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Exploring the Potential of Natural Fibers to Enhance Stability and Load-Bearing Capacity in Shallow Foundations

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ABSTRACT: This study investigates innovations in soil reinforcement in civil engineering, employing sisal natural fibers. The primary objective is to enhance load-bearing capacity, stability, and prevent settlements. The research utilized the transparent soil technique, presenting a scaled-down model of a shallow foundation on sand reinforced with varying concentrations of sisal fibers (0%, 0.5%, 1%, and 2%). In the experimental phase, comprehensive tests were conducted, encompassing the physical characterization of materials, fiber tensile strength tests, and load-bearing capacity assessments of the studied solution. Results indicated a substantial enhancement in load-bearing capacity with increasing concentrations of sisal fibers, underscoring the effectiveness of these natural fibers as reinforcement agents. The sustainable and eco-friendly approach of these plant fibers emerges as a promising alternative for soil reinforcement, aligning with principles of sustainability in civil engineering. The conclusion emphasizes the significance of laboratory tests as indispensable tools to evaluate and validate the performance of these innovative solutions, providing valuable insights for future practical applications in engineering projects.

KEYWORDS: Soil Reinforcement, Natural Fibers, Shallow Foundations, Load-Bearing Capacity.

RESUMO: Este estudo investiga inovações em reforço de solo na engenharia civil, utilizando fibras naturais de sisal. O objetivo principal é aprimorar a capacidade de suporte de carga, estabilidade e prevenir recalques. A pesquisa empregou a técnica de solo transparente, apresentando um modelo em escala reduzida de uma fundação rasa sobre areia reforçada com concentrações variadas de fibras de sisal (0%, 0,5%, 1% e 2%). Na fase experimental, foram realizados testes laboratoriais, englobando a caracterização física dos materiais, testes de resistência à tração das fibras e avaliações da capacidade de suporte de carga da solução estudada. Os resultados indicaram um aprimoramento substancial na capacidade de suporte de carga com o aumento das concentrações de fibras de sisal, destacando a eficácia dessas fibras naturais como agentes de reforço. A abordagem sustentável e ecologicamente amigável dessas fibras vegetais surge como uma alternativa promissora para o reforço de solo, alinhando-se aos princípios de sustentabilidade na engenharia civil. A conclusão enfatiza a importância dos testes laboratoriais como ferramentas indispensáveis para avaliar e validar o desempenho dessas soluções inovadoras, fornecendo contribuições para futuras aplicações práticas em projetos de engenharia.

PALAVRAS-CHAVE: Reforço de Solos, Fibras Naturais, Fundações Rasas, Capacidade de Carga.

1 INTRODUCTION

At the outset of any construction project, one of the primary considerations is the condition of the soil, given the pathological manifestations that may arise due to its geotechnical properties. As highlighted by Das

(2016), the soil at a construction site is not always in suitable conditions for building, often due to issues related to soil type or its presentation, necessitating the preparation of the material through compaction or soil modification to ensure its suitability for construction.

Generally, sandy soils exhibit bearing capacity and permeability compatible with shallow foundations. However, the magnitude of settlements can be significant for such solutions, depending on the applied loads, sometimes necessitating the use of deep foundations. One potential technique to address or at least control this characteristic is soil reinforcement using fibers, which, when incorporated into the soil, can enhance its strength and cohesion, thereby enabling safer construction practices.

Among the various types of fibers that can be utilized, sisal fiber stands out due to its low cost, high production rate, and natural origin, thereby avoiding any chemical contamination of the soil and enhancing the bearing capacity of sandy soil. It can be applied directly to the soil or through the use of geotextiles and geogrids for further support enhancement.

Indeed, adding fiber can significantly increase the load-bearing capacity and strength of the soil, as concluded by Silva (2016) from compaction and compression tests, considering that there is a limit to the amount of fiber that can be added to the soil before it reaches its maximum strength.

Several soil reinforcement techniques have been studied, and the choice among them depends on the characteristics of the soil being addressed. As noted by Vertematti (2015), various ancient structures such as those in the Roman Empire, the ziggurats of Mesopotamia, and the Great Wall of China employed plant materials consisting of fibers to enhance soil quality, such as bamboo fibers.

Casagrande (2005) suggests that the inclusion of fibers in the soil contributes to the development of a new geotechnical material with unique properties, based on the improvement of the mechanical properties of the new material.

Visualizing the interior of soil typically involves advanced techniques such as magnetic resonance imaging, which incur high costs. To overcome these challenges, the transparent soil technique allows visualization of soil interiors during laboratory tests, facilitating the assessment of soil behavior under specific loads and corresponding deformations (Lopes, 2019).

The basic concept of transparent soil involves creating a homogeneous medium for the passage of light, employing transparent saturated aggregates with a refractive index fluid equivalent to that of the aggregate, allowing a significant portion of light to be transmitted through the medium, enabling non-intrusive internal visualization (Iskander et al., 2002).

This study aims to analyze the load-displacement behavior of reinforced transparent sand with sisal fibers for potential applications in civil engineering projects, utilizing the transparent soil technique. For this purpose, the research methodology is predominantly experimental, involving scaled-down tests using transparent soils to evaluate the proposed solutions, as well as geotechnical and optical characterization tests of the materials involved.

2 MATERIALS AND METHODS

The following section outlines the main materials and methods employed in the research.

2.1 Transparent Soil

Fused quartz was utilized in this study to simulate a granular soil. This material, according to the supplier, possesses a content of amorphous silica greater than 99.995%, granting it high transparency and a refractive index of 1.4585.

The fused quartz was obtained in fragments of various dimensions, requiring a cleaning process with isopropyl alcohol, followed by fragmentation using a mortar and pestle. The material passing through a 2.36 mm sieve and retained on a 2 mm sieve was adopted for testing. The saturation fluid consisted of mineral oil and turpentine. Seven samples with different concentrations of the solvent and mineral oil mixture (Table 1) were prepared to evaluate the transparency achieved with each mixture. These measurements were conducted to determine the refractive index and turbidity for each sample, aiming to identify the mixture concentration where the refractive index closely matched that of the fused quartz, thus ensuring transparency. Based on the results, an optimal mixture ratio of 69.2% mineral oil and 30.8% solvent was adopted.

Table 1. Mixture ratios between turpentine and mineral oil.

Sample	Turpentine concentration (%)	Mineral oil concentration (%)	Turbidity (NTU)	Refractive index (-)
1	0	100	54	1.4746
2	25	75	22	1.4624
3	45	55	26	1.4528
4	50	50	32	1.4506
5	55	45	39	1.4476
6	75	25	65	1.4393
7	100	0	140	1.4287

The test to determine the minimum void ratio was conducted according to NBR 16843 (ABNT, 2020a), resulting in a value of 0.76. Conversely, the maximum void ratio was determined in accordance with NBR 16840 (ABNT, 2020b), yielding a value of 0.46. Based on these values, the relative compactions were determined using the sand raining method, employing a funnel for soil deposition. The calibration for this method considered drop heights ranging from 2 cm to 10 cm. Based on the relative compaction calibration, a drop height of 5 cm was adopted, corresponding to a relative compaction of 80%.

In order to quantify the transparency of the materials involved in the research, a transmittance test was conducted using the PHOX UV-12 spectrophotometer [Fig. 1(a)]. With this equipment, the analysis was performed on the amount of light transmitted through the samples. This test is conducted at different wavelengths, ranging from 200 nm to 800 nm, to determine the range of values where the highest transmittance occurs, as higher transmittance values indicate greater transparency of the material. The optical lengths used in the research were 10 mm, 20 mm, and 50 mm, corresponding to the cuvettes shown in Fig. 2(b).

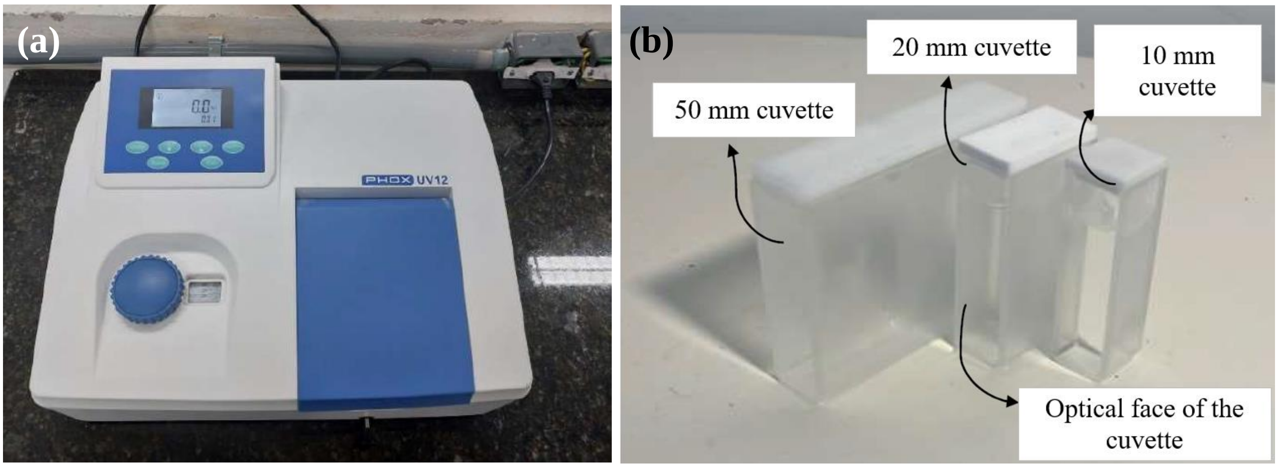

Figure 1. Determination of transmittance of transparent soil: (a) Spectrophotometer; and (b) Cuvettes with optical lengths of 10 mm, 20 mm, and 50 mm.

The results of the spectrophotometry test are presented in Figure 2, indicating that visibility distances around 5 cm are suitable for constructing the reduced model. In particular, this study considered a visibility distance of 7.5 cm, which corresponds to half the width of the acrylic box used for constructing the reduced models.

2.2 Sisal Natural Fibers

The sisal fibers used in this research were acquired from a company in the state of Bahia, as indicated in Fig. 3(a). Initially, the sisal fibers were cut to lengths of 5 cm, then weighed and separated for use as sand reinforcement, as shown in Fig. 3(b). Measurements of fiber diameter using image analysis indicated an average diameter of 0.112 mm. Evaluation of the linear mass of the fibers, on the other hand, indicated a value of 0.042 g/mm.

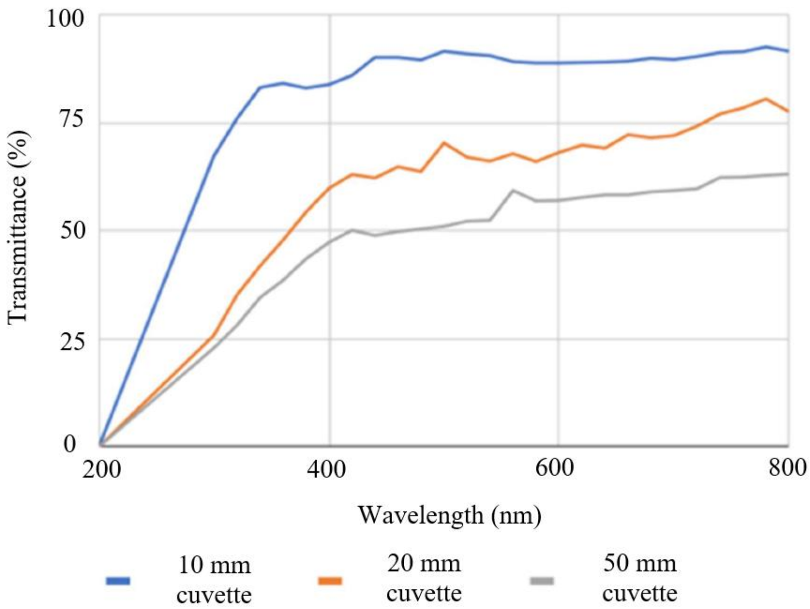

Figure 2. Transmittance of transparent soil samples at different optical lengths.

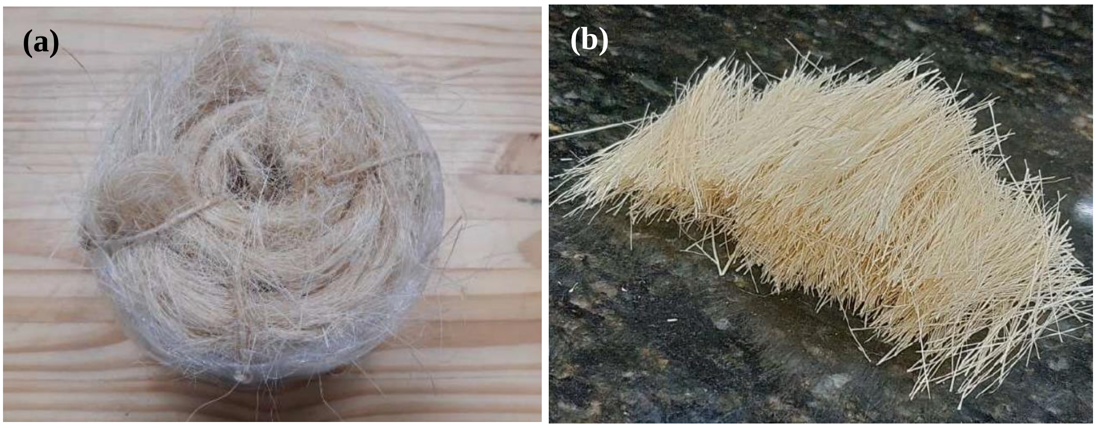

Figure 3. Natural sisal fibers: (a) Visual appearance of commercially available fibers; and (b) Fibers after preparation for testing.

The natural sisal fibers were also subjected to tensile testing to assess the strength of these elements, for which the EMIC universal press shown in Fig. 4(a) was employed. It is noteworthy that the testing device is located on the right-hand side of the equipment, with a load cell compatible with the low level of applied loading (0.1 kN). In Fig. 4(b), a detail of the grip used to secure the fibers during the tensile tests is presented. The results of this analysis are presented in Figure 5.

2.3 1-g Load Tests

The physical model was constructed in an acrylic cube with sides measuring 15 cm. Initially, a layer of approximately 1 cm of quartz was added to the cube using the sand raining technique, and the saturation fluid was poured. A metal rod was used to remove air bubbles trapped by the solid skeleton of the material. This process was carried out in consecutive layers. In the case of the reinforced soil samples, compaction was performed using a properly calibrated manual compactor to achieve a relative compaction of 80%. The experiment on reinforced sands involved the use of sisal fibers at concentrations of 0%, 0.5%, 1.0%, and 2.0% relative to the mass of quartz. Subsequently, a load test was conducted using a universal testing machine (EMIC) equipped with a displacement transducer and load cell to collect displacement and applied force data, respectively.

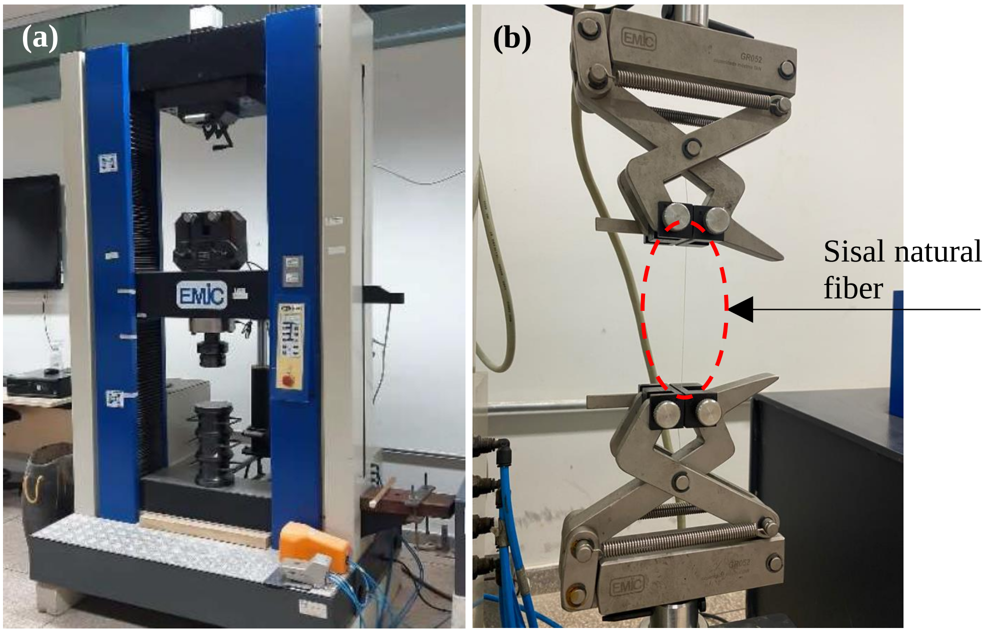

Figure 4. Tensile testing on natural sisal fibers: (a) EMIC universal press; and (b) Grip used for fiber fixation.

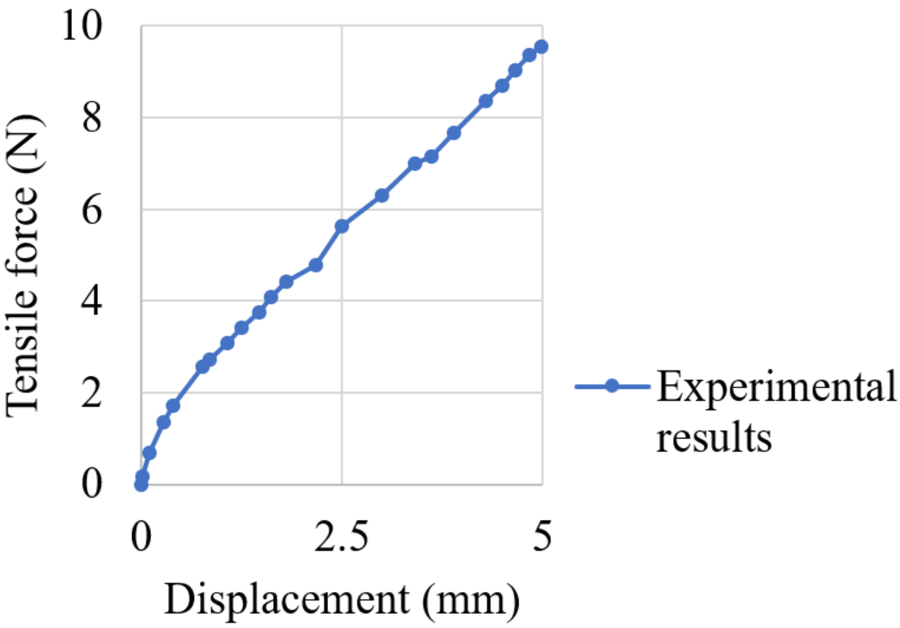

Figure 5. Force-displacement behavior of sisal fibers, considering the average of results from 5 samples.

The press was set up with a displacement speed of 1 mm/min, using a load cell with a capacity of 5 kN. The force application was carried out through a circular cross-section surface with a diameter of 4 cm, simulating a shallow foundation. Each test had an approximate duration of 20 minutes, allowing for the observation and recording of the variables of interest during the test. In Fig. 6(a), an overview of the physical model at the beginning of the test is presented, while in Fig. 6(b), an overview of the model at the end of the test is shown.

3 RESULTS AND DISCUSSION

The load-displacement behavior of sand without fibers and of composites formed by sand reinforced with natural sisal fiber, at concentrations of 0.5%, 1.0%, and 2.0%, is depicted in Figure 7.

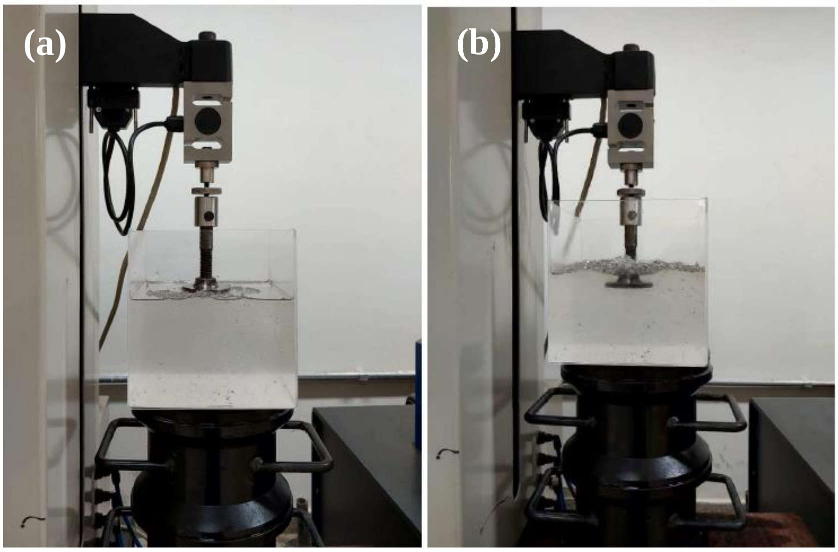

Figure 6. Test on a physical model of shallow foundation on sand reinforced with sisal fibers: (a) Beginning of the test; and (b) End of the test.

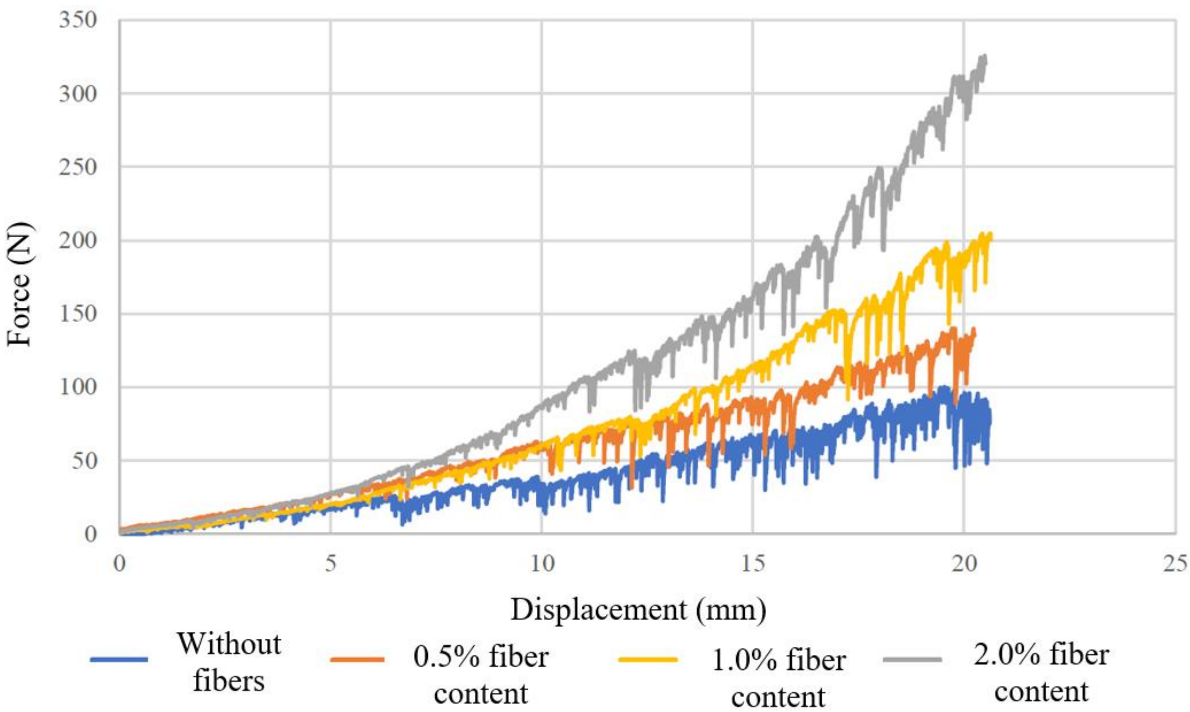

Figure 7. Load-displacement behavior of sand without fibers and of composites formed by sand reinforced with fibers, at concentrations of 0.5%, 1.0%, and 2.0%.

As illustrated in Figure 7, it is concluded that the increase in fiber content is directly related to the enhancement of the load-bearing capacity of the composites. Based on these findings, it was possible to tabulate the values of strength associated with a displacement of 20 mm, as depicted in Table 2.

Table 2. Summary of the results of the load test experiments considering a displacement of 20 mm.

Sisal fiber content (%)	Rupture force (N)	Displacement (mm)
0	75	19.53
0.5	125	19.72
1.0	180	20.43
2.0	300	20.48

The results of this analysis indicate that the use of sisal fibers can be viable for soil reinforcement, especially under the application of stresses from shallow foundations. However, it is worth noting that this solution is particularly suitable for temporary structures, as sisal fibers tend to degrade over time. Further studies are needed to quantify the influence of untreated fibers and fibers treated with any specific treatment in this regard.

It is worth highlighting that Carvalho (2019), when evaluating the mechanical behavior of a sandy soil reinforced with sisal, curauá, and coconut fibers through medium-scale direct shear tests, observed that sisal fibers significantly contribute to the material's strength, even during preliminary stages of the test, such as for horizontal displacements of less than 5 mm. Thus, the proposed solution can be considered a viable alternative for the development of sustainable projects.

4 CONCLUSIONS

This study addressed the load versus displacement behavior of reinforced a transparent sand. The methodology involved constructing physical models using transparent soil, allowing the researchers to investigate the proposed solutions. Additionally, tests were conducted to characterize the different materials used in the research. Based on the results of this study, the following conclusions can be drawn:

- Inclusion of sisal fibers: This contributed to increasing the load-bearing capacity of the foundation soil by restricting vertical deformations, resulting in improved soil stability.
- Controlled inclusion of sisal fibers: This can be an effective strategy for strengthening soil and improving its mechanical properties, especially for temporary solutions, as it does not generate environmental liabilities.
- Use of transparent soils: This provided a viable alternative to conventional laboratory testing methods, both for transparent sand and transparent clay, as long as the inherent limitations of these techniques are respected.

Physical modeling using transparent soil techniques is a promising approach for analyzing soil behavior under different loading conditions and considering various reinforcement methods. To further advance this line of research, it is suggested to investigate other factors such as:

- Use of other polymeric or natural materials as soil reinforcement: This includes exploring other types of plant fibers, polypropylene fibers, and geogrids with different dimensions.
- Utilization of soils with distinct geotechnical properties: This includes employing transparent soil techniques to facilitate internal visualization of models during tests.

By exploring these factors, future research can provide valuable insights into the effectiveness of soil reinforcement techniques and contribute to the development of sustainable and resilient infrastructure solutions.

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