The Performance of a Sand Reinforced with Coconut Fibers Through Plate Load Tests on a True Scale Physical Model

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Abstract. The use of recycled materials has experienced a growing global interest in the last decades. Products like natural fibers are being studied to replace synthetic fibers in some applications because they are renewable resources that have a lower cost. Fibers can be used as reinforcement for covers of landfill sites, landfilling over soft soils, and evapotranspiration covers. The use of coconut fibers represent an opportunity to reduce the environmental issue waste of this fruit in tropical countries. The main objective of this research is to evaluate the load-settlement behavior of non-reinforced and reinforced sand with coconut fibers using either a random or a layered distribution. In that sense, plate load tests with both non-reinforced and reinforced sand were performed fixing the moisture content and percentage of fibers for all tests. The results show that the greatest settlement reduction is obtained with layered distribution. Conversely, random distribution provides more ductility and, consequently, the mixture can resist a highest load than layered distribution.

Keywords: coconut fiber, layered distribution, plate load test, random distribution.

1. Introduction

In the literature, one of the firsts investigations about the influence of root reinforcement on soil strength has been conducted by Endo & Tsuruta (1969) who showed that the shear strength of soil with tree root system could be expressed by the same forms as Coulomb law. The growing interest led researchers to study the effect of discrete fibers on soil shear strength. In that sense, researchers as Gray & Ohashi (1983) began to develop models based on force equilibrium to correctly predict the influence of various soil-fiber parameters. The better characteristics of synthetic fibers than natural fibers attracted the attention of researchers. Studies carried out on reinforced soil with synthetic fibers have demonstrated that the principal parameters on the shear strength are soil particle size and shape (Maher & Gray, 1990; Al-Refeai, 1991; Sadek et al., 2010; Pino & Baudet, 2015), sand relative density (Consoli et al., 2009a; Sharma & Kumar, 2017), fiber percentage and length (Maher & Ho, 1994; Yetimoglu & Salbas, 2003; Consoli et al., 2007b; Li & Zornberg, 2012) and fiber aspect ratio (Maher & Woods, 1990; Ranjan et al., 1994; Chou et al., 2016). The understanding of the soil-fiber mechanism has led researchers to study ecofriendly materials as Tolêdo Filho et al. (1997), Ahmad et al. (2010) and Estabragh et al. (2013) developed studies using natural fibers to reinforce silty sand, clays and mortar, respectively. A review study about synthetic (PP, PE, PET, Nylon, Glass, PVA; and steel) and natural (coir, sisal, palm, jute, flax, straw, bamboo; and cane) fibers was carried out by Hejazi et al. (2012) showing that, in all cases, fibers help to reduce the brittleness of the composite soil. The literature concludes that the use of natural-synthetic fibers in geotechnical engineering is feasible in embankments and road construction (Santoni et al., 2001; Tingle et al., 2002; Chauhan et al., 2008), retaining walls (Arenicz & Chowdhury, 1988; Park & Tan, 2005), earthquake engineering (Leflaive, 1988; Amir-Faryar & Aggour, 2016), slope protection (Zornberg, 2002; Bhardwaj & Mandal, 2008), and foundation engineering (Sharma & Kumar, 2017; Wasti & Büttin, 1996).

The Brazilian Institute for Geography and Statistics (IBGE) revealed that, in Brazil, the coconut production has grown from 1,300,000 to 2,000,000 tons in ten years. According to the Brazilian Agricultural Research Corporation, the coconut shells represent between 80% and 85% of weight of the fruit and about 70% of the waste generated in Brazilian beaches, thus becoming a serious environmental issue, particularly in tropical countries, however, the coconut fiber applications are reduced to evapotranspiration coverage. Researchers have shown interest in using coconut fiber as concrete reinforcement (Majid et al., 2011; Ramli et al., 2013), nevertheless few studies are carried out for uses in soil reinforcement. The main objective of this research is the applicability of coconut fibers as reinforcement of soil embankments, soil foundation and other engineering applications. A secondary objective is to compare random with layered reinforcement distribution fixing
the moisture content and percentage of fibers. Static and dynamic plate load tests are often used for bearing capacity evaluation of shallow foundations (Moraes et al., 2007). No studies have used the plate load test to evaluate reinforced soil with coconut fiber. This paper reports static plate load test results under controlled conditions on non reinforced and reinforced sand evaluating the load-settlement behavior and compares a random with a layered reinforcement distribution. The use of coconut fiber represents an opportunity to reduce the environmental issue of waste. One of the study limitations is that there was no analysis of resistance to fiber degradation, however, Hejazi et al. (2012) showed that the high lignin content of coconut fibers makes the degradation slower compared to other vegetable fibers.

2. Materials

2.1. Coconut fiber

Coconut fibers were collected by a partnership between the municipal company of urban cleaning and the department of public services conservation. The fibers were received in sacks, subsequently going through shredding, cleaning of all solid residues, manually cut, and stored into bags (Fig. 1). The fiber average dimensions were 50 mm in length and the content used was 0.5% by dry weight of soil. Previous studies have demonstrated that a fiber content of 0.5% is an upper limit considering workability and homogeneity (Consoli et al., 2003a; Consoli et al., 2009b; Consoli et al., 2007a; Anagnostopoulos et al., 2013).

2.2. Soil matrix

The Unified Soil Classification System (USCS) classifies the sand, obtained from the region of Santa Cruz in southern Brazil, as non plastic poorly graded SP. The sand has a mean diameter of 0.89 mm and non-uniformity and curvature coefficients of 5.08 and 1.01, respectively. The specific gravity of the solids was 2.642, the maximum and minimum void ratios were 0.70 and 0.50, respectively. The fines content was 2.2% with no organic matter. The layers were compacted to a relative density of 50% because, in practice, covers and landfill sites do not possess high compaction values. The moisture content was 10.0% and dry unit weight 16.5 kN/m³.

3. Preparation of Layers

First was placed half of the sand into mixer of 20 L, a bit of water was spread over the surface to avoid dust, fibers were manually placed covering all surface, then the other sand half was added. The mixer was turned on, while the water was added to reach the moisture content calculated. The fibers were added as a replacement of sand using Eqs. 1 and 2.

\[ W_R = V \times \gamma_R \]  
\[ W_R = W_S + W_F = P_S \times W_R + P_F \times W_R \]  

where, \( W_R \), \( W_F \), and \( W_S \) are dry weight of reinforced layer, sand and fibers, respectively; \( \gamma_R \) is dry unit weight of reinforced layer; \( V \) is the total volume of reinforced layer to be placed; \( P_S \) and \( P_F \) are the percentages of sand and fibers in reinforced layer, respectively.

In layered distribution did not mixture the sand with the fiber, the fiber percentage was placed between each layer of sand.

A wooden box, 1.4 m x 1.4 m in plan dimensions, and 1.5 m high was used as test box. The mixture thickness is 1.2 m which is equivalent to 4 times the plate diameter. The test box was filled with 12 consecutive layers with a 0.1 m thickness.

4. Equipment Setup

A load transmission/reaction system was developed by the Materials and Structures Laboratory of Pontificia Universidade Católica do Rio de Janeiro to conducted the plate load test. It was built on a steel gantry with a 1000 kN workload (Fig. 2). The load was applied by a hydraulic jack with a 600 kN maximum load connected to a hand pump and one load transducer with a 20 kN capacity was placed below the jack. A circular steel plate with 0.3 m in diameter and one inch in thickness was used. Displacement transducers TD1, TD2, and TD3 were radially placed over the plate at every 120°. Transducers TD4 and TD5 were placed off the plate at 0.05-0.10 m distance in order to register the settlements around the plate (Fig. 3). The displacement transducers were fixed to a reference beam and held by external supports to ensure a stable reference. The main scale limitation of the plate loading test is found in the dimensions of the test box, which, although it was 4 times the diameter of the plate in depth, did not support the greater range of stresses permitted by the addition of fibers to the sand. This large increase in deformation energy was not previously considered in the determination of the dimensions of the test box.

Figure 1 - Coconut fibers 50 mm in length.
5. Results and Analyses

Non-reinforced sand was tested in order to determine the material basic behavior. Sand was then reinforced with randomly distributed fibers to observe the fiber influence on the load-settlement behavior. Finally, reinforced sand with layered distributed fibers was tested to compare the influence of fiber distribution layout, by maintaining the same fiber content in each layer.

The tests ended when the plate presented rotations over its axis. During test, sand becomes stiff beneath the plate and does not allow larger settlements.

5.1. Load-settlement behavior

The non reinforced sand fails at the point where the load-settlement relation changes its inclination; this point is defined as bearing capacity of the foundation, \( q_u \). This change occurs for random distribution in low settlements while for the layered distribution in large settlements.

Most methods to estimate \( q_u \) have been developed based on the expression proposed by Terzaghi (1951). The expression adapted for a plate load test on cohesionless soils using a circular footing is defined as

\[
q_B N_u = \frac{\gamma B N_y}{c_{103} / c_{103}}
\]

(3)

where \( \gamma \) is the sand unit weight; \( B \) is the plate diameter and \( N_y \) is a bearing capacity factor which depends of the sand friction angle, \( \phi \). There are many methods to define \( N_y \), the lack of consensus in the methods being due to complexity in obtaining \( q_u \) by experimental tests. Sixty methods to determine the bearing capacity factor \( N_y \) presented by Diaz-Segura (2013), were used to calculate \( q_u \) using the Eq. 3. Triaxial tests with the non reinforced sand obtained an angle of friction of 32.5°. Figures 4(a) and 4(b) show the variation range of \( q_u \) calculated, and the \( q_{\text{test}} \) obtained in the test, respectively. The physical model is validated by the numerical methods because \( q_{\text{num}} = 40 \text{ kPa} \) is inside the values range calculated (35-40 kPa).

Load-settlement curves in large deformations are presented in Fig. 5. Initially, non-reinforced sand shows a parabolic curve and then a linear tendency. This linearity is typical of granular soils: the grains keep rearranging themselves, and therefore, the mass of soil does not have a well-defined shear failure.

Normally, plate load tests on granular soils achieved a proportionality between load and settlements, therefore, the results in large deformations are compatible. The strain hardening response shows the reinforced sand as more duc-
tile. At the 400 kPa value there is an intersection between the three curves: at this stress level the fibers have occupied most of the void spaces increasing interaction with the sand grains and activating the development of the fiber tensile strength that produces the strain hardening behavior.

The reinforced (random distribution) and the non-reinforced curves are almost parallel until 400 kPa: after the reinforced curve shows a continuous stress increase, while stress in non-reinforced sand decreases. In this range, the layered distributed reinforced curve presents a lower settlement resistance than the non-reinforced sand, however, after 400 kPa this distribution presents the best settlement resistance.

Lateral movement of the grains is produced by the stress transfer from plate to sand which affects the grains stability. Fibers distributed in layers act as a restraint against this movement (Fig. 6), however, generate a major layer stiffness, consequently, the layered reinforcement test endure a minor load than randomly reinforcement test. Consoli et al. (2003b) also observed a stiffer response due to a combined effect between the continued increase in the material strength at large deformations and the increase in the horizontal stresses below the plate.

The transducers TD1 and TD2, in Figs. 7(a) and 7(b), placed 0.05 and 0.10 m from the plate border showed that non-reinforced sand has a vertical upward expansion while in the reinforced case the sand is pulled down in the direction of the plate, this mechanism also having been observed...
by Consoli et al. (2009a). Fibers generate an additional confinement effect around the sand grains, the restriction for grains movement and the fiber capacity to work in tension reduces the sand dilative behavior. According to Consoli et al. (2003b), fibers reduce the movement of sand due to the transfer mechanism by the fiber-sand friction distributing the energy over a larger area.

The overall evaluation of the results shows that the fiber addition initially restricts the natural rearrangement of sand grains as the displacement increases to a certain limit. Once this limit is reached, the grains have no direction to move without strongly interacting with the randomly distributed fibers or the fibers distributed in layers, which start to contribute to the displacement resistance as shown in the Fig. 5.

5.2. Shear failure mechanism

Figure 8 shows the exhumation after the tests. The change in the shear mechanism showed by the transducers TD1 and TD2 was verified. Vesic (1975) explained that the failure characterized by the vertical upward expansion presented by the non reinforced sand corresponds to local shear failure. However, the reinforced cases presented a punching shear failure. In Fig. 9 the maximum stress reached in non reinforced sand was 770 kPa, while layered and randomly reinforced sand reached 1200 and 1500 kPa, respectively.

The size and shape of fissures indicate stress release, if the sand does not have enough tenacity to keep absorbing energy the affected area will be bigger. In non reinforced sand, the Fig. 10(a) shows radial cracks appearing normal to the circumference of the plate. The concentration of stresses was dissipated from the layer base to the surface, superficially cracks appeared perpendicular to the radial crack trying to propagate in all directions. In the reinforced cases, cracks were concentric with the plate and there were no perpendicular cracks, therefore, fibers improve the sand behavior avoiding the appearance of cracks.

6. Conclusions

The performance of a medium density compacted sand reinforced with coconut fibers was studied through plate load test in true scale with an equipment setup detailed in this paper. The following conclusions were based in the obtained results.

Figure 8 - Shear mechanism: (a) local shear (non-reinforced sand), (b) punching shear (randomly and layered reinforced sand).
In low stresses, fibers add voids around themselves reducing the normal rearrangement of grains and the bearing capacity. In large stresses, grains occupy the voids around the fibers improving the fiber-sand interaction, coconut fibers activate the tensile resistance significantly improve the load-settlement behavior and influence the change of shear mechanism.

The non reinforced sand showed a vertical shear from a bottom layer to surface, displaying a stress concentration in the loading area, whereas the reinforced sand presented shear failures that propagated off the loading area around the plate, showing that the fibers distribute the stresses over a larger area.

The membrane effect generated under the layered distribution got the higher settlement reduction due to restraint of grains lateral movement, however, this stiffens the layer and creates potential planes of weakness. This effect does not happen with the random distribution.

It is recommended a combination to provide the advantages of each one. In superficial layers can be used the random distribution to reduce the cracks while in the intermediate layers can be used the layered distribution. The use of recycled coconut fiber is an opportunity to reduce the environmental problem in tropical countries.

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List of Symbols

mm: millimeters
m: meters
°: degree
kPa: kilopascal
ϕ: friction angle
\( W_g \): dry weight of reinforced layer
\( W_s \): dry weight of sand
\( W_f \): dry weight of fibers
\( \gamma_u \): dry unit weight of reinforced layer
\( V \): total volume of reinforced layer
\( P_s \): percentage of sand
\( P_f \): percentage of fiber
kN: kilonewton
\( q_{ult} \): bearing capacity
\( B \): plate diameter
\( N_Y \): bearing capacity factor
TD: displacement transducers