Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

Drained tests on sandy soils reinforced with microgrids

Ricardo César Bezerra Teles Júnior[1#], Anderson Borghetti Soares[1], Marcos Fábio Porto de Aguiar[2]

Article

Keywords
Soil reinforcements
Geosynthetics
Triaxial tests
Microgrids

Abstract

A subject of great relevance for geotechnical engineering is the search for economical solutions to improve soil mechanical characteristics. Due to the constant evolution of the industry and the regular launching of new products – developed to compensate for various soil deficiencies - the need for applied research continually arises. Geosynthetics are reinforcement materials that increase soil strength and its traction features. Among them, microgrids have been used as a separating element for distinct materials, but studies on microgrids as reinforcement materials are still not quite common in the literature. This research aimed to evaluate on a small scale the mechanical behavior of microgrids as reinforcement materials in sandy soils by analyzing the strength parameters obtained through consolidated-drained triaxial tests (CD) of specimens with none to 3 layers of the material. The study also compared the performance of sandy soil reinforced with microgrid and non-woven geotextiles of different weights (200 g/m^2 and 300 g/m^2). Results showed that the insertion of microgrid layers in sandy soils increased the strength parameters, and the behavior of reinforced soil has changed from strain-softening to strain-hardening. The sample reinforced with one layer of microgrid had improved cohesion and friction angle compared to samples with one layer of non-woven geotextiles.

1. Introduction

Soils are heterogeneous materials from different formations with distinct textural, structural, and mineralogical characteristics. Many times, soil deposits can be unsuitable for geotechnical work. Still, expressive improvement of their properties and performance can be obtained by coupling with other materials and through chemical or physical ameliorations. Research and studies carried out along these lines include, for example, additions of chemical binders and the use of geosynthetics.

Geosynthetics, as polymeric products, offer a wide range of applications in geotechnical engineering. They can be used for soil reinforcement, stabilization, drainage, and filtration, as physical barriers against flow (fluid or gas), for waterproofing, erosion control, and environmental protection. This versatility opens up possibilities for innovative solutions (Palmeiras, 2018).

Different materials can be used for soil reinforcements: geogrids, natural (or polypropylene) fibers, geotextiles, metallic meshes, and geocomposites. Geosynthetics increase soil strength due to the additional tensile strength they provide.

Several authors have studied the improvement of the mechanical behavior of soils with synthetic materials. Sieira (2003) examined the effect of inserting geogrid layers in sandy and silty-clayey soils. In contrast, Chandrasekaran et al. (1989) evaluated the insertion of layers of woven and non-woven geotextiles in sandy soils. Unnikrishnan et al. (2001) assessed the use of sand layers between layers of geosynthetics (woven geotextile, non-woven geotextile, and microgrid) in clayey soils, while Carlos (2016) studied the influence of geocomposites on fine soils. Latha & Murthy (2007) evaluated the effect of the reinforcement form on the strength of reinforced sandy soils.

The abovementioned studies used triaxial tests and concluded that the insertion of geosynthetics was highly beneficial to the assessed soils, for there was a considerable improvement in the strength parameters. The geosynthetics justified this induced an effect similar to an increase in soil confinement.

In general, when adequately compacted, soils present an excellent compressive strength. Yet, they have low tensile strength. According to Wheeler (1996), when soil is vertically loaded, the vertical strains compress it in that direction but tend to expand the soil mass horizontally, where traction forces appear.

[#]Corresponding author. E-mail address: ricardojunior1901@hotmail.com
[1]Universidade Federal do Ceará, Departamento de Engenharia Hidráulica e Ambiental, Fortaleza, CE, Brazil.
[2]Instituto Federal de Educação, Ciência e Tecnologia do Ceará, Departmento de Construção Civil, Fortaleza, CE, Brazil.

Submitted on March 8, 2022; Final Acceptance on October 10, 2024; Discussion open until May 31, 2025.

Editor: Renato P. Cunha

https://doi.org/10.28927/SR.2025.003222

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Due to their high tensile strength (which limits the deformability), reinforcements will act to reduce lateral strains, providing the soil-geosynthetic set with a feature that is similar to an increase in the confining stress.

Ehrlich & Becker (2009) highlighted that the pullout strength increases the general strength of the composite and also that different types of reinforcements will present different mechanisms of strength mobilization. For example, sandy soils will have stronger traction forces in the interface soil reinforcement due to the interlocking of soil grains in the empty spaces of the reinforcement. On the other hand, the mechanism in clays and silts will involve friction between the contact surfaces in the soil-geosynthetic set.

The use of microgrids as reinforcements has not been widely discussed in the literature, even though the approach is not recent. Leshchinsky et al. (2016) evaluated the gain in strength caused exclusively by inserting microgrids in poorly graded sands. Triaxial tests were carried out in samples where pieces of microgrid were randomly added to the soil, showing that there was indeed an increase in strength and stiffness. In the abovementioned study, the concentration of 0.5% by weight (microgrid/soil) showed the best results.

Microgrids are composed of high-tenacity filaments manufactured by the flexuous intertwining of the elements. The material is coated with a high-strength polymeric coating that can resist installation damages and chemical, biological, and environmental aggressions (ABNT, 2013).

These features make microgrids suitable for civil construction, infrastructure, and environmental works, such as sanitary landfills, tailings dams, and construction and demolition waste (CWD) landfills. Microgrids are versatile materials that combine hydraulic and physical properties—good permeability, small apparent openings, and high tensile strength.

This study aimed to contribute to understanding the use of microgrids as a material for soil reinforcement, evaluating their mechanical behavior in sandy soils through triaxial tests. The strength parameters (cohesion and friction angle) and the stress *versus* strain curves were obtained for soil samples reinforced with up to three layers of microgrids. Lastly, these results were compared with those obtained for soils reinforced with non-woven geotextiles of different weights and with results from other studies that used other geosynthetics (woven geotextiles, and geogrids).

2. Materials and methods

The sandy soil assessed in this study was collected at the Experimental Field for Geotechnics and Foundations (EFGF) of the Federal University of Ceará (UFC) in Fortaleza, State of Ceará, Brazil. The procedure to obtain the samples comprised removing the upper layer of existing soil, delimiting a 1m x 1m area, digging a hole, and collecting 20 kg of soil at a depth of 0.5 m.

The microgrids and non-woven geotextiles used in this study were provided by the company Maccaferri do Brasil. The microgrid, marketed under MacGridNet, has a longitudinal tensile strength of 45 kN/m and a maximum elongation of 15%. The mesh opening is 0.2 cm x 0.15 cm.

MacTex H.2, Maccaferri's non-woven geotextiles used in this study, had two different weights: (*i*) 200 g/m^2, with a longitudinal tensile strength of 10 kN/m, and (*ii*) 300 g/m^2, with a longitudinal tensile strength of 16 kN/m.

Grain size analysis (NBR 7181 – ABNT, 2016b), tests to determine water content (NBR 16097 – ABNT, 2012), specific gravity (ME 093 – DNER, 1994), and compaction parameters (NBR 6457 – ABNT, 2016a), and compaction tests were performed using valid Brazilian standards. Compaction tests were conducted using Standard Proctor compaction energy (small cylinder and soil reuse).

Consolidated-drained (CD) triaxial compression tests were used to assess the mechanical behavior of the soil samples (sands), according to ASTM D7181 (ASTM, 2020b), and for the confining stresses of 50 kPa, 100 kPa, 150 kPa, and 200 kPa.

The experimental program encompassed six soil-geosynthetic scenarios: (A) soil without reinforcement (natural soil); (B) soil with one layer of microgrid; (C) soil with two layers of microgrid; (D) soil with three layers of microgrid; (E) soil with one layer of non-woven geotextile (200 g/cm^2); and (F) soil with one layer of non-woven geotextile (300 g/cm^2).

Four triaxial tests were carried out for each scenario, considering the different confining stresses (50 kPa, 100 kPa, 150 kPa, and 200 kPa). Thus, 24 tests were performed in total.

The specimens were cylindrical and had 10 cm in height (H) and a diameter of 5 cm. For those with one reinforcement layer (Groups B, E, and F), the geosynthetic was placed right in the specimen's middle (i.e., $H/2$), as shown in Figure 1. For the specimens with two layers (Group C), the geosynthetic was placed between every third of its total height (i.e., $H/3$ and $2H/3$). For three-layered specimens (Group D), the reinforcement was placed in every quarter of the height (i.e., $H/4$, $H/2$, and $3H/4$ - see Figure 1). The pattern described above is also detailed in Table 1. The microgrid used in this study is shown in Figure 2.

To validate the results obtained in triaxial tests, the technical standard D5321 (ASTM, 2020a) recommends that the molded specimens have a diameter at least five times bigger than the largest opening of the microgrid/geogrid. As the opening of the used microgrid was 0.2 cm x 0.15 cm, the molded specimens met the standard recommendation.

The specimens were molded in the optimal water content obtained in the compaction tests, which used a cylindrical mold (volume ~ 196 cm^3) and a socket of 1.25 kg, dropping from a height of 20 cm, and blown 15 times per compacted layer.

The authors used the maximum axial strain of 10%, corresponding to the maximum strain allowed by equipment settings. It is worth mentioning also that in failure, the test was carried out with controlled strain. The maximum speed to be imposed on the tests (mm/min) was determined following the recommendations of Head (1998). The consolidation time (T_{100}) was multiplied by a failure factor to calculate the

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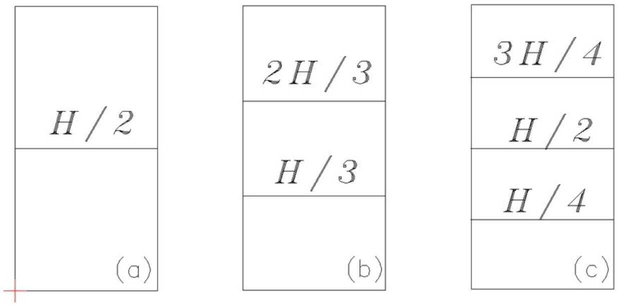

Figure 1. (a) Positioning of reinforcement in the one-layered specimens (Groups B, E, and F); (b) Positioning of reinforcement layers in the two-layered specimen (Group C); (c) Positioning of reinforcement layers in the three-layered specimen (Group D).

Table 1. Positioning of the reinforcements (microgrid and non-woven geotextile) inside the soil samples.

Number of layers	Layer position in specimen
0	-
1	*H*/2
2	*H*/3 and 2*H*/3
3	*H*/4, *H*/2, and 3*H*/4

Figure 2. Microgrid (MacGrid Net – Macaferri).

failure time. For the axial deformation on failure of 10%, the controlled deformation speed calculated was 0.28 mm/min. The tests used a controlled deformation speed of 0.18 mm/min.

3. Results and discussion

The grain-size distribution curve (Figure 3) showed the soil was well-graded silty sand, classified as SW-SM in the UCS structure. Standard Proctor compaction tests revealed an optimal moisture content (*OMC*) of 11.8% and a maximum dry density of 1.9 g/cm^3 (Figure 4).

Figures 5 to 7 show the curves "axial strain versus deviator stress" and "axial strain versus volumetric strain" of the analyzed soil samples (natural soil and those reinforced with microgrid layers) for the confining stress of 50, 100, and 150 kPa. Table 2 shows each test's peak deviation stress and axial and volumetric strains at failure. When the failure was not obtained, the maximum deviation stress was considered to be 10% of axial strain.

For all confining stresses, there was an increase in the deviation stress with the increase in the number of reinforcements (or decrease in spacing between reinforcements), as it was observed in sandy soil reinforced with other geosynthetics, such as geogrid and geotextiles (Markou, 2016; Sieira, 2003; Chandrasekaran et al., 1989; Nouri et al., 2016; Carlos, 2016). An increase in axial strain at failure was also observed with increasing reinforcements (Figure 8), and all specimens exhibited initial volumetric contraction and dilatancy at failure. Sieira (2003) observed an increase in axial strain at failure in sandy soils reinforced by geogrids in triaxial tests with an increase in reinforcements. In triaxial tests, coarse soils (sandy and silt-sandy) reinforced with geosynthetics show an initial contraction and increased volume at failure. Other researchers observed this behavior (Chandrasekaran et al., 1989; Nouri et al., 2016; Carlos, 2016). In this study, the dilatancy of the samples was found to increase with the decreasing reinforced spacing.

Figure 8 shows axial strain at failure with the confining stress. There was an increase in axial strains when failure occurred and when the number of reinforcement layers and confinement stresses increased. Note that, for the confining stresses of 50 kPa and 100 kPa, the axial strains when the failure happened were like those in Groups A (unreinforced) and B (1 layer of microgrid).

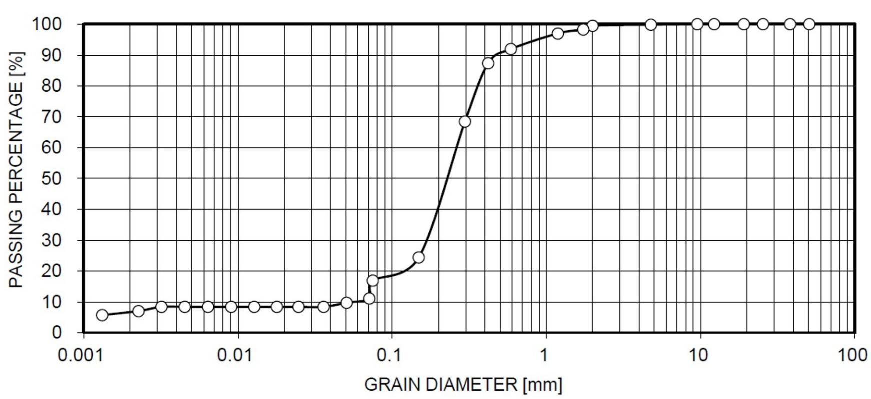

Figure 3. Grain-size distribution curve.

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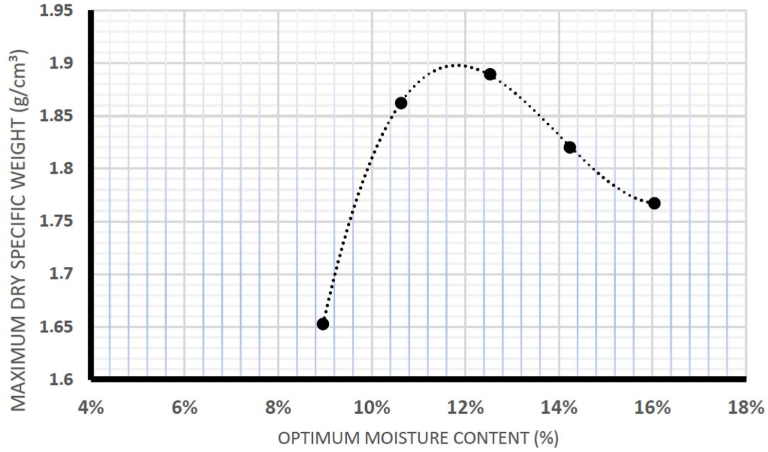

Figure 4. Soil compaction curve.

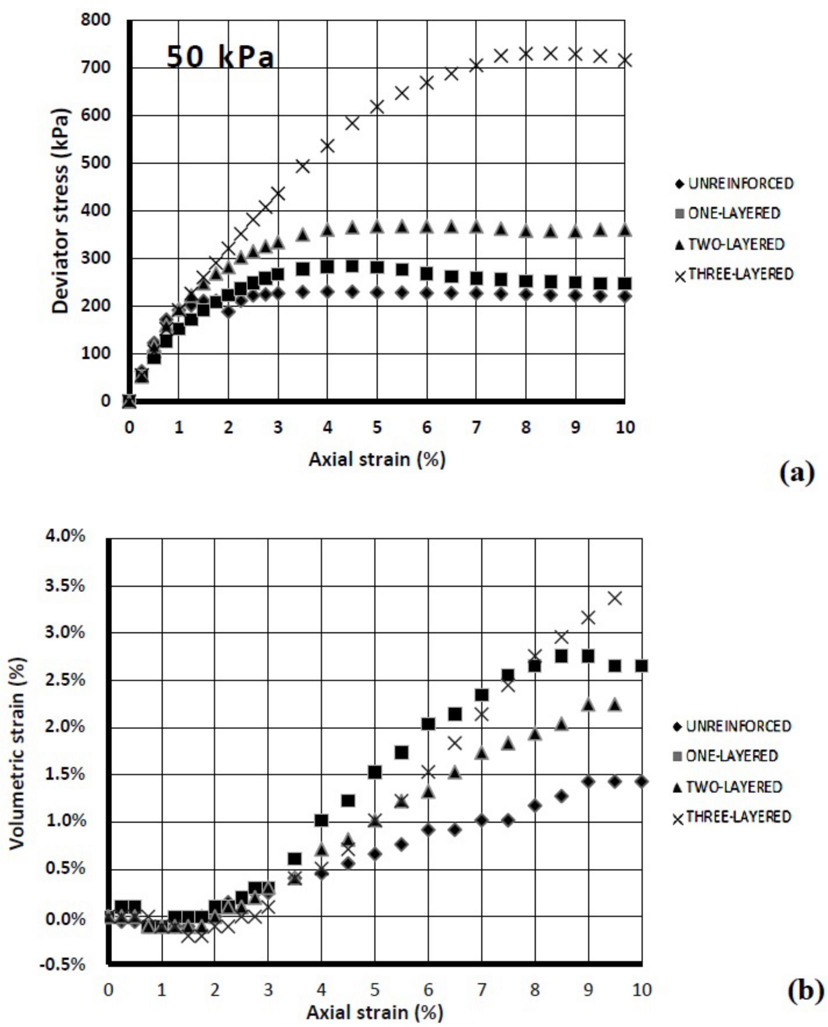

Figure 5. (a) Curve "axial strain versus deviator stress"; (b) Curve "axial strain versus volumetric strain" for unreinforced and reinforced specimens and a confining stress of 50 kPa.

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Table 2. Peak deviator stress, axial and volumetric strain for all tests.

Group	σ_3 (kPa)	$\sigma_{1\ failure}$ (kPa)	$\sigma_{d\ failure}$ (kPa)	e_{axial} (%)	e_{vol} (%)
Unreinforced	50.00	281.00	231.00	4.00	0.50
	100.00	483.85	383.85	6.50	0.71
	150.00	700.00	550.00	5.50	0.76
One Layered	50.00	334.00	284.00	4.50	1.22
	100.00	592.95	492.95	5.50	0.92
	150.00	790.00	640.00	7.50	0.51
Two Layered	50.00	418.00	368.00	5.00	1.02
	100.00	754.00	654.00	10.00	1.53
	150.00	941.00	791.00	10.00	0.87
Three Layered	50.00	780.00	730.00	8.50	2.95
	100.00	1067.00	967.00	10.00	2.14
	150.00	1420.00	1270.00	10.00	1.02

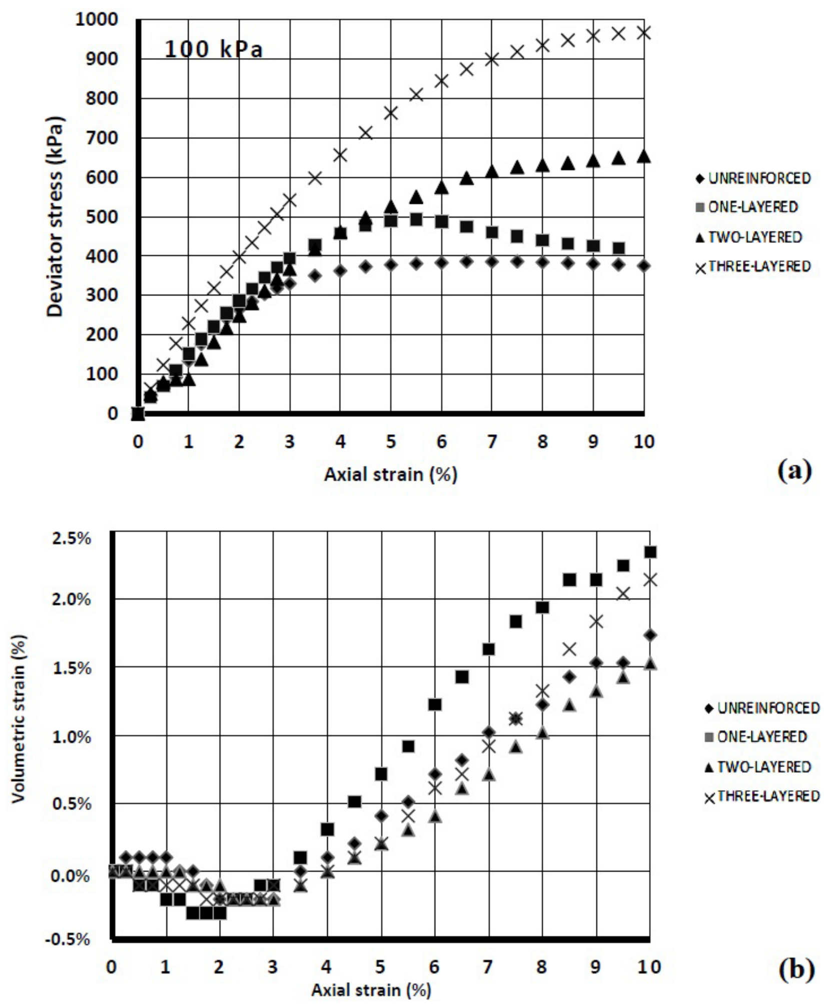

Figure 6. (a) Curve"axial strain versus deviator stress"; (b) Curve "axial strain versus volumetric strain" for unreinforced and reinforced specimens and a confining stress of 100 kPa.

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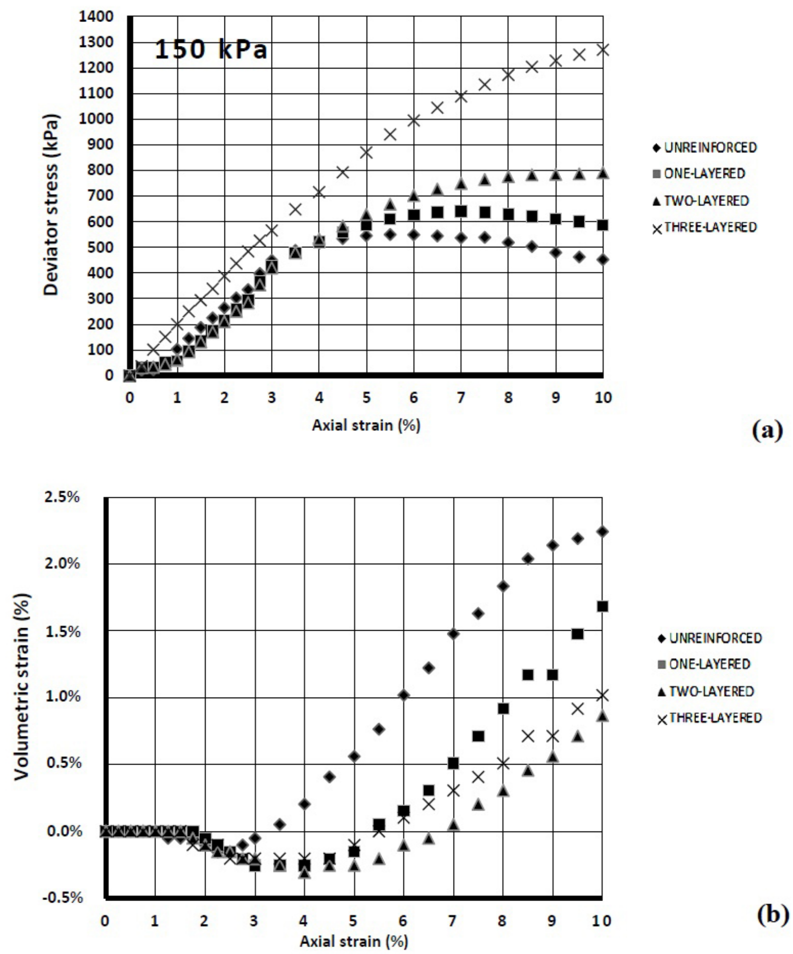

Figure 7. (a) Curve "axial strain versus deviator stress"; (b) Curve "axial strain versus volumetric strain" for unreinforced and reinforced specimens and a confining stress of 150 kPa.

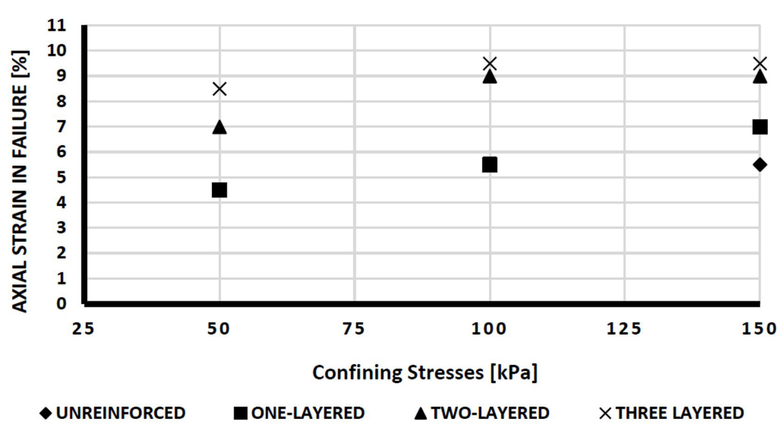

Figure 8. The behavior of axial strain versus deviator stress when the failure occurred for the tested specimens.

For the confining stress of 150 kPa, Group B specimens presented an axial strain higher than that of the unreinforced soil (Group A). For specimens in Groups C and D (2 and 3 layers of microgrid), it was observed that beyond the confining stress of 100 kPa, the axial strains did not increase when failure occurred.

The results also indicated an increase in the peak deviation stress with the increase in the number of reinforcements,

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regardless of the confining stress, and with the increase in the confining stress, as shown in Figure 9. Studies in large triaxial tests reinforced with geogrids indicated the same behavior (Chen et al., 2014).

Increased confining stresses for the tests with reinforced soils resulted in decreased volumetric strains at failure. Comparing the axial strains at failure of specimens reinforced with microgrid with the unreinforced ones, it was observed that, when surpassing the confining stress of 150 kPa, the volumetric strains at failure were higher in the unreinforced specimens.

After failure, when examining the reinforcements in the specimens, it was observed that there was no failure or strain caused by traction, suggesting that the friction between the surfaces was the mobilizing mechanism of strength.

The tests indicated that for lower confining stresses and reinforcement layers, the soil exhibited strain-softening behavior at failure, with failure at lower axial strains. The inclusion of reinforcements and the increase in the confining stress resulted in a strain-hardening behavior at failure, with the peak deviator stress being obtained for greater deformations or without a defined rupture point in the stress curve -deformation. An increase in strength was observed with the increase in reinforcement layers, as shown in Figures 10 and 11.

Table 3 summarizes the effective strength parameters (cohesion and friction angle) obtained through the triaxial tests carried out in this study.

The increase in the number of reinforcement layers caused an increase in the strength parameters. This can be explained by the presence of the microgrid, which was mobilized through different mechanisms, such as friction forces in the interface soil reinforcement, rolling resistance of the soil particles on surfaces normal to the direction of movement, and pullout resistance of the reinforcement. These mechanisms cause tensile stresses on the reinforcement.

The effective friction angle was 24% higher in Group D (3 layers of microgrid) than in the unreinforced ones (Group A). The effective cohesion for Group D specimens also increased by 400% compared with the unreinforced soil.

Failure was observed for the unreinforced specimen, but for some reinforced specimens, no failure was detected up to 10% of axial strain, chiefly for higher confining stress. An additional test with a confining stress of 200 kPa was carried out, as seen in Figure 12. For all reinforced samples,

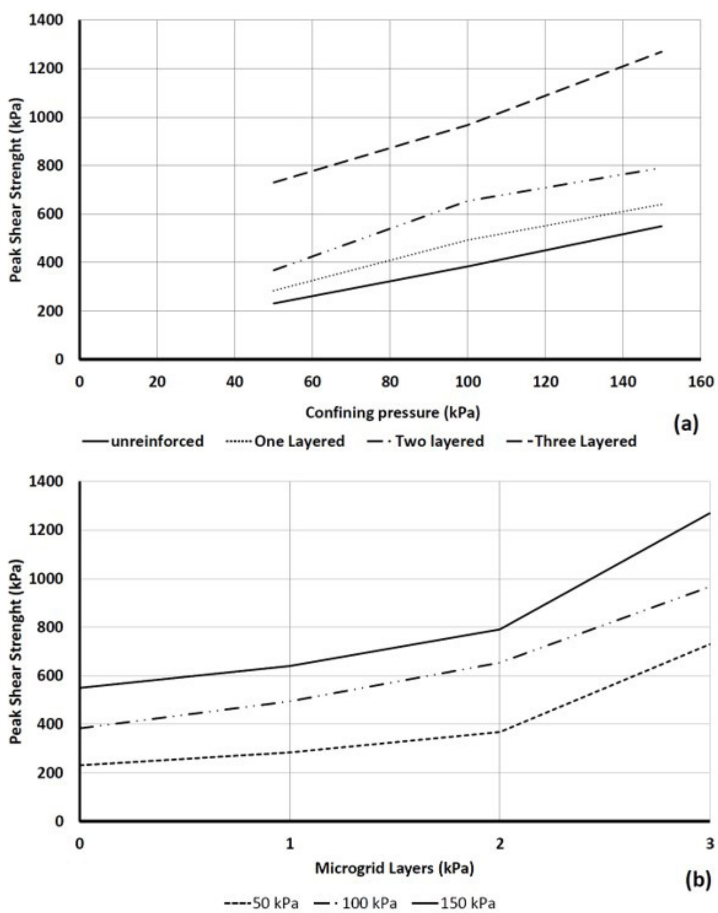

Figure 9. Deviator stress peak for different confining pressures and number of microgrid layers.

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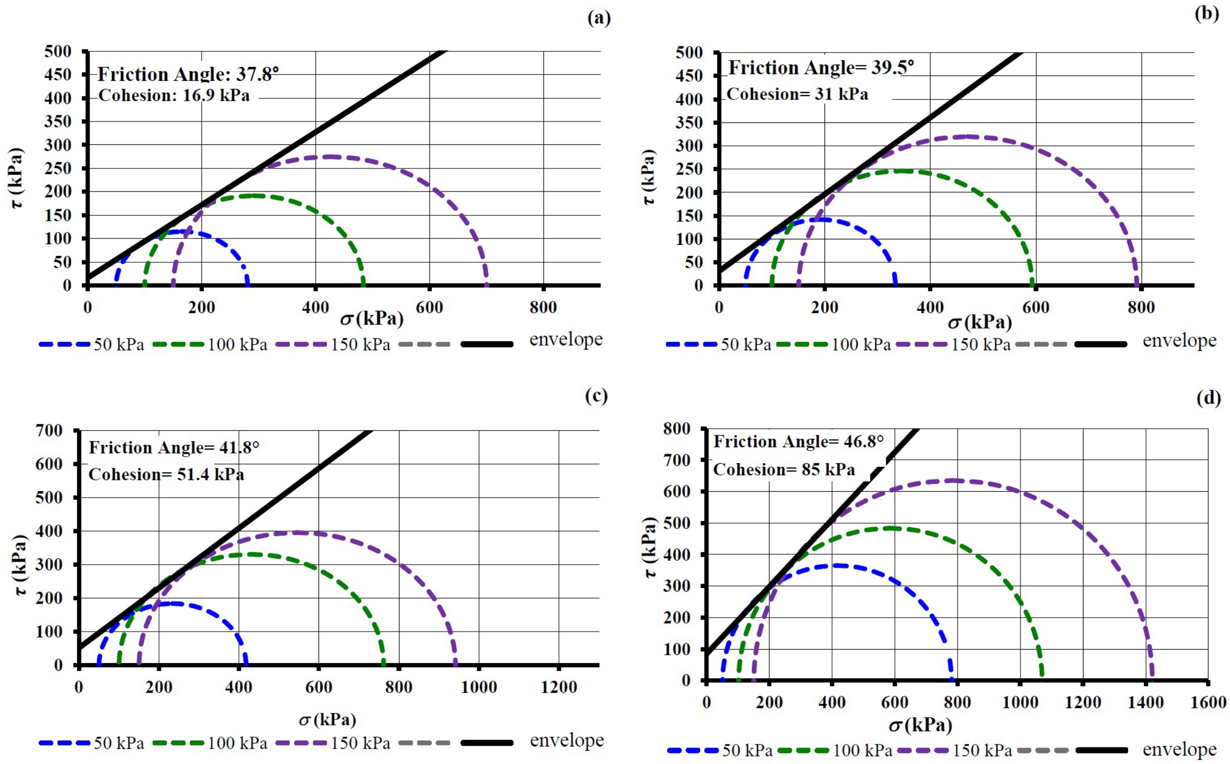

Figure 10. Envelope Effective Morh-Coulumb of reinforced soil: (a) without reinforcement; (b) one layer of reinforcement; (c) two layers of reinforcement; (d) three layers of reinforcement.

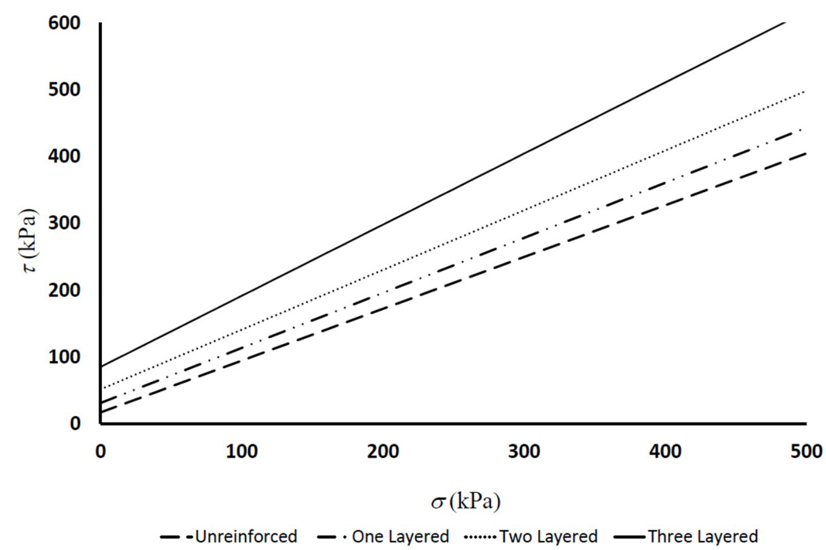

Figure 11. Envelope Mohr-Coulomb for different samples.

Table 3. Effective strength parameters for the tested microgrid specimens.

Reinforcement type	Number of layers	Effective cohesion [kPa]	Effective friction angle [°]
Microgrid	0	16.9	37.8
	1	31.0	39.5
	2	51.4	41.8
	3	85.0	46.8

the deviation stress increases with the axial deformations without reaching a maximum value. Because of this, the results for the confining stress of 200 kPa were not used to draw the failure envelope or to evaluate the strength parameters of the reinforced soil.

According to Mitchell (1987) and Wheeler (1996), the more significant increase in cohesion intercept than friction angle in reinforced samples is due to the transmission mechanisms of efforts. The reinforcement increases the apparent cohesion, causing an effect similar to the increase in confining stress.

This study also compared the stress versus strain curves for the microgrid soil with those for soils reinforced with non-woven geotextiles (Figure 13). For these additional scenarios, the specimens were molded with one layer of non-woven geotextile of two different weights: 200 g/m^2 (Maccaferri's H 40.2, Group E) and 300 g/m^2 (Maccaferri's H 60.2, Group F). This helped compare the behaviors of the soil with different types of reinforcements.

For the confining stress of 50 kPa, the stress versus strain curves were similar for all reinforced specimens. Failure with dilation also occurred in all specimens. For the confining stress of 100 kPa, the soil reinforced with one layer of microgrid presented a higher maximum deviator stress than that of the soil reinforced with one layer of geotextile.

For the confining stress of 150 kPa, the axial strains, when failure occurred, were similar for the soil reinforced with microgrid and the soil reinforced with geotextile. The microgrid specimens presented a slightly higher maximum deviator stress than those reinforced with geotextiles.

Table 4 summarizes the effective strength parameters for the evaluated reinforcements (one-layer microgrid and one-layer non-woven geotextile). Results show that specimens reinforced with microgrids presented higher friction angle and cohesion values than those reinforced with geotextiles.

Castro (2020) performed triaxial tests on specimens reinforced with fibers in saturated condition and small-scale equipment, observing an increase of 7% in the effective friction angle and 10% in the effective cohesion. Table 2 shows a much more significant increase in the strength parameters obtained using microgrids.

Results of triaxial tests in soil reinforced with microgrid present here agree with other studies that showed increased strength parameters in soil reinforced with other geosynthetics. This increase was higher in the cohesive intercept, with the insertion of reinforcements: (a) Chen et al. (2014) assessed a clayey-silty soil with a three-layered geogrid reinforcement in a large-scale (30x60 cm) equipment for triaxial tests. (b) Gali (2006) used small-scale equipment (3.8x7.6 cm) for triaxial tests, with a sandy soil reinforced with three layers of woven geotextile. (c) Yang (2016) analyzed the results of triaxial consolidated-undrained (CU) tests, also with small-scale equipment (5x10 cm), for a clayey soil reinforced with non-woven geotextile (200 g/cm^3).

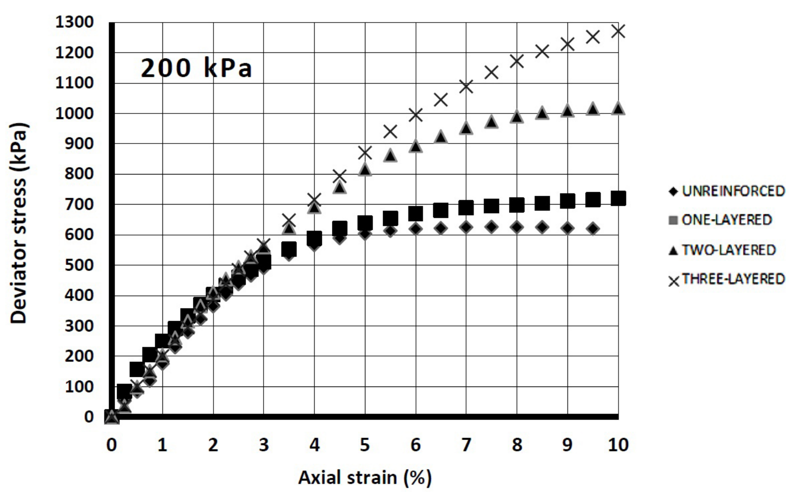

Figure 12. Curves "axial strain versus deviator stress" for unreinforced and reinforced specimens and a confining stress of 200 kPa.

Table 4. Effective strength parameters for the tested reinforcements.

Reinforcement type	Number of layers	Effective cohesion [kPa]	Effective friction angle [°]
Microgrid	1	31.0	39.5
Non-woven geotextile H 40.2	1	19.1	37.0
Non-woven geotextile H 60.2	1	17.5	38.5

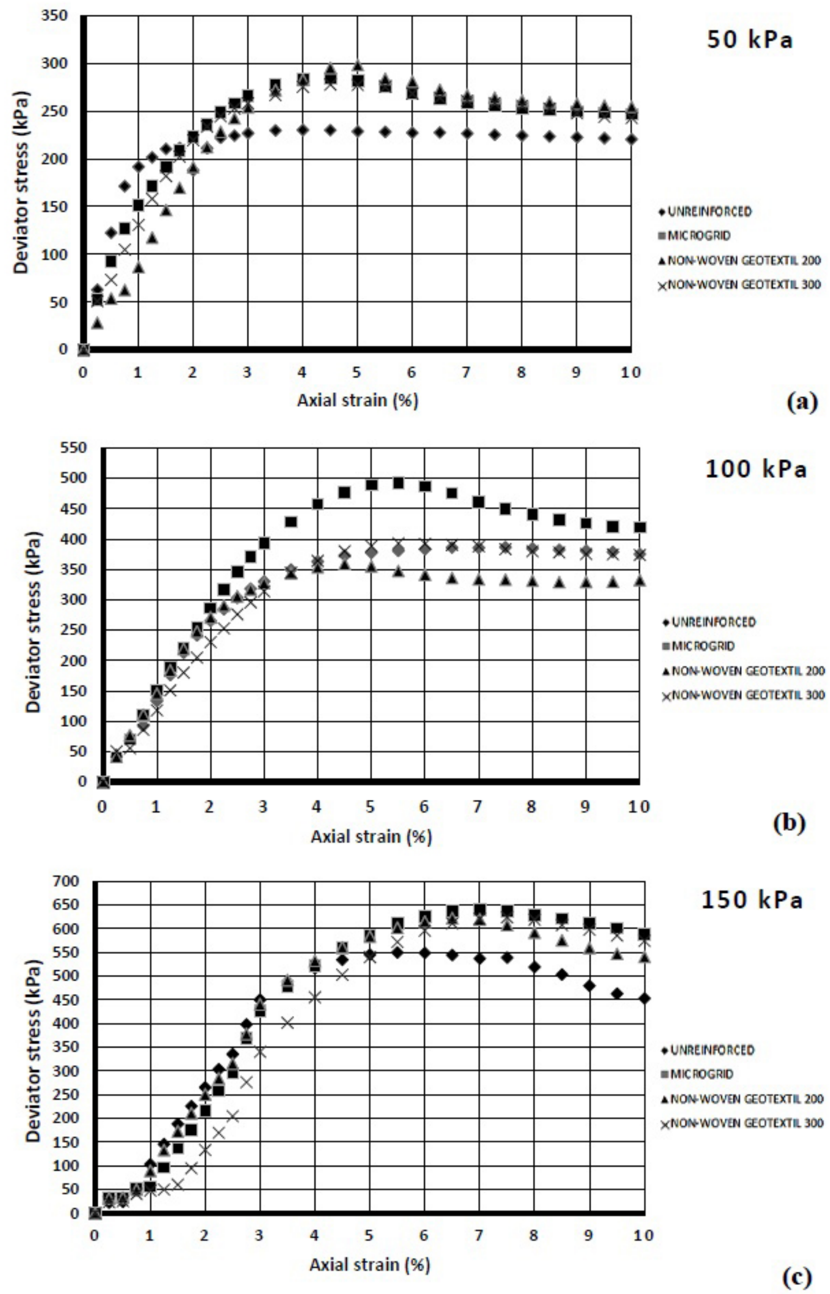

Figure 13. Stress versus strain curves for microgrid reinforced and non-woven geotextile reinforced specimens, considering the confining stresses: (a) 50 kPa, (b) 100 kPa, and (c) 150 kPa.

4. Conclusions

This study evaluated the mechanical behavior of sandy soil reinforced with multiple layers of microgrid through consolidated-drained (CD) triaxial tests. Results showed that increasing the number of layers of this reinforcement caused an increase in the deviator stress and the axial strain when failure occurred.

The specimens had dilatancy at failure in the triaxial tests performed with confining stresses of 50 kPa, 100 kPa, and 150 kPa. The insertion of more layers of the reinforcement increased the maximum deviator stresses, and this difference was more prominent for lower confining stresses, as observed by Sieira (2003).

In the CD triaxial tests carried out for the confining stress of 200 kPa, the test was interrupted because the specimens did not reach failure until the axial strain of 10%, which corresponded to a physical limitation of the equipment. Therefore, these results were not used to draw the failure envelope.

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The microgrids and non-woven geotextiles were inspected after the laboratory testing phase. No strain or signs of failure were observed in those reinforcements, suggesting that friction in the interface soil reinforcement was the primary mechanism that mobilized the strength. A discrete volumetric strain of the specimens was observed for higher confining stresses.

Regarding the samples with the microgrid, the insertion of more layers of reinforcement increased the effective strength parameters (cohesion and friction angle), with the specimen reinforced with the three layers of microgrid showing the best results: cohesion was four times higher than that of the natural soil (i.e., the unreinforced specimen), and the friction angle was 24% higher than that of the unreinforced soil.

When comparing the results of the soil reinforced with one layer of microgrid and one layer of non-woven geotextiles with weights of 200 g/m^2 and 300 g/m^2, it was observed that the maximum deviator stresses were obtained for the soil samples reinforced with microgrids.

The strength parameters obtained for the soil reinforced with one layer of microgrid were also higher than those obtained for the soil reinforced with geotextile. The friction angle for the specimens with the microgrid was 2.5% higher, and the cohesion was 62% higher than the soil reinforced with geotextile.

Also, the increase in the strength parameters of the evaluated sandy soil when reinforced with microgrids was significant compared with the increase observed in soils reinforced with other types of geosynthetics (e.g., geotextiles and geogrids) obtained through triaxial tests presented by different authors in the literature.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the paper's contents, and there is no financial interest to report.

Authors' contributions

Ricardo César Bezerra Teles Júnior: conceptualization, funding acquisition, investigation, data curation, methodology, software, visualization, writing – original draft. Anderson Borghetti Soares: conceptualization, investigation, formal analysis, data curation, methodology, supervision, validation, writing – review & editing. Marcos Fábio Porto de Aguiar: Supervision, validation.

Data availability

The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was not prepared with the assistance of generative artificial intelligence (GenAI).

List of symbols and abbreviations

e_{axial}	Axial strain
e_{vol}	Volumetric strain
CD	Consolidated-drained triaxial tests
CWD	Construction and demolition waste
EFGF	Experimental Field for Geotechnics and Foundations
H	Specimen Height
OMC	Optimal moisture content
SW-SM	Well-graded silty sand
T_{100}	Consolidation time
SW-SM	Well-graded silty sand
UCS	Universal Classification System
UFC	Federal University of Ceará
σ	Normal stress
σ_d	Deviator stress
$\sigma_{d\,failure}$	Deviator stress in failure
σ_1	Major principal stress
$\sigma_{1\,failure}$	Major principal stress in failure
σ_3	Confining stress
τ	Shear stress

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