MECHANICAL ANALYSIS OF A REINFORCED CLAY SOIL WITH AÇAÍ (EUTERPE OLERACEA) FIBERS

M.M. Lopes, Department of Civil and Environmental Engineering-FT, University of Brasilia, Brasilia, Brazil, machadomlopes@gmail.com
M.D.T. Casagrande, Department of Civil and Environmental Engineering-FT, University of Brasilia, Brasilia, Brazil, mdtcasagrande@unb.br

ABSTRACT
The growing research for environmental sustainability applied in technological engineering works, with natural, non-polluting, renewable and without adequate destination materials guided this experimental research. The objective is to analyze the mechanical behavior of a clay soil reinforced with açaí fibers distributed randomly. The açaí fibers were chosen as reinforcement due to the large production that occurs in the north region of Brazil, that region is known for a strong consumption of açaí that generates lots of this waste, besides that these fibers presents great mechanical properties and are completely natural. Characterization, Uniaxial Compression Strength (UCS) and direct shear experiments were done in several samples with fiber contents of 0.5% and 1.0% in relation to the dry soil weight. The results obtained demonstrate that the addition of the açaí fibers significantly improved the mechanical properties of the soil, altering the material rupture behavior and providing a greater peak resistance and a decrease in the post-peak fall when the composite soil-fiber is compared to the natural soil. This kind of composite has a great application in regions of larger generation of this natural waste using it in geotechnical Works as slopes reinforcements and temporary landfills on soft soils.

RESUMO
A crescente busca por sustentabilidade ambiental na tecnologia aplicada a obras de engenharia, através do uso de materiais renováveis, naturais, não poluentes e sem destinação adequada guiou o estudo realizado nesta pesquisa experimental, que tem como objetivo analisar o comportamento mecânico de um solo argiloso reforçado com fibras de açaí distribuídas de forma aleatória. A escolha da fibra de açaí como reforço se deu pela grande produção observada no Nordeste Paraense, onde a “cultura do açaí” é muito forte, e pela qualidade de suas propriedades mecânicas, além do fato de ser uma fibra completamente natural. Foram realizados ensaios de caracterização, compressão simples e cisalhamento direto em diversas amostras com teor de fibras de 0,5% e 1%, em relação ao peso do solo seco. Os resultados obtidos demonstraram que a adição das fibras de açaí melhorou significativamente as propriedades mecânicas do solo, alterando o comportamento de ruptura do material e proporcionando uma maior resistência de pico, bem como diminuição da queda de resistência pós-pico, quando a mistura solo-fibra se compara ao solo puro. A aplicação deste tipo de compósito solo-fibra tem grande aplicação regional, em regiões de maior geração deste resíduo natural, podendo ser aplicado em obras geotécnicas, como por exemplo, reforço de taludes e aterros sobre solos moles.

KEYWORDS
Açaí Fibers - Alternate Materials – New Geotechnical Materials - Reinforced Soils - Geosynthetics

1. INTRODUCTION

The physical-mechanical properties exploitation of soils in engineering works is the most important assignment of a geotechnical engineer, often these properties are not enough to use in civil works and is needed to adapt these characteristics to those needs. Is possible to improve the soil properties using different techniques as mechanical compaction, physical-chemical stabilization and soil reinforcement with the inclusion of resistant elements as geotextiles, fibers, grills, strips (Casagrande 2005).
The reinforcement of soils technique refer to antiquity which were used by ours ancestors mixing soil with roots, logs or wool on civil works (Palmeira 1993). These techniques were forgotten by unknown reasons until the XX century where were rescued on sixties and the elements related to their uses were studied and understood (Silveira 2018).
The inclusion of fibers can be a great technique of improvement, depending on the interactions between the soil and fibers, due to the possibility to reduce cracking as well as the increase of soil ductility. For the fibers to perform is usually necessary the presence of certain granular fraction (Sales 2011).
The vegetable fibers use is relevant when compared to synthetics, those natural fibers has shown to be economically viable, have great availability, is easy to find and to handling (Ghavami et al. 1999; Dittenber and Gangarao 2012; Martins 2014; Silveira 2018). The natural fibers can be obtained from different parts of plants. There are fibers that can

be extracted from the stalk as jute, flax and hemp; you can extract fibers of leaves as sisal and curauá, from seeds as cotton and coconut fibers are obtained from the fruit (Thomas et al. 2011; Silveira 2018).
Is important to notice that the own vegetable fibers are natural composites of numerous individual fibers and part of this structure contributes to flexibility characteristics of them, due to high water absorption and low apparent specific mass (Tolêdo Filho 1997; Silveira 2016).
One of the relevant gains of using fibrous materials that is approached in this study is related to the contribution to the compressive strength parameters, potentially in the post-peak state (Taylor 1994; Illston 1994; Hannant 1994) e the constant increase of the resistance with gains in the axial deformation that shows an elastoplastic hardening behavior (Casagrande & Consoli 2002; Santiago 2011).

2. EXPERIMENTAL PROGRAM

The steps taken to accomplish this research was based on characterizing the soil, performing compaction tests on soil and the composites fiber-soil to determine the optimum moisture content and the matching maximum specific dry weight then Uniaxial Compression Strength (UCS) and direct shear to determine the resistance parameters and the açaí fibers scattered randomly addition effect on the mechanical properties of a clay soil.

2.1 Materials

2.1.1 **Clay Soil**

The soil used in the experiments came from Brasília, Distrito Federal, Brazil and the granulometry is shown in the Figure 1 and in Figure 2 is possible to visualize de soil appearance.

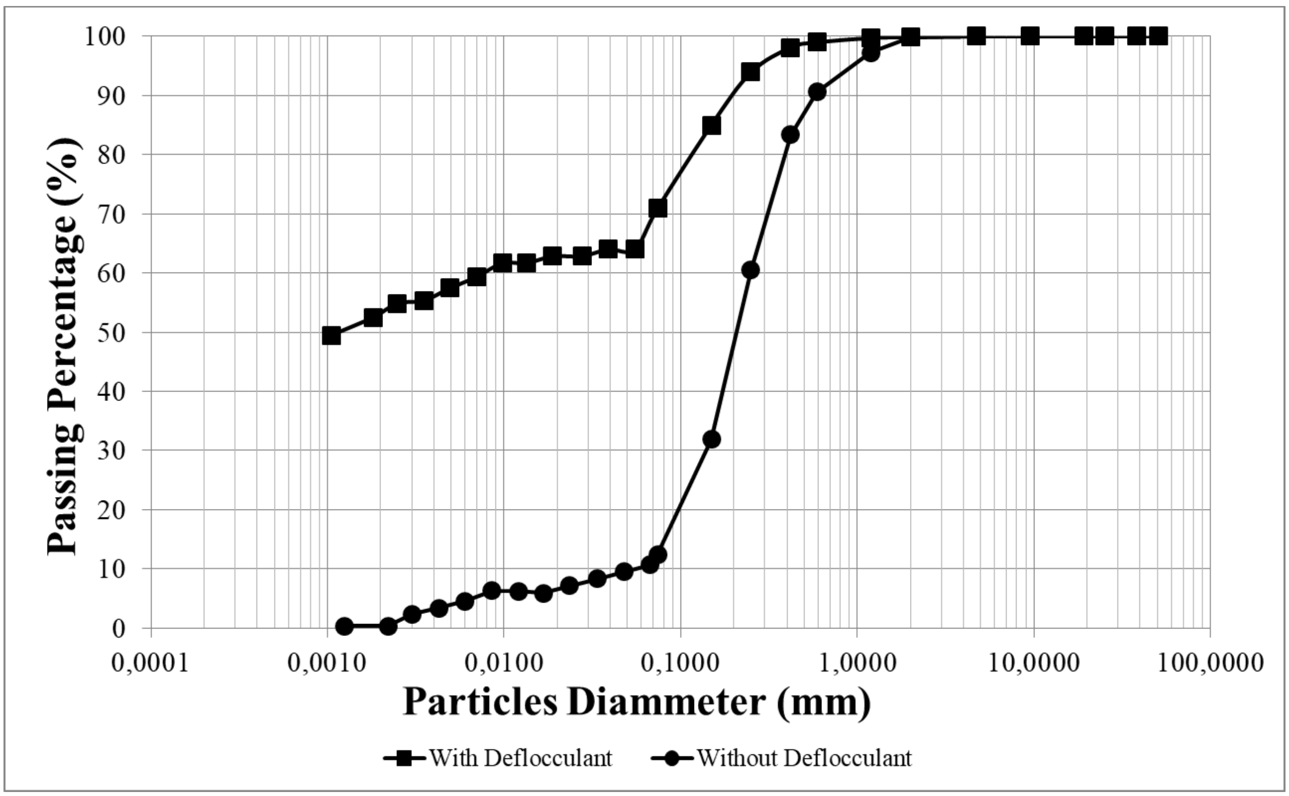

Figure 1. Clay Granulometry (Source: Author).

Figure 2. Clay Soil (Source: Author).

Based on the granulometric analysis is possible to notice that the studied soil is composed mostly by clay, representing 53.3%, followed by 36% of sand and 10.7% of silt. The Specific Gravity of Soil Solids obtained by the Penta pycnometer is 2.69 g/cm³. The Atterberg limits are: 42% of Liquid Limit, 27% of Plastic Limit ad 15% of Plastic Index. The results of granulometric analysis and Atterberg Limits allow classifying the soil according to the TRB Classification as a clay material belonging to the A-7-6 group and Group Index 10. This material has a regular to bad behavior for application in paving.

2.1.2 Fibers

Açaí fibers (Euterpe oleracea) were used as reinforcing elements, coming from fruit bagasse after the removal of the pulp. These fibers have diverse mechanical properties that can be exploited for a variety of purposes; there are researches that study fiber for the manufacture of eco panels that can be applied for acoustic insulation, for example (Mesquita 2013).
The açaí chain is one of the main sources of wealth and employment in the Northeast of Pará. Only in the city of Belém, there are about 2,500 establishments that daily trade around 305 tons of açaí (IBGE 2008), generating approximately 253 tons of organic waste, consisting mainly of discarded lumps in landfills and waterways (EMBRAPA 2012). The significant production of this material that is considered waste justifies and makes the use of this fiber economically feasible in the region of production. Is possible to observe more details about these fibers below:

Figure 3. Açaí: (a) Fruit (Source: Moscoso, 2012);
(b) Seed with fibrous tissue (Source: Mesquita, 2013);
(c) Açaí Fibers (Source: Author).

Fiber and core separation were done manually and randomly mixed to the ground as well as the length of the fibers, which are naturally small, varying from 1.0 to 1.8 centimeters. Is shown some numbers available about these fibers physical properties on table 1 below:

Table 1. Açaí Fibers Physical Properties.

ρ (g/cm³)	Section area (μm²)	D (μm)	L (μm)	L/D	Reference
1.11	2,017.29	129.93	18,410.00	142.32	Lima Junior (2007)
0.74	-	104.00	15,320.00	147.00	Gehlen (2014)

Notes: ρ = specific mass, D = diameter, L = length

2.2 Tests and Equipments

Following next is shown the tests methods and procedures used during the experimental program. The tests were based on standard methods and they will be referenced accordingly.

2.2.1 Compaction Tests

A Brazilian standard method proposed by the National Department of Highways and running-in, DNER-ME 288/94 (DNER 1994) describes the procedures to relate the soil moisture content and the dry apparent specific mass (compaction curves). The soils is sifted through a 2mm sieve and compacted in a miniature compaction device (cylindrical molds with 50mm diameter and 1000mm of high) in intermediary energy (procedure B) with unworked samples.

The compaction curves were determined for the pure soil, soil + 0.5% of fibers and soil + 1.0% compacting five samples with a 2.0% range of moisture content between them. This way, is possible to know the optimum moisture content and maximum specific dry weight correspondent to each curve.
Is possible to identify as well the void ratio to each composite using the correlation formula below:

$$e = \frac{\gamma_s}{\gamma_d} - 1 \quad [1]$$

Where:
e = Void Ratio
γ_s= Specific Gravity of Soil Solids
γ_d= Specific Dry Weight

2.2.2 Uniaxial Compression Strength (UCS)

The UCS was based on the Brazilian standards NBR 12770 (ABNT 1992). The test consists in break an unconfined sample using a plunger which is possible to control the displacement speed and measure the strength applied and the vertical displacement. The speed adopted must be ranged between 0.5% and 2.0% of the specific axial strain per minute (ε). These tests the speed used were 1.27 mm/min. The final results are expressed as a graphic of Stress X Strain (ABNT 1992).
The results show the influence of the fibers content in the peak and post-peak shear resistance of the composites soil-fibers.

2.2.3 Direct Shear Tests

The direct shear tests were executed according to the standard D3080/D3080M – 11 (ASTM 2011) to soil + 0.5% of fibers and soil + 1.0% of fibers with loads of 50 KPa, 100 KPa and 200 KPa. The first step is to execute the consolidation phase of the experiment and with the consolidation curve define the shear speed by Taylor's method (Taylor 1994) using the time necessary to occur 90% the primary consolidation. Based on that, was determined a speed of 0.05 mm/min to shear the samples and used the same for every sample.
The results show the influence of the fibers content in the shear resistance of the composites soil-fibers as well as the influence on the friction angle and cohesion.

3. DATA ANALYSIS AND DISCUSSIONS

From the compaction curves it is possible to notice that with the fiber insertion in the soil there is a reduction of the apparent specific dry weight of 17 KN /m³ for the pure soil, to 16.45 KN/m³ for the soil with 0.5% fiber and to 16.28 KN/m³ for the soil with of 1.0% of fiber and an increase of the optimum moisture content of 19.65% for the pure soil, to 22.71% for the soil with 0.5% of fiber and to 24.00% for the soil with 1.0% of fiber as shown on Figure 5:

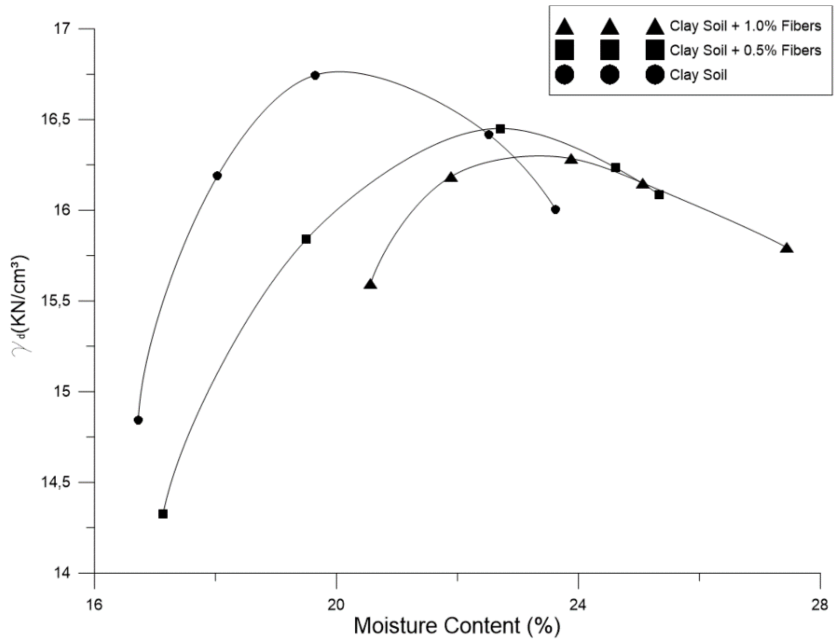

Figure 4. Compaction Curves.

One possible explanation to the reduction of the apparent specific dry weight is that the fibers are lighter than the soil, and the substitution of the soil for them may be the reason why the reduction occurs. The increase of the optimum moisture content can be explained as well because of the fibers insertion where they have the characteristic of absorbing water.

Through the compaction tests results, using a correlation formula, were possible to evaluate the influence on the void ratio of the samples (Figure 6). Is possible to notice that the addition of fibers made the void ratio to decrease as the fiber content increase which can be explained by the accommodation of the particles and fibers filling the voids or by the increase of the moisture content where the water can fill the voids as well.

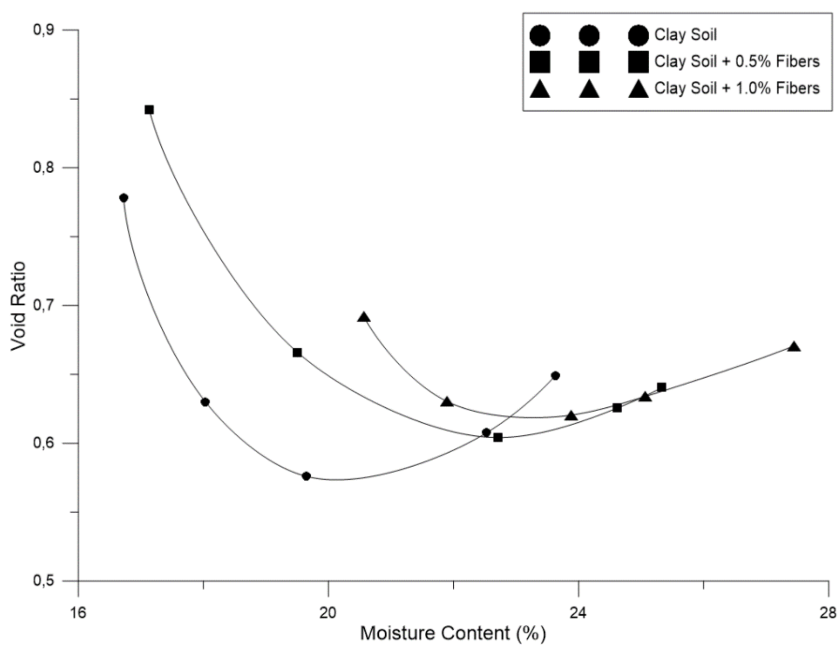

Figure 5. Void Ratio.

With the UCS (Figure 6), was possible to observe that, in fact, the addition of the fibers not only considerably increased the parameters of shear strength but also gave the soil an additional post-peak resistance that the soil did not have. The peak resistance observed for pure soil was 486.79 KPa, whereas for the soil with 0.5% fiber addition it was 763.39 KPa, that is, 156% higher than that of pure soil; for soil with 1.0% fiber added, the peak resistance value was 1220.35 KPa, representing a value 250% higher than that of pure soil and 160% higher than the soil with addition of 0.5% of fiber.

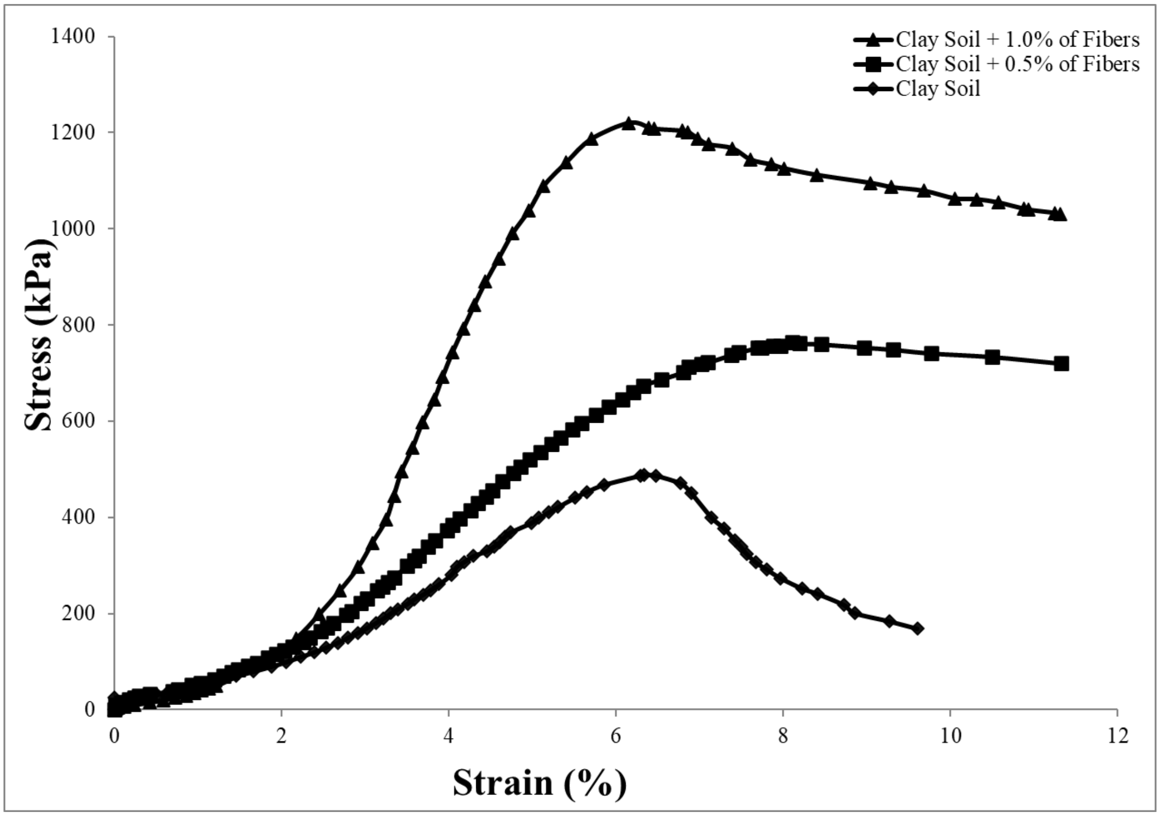

Figure 6. Stress-Strain Curves.

Regarding the post-peak, the soil with 0.5% fiber addition was able to maintain a resistance approximately four times higher than that of the pure soil and the one with the addition of 1.0% fiber six times greater.

The Figure 7 shows the results of the Direct Shear tests. As said previously the tests were made to the Clay Soil for 50 KPa, 100 KPa and 200 KPa, to the Clay Soil + 0.5% of Açaí Fibers for 50 KPa, 100 KPa and 200 KPa and Clay Soil + 1.0% of Açaí Fibers and the results show that the addition of fibers improved the soil shearing resistance to all cases. The Clay Soil + 0.5% of Açaí Fibers for 50 KPa had a 49.17 KPa of peak resistance, 44% bigger than the Clay Soil for 50 KPa (34.17 kPa) and the Clay Soil + 1.0% of Açaí Fibers for 50 KPa showed a peak resistance of 35.07 kPa, only 3% bigger than the Clay Soil for 50 kPa.

The Clay Soil + 0.5% of Açaí Fibers for 100 KPa had a 72.92 KPa of peak resistance and the Clay Soil + 1.0% of Açaí Fibers for 100 KPa had a 73.33 KPa of peak resistance, 34% an 35% bigger than the Clay Soil for 100 kPa (54.33 kPa). The Clay Soil + 0.5% of Açaí Fibers for 200 KPa showed the biggest peak resistance, 146.56 KPa, 62% bigger than the Clay Soil for 200 KPa (90.72 kPa) and the Clay Soil + 1.0% of Açaí Fibers for 200 KPa showed a close result, 135.17 KPa, being 49% bigger than the Clay Soil for 200 KPa.

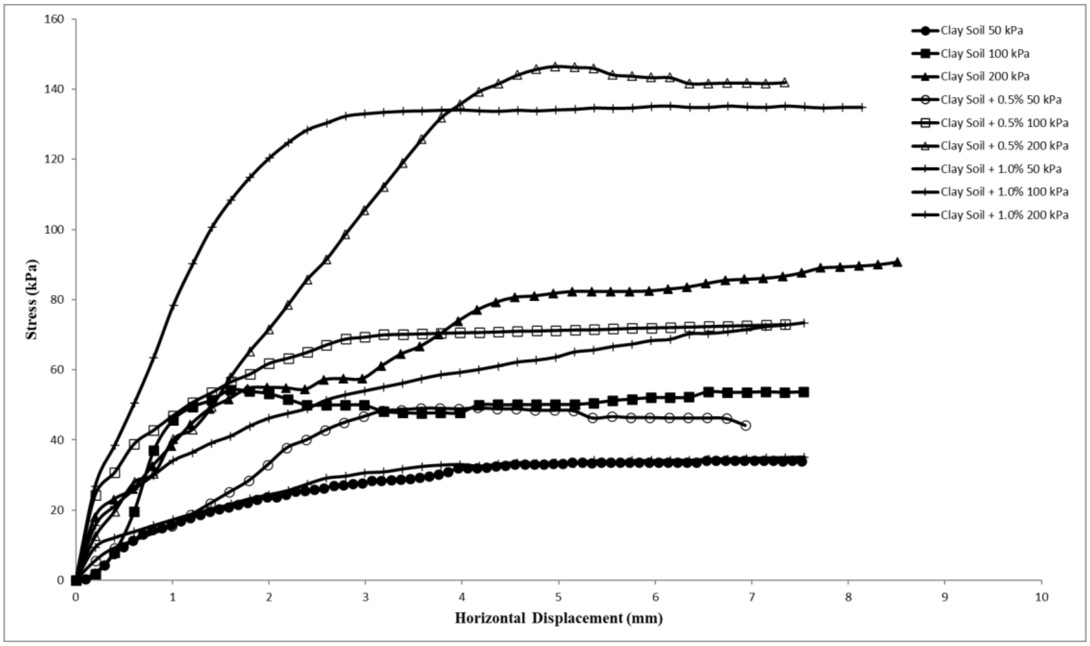

Figure 7. Direct Shear Stress versus Horizontal Displacement Curves.

The Figure 8 shows the adjustment of the maximum shearing resistance versus the confining stress. Is possible to evaluate the influence of the fibers addition onto the friction angle and cohesion.

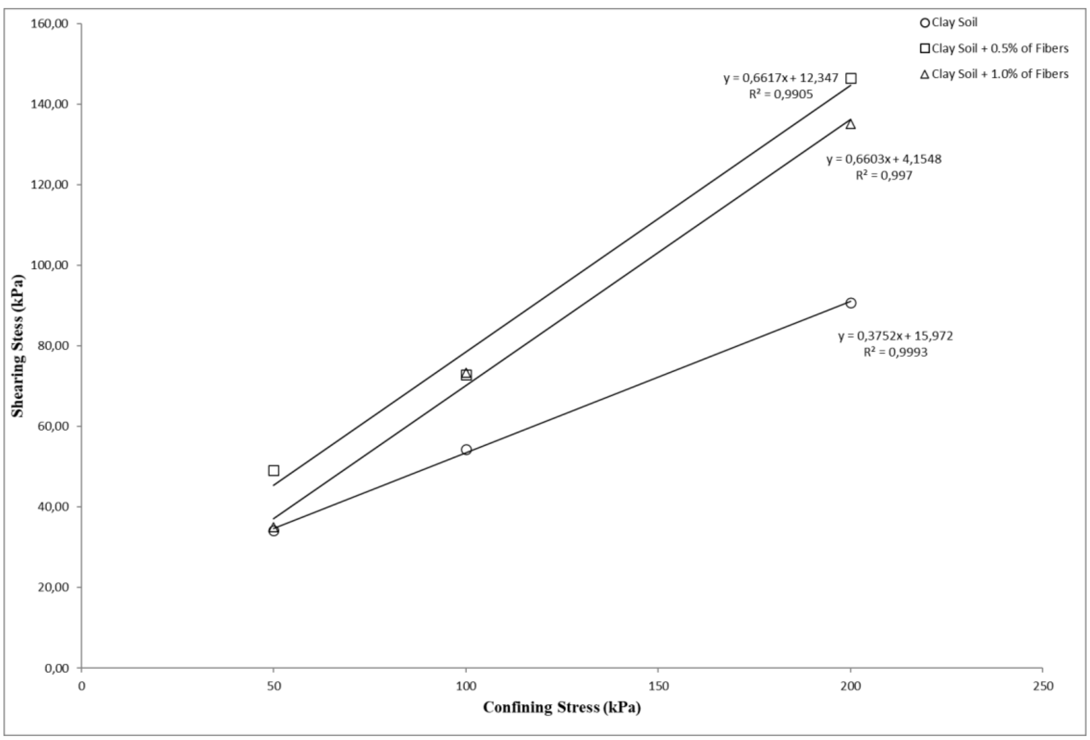

Figure 8. Confining Stress versus Shearing Stress.

The Table 2 shows the difference on the friction angle and cohesion between the Clay Soil and the composites. Is possible to notice that the addition of fibers decreases the cohesion and increase the friction angle. One possible explanation is that the improvement of the friction angle caused a decrease of the on the cohesive intercept, graphically, but the composites still have physical cohesion of clay.

Table 2. Friction Angle and Cohesion.

Sample	Friction Angle (º)	Cohesion (KPa)
Clay Soil	20.56	15.97
Clay Soil + 0.5% of Fibers	33.49	12.35
Clay Soil + 1.0% of Fibers	33.44	4.15

4. CONCLUSIONS

It is possible to conclude that the use of açaí fibers in the percentage of 0.5% and 1.0% as a reinforcement for clay soils is satisfactory from the geotechnical point of view, fulfilling its role mainly in the performance on both peak shear strength and post-peak shear strength, opening possibilities for the application study in works such as pavement and landfill bases on soft soils. Also, is noticed that the reinforcement with açaí fibers showed better results for bigger confining stress.
It is believed that this research is innovative, considering that this is a new studied material for this application, which leads to a greater need for research and deepening for consistency. Although, is necessary to perform more studies with these fibers including researching the degradation of these fibers considering that they are biodegradable.
It is worth mentioning that, although the research was developed at the Geotechnical Laboratory of the University of Brasília, what actually makes the implementation of this new geotechnical material economically feasible is its application at the site of the generation of this waste, namely, the northeast of Pará.

REFERENCES

ABNT - Associação Brasileira de Normas Técnicas (1992). Solo Coesivo – Determinação da resistência à compressão não confinada: NBR 12770. Rio de Janeiro, 4p.

Casagrande, M.D.T. (2005). Comportamento de solos reforçados com fibras submetidos a grandes deformações. Tese (Doutorado) - Universidade Federal do Rio Grande do Sul. Escola de Engenharia. Programa de Pós-Graduação em Engenharia Civil. Rio Grande do Sul.

Casagrande, M.D.T.; Consoli, N. (2002). Estudo do comportamento de um solo residual areno-siltoso reforçado com fibras de polipropileno. Solos e Rochas: Revista Latino-Americana de Geotecnia, v. 25, n. 3, p. 223–230.

Dittenber, D. B., GangaRao, H. V. S. (2012). Critical Review of Recent Publications on Use of Natural Composites in Infrastructure. Composites Part A: Applied Science and Manufacturing, 43(8), 1419-1429.

DNER – Departamento Nacional de Estradas e Rodagem (1994). DNER-ME 228/94 "Solos – compactação em equipamento miniatura".

Embrapa (2012). Tecnologias para Inovação nas Cadeias Euterpe. Brasília.

Gehlen, L.R. (2014). Efeito da Utilização de Fibras Lignocelulósticas (Açaí e Curauá) em Compósitos com Matriz de Resina Poliéster Insaturado. Dissertação (Mestrado) - Programa de Pós-Graduação em Engenharia e Ciência dos Materiais – PIPE. Setor de Tecnologia, Universidade Federal do Paraná. Curitiba.

Ghavami, K., Toledo Filho, R. D., Barbosa, N.P. (1999). Behaviour of composite soil reinforced with natural fibres. Cement and Concrete Composites 21.

Hannant, L. (1994). Polymers and polymers composities. In: J.M. ILLSTON. Construction materials: their nature and behavior. 2ed., London: J.M. Illston/E & FN Spon, pp. 359-403.

Illston, J.M. (1994). Constrution materials; their nature and behavior. 2ed. London: E & FN Spon, 518p.

Lima Júnior, U.M. (2007). Fibras da Semente do Açaizeiro (*Euterpe Oleracea* Mart.): Avaliação Quanto ao Uso como Reforço de Compósitos Fibrocimentícios. Dissertação (Mestrado) - Pontifícia Universidade Católica do Rio Grande do Sul, Porto Alegre.

Martins, A.P.S. (2014). Desenvolvimento, caracterização mecânica e durabilidade de compósitos solo-cimento autoadensáveis reforçados com fibras de sisal. Tese (Doutorado) – UFRJ/COPPE. Rio de Janeiro.

Mesquita, A. de L. (2013). Estudo dos processos de extração e caracterização de fibras do fruto do açaí (*Euterpe oleracea* MART.) da Amazônia para produção de ecopainel de partículas de média densidade. Tese (Doutorado) -

Programa de Pós-Graduação em Engenharia de Recursos Naturais da Amazônia, PRODERNA/ITEC, da Universidade Federal do Pará. Pará.

Moscoso S.V.B. (2012). Modelagem da distribuição geográfica de doze espécies vegetais (seis madeireiras e seis palmeiras) na Amazônia, usando dados de coleção e inventários. Dissertação (Mestrado). Universidade Federal rural da Amazônia e Museu Paraense Emilio Goeldi, Programa de Pós-Graduação em ciências Biológicas, Área de concentração Botânica Tropical. Pará

Palmeira, E.M. (1993). Curso de Estabilização e Reforço de Solos: Introdução à Utilização de Geossintéticos. Publicação No. GAP002B/93 2a. Edição, Mestrado em Geotecnia, Universidade de Brasília. Brasília.

Sales, K. C. dos S. (2011). Melhorias de Solos por Inclusão de Fibras Naturais. 113 p. Dissertação (Mestrado) - Universidade de Brasília. Programa de Pós Graduação em Geotecnia. Brasília.

Santiago, G. A. (2011). Estudo do Comportamento Mecânico de Compósitos Solo-Fibras Vegetais Impermeabilizadas com Solução de Poliestireno Expandido (EPS) e Cimento Asfáltico de Petróleo (CAP). Tese (Doutorado) — Universidade Federal de Ouro Preto. Escola de Minas.

Silveira, M.V. (2018). Análise do comportamento mecânico e da durabilidade em compósitos de areia reforçada com fibras naturais de curauá e sisal. Tese (Doutorado) — Departamento de Engenharia Civil. Pontifícia Universidade Católica do Rio de Janeiro.

Taylor, G.D. (1994). Materials in construction. 2ed. London: Longman Scientific & Technical, 284p.