	1.66
S99.5F0.5	2.67	43.79	20.20	23.59	Highly Plastic	18.7	1.65

Table 3: Physical and mechanical properties of babassu coconut fiber [25]

Fiber	Density (g/cm³)	Modulus of elasticity (GPa)	Tensile Strength (MPa)	Moisture absorption (%)
Babassu coconut	0.91	8.5	183.8	2.0

The analysis of the material properties was based on tests standardized by the Brazilian Association of Technical Standards (ABNT): NBR 6457/2016 - Soil Samples - Preparation for compaction and characterization tests; NBR 7181/2016 - Soil - Particle Size Analysis; NBR 6459/2016 - Soil - Determination of the Liquidity Limit; NBR 7180/2016 - Soil - Determination of the Plasticity Limit; NBR 12007/1990 - Soil - One-dimensional densification test - Test method. The Non-Destructive Testing (END) technique was also used. The one-dimensional densification and computed tomography tests took place at the Geology Laboratory of the Catholic University of Pernambuco - UNICAP and in the Soil Physics Laboratory of the UFPE Department of Nuclear Energy, respectively.

2.1. Section headings One-dimensional densification

The one-dimensional densification test for the soil, the CCW, and the composites was carried out with the objective of better understanding the effects of the inclusion of babassu fiber in the void index curves (e) versus the log of the effective tension (σ'), in the porosity content (η) and the decompressibility parameter - compression index (Cc). For the test, a Solotest press was used. The samples were extracted from the compacted specimens at the maximum dry density and optimum moisture content. The metallic ring (mold) used had 40 cm² in area and height of 2 cm; the endometrial cell was of the fixed ring type. The vertical deformations were read using strain gauges with a sensitivity of 0.01 mm, and in a time interval determined by [26]. Initially, the samples were kept in saturation for 24 hours (Figure 4.10), recording the material expansion as a function of time. Then, loads were carried out, doubling the load every 24 hours. The sequence of pressures applied to the samples was 10, 20, 40, 80, 160, 320, 640, and 1280 kPa. The compression index (Cc) was determined by tilting the compression line, obtained in the loading steps. The Pacheco e Silva method was used to determine the density stress [26]. The porosity content (ɳ) of the samples was obtained from the final void index (e), according to Equation 1.

$$\eta\,(\%) = \frac{e}{e+1} \qquad (1)$$

2.2. Non-Destructive Testing (END)

The molding of specimens (CP's) used the static form, where the filling of the cylindrical mold (50 mm in diameter and 100 mm in length) took place in three layers, with scarification between layers.All CP's were digitalized using a third generation X-ray microtomograph model NICON XT H 225 ST (Figure 2), at 150kV, with 0.5 mm thick copper (Cu) filter, and with an integration time of 3,500 milliseconds, generating an axial sequence of x-ray attenuation images. During CT scans, samples were wrapped in plastic wrap to minimize possible moisture loss. The three-dimensional reconstruction of the images was performed using the CT Pro 3D XT 3.0.3 software (Nikon Metrology NV) for a final size of 40µm voxel and, from the selected area (Figure 4,12), 683 images were generated for each PC, with a 16-bit intensity.

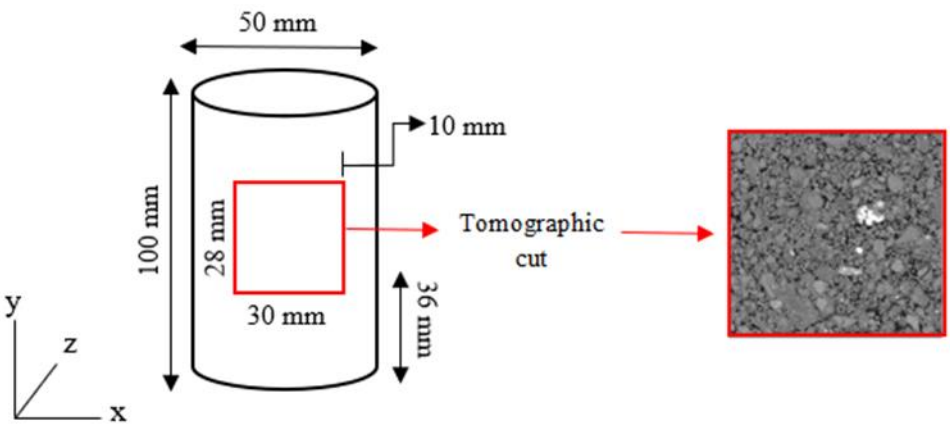

Figure 2: Process of processing babassu coconut fibers

The tomographic images of the soil, CCW, and composites were obtained with an area of 8.4 cm² and a volume of 22.68 cm³ (with 752 x 716 x 683 Voxels), approximately. The selection of the area for reconstruction was necessary due to the inability to reconstruct images of large samples. To view the reconstructed image, the VGStudio MAX software was used with the application of the Gauss filter to minimize noise and the transformation of the scale (radiodensity) was dimensioned according to the Hounsfield Field Scale (Hu), where the air is equal to 0 Hu and the water is equal to 1000 Hu. The ImageJ software was used for image processing. Initial image binarization involved the use of standardized and thresholding procedures [27], developed by [28], which included manual thresholding, image multiplication to convert the binary into Hu. For manual thresholding, the Threshold tool of the ImageJ software was used. With this tool it is possible to visualize the histogram of the images and, from there, select the region of interest, that is, the peak that best represents the voids and/or the material matrix. To better represent the interaction between the material phases, the region selected in the manual thresholding process was the sum of the region that represents the voids and the region close to the peak of the histogram. After the procedure of analysis and treatment of the images in the ImageJ software, the porosity of the materials was calculated by the relation between the sum of the pore volumes (mm³) and the reconstructed subvolume of the sample area (Equation 2). So, the pore volumes were calculated by multiplying the volume (in voxel) provided by the software and the image resolution (voxel size) [29], Zaccording to Equation 3.

3. Results and Discussion

$$\eta = \frac{V\ poro}{V\ subvolume} \times 100 \quad (2)$$

$$V_{poro} = V_{Voxel}.(Voxel^3) \quad (3)$$

3.1. One-dimensional densification

Figures 3 and 4 show the vertical stress versus void index curves obtained in the unidimensional densification of the soil, the CCW and the composites. The test was performed only for the flooded condition.

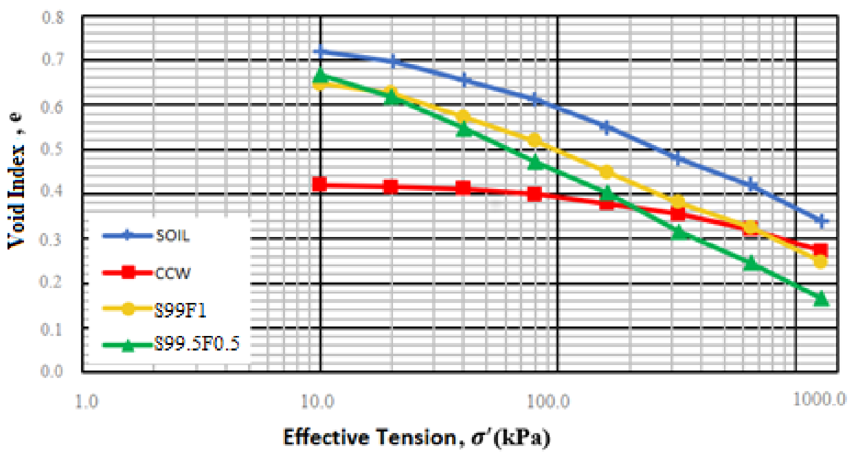

Figure 3: Void index curve vs. Effective soil tension, CCW and composites soil-CCW-fiber

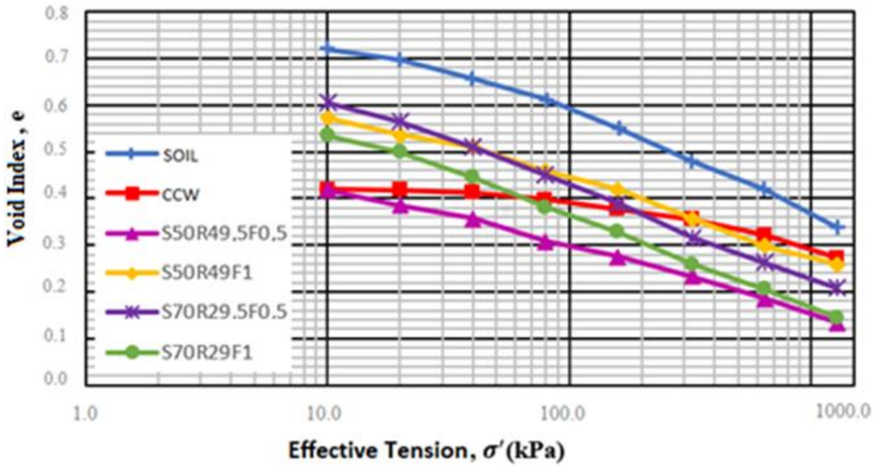

Figure 4: Void index curve vs. Effective soil tension, CCW and soil-fiber composites

The void index curves versus the effective tension of the soil and the composites presented similar formats, with gradual decreases in stiffness as the effective tension increased. For the CCW curve, a different behavior was observed, so that the drop in stiffness was more evident from the tension of 300 kPa. Still observing the behavior of the void index curves versus effective stress, it is possible to notice that the soil-fiber composites (S99F1 and S99.5F0.5) presented very close and that there was the meeting of the curves in the second compression section where the stress effective (σ') was between 20 kPa to 30 kPa, resulting in similar behavior in the curves for this stretch. The addition of different levels of CCW and babassu coconut fibers in the soil did not cause a reduction in the slope of the virgin compression line. This means that the addition of the materials did not increase the compressibility of the composites, a result that differs from [30], who observed that the higher the green coconut fiber incorporation content, the greater the slope of the virgin compression line. Table 4 shows the indices of initial (e_0) and final (e_f) voids (of the materials, the initial (η_0) and final (η_f) porosity contents, as well as the difference between these values.

Table 4: Variation in void indices and soil porosity levels, CCW and composites obtained in the one-dimensional densification test

Sample	e_0	e_f	Δe	η_0	η_f	Δ η (%)
Soil	0.720	0.339	0.381	42%	25%	**- 17**
CCW	0.421	0.273	0.148	30%	21%	**- 8**
S50R49.5F0.5	0.479	0.134	0.345	32%	12%	**- 21**
S50R49F1	0.572	0.260	0.312	36%	21%	**- 16**
S70R29.5F0.5	0.676	0.209	0.467	40%	17%	**- 23**
S70R29F1	0.589	0.144	0.445	37%	13%	**- 24**
S99F1	0.647	0.248	0.399	39%	20%	**- 19**
S99.5F0.5	0.667	0.166	0.501	40%	14%	**- 26**

The S99.5F0.5 composite was the material that showed the greatest volumetric variation due to the increase in effective tension (σ'), so that the initial void index (e_0) from 0.667 was reduced to 0.166 (e_f) when reaching 1280 kPa. As for the CCW, it showed the smallest volume reduction, being e_0 0.421 and e_f 0.148. Thus, it is clear that thin materials (clayey) have a higher void index than thicker materials (sand). Reference [31] verified the linear correlation between the physical properties of the soil and found that clay soils have a void index around 0.86 and sands have an index of 0.31. The composite S50R49.5F0.5 obtained the lowest index of the initial (e_0) and final (e_f) voids among all other tested composites. This result can be justified by the cohesive effect that babassu coconut fibers provide to the material. Reference [32] also verified this effect with the addition of sisal fibers in clayey soil, in which composites with 0.5% fiber increased the cohesion from 93 to 115 kPa. In turn, the S50R49.5F0.5 composite also resulted in the lowest initial (η_0) and final (η_f) porosity levels, being 32% and 12%, respectively, which means a 21% reduction in the porosity of the composite. We have the composite S70R29F1 with η_0 37% and η_f 13%, thus guaranteeing a 24% reduction in porosity content. Table 5 presents the compression index (Cc) - compressibility parameter - obtained through the curves of Figures 3 and 4. It is verified that the composites presented Cc lower than the value obtained for natural soil, with reductions between 0% to 57%, approximately.

Table 5: Compression index (Cc) of natural soil and composites

Sample	Cc	Δ de Cc
Soil	0.227	-
CCW	0.017	-
S50R49.5F0.5	0.098	57%
S50R49F1	0.149	34%
S70R29.5F0.5	0.178	22%
S70R29F1	0.178	22%
S99F1	0.203	11%
S99.5F0.5	0.226	≈ 0%

Concerning the compression index (Cc), it can be seen that there were reductions of 57% to 11% as CCW and/or babassu coconut fibers were incorporated in the composites, except for the S99.5F0.5, which reached the same Cc obtained by the soil, approximately. It should be noted that the greatest reduction in Cc was recorded for the composite S50R49.5F0.5. Reference [30] found that composites of clay soil reinforced with 0.5% and 1% green coconut fiber presented Cc of 0.218 and 0.256, respectively. The author's results are close to the values of 0.203 and 0.226 found for the Cc of composites S99F1 and S99.5F0.5. Regarding the behavior of the materials during the saturation period, it was found that the soil and the composites, therefore, had an expansive character with deformations about the height of the specimen from 0.8mm to 1.46mm, confirming the results obtained by [20] during soil characterization. Reference [20] investigated the same soil and the CCW used in this article. The objective was to evaluate the properties of the recycled aggregate for a landfill coverage system. The expandability test (ε) resulted in a ε of 14.57%, which means poor soil behavior in the face of erosion.

3.2. Characterization by Computed Tomography

Using high-resolution images from computed tomography, a qualitative comparison of porosity was performed between soil samples, CCW, and composites. In Figure 5, the dark dots represent the pores; the white dots are fragments of rock; the distribution of fibers in the composites is observed.

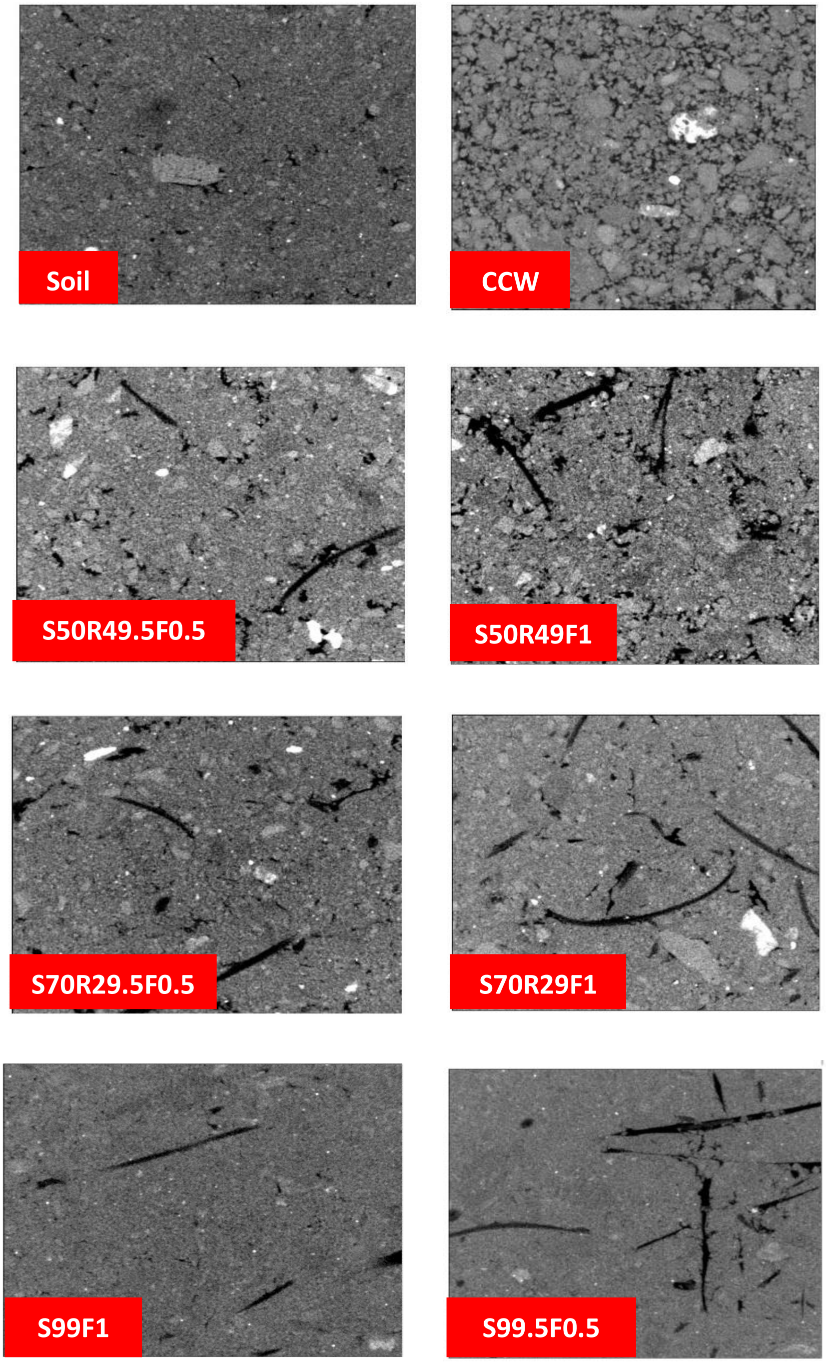

Figure 5: Images obtained by computed tomography

Using the ImageJ software, it was possible to calculate the porosity content (ɳ) for the soil, CCW, and composites, as described in Table 6.

Table 6: Content of soil porosity, CCW, and composites obtained in the computed tomography test

Sample	Porosity content (ɳ)
Soil	27%
CCW	24%
S50R49.5F0.5	12%
S50R49F1	23%
S70R29.5F0.5	19%
S70R29F1	15%
S99F1	18%
S99.5F0.5	15%

In the soil-fiber composites S99F1 and S99.5F0.5, it was found that the higher the fiber concentration, the higher the percentage of the composite porosity, a result also observed by [30]. Thus, the variation in fiber content from 0.5% to 1% caused an increase of 17% in porosity. Reference [30] when carrying out the compaction test for a soil – reinforced with 0.5% and 1% green coconut fibers –, verified reduction in dry density by 0.02 and 0.04 g/cm³ as well as an increase in moisture content excellent of 0.2% and 0.6%, respectively, leading to the conclusion that the fiber content resulted in mixtures with greater porosity. The porosity of the composites S50R49F1 and S70R29,5F0,5 was 23% and 19%, respectively, showing that they were the highest percentages among the tested composites. Reference [33] studied the behavior of the soil-CCW-lime mixture for use in road works and found that the increase in the void index and soil porosity was due, in part, to the presence of the recycled aggregate, corroborating the results found. In this way, it was considered that all composites are recommended for the reduction of pores of the studied soil, since their percentages of posts are lower than that of the soil itself, with the composite S50R49.5F0.5 being the most suitable. The analysis of the porosity content of the materials, based on the X-ray CT, also made it possible to verify that the soil was the material that reached the highest percentage with 27%, registering the lowest percentage (12%) for the composite S50R49, 5F0.5. This result is in line with the observations made during the one-dimensional densification test. The porosity levels found in the CT and unidimensional densification tests had variations of ± 3%, as shown in Figure 6. It is possible to compare the results of the mechanical method (densification) with the results of the non-destructive CT test, not yet standardized for geotechnical purposes. That ensures that the latter provides data with a tolerable confidence margin and they can be obtained in less time, streamlining and/or optimizing laboratory tests.

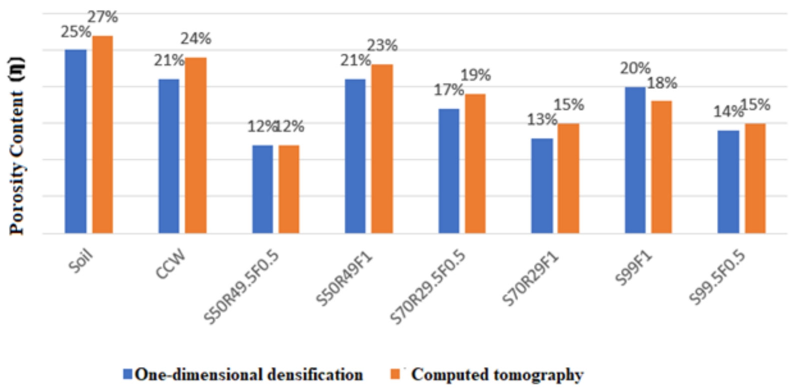

Figure 6: Comparison between the porosity levels obtained in the one-dimensional densification tests and computed tomography

4. Final considerations

This study showed that the use of civil construction waste (CCW) and babassu coconut fibers in soil reinforcement presents favorable results in reducing voids present in the soil. This reduction points to better soil behavior against erosion caused by the action of water. The S50R49.5F0.5 composite showed the lowest initial (0.479) and final (0.1364) void index, among all other composites, guaranteeing a 21% reduction in porosity. Finally, it was possible to verify that the X-ray computed tomography test can be used in geotechnical studies in determining the porosity of materials and that the test provides results compatible with the one-dimensional densification test, with variations of ± 3%.

5. Recommendations

In view of the results, it is recommended (1) to analyze the behavior of the maximum dry density curves versus soil moisture content, the CCW, and the composites for compaction in humidity above and below the optimum humidity; and (2) identify the compressibility parameters for soil, CCW and composites, especially the decompression index (Cd), to observe the potential deformation suffered by the materials after relieving the effective stress, in boh flooded and not flooded conditions.

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