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Study on microgrid - strength parameters of the soil-geosynthetic interface based on direct shear tests

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Article

Keywords
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Abstract

Soil reinforcements positively influence the mechanical behavior of soil by inserting external elements, such as geosynthetics, which improve strength and reduce deformability of the composite. Over the years, new geosynthetics have been developed and upgraded. In the last decade or so, microgrids have emerged as an appropriate choice for strengthening and separating soil layers. This research aimed to evaluate the strength parameters of the soil–microgrid interface using direct shear tests under different testing conditions and to compare the results with those for other geosynthetics (geomembrane and geotextile). The support base type (rigid and soil) for the geosynthetics was varied in the direct shear tests. When a soil base was used beneath the microgrid, performance was more efficient than with a rigid wooden base due to the higher soil friction angle. The results for all soil–geosynthetic interface strength parameters obtained using the rigid base indicated that the microgrid exhibited higher strength than the geomembrane and comparable strength to the geotextile, though slightly lower.

1. Introduction

Geosynthetics are polymeric materials, either manufactured or derived from natural polymers, widely used in geotechnical and environmental engineering applications (Palmeira, 2018). Over the past decades, these materials have been extensively employed in drainage systems, hydraulic works, soil retention structures, pavement reinforcement, and embankments on soft soils. Their widespread adoption is attributed to their ease of installation, cost-effectiveness, and ability to significantly enhance soil mechanical performance and durability. Geosynthetic-reinforced engineering works may improve the long-term performance of soil structures and reduce the required thickness of soil layers, thereby lowering construction costs and material demand (Kakuda, 2005).

The performance of geosynthetic-reinforced systems is strongly influenced by the properties of the backfill soil and the quality of compaction, which govern the stress transfer mechanisms between soil and reinforcement. Granular soils, particularly sands, are generally preferred in reinforced soil structures due to their favorable geomechanical behavior and high drainage capacity (Sayão et al., 2009). In this context, the interaction mechanisms at the soil–geosynthetic interface play a critical role in the stability and deformation behavior of reinforced systems.

The design of geosynthetic-reinforced structures requires determining soil–geosynthetic interface shear strength parameters, which are commonly obtained from direct shear tests. These parameters include the friction efficiency (E_φ) and the cohesion efficiency (E_c). The friction efficiency is defined as the ratio between the interface friction coefficient ($tan\ \delta$) and the soil internal friction coefficient ($tan\ \varphi$), whereas the cohesion efficiency corresponds to the ratio between the apparent soil–geosynthetic cohesion (c_a') and the effective cohesion of the soil (c'). These parameters are determined using small or large-scale direct shear apparatuses in accordance with NBR ISO 12957-1 (ABNT, 2013a), as well as inclined plane tests following NBR ISO 12957-2 (ABNT, 2013b).

In addition to these efficiencies, the coefficient of interaction (c_i) has been proposed as a complementary parameter to correlate the peak shear strength of the soil–geosynthetic interface with that of the soil alone under identical testing conditions (Ferreira et al., 2015). According to NBR ISO 12957-1 (ABNT, 2013a), c_i is defined as the ratio between the maximum shear stress obtained in a soil–geosynthetic interface test and that obtained in a soil-only test under the same normal stress.

Several authors, such as Tupa & Palmeira (1995), Ingold (1984), Saez (1997), Aguiar (2003), Sieira (2003), Izgin & Wasti (1998), and Lopes (2001), have obtained interface strength parameters for various soils and geosynthetics.

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The use of small direct shear boxes for determining these parameters is documented by Anubhav & Basudhar (2013), Tupa & Palmeira (1995), Izgin & Wasti (1998), Markou (2018), and Infante et al. (2016). For geotextiles and geomembranes, a 10 × 10 cm shear box is sufficient. The shear box size must allow full shear zone propagation, depending on the soil's grain size and geosynthetic type (Moraci et al., 2014).

In addition, Jewell & Wroth (1987) suggest that the ratio of the box length to the soil's median particle diameter (D_{50}) should be over 50 to fully mobilize the shear zone, ensuring that the shear box size does not significantly affect the values of c' and effective friction angle of the soil (φ'). Markou (2018) tested soil-geosynthetic interfaces with both conventional (10 × 10 cm) (ASTM, 1998) and large-scale (30 × 30 cm) direct shear boxes using sand and geotextile. Despite the recommendation of the large-scale box by NBR ISO 12957-1 (ABNT, 2013a), the results showed only minor differences in the interface friction angle (δ') between the two methods. Thus, the conventional shear box is suitable for determining soil-geosynthetic parameters.

Typical friction efficiency values reported in the literature range from 60% to 90% for geotextiles and below 60% for HDPE geomembranes, while cohesion efficiency generally varies between 40% and 100% for geotextiles and is often negligible for geomembranes. Due to the typically low or nonexistent soil–geosynthetic adhesion, E_c is frequently associated with significant uncertainty. Moreover, despite the extensive research on conventional geosynthetics, a notable lack of experimental data remains regarding the behavior of the soil–microgrid interface.

Microgrids represent a relatively recent class of geosynthetics designed for soil reinforcement and separation. They are characterized by small openings and PVC protection, which enhances resistance to chemical, environmental, and biological degradation. However, their interaction mechanisms with soils and the corresponding interface shear strength parameters are still poorly understood, highlighting the need for systematic laboratory investigation.

In this context, the present study aims to evaluate the soil–microgrid interface shear strength parameters under different direct shear testing conditions. The effects of geosynthetic type and placement configuration, either on a rigid base or over a sandy soil layer, are investigated through shear stress–displacement responses and failure envelopes. The interface behavior of microgrids is further compared with that of conventional geosynthetics, including geotextiles and geomembranes, to provide a comprehensive assessment of their mechanical performance.

2. Materials and methods

This study used a sandy soil collected from the Experimental Field of Geotechnics and Foundations at the Universidade Federal do Ceará (UFC), an outdoor area designated for geotechnical testing. The sampling procedure involved removing the superficial layer and vegetation, after which approximately 60 kg of soil was manually collected at a depth of 0.30 m using a shovel and a pickaxe.

The collected soil was then subjected to laboratory tests, which included (a) grain-size analysis (ABNT, 2016c); (b) Atterberg limits (ABNT, 2016a, 2016b); (c) specific gravity (DNER, 1994); (d) soil compaction (ABNT, 2020); and (e) direct shear (ASTM, 1998; ABNT, 2013a) with adaptations from Markou (2018) to obtain soil strength parameters with and without reinforcement, in which normal stresses (σ) of 50, 100, and 200 kPa were applied using a 10 × 10 cm shear box.

The particle size distribution curve of the soil is presented in Figure 1. Table 1 presents the geotechnical characterization of the soil used in the experimental program, including particle-size distribution, compaction parameters, and soil classification according to the Transportation Research Board (TRB) and the Unified Soil Classification System (USCS).

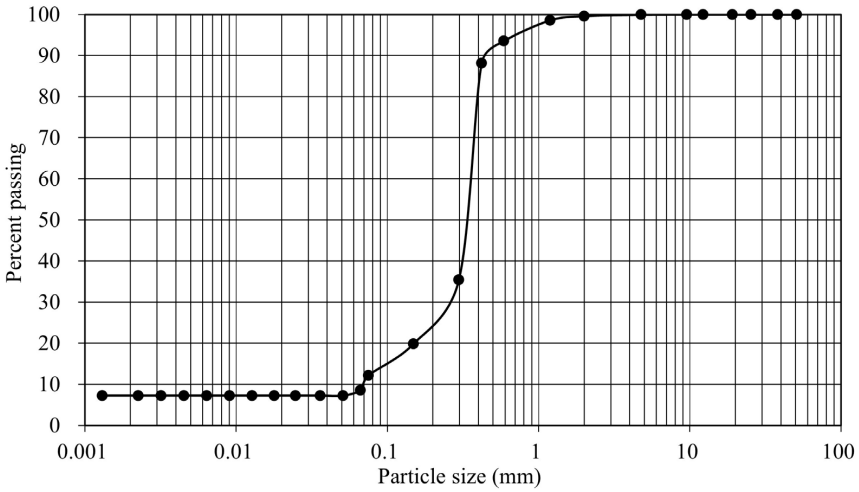


Figure 1. Particle size distribution of the soil.

The soil is classified as fine sand (A-3) by the TRB system and as silty sand (SW) according to the USCS, with clay and silt contents of 7% and 14%, respectively. The Atterberg limits were not applicable, indicating a predominantly non-plastic granular material. The soil exhibits an optimum moisture content of 10.2% and a maximum dry density of 1.86 g/cm^3, with a specific gravity of solids of 2.64. The soil presents a uniformity coefficient of 5.14 and a curvature coefficient of 2.68, characterizing a well-graded granular material (Caputo, 2014).

Furthermore, given a D_{50} of 0.32 mm, the adopted shear box (10 × 10 cm) satisfies the geometrical criterion proposed by Jewell & Wroth (1987), which recommends a ratio of the box length (L) to the soil's D_{50} greater than 50 to fully mobilize the shear zone. In this study, L/D_{50} = 294, which is nearly six times the minimum recommended value, thereby ensuring full mobilization of the shear zone and representative interface shear parameters.

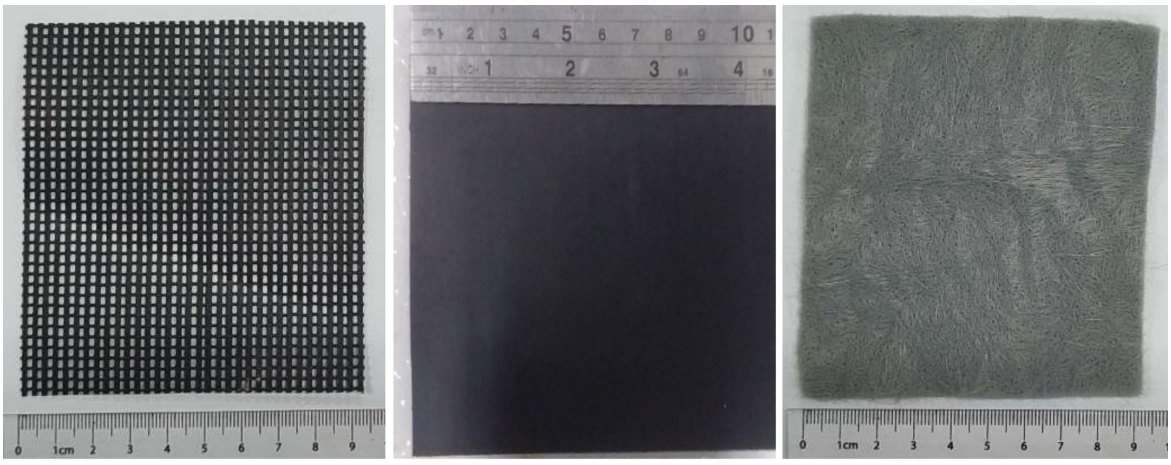
The geosynthetic materials used were a microgrid, a geomembrane, and a geotextile, all from Maccaferri Brazil LTDA (Figure 2). The microgrid MacGrid®Net (Figure 2a) had a minimum tensile strength of 45 kN/m in both directions, an elongation at break of 15%, mesh openings of 1 × 2 mm, and a thickness of 0.6 ± 0.05 mm. The geomembrane McLine SDH had a tensile strength of 29 kN/m and an elongation at break of 12%. The geotextile MACTEX® H.2 had a weight of 200 g/m^2, a tensile strength of 10 kN/m, and an elongation at break of 50%.

Different conditions were set for direct shear tests to evaluate the geosynthetic's influence on interface parameters (c_a' and δ'), varying as follows:

- Type of supporting base for microgrid (Figure 3): a rigid (R), wooden base or a soil base (S).
- Types of geosynthetic (rigid base): microgrid, geotextile, or geomembrane.

An external anchoring piece (Figure 4) was designed to prevent the geosynthetic from sliding. This piece includes a metal base with seven screws. For rigid bases, the geosynthetic was securely attached to the wooden base with contact adhesive. The screw-based anchoring system was employed in both test configurations (soil base and rigid base). The geosynthetics were bonded to the wooden base using PolyPlac®, a high-strength rubber-based contact adhesive suitable for vinyl, wood, high-pressure laminates (HPL), and medium-density fiberboard (MDF).

Before compaction, the soil was oven-dried for 24 h. Water corresponding to the optimum moisture content (OMC) was then added to the dried soil, and the specimen was compacted in three layers, each receiving 26 blows from a 2.5-kg rammer dropped from a height of 30.48 cm. The resulting soil specimen, measuring 10.16 cm in height and 10.60 cm in diameter, was compacted at Standard Proctor energy (Table 1), corresponding to an OMC of 10.2%, a maximum dry density of 1.86 g/cm^3, and a void ratio of 0.42. The rectangular specimens used in the shear tests were subsequently cut from this compacted soil specimen.



(a) (b) (c)

Figure 2. Geosynthetics used in the tests: (a) Microgrid, (b) Smooth geomembrane, (c) Geotextile.

Table 1. Geotechnical properties of the tested soil.

D_{50} (mm)	Clay content (%)	Silt content (%)	wL	PI	OMC (%)	$\rho_{d,max}$ (g/cm^3)	e	G_s	Classification TRB/USCS
0.32	7	14	N/A	N/A	10.2%	1.86	0.42	2.64	Fine sand (A-3)/Silty sand (SW)

Legend: N/A = not applicable. wL = liquid limit; PI = plasticity index; OMC = Optimum Moisture Content; $\rho_{d,max}$ = maximum dry density; and e = void ratio.

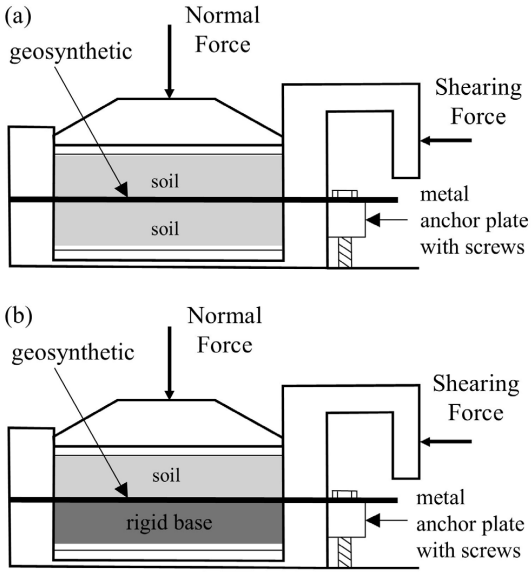


Figure 3. Soil–geosynthetic interaction test setups: (a) Soil base and (b) Rigid base.



Figure 4. Direct shear test apparatus to assess soil–geosynthetic interaction, rigid base (wood block).

The direct shear tests were performed at a displacement rate of 0.4594 mm/min, determined from the consolidation characteristics of the specimens in accordance with ASTM D3080 (1998). This displacement rate is consistent with values commonly used for sandy soils in laboratory direct shear testing. Each test was terminated when a horizontal displacement of at least 10% of the specimen length was reached.

The experimental program included a series of five tests (each duplicated), totaling ten direct shear tests under wetting conditions. Table 2 presents details about the tests performed.

3. Results and discussion

Figure 5 presents the shear stress–horizontal displacement responses obtained for the soil-base tests (TSS-S) and for the soil–geosynthetic interfaces tested over a rigid base and soil base with microgrid (TSMG-R, TSGM-R, TSGT-R, TSMG-S).

Figure 6 presents the volumetric variation versus horizontal displacement curves obtained from the five test configurations described previously. The curves show that dilatancy occurred in the tests involving geosynthetics (Figures 6b–e), which may explain the nonzero cohesive intercept.

For all testing conditions, the soil–geosynthetic interface shear strength parameters were lower than those obtained for the soil alone, reflecting partial mobilization of interparticle friction and reduced contact efficiency at the interface. This trend is consistent with previous experimental studies (Abu-Farsakh et al., 2007; Ferreira et al., 2015; Stacho et al., 2023) and confirms that interface behavior governs the overall shear response of reinforced soil systems.

Table 3 summarizes the average shear strength parameters obtained from the tests performed with and without geosynthetics, including the effective cohesion (c') and effective internal friction angle (φ') for the soil, as well as the apparent soil–geosynthetic cohesion (c_a'), interface friction angle (δ'), cohesion efficiency (E_c), and friction efficiency (E_φ) for the soil–geosynthetic interfaces.

The results obtained for the soil–geomembrane (TSGM-R) and soil–geotextile (TSGT-R) interfaces are within the expected range reported in the literature. In particular, the friction efficiency (E_φ) of 79% obtained for TSGT-R is in good agreement with the 71–104% range reported by Markou (2018) for geotextiles, confirming adequate mobilization of interface friction.

For the soil–microgrid interface, friction efficiencies ranged from 66% (TSMG-R) to 81% (TSMG-S). The higher E_φ obtained for the microgrid tested over a soil base reflects enhanced confinement and improved mechanical interlocking between soil particles and the microgrid structure. This behavior is strongly associated with the small mesh openings of the microgrid (1 × 2 mm), allowing particles to penetrate and become partially mechanically anchored within the apertures. Such granular interlocking increases the effective roughness of the interface and promotes the mobilization of shear resistance through particle-to-particle contact across it. This mechanism explains the higher interface friction angle obtained for TSMG-S (δ' = 31.2°). However, the cohesion efficiency decreased from 57% (TSMG-R) to 31% (TSMG-S).

Table 2. The conditions under which direct shear tests were conducted.

Test	Interface	Base
TSS-S	Soil–Soil	Soil
TSMG-R	Soil-Microgrid	Rigid
TSMG-S	Soil-Microgrid	Soil
TSGM-R	Soil-Geomembrane	Rigid
TSGT-R	Soil-Geotextile	Rigid

3.1 Effect of base type on strength parameters of the soil-microgrid interface

A comparison between the tests performed with the microgrid glued to a rigid base (TSMG-R) and those conducted with the microgrid placed between soil layers (TSMG-S) indicates a clear influence of the base type on the mobilized interface shear strength. Although both configurations exhibited relatively low values of apparent soil–geosynthetic cohesion (c_a'), the TSMG-S condition presented a markedly higher interface friction angle (δ'), resulting in a friction efficiency (E_φ) of 81%, compared to 66% obtained for TSMG-R.

The E_φ values obtained in this study for the microgrids (TSMG-S and TSMG-R) fall within the range of 65–100% reported by Sieira (2003) and Tupa & Palmeira (1995) for satisfactory soil–geosynthetic contact. The present results also corroborate the findings of Ingold (1984) and Saez (1997), who demonstrated that positioning geosynthetics between soil layers provides a more representative assessment of interface shear strength. These authors emphasized that tests performed on rigid bases neglect contributions from soil–soil friction and tend to yield lower interface parameters, particularly for open-structure geosynthetics such as geogrids and microgrids.

3.2 Effects of geosynthetic type

The tests with the geomembrane (TSGM-R) and the geotextile (TSGT-R) were used as a reference to compare the soil–microgrid interface behavior obtained in TSMG-R. Among all materials, TSGM-R exhibited the lowest apparent soil–geosynthetic cohesion (c_a' = 1.5 kPa) and interface friction angle (δ' = 18.2°), resulting in the smallest cohesion efficiency (E_c = 17%) and friction efficiency (E_φ = 44%). These values are consistent with the typical behavior of smooth geomembranes, which generally mobilize limited interface friction due to their low surface roughness and reduced mechanical interlocking capacity (Triplett & Fox, 2001).

Among rigid-base tests, the soil–geotextile interface (TSGT-R) exhibited a markedly higher interface friction angle (δ' = 30.7°) and friction efficiency (E_φ = 79%), exceeding those obtained for the microgrid tested over a rigid base (TSMG-R, E_φ = 66%). The δ' values obtained for TSGT-R are in close agreement with those reported in the literature for woven and

Table 3. Average interface parameters for direct shear tests.

Test	Interface	c' (kPa)	φ' (°)	c_a' (kPa)	δ' (°)	E_c (%)	E_φ (%)
TSS-S	Soil–Soil, Soil base	8.3	36.9	-	-	-	-
TSMG-S	Soil-Microgrid, Soil base	-	-	2.6	31.2	31	81
TSMG-R	Soil-Microgrid, Rigid base	-	-	4.7	26.3	57	66
TSGM-R	Soil-Geomembrane, Rigid base	-	-	1.5	18.2	17	44
TSGT-R	Soil-Geotextile, Rigid base	-	-	3.2	30.7	38	79

nonwoven geotextiles (Tupa & Palmeira, 1995; Lopes, 2001; Abu-Farsakh et al., 2007; Ferreira et al., 2015; Muluti et al., 2023). Moreover, Tupa & Palmeira (1995) considered E_φ values above 70% indicative of good soil–geotextile interaction, while Abu-Farsakh et al. (2007) reported typical E_φ values of around 74%. These findings indicate that the soil–microgrid interface tested on a rigid base exhibits lower frictional resistance than conventional geotextiles, while still maintaining moderate interface performance.

Despite its lower friction efficiency, the soil–microgrid interface (TSMG-R) exhibited a higher apparent soil–geosynthetic cohesion (c_a' = 4.7 kPa) than the soil–geotextile interface (TSGT-R, c_a' = 3.2 kPa). The geotextile interface presented higher δ' but comparatively lower c_a' values. These complementary mechanisms highlight the distinct soil–geosynthetic interaction mechanisms mobilized by microgrids and geotextiles.

Figure 7 presents the Mohr–Coulomb failure envelopes obtained for the soil-base condition (TSS-S) and for the soil–microgrid (TSMG-R), soil–geomembrane (TSGM-R), and soil–geotextile (TSGT-R) interfaces tested over a rigid base.

For all reinforced-soil conditions, the interface failure envelopes lie below the soil failure envelope (TSS-S). Among the reinforced interfaces tested over a rigid base, the soil–geotextile interface (TSGT-R) exhibited the highest shear strength, followed by the soil–microgrid interface (TSMG-R), whereas the soil–geomembrane interface (TSGM-R) presented the lowest resistance.

Table 4 summarizes the coefficients of interaction (c_i) obtained for the soil–geosynthetic interface tests.

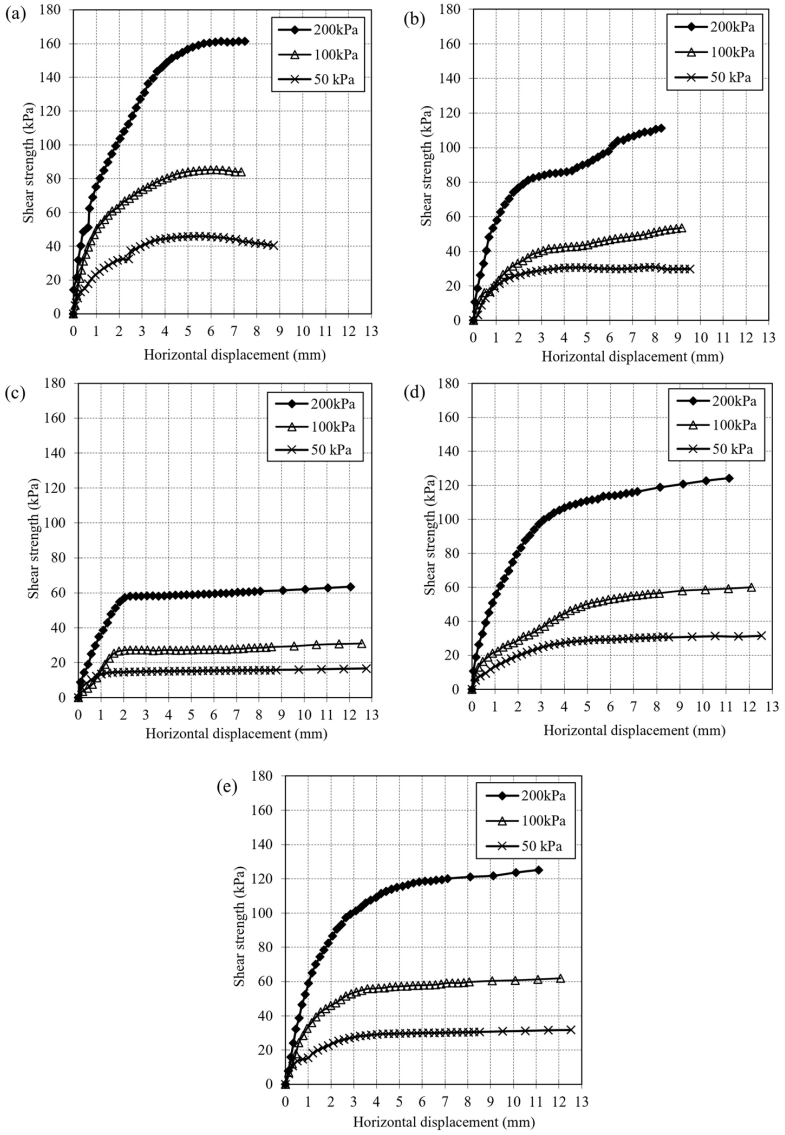


Figure 5. Shear strength versus horizontal displacement for the soil base condition (a) TSS-S, and for rigid-base interfaces: (b) TSMG-R, (c) TSGM-R, (d) TSGT-R, and (e) TSMG-S.

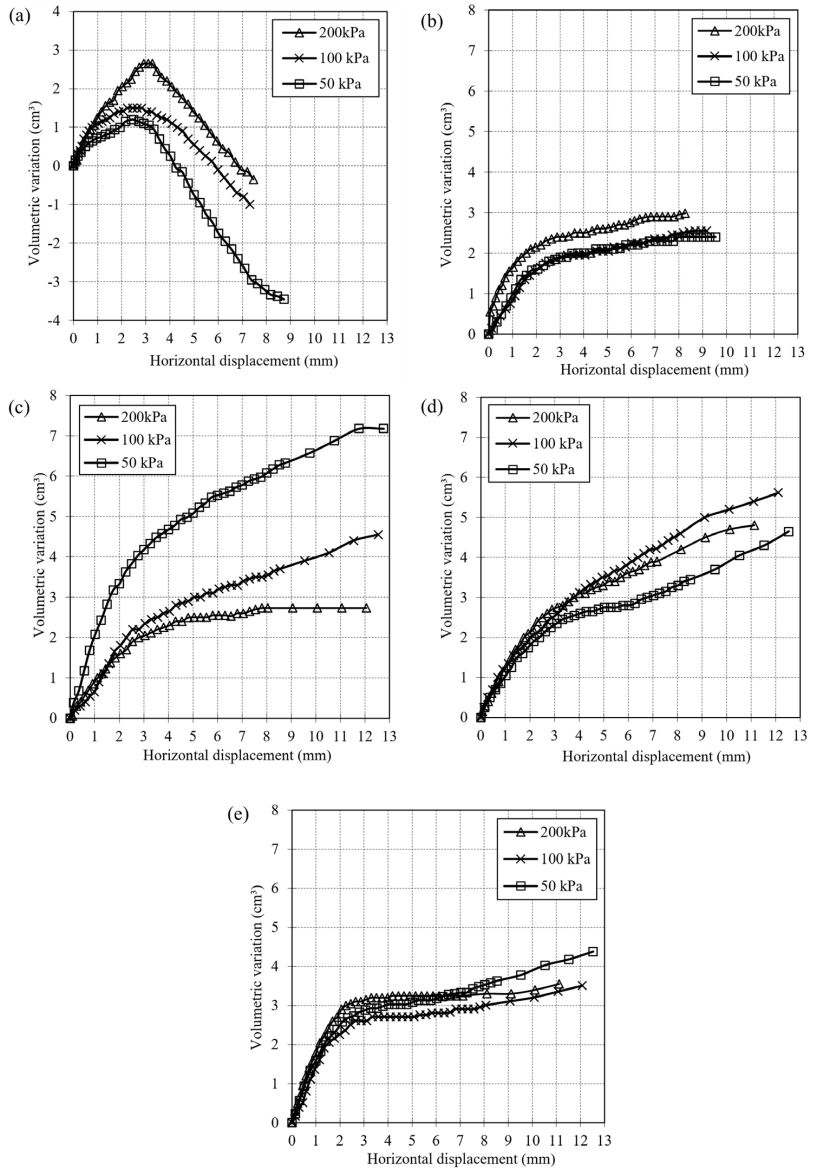


Figure 6. Volumetric variation versus horizontal displacement for the soil base condition (a) TSS-S, and for rigid-base interfaces: (b) TSMG-R, (c) TSGM-R, (d) TSGT-R, and (e) TSMG-S.

Table 4. Coefficients of interaction (c_i) from duplicate tests under the same experimental conditions.

Test	Analyzed Tests	Normal Stress (kPa)		
		50	100	200
1	TSS-S and TSMG-R	0.67	0.63	0.69
2	TSS-S and TSMG-R	0.68	0.62	0.63
1	TSS-S and TSMG-S	0.69	0.73	0.77
2	TSS-S and TSMG-S	0.77	0.76	0.79
1	TSS-S and TSGM-R	0.36	0.36	0.39
2	TSS-S and TSGM-R	0.34	0.36	0.43
1	TSS-S and TSGT-R	0.69	0.70	0.77
2	TSS-S and TSGT-R	0.75	0.76	0.77

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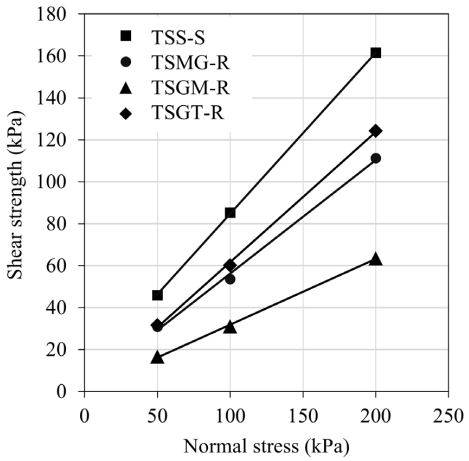


Figure 7. Failure envelopes for soil base (TSS-S), and rigid base (TSMG-R, TSGM-R, and TSGT-R) tests.

The lowest interaction coefficients were observed at the soil–geomembrane interface, reflecting its limited capacity for mechanical interlocking and particle engagement. In contrast, the highest c_i values were observed at the soil–microgrid interface tested between two soil layers and at the soil–geotextile interface, indicating enhanced interlocking and stronger soil–geosynthetic interaction mechanisms. Ferreira et al. (2015) reported c_i values ranging from 0.54 to 0.85 for soil–geotextile interfaces, which are consistent with the magnitudes observed in the present study.

4. Conclusion

This research evaluated the soil-geosynthetic interface strength of microgrid, geomembrane, and geotextile using direct shear tests with sandy soil, focusing on the recently introduced microgrid, which has received limited research on its interface parameters. Tests with different base conditions were performed with the microgrid.

Results showed that soils reinforced with a microgrid (between two soil layers) and a geotextile (on a rigid base) have similar interface shear strength, with c_a' and δ' values in the same range.

Changing the base beneath the geosynthetic revealed that a microgrid on a soil base exhibits better interface behavior than on a rigid base. The soil base resulted in a higher δ' (31.2°) and $tan\ \delta$ (0.81) compared to the rigid base (26.3° and 0.66).

At the soil-microgrid interface, soil grains interacted more effectively through the microgrid's hollow mesh, whereas at the soil-geotextile interface, the disordered filaments interacted with the soil grains. Both reinforced samples had satisfactory strength, high E_φ (79% for soil-geotextile and 81% for soil-microgrid), and coincident failure envelopes.

The lowest c_a' and δ' were observed for the soil-geomembrane interface due to its smoother structure, which hindered soil interaction and facilitated sliding. The highest c_a' and δ' values were found for the microgrid (with a soil base) and geotextile. Regarding the c_i parameter, those reinforcements had the highest values: 0.77 for soil-geotextile and 0.79 for soil-microgrid.

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Declaration of interest

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

Authors' contributions

Thiago de Sá Sena: writing – review & editing, data curation, visualization, writing – original draft. Ana Karine Santiago Bessa: conceptualization, data curation, methodology, supervision, validation, writing – original draft. Anderson Borghetti Soares: formal analysis, funding acquisition, investigation, methodology, project administration, resources. Marcos Fábio Porto de Aguiar: supervision, validation, writing – review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

c'	Effective cohesion of the soil
c_a'	Soil–geosynthetic apparent cohesion
c_i	Coefficient of interaction, defined by NBR ISO 12957-1
D_{50}	Median particle diameter
e	Void ratio
E_c	Cohesion efficiency

E_{φ}	Friction efficiency
G_s	Specific gravity of soil solids
HDPE	High-density polyethylene
HPL	High-pressure laminate
L	Shear box length
MDF	Medium-density fiberboard
OMC	Optimum moisture content
PI	Plasticity index
$tan\ \delta$	Soil–geosynthetic interface friction coefficient
$tan\ \varphi$	Internal friction coefficient of the soil
TRB	Transportation Research Board
TSGM-R	Soil–geomembrane interface test with rigid base
TSGT-R	Soil–geotextile interface test with rigid base
TSMG-R	Soil–microgrid interface test with rigid base
TSMG-S	Soil–microgrid interface test with soil base
TSS-S	Soil–soil interface test with soil base
USCS	Unified Soil Classification System
wL	Liquid limit
δ'	Interface friction angle
$\rho_{d,max}$	Maximum dry density
σ	Normal stress of the soil
φ'	Effective internal friction angle of the soil

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