Natural aging evaluation of clayey soil reinforced with sisal fibers

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ABSTRACT
This experimental study reports the mechanical behavior of a reinforced and unreinforced clayey soil with the addition of short sisal fibers randomly distributed submitted to natural aging by their exposure to diverse environmental conditions. This vegetable fiber was chosen because it has good mechanical properties and the need for new renewable materials, which can successfully replace synthetic fibers. A series of unconfined compressive strength tests was performed on clay and clay-fibers samples at zero time (sample control) and on composites exposed to agents from the external environment for up to 8 months to seek to establish patterns of behavior that might explain the influence of the addition of sisal fibers, relating it to the shear strength parameters of the soil. The tests were performed on samples subjected to a maximum dry density and optimum moisture content, fibers content in proportions of 0 and 0.5% of the dry weight of the soil and the fibers lengths of 25 mm. Through the obtained results, it was observed that the addition of sisal fibers randomly distributed leads to significant improvements in the mechanical properties of the soil. It was possible to identify that the effects of natural aging had a significant effect on the mechanical behavior of the vegetable fibers, which consequently affected the mechanical behavior of the clay-fiber composites.

KEYWORDS
natural fibers; soil reinforcement; mechanical behavior; natural aging; degradation.

1. INTRODUCTION

Most reinforcements and related products that are used in engineering applications are made from synthetic materials. However, due to the problems of waste disposal and the depletion of petrochemical resources coupled with greater environmental awareness on the part of society, sustainable alternatives have been sought motivating the development of composite materials reinforced with vegetal fiber (Venkatappa Rao 2002).

Vegetable fibers, compared to synthetic fibers, have a number of advantages. They are low cost, easier to handle, have good mechanical properties and require less energy in the production process, and are from renewable sources (Dittenber & GangaRao 2012). Research evaluating the mechanical behavior of vegetable fiber-reinforced soils has been carried out (*eg.* Ghavami *et al.* 1999; Prabakar & Sridhar 2002; Sivakumar Babu & Vasudevan 2007; Ramesh *et al.* 2010; Sarbaz *et al.* 2013; Lekha *et al.* 2015; Diab *et al.* 2018). In them it is consensus that the addition of these fibers increases peak strength, toughness and ductility.

However, vegetal fibers have a great variability of physical and mechanical properties (around 40%), which affects the reproducibility of composites, susceptibility of degradation in alkaline and natural environments, and dimensional variations due to changes in moisture content and / or temperature (Ghavami *et al.* 1999). As fiber degradation may affect the strength parameters of the composite, the evaluation of composite durability should be evaluated.

This work seeks to contribute to a better interpretation and understanding of the mechanical behavior of soil reinforced with randomly distributed plant fibers, and may enhance the use of soil-vegetal fiber mixtures in earthworks, thus offering an environmentally correct alternative that will replace synthetic products.

2. MATERIALS AND METHODS

2.1 Clay soil

The soil used as matrix of the composite is clay from the slope of Experimental Field II of the Pontifical Catholic University of Rio de Janeiro (PUC-Rio). The soil consists of a yellow-red colluvial soil due to the presence of iron and aluminum oxide. The particle size curve (Figure 1), and the physical indexes of the material (Table 1) were determined at the Laboratory of Geotechnics and Environment (LGMA) from PUC-Rio. According to the Unified Soil Classification System (USCS), this soil can be classified as a high plasticity inorganic clay (CH).

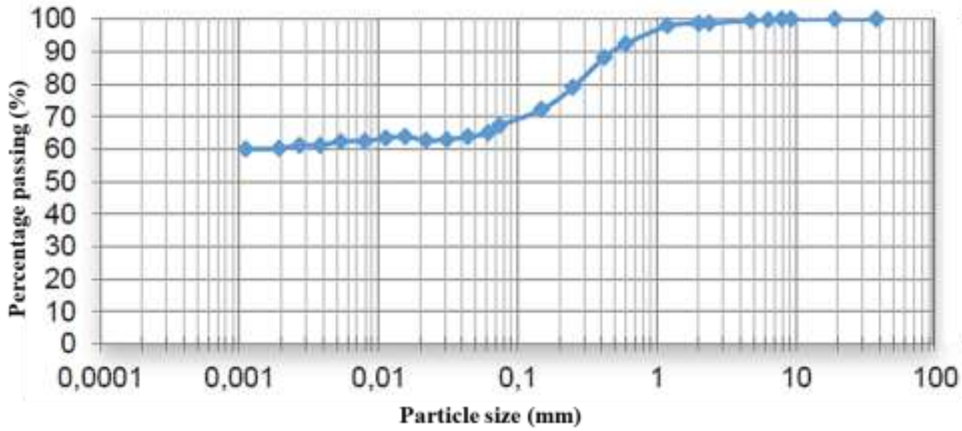

Figure 1. Particle size curve of the clay soil

Table 1. Physics index of the clay soil.

Physics Index	Values
Specific gravity	2.69
Liquid limit	52%
Plastic limit	34%
Plasticity index	18%
Maximum Dry Density of Soil	1.55
Optimum Moisture Content	26%

2.2 Vegetal fiber

The fibers used as reinforcement element were sisal (*Agave sisalana*). This fiber is derived from the leaf of a plant that is considered indigenous in Central and South America (Costa 2013). Sisal culture, one of the most widely used fibers in the world, is of extreme socioeconomic importance for Brazil, as it is the only economically viable in the semiarid region of the Northeast (Mattoso *et al.* 1997).

The sisal fibers were purchased from the Sustainable and Solidarity Development Association of the Sisaleira Region (APAEB), in the municipality of Valente, Bahia. Table 2 shows the values available in the literature for the main characteristics of the fiber used.

2.3 Sample Preparation

Composites of clay soil reinforced with sisal fibers dispersed in the matrix were tested. The variables investigated were fiber content (0 and 0.5%) and weather exposure time (0, 2, 4 and 8 months). Table 3 summarizes the variables investigated and adopted abbreviations.

Table 2. Properties of the sisal fiber.

Tensile strength (MPa)	Young's Modulus (GPa)	Strain at rupture (%)	Reference
227.8 - 1002.3	10.9 - 26.7	2.8 - 4.2	Tolêdo Filho, 1997
340	12	3.3	Santiago, 2011
484	19.5	3.3	Fidelis, 2014
270.86	5.51	5.21	Silveira, 2018

Table 3. Variables investigated and adopted abbreviations.

Fiber Content (%)	Time (months)	Abbreviation
0	0	C0
0.5	0	CS0
	2	CS2
	4	CS4
	8	CS8

The preparation of clay soil specimens with and without reinforcement for simple compression tests was done by compaction in a bipartite cylindrical mold of 4.7 cm diameter and 9.2 cm height. The samples were prepared at their maximum dry unit weight and optimum moisture content. For each analysis made (C0, CS0, CS2, CS4 and CS8) 5 (five) specimens were made. The composites were prepared with a 0.5% fiber content, calculated in relation to the dry soil mass, and the fibers had a length of 25mm.

The compounds made to evaluate the effect of natural aging were exposed outdoors for a period of eight months (starting in January / February - summer in the southern hemisphere). Samples were taken after an exposure period of 60, 120 and 240 days to perform the tests in order to draw curves that relate the variables resistance and time.

These samples were subjected to the action of various climatic agents such as soil temperature variations, resulting not only from the transition from day to night, but also from seasons, soil moisture variations resulting from precipitation, and also from the incidence of solar radiation, which influences the process of fiber biodegradation.

The sample preparation for performing the simple compression test consisted of (i) immersing the specimens (into the cylindrical molds) in water for 12 hours; (ii) then, the specimen was wrapped in film paper, identified and placed in a humid camera for 7 (seven) days; (iii) after this period, the specimen was unwrapped, its weight, height and diameter noted; (iv) finally the specimen was taken to the press of the simple compression equipment to be tested; (v) after the test, a specimen sample was used to determine the moisture content.

2.4 Unconfined Test

For the simple compressive strength tests, the procedures determined by NBR 12770 (ABNT 1992) were adopted. The available press at PUC -Rio is of controlled displacement velocity, with a maximum capacity of 10 kN, and the strain rate used was 0.91 mm/min.

3. RESULTS AND ANALYSES

Figure 2 shows the stress-strain behavior of unreinforced and fiber reinforced clay soil specimens without exposure (zero time). Unreinforced clay specimen showed a very brittle behavior with a failure of 3.8%. It is possible to observe the clear increase of compressive strength, without peak formation, due to the addition of the fibers in relation to the unreinforced material, and that the fibers contribute at the beginning of the test, when the axial deformation is around 2.5%. From this deformation it becomes evident the difference in behavior between the curves, and that the contribution of fiber addition remains visible until the axial limit deformation evaluated.

The addition of fiber in the clay matrix caused an increase in failure strain and a change in failure mode from a brittle behavior to a ductile behavior. The strain-hardening behavior, ie, a constant increase in resistance with increasing axial deformation, was observed. According to Mirzababaei *et al.* (2013), this observed change in mechanical behavior is caused by the contribution of the tensile strength of fibers at higher strain values.

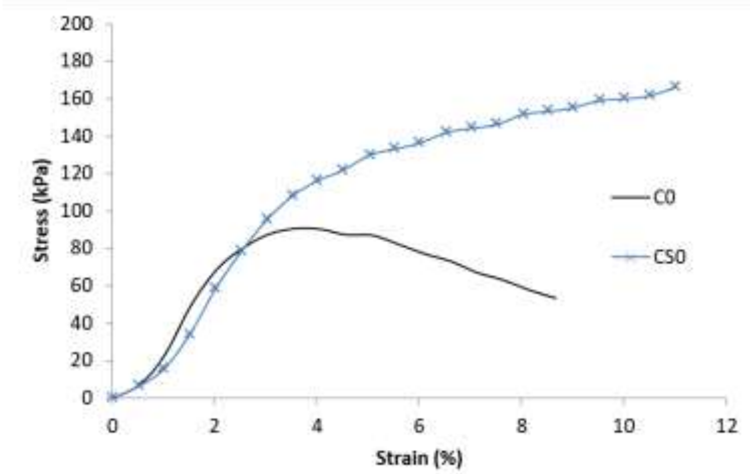

Figure 2. Stress-strain behavior of clay soil with and without reinforcement at time zero

Figure 3 shows the stress-strain behavior of fiber reinforced clay soil specimens exposed to climatic agents for 2, 4 and 8 months. It is possible to observe that natural aging affected the rupture mechanism of clay-fiber composites. The hardening behavior acquired with the addition of fibers in the control samples was gradually lost as the exposure time increased. This observation indicates that the sisal fiber is susceptible to degradation in natural environments, and after eight months of exposure to soil and climatic agents this vegetal fiber ceased to contribute as a reinforcing element. The physical and mechanical indexes of the specimens analyzed are presented in Table 4.

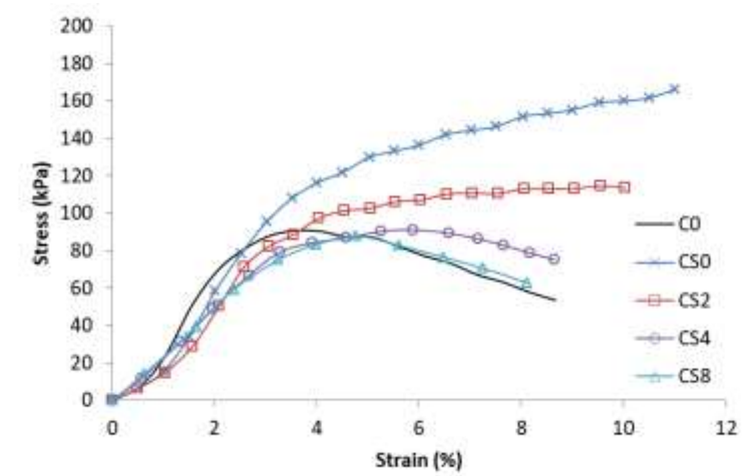

Figure 3. Stress-strain behavior of clay-fiber composite exposed to natural aging

Table 4. Physical-mechanical indexes of the of the tested specimens

Sample	Physics index				Mechanical indexes	
	w (%)	S (%)	e	ρ (g/cm³)	q_u (kN/m²)	s_u (kN/m²)
C0	26.90	78.36	0.93	1.78	91.77	45.88
CS0	26.77	82.25	0.88	1.82	171.80	85.90
CS2	27.49	85.11	0.87	1.84	117.08	58.54
CS4	21.95	75.38	0.79	1.84	90.80	45.40
CS8	24.81	85.66	0.78	1.89	87.77	43.89

Silveira (2018) also found that natural aging caused the loss of mechanical behavior affecting the rupture mechanism of sand-sisal and sand-curauá fiber composites. It was observed a gradual loss of mass and loss of tensile strength of fiber with increasing exposure time. The attack by fungi and bacteria present in the soil was pointed as responsible for the biodegradation process.

Carvalho *et al.* (2014) exposed a granitic residual soil (SM classification) reinforced with 3 types of fibers (sisal, banana and coconut) to a natural and accelerated aging. In general, the greatest loss of strength occurs within the first 15 days of exposure (360 hours), causing tensile strength to be reduced by more than 50% of its initial strength, and at the end of the first month of exposure stabilization of the loss of strength occurred, remaining almost unchanged.

4. CONCLUSION

From the unconfined compression strength test performed on clay soil and clay-sisal fiber mixtures with and without exposure to natural aging were established some conclusions reported below:

The inclusion of sisal fibers in a clay matrix caused an increase in compressive strength.

Sisal fiber was affected by exposure to soil, weather agents and time, indicating that this fiber is susceptible to degradation in natural environments.

Exposure of clay-vegetable fiber composites to natural aging resulted in loss of mechanical behavior. The composites showed compressive strength losses in the first test battery after 2 months of exposure.

Natural aging affected the rupture mechanism of the clay-fiber composites exposed to climatic agents. The strain-hardening behavior acquired with the addition of fibers in the control samples was gradually being lost as the exposure time increased.

After 8 months of exposure to various climatic agents (natural aging), vegetal fibers no longer contribute as a reinforcement element in the composite.

General analysis of the results indicates that vegetal fibers can be used in construction where the critical case for stabilization or functionality of the construction site is immediately after construction. For these cases vegetal fibers may be used as long as the temporal variation of their mechanical behavior is known and / or an appropriate treatment is applied to improve their characteristics.

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