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Influence of the structure on the collapse potential and shear strength of a residual soil in the semiarid region of Northeast Brazil

Valteson da Silva Santos[1], *Allan B. Silva de* Medeiros[1], *Romário S. Amaro da* Silva [1], *Olavo F.* Santos Jr.[1], *Osvaldo de* Freitas Neto[1], and *Bruna Silveira* Lira[2]

[1] Federal University of Rio Grande do Norte, Brazil
[2] Federal University of Campina Grande, Brazil

Abstract. In the last decades, several engineering works have been developed in the Northeast of Brazil, a region marked by the occurrence of collapsible and expansive soils. This work aimed to characterize and study the behavior of two samples of residual soils collected in the municipality of Salgueiro-PE regarding their collapse potentials and shear strength parameters, in natural and disturbed conditions, evaluating the influence of the applied vertical stresses and the structural arrangement in these properties. The results obtained showed that the two samples analyzed show collapsible behavior, however, the observed potential for collapse was lower after the original structure arrangement was undone. From the direct shear strength tests, the strength parameters of the two soils were obtained, which pointed effective friction angle close to 30º and cohesive intercept close to 0 kPa. The destructuring of the samples did not cause a considerable variation in these parameters. Thus, it was possible to conclude that for these samples the microstructure has a predominant influence on the occurrence of collapsibility, but does not have the same relevance on the shear strength, such that the material's destructuring can be considered as an effective measure to reduce the potential collapse.

1 Introduction

In the last decades, major infrastructure constructions have been developed in the interior of Northeast Brazil. The transposition of the São Francisco River and the Transnordestina Railway are examples of these constructions. In addition, urban growth resulting from the emergence of regional development hubs demands greater real estate developments and structural constructions. As a consequence, more and more characteristics concerning this region become of interest to the practice of engineering and motivate the realization of research. In this sense, the geological and geotechnical characterization of local soils stands out as an important addition to the technical literature, capable of guiding the initial phases of project design and the definition of field and laboratory testing campaigns to be adopted.

For the case of soils in the interior of Northeastern Brazil, in addition to the traditional data regarding physical indexes, shear strength parameters, compressibility and permeability; the investigation of phenomena related to the unsaturated condition of the materials is especially relevant. This is due to the geology, topography and climate of the region, favoring the formation of so-called "problematic" soils, such as collapsible soils.

Soils of this nature are characteristic of arid and semi-arid climates. Its formation is associated with the alternation between dry weather and short rainy periods. This is the case in the city of Salgueiro, located in the state of Pernambuco and at a distance of 518 km from Recife, capital of the state. According to Ferreira and Fucale (2013), in Salgueiro the average annual temperature is 25 °C and the amount of rain varies between 450mm and 600mm per year, concentrated mainly between the months of December and March.

Soils with collapsible behavior are called metastable, since they are subject to a sudden reduction in volume due to the increase in their degree of saturation, even if under the effect of constant loading from overloads or only due to their own weight. Vilar and Ferreira (2015, p.415) point out that these soils are typically of low density and the volume variation observed is due to the decrease in strength in the interparticle contacts, commonly due to reduced suction as a result of the increase in moisture content, which results in a structural rearrangement and a new equilibrium condition.

Soils of this nature are the reason for several pathologies in construction and incur significant financial costs, either due to their treatment or to remedy the consequences arising from negligence or underestimation of their harmful capacity.

* Corresponding author: valtesomdasilva3@gmail.com

For collapsible soils, the microstructure is one of the most important factors. Alonso et al. (1987) apud Silva (2003) highlight that this is due to the fact that the microstructure controls the water conditions inside the soil, specifically its potential or suction.

Thus, in order to minimize the potential for soil collapse, its disruption and subsequent compaction is one of the most applicable methods. Houston and Houston (1997) report that in southern California, in the United States, the problems found in collapsible soil deposits from 6 to 10m deep are often resolved by compacting the material. However, it is also necessary to evaluate the influence of this process from the perspective of shear strength, in order to guarantee the suitability of all conditions.

This study is dedicated to the analysis of the behavior of two soil samples collected in the municipality of Salgueiro, state of Pernambuco, regarding their potential for collapse and shear strength parameters in undisturbed and remolded conditions. Thus, it intends to contribute to the existing database for the soils of this region and to evaluate the effect of the microstructure and the inundation stress on the behavior of the material.

2 Materials and Methods

Two undisturbed soil samples were collected in the municipality of Salgueiro, located in the state of Pernambuco, Brazil. The sampling followed the recommendations proposed in ABNT NBR 9604/2016. In the tactile-visual inspection, the soils present a yellow or orange color, a remarkable amount of sand and fines, and little presence of gravels. The samples were named as sample A and sample B.

For each sample, grain size analyses were carried out by sieving and sedimentation, following the procedures of ABNT NBR 7181/2016, tests for determining the specific gravity, according to ABNT NBR 6508/2016, tests for determining the plasticity limit, ABNT NBR 7180/2016, and tests for determining the liquidity limit, according to ABNT NBR 6459/2016. The materials for these tests were obtained from the disintegration by breaking down the clumps after molding the specimens and were prepared in accordance with ABNT NBR 6457/2016.

The specimens in the undisturbed condition were carved directly from the samples, using metal rings as molds. The remolded specimens were rebuilt by means of static compaction, from the broken material corresponding to each sample, with the amount of material determined in order to reproduce the same void ratio of the undisturbed samples. As a reference, the void ratio value of each sample was adopted as the arithmetic mean between the void ratios determined for each of the specimens extracted from the samples in the undisturbed condition. No water was added for the compaction process, as the broken materials kept the same moisture content as the undisturbed samples.

In order to carry out tests to evaluate the collapsibility of the samples, 5 specimens were obtained in the undisturbed condition and 5 specimens in the remolded condition, both with the same moisture content, with average dimensions of 50 mm in diameter and 19,5 mm in height, for each of the two samples.

Conventional oedometric presses were used, with a hanging-type load system, 1:10 lever arm ratio, and rigid ring cells. The specimens in the undisturbed condition and in the remolded condition were subjected to oedometric compression tests with inundating in one of these stress stages: 12.5 kPa, 25 kPa, 50 kPa, 100 kPa and 200 kPa. The tests were conducted up to 200 kPa of vertical stress, with the exception of the samples inundated in that referred stage, for which the tests were conducted up to 400 kPa of vertical stress. Two unloading stages were adopted, which for samples subjected to vertical tension of 200 kPa, corresponded to vertical stresses of 100 kPa and 25 kPa. For samples submitted to stress levels below 200 kPa, the vertical stresses applied at the unloading were 50 kPa and 12.5 kPa. The readings of the vertical displacements in the specimens were taken from dial indicators associated with the oedometric compression cells. For the change of stress stages during the tests, a deformation stability criterion was adopted, which consisted of the consideration that the primary density of the soil can be considered to have ceased if the displacement verified in the extensometer during an interval of 30 minutes is equal to or less than 0.1% of the initial height of the specimen. For the calculation of the collapse potential (CP) the equation [1] was used.

$$CP = \frac{\Delta e}{1 + e_0} \tag{1}$$

Where:
Δe is the variation in the void ratio due to the inundating of the sample
e_0 is the sample's initial void ratio

The Direct Shear Strength tests followed the guidelines of the ASTM-D 3080/98 standard. The specimens used in the direct shear test had dimensions of 60 mm in diameter and 32 mm in height. The direct shear strength tests were carried out under inundated condition with vertical stresses of 50, 100 and 200 kPa, for the two samples studied, both for the undisturbed and the remolded condition. All specimens were subjected to inundating for at least 24 hours and consolidation before being subjected to shear.

3 Results and Discussions

The results obtained in this study are shown below. These results are divided into three parts: characterization of the samples; results of oedometric tests and results of direct shear tests.

3.1 Characterization of the samples

Laboratory tests were carried out to determine the specific gravity of the solids, in addition to consistency and grain size characterization tests by sieving and sedimentation. Table 1 shows the results obtained and the soil classification according to the Unified Soil Classification System (USCS).

The two samples show similarities in the specific gravities of solids and consistency indexes. Sample A was classified through USCS as a silt clay with low compressibility (CL - ML) and sample B is classified as a clay sand (SC). The clay fraction activity index, which correspond to the ratio between their respective plasticity indexes and clay fraction percentage, were 0.24 and 0.55, respectively for samples A and B. According to Skempton's criterion (1953), both samples were classified as inactive.

Table 1. Result of the characterization of the samples.

Sample	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	γ_s (kN/m³)	LL (%)	PL (%)	PI (%)	USCS Classification
A	2.2	24.1	49.6	24.1	26.81	16.4	10.7	5.7	CL - ML
B	10.3	48.2	27.9	13.6	26.87	18.4	10.9	7.5	SC

3.2 Oedometric tests

Figures 1 to 10 represent the variation in the void ratio resulting from the variation of the applied vertical stress. All tests started with the specimen in its natural moisture content. After a certain vertical stress applied, the specimen was inundated through the addition of distilled water. The nomenclature used for the representation of the specimens initially contains the sample code, followed by the inundation stress and the molding condition of the specimen. UND represented the undisturbed specimens and REM the remolded specimens.

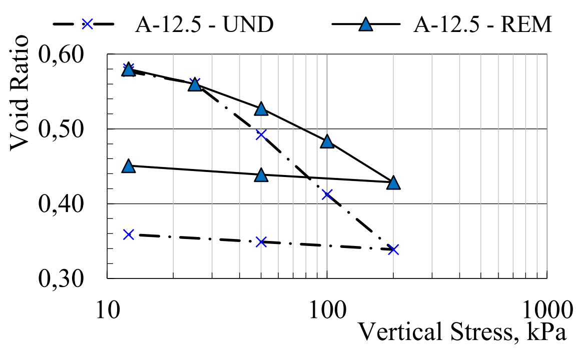

Fig. 1. Variation in the void ratio as a function of the applied stress for sample A subjected to inundating at 12.5 kPa.

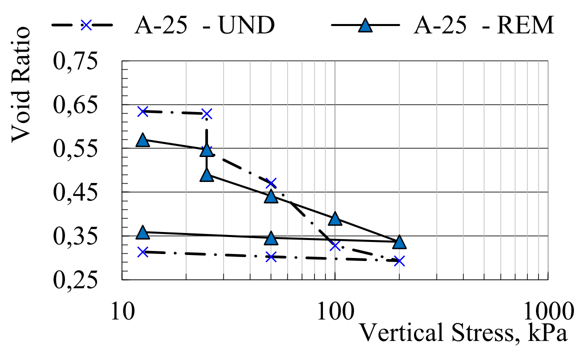

Fig. 2. Variation in the void ratio as a function of the applied stress for sample A subjected to inundating at 25 kPa.

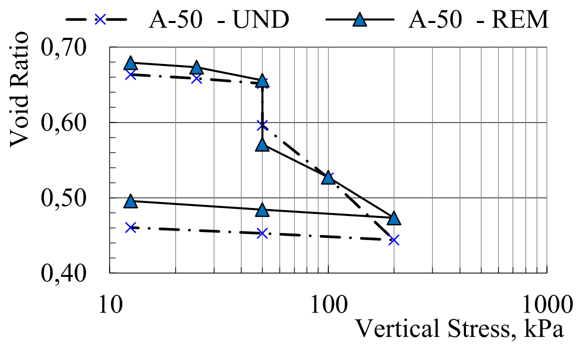

Fig. 3. Variation in the void ratio as a function of the applied stress for sample A subjected to inundating at 50 kPa.

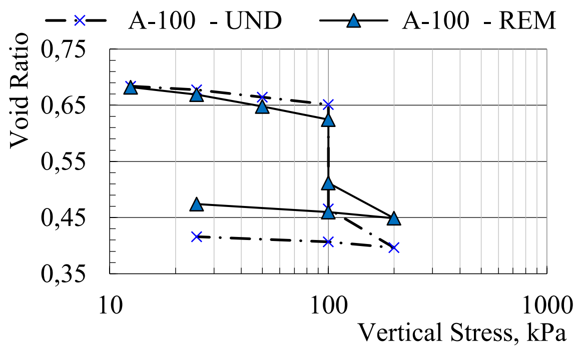

Fig. 4. Variation in the void ratio as a function of the applied stress for sample A subjected to inundating at 100 kPa.

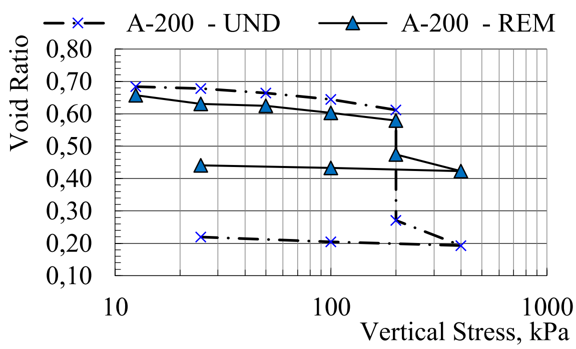

Fig. 5. Variation in the void ratio as a function of the applied stress for sample A subjected to inundating at 200 kPa.

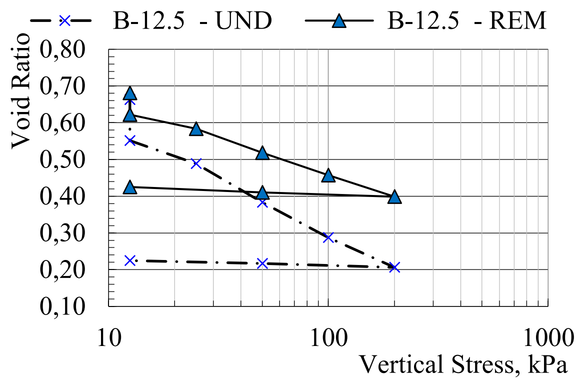

Fig. 6. Variation in the void ratio as a function of the applied stress for sample B subjected to inundating at 12.5 kPa.

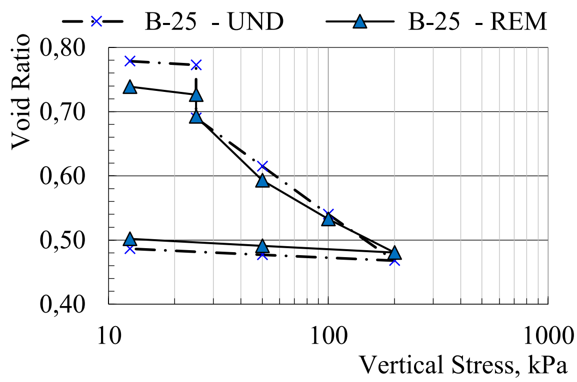

Fig. 7. Variation in the void ratio as a function of the applied stress for sample B subjected to inundating at 25 kPa.

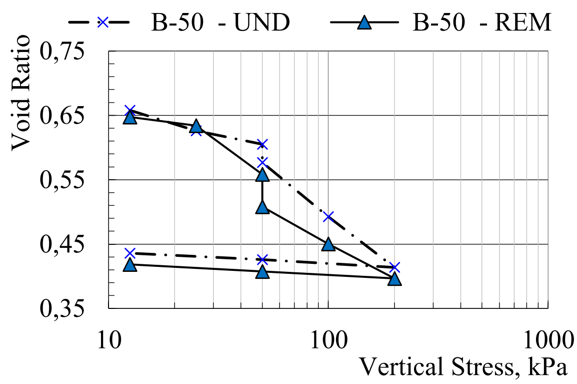

Fig. 8. Variation in the void ratio as a function of the applied stress for sample B subjected to inundating at 50 kPa.

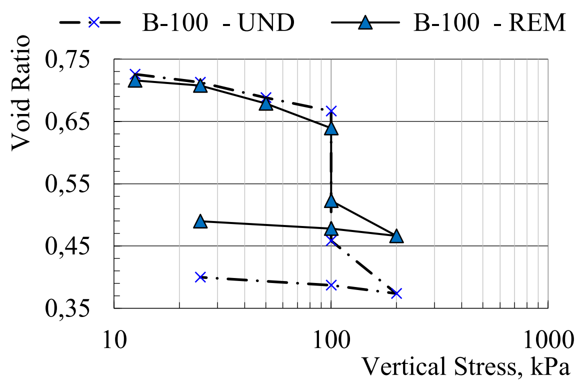

Fig. 9. Variation in the void ratio as a function of the applied stress for sample B subjected to inundating at 100 kPa.

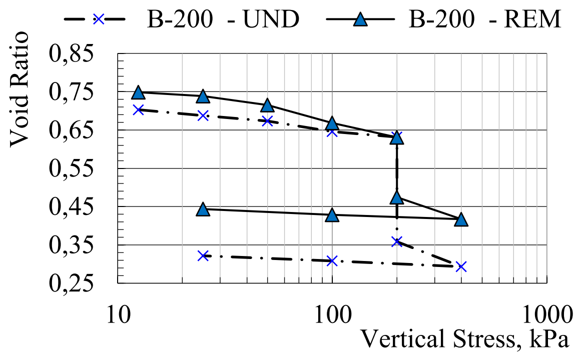

Fig. 10. Variation in the void ratio as a function of the applied stress for sample B subjected to inundating at 200 kPa.

Table 2 presents the summary of the test results for assessing the potential for collapse for the two samples.

Table 2. Collapse potential for samples A and B in undisturbed and remolded conditions.

Sample	Inundation Stress	UND	REM	Proportional Decrease
A	12.5	0.24%	0.04%	83.0%
	25.0	5.21%	3.51%	33.0%
	50.0	3.33%	5.05%	0.0%
	100.0	10.93%	6.68%	39.0%
	200.0	20.07%	6.22%	69.0%
B	12.5	6.59%	3.51%	47.0%
	25.0	4.65%	1.93%	59.0%
	50.0	1.70%	3.02%	0.0
	100.0	11.96%	6.62%	45.0%
	200.0	15.27%	8.76%	43.0%

For the results summarized in Table 2, according to the criterion proposed by Vargas (1978), which establishes a minimum collapse potential value equal to 2% for any inundation stress, only sample A at inundation stress of 12.5 kPa would not be considered collapsible. Assuming the classification proposed by Jennings and Knight (1975), which observes the potential of collapse obtained for the 200 kPa inundation stress, the soil corresponding to sample A is considered to be capable of generating very severe trouble in buildings, while the soil corresponding to sample B is considered to be capable of generating severe trouble for buildings. The observation of Figures 1 to 10 leads to the realization that the collapse suffered by undisturbed samples was superior to the remolded samples in almost all collapse stresses, with the exception of both samples for the 50 kPa stress. Due to the remolding there was also a decrease in the compressibility of the samples, evidenced by the difference between the final void ratios of the undisturbed and remolded samples for the same test conditions. This difference is more significant in the tests where inundation occurred during the application of the vertical stresses of 12.5 kPa and 200 kPa, for the two samples, and it was not verified for the case of sample B, in the vertical inundation stress corresponding to 50 kPa. For the two samples, except for the tests where the inundation occurred during the application of a vertical stress equal to 50 kPa, it can be considered that the destructuring of the soil contributed to the reduction of its potential for collapsibility. The destructuring of the samples caused, according to the criterion of Jennings and Knight (1975), the transition of the previously mentioned classifications to the condition of “Trouble”. Thus, although they still require intervention, they present a less harmful capacity when compared to the initial condition.

It was also possible to observe that the compression index values obtained for the remolded samples were lower than those obtained for the undisturbed samples, except for sample B for 25 kPa inundation stress, as shown in Figure 11. On the other hand, higher decompression coefficients were obtained for the remolded sample, in comparison with the undisturbed sample, as shown in Figure 12.

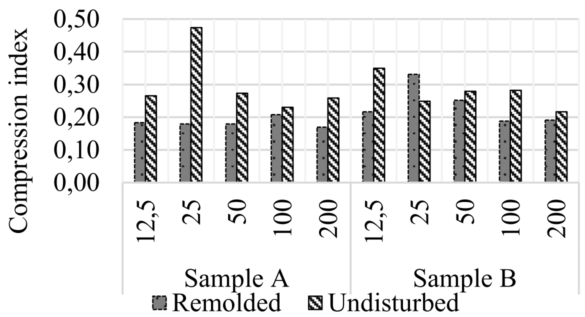

Fig. 11. Compression index of the tested samples.

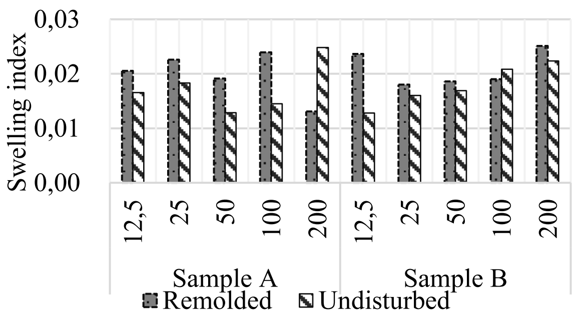

Fig. 12. Decompression index of tested samples.

3.3 Direct shear tests

Figure 13 shows the Stress versus Horizontal Displacement curves of sample A in the undisturbed condition.

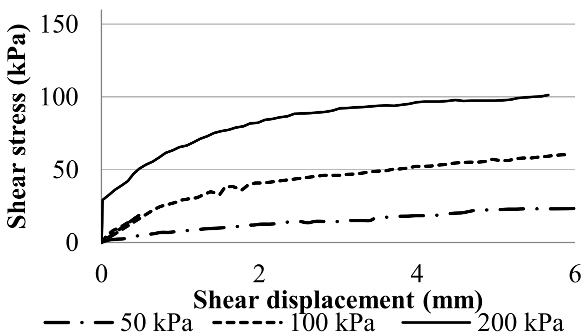

Fig. 13. Stress (kPa) x Horizontal Displacement (mm) curves of sample A in undisturbed condition.

As shown in Figure 13, the tested samples, regardless of the applied vertical stress, did not show shear stress peaks. The maximum values of shear stress strength obtained are related to horizontal displacements above 5 mm, since the samples did not reach rupture until the end of the tests, as indicated by the trend of growth of the curves.

Curves without peak strength such as those obtained indicate a soil with a behavior similar to that of soft sand, with little or no cementation, and, therefore, little influence of the structure on the obtained strength values.

Figure 14 shows the Stress versus Horizontal Displacement curves of sample A in the condition of disturbed sample.

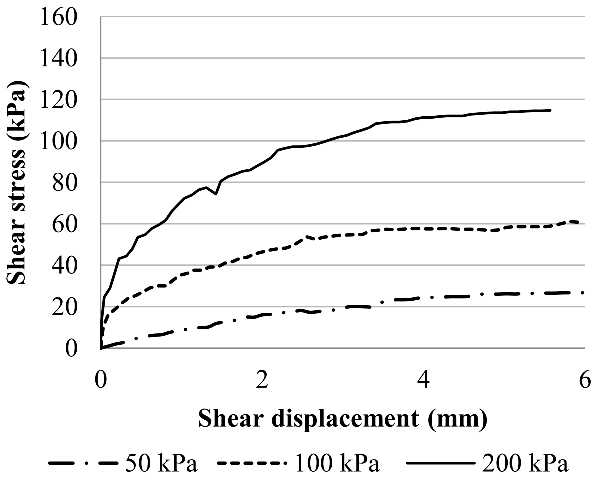

Fig. 14. Stress curves (kPa) x Horizontal displacement (mm) of sample A in the disturbed condition.

As in the undisturbed condition, the samples tested, regardless of the applied normal stress, did not show peak strength. The maximum values of shear stress strength were obtained for values above 5 mm of deformation, as observed for the undisturbed samples. However, for the curves shown in Figure 14 there is a tendency towards stabilization in terms of shear stresses, which indicates that the rupture of the remolded samples tends to occur for smaller horizontal displacements than that of the undisturbed samples.

The curves obtained in the remolded condition also do not have peaks, thus remaining close to the expected behavior for soft sand, with little or no cementation.

Comparing the results of the tests carried out for the samples in the undeformed and remolded conditions, it is observed that the remolded samples presented values of maximum strength superior to those of the undisturbed samples, with increases of 13.3%, 3.3% and 13.1% for the vertical stresses of 50, 100 and 200 kPa, respectively. The registered increase can be explained by the fact that the undisturbed samples had not yet reached rupture when the tests were completed.

Figure 15 shows the Strength Envelopes of sample A.

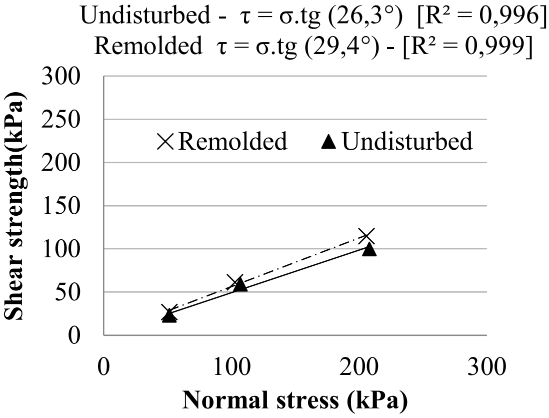

Fig. 15. Strength envelopes of sample A.

As shown in Figure 15, the shear strength envelops for the soil in the two conditions are similar. For the undisturbed and remolded conditions, zero cohesive intercepts and effective friction angles equal to 26.3º and 29.4º were obtained, respectively.

Correlation coefficients equal to 0.996 were determined for the undisturbed sample and 0.999 for the remolded sample. These values indicate low dispersion between the results in relation to the ploted envelopes.

Both envelopes indicate the absence of significant influence of the microstructure on the soil's strength capacity. Thus, it is noted that the destructuring did not cause loss of strength capacity regarding shear, which is shown to be mainly a function of the void ratio of the material and the applied vertical stress. A small increase in the effective friction angle of the material was registered in the remolded condition, in the order of 3º.

Figure 16 shows the Vertical Displacement versus Horizontal Displacement curves of sample A in undisturbed condition.

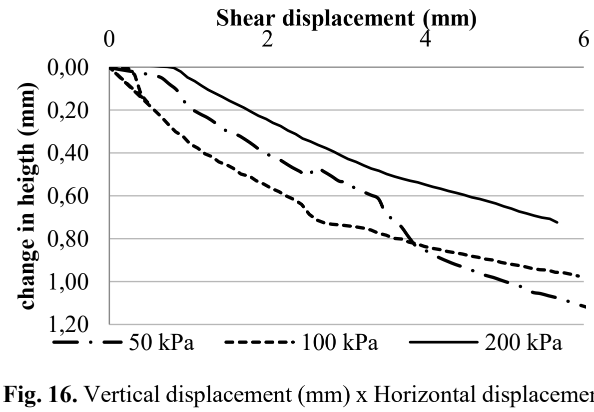

Fig. 16. Vertical displacement (mm) x Horizontal displacement (mm) Curves of sample A in undisturbed condition.

The results presented in Figure 16 indicate a tendency of contractile behavior for the material, in line with the absence of strength peaks in the stress curves versus vertical displacement. Smaller vertical deformations were registered with the application of higher vertical stresses, with the maximum vertical deformations close to 1.1mm for an applied vertical stress of 50 kPa, close to 1mm for the vertical stress of 100 kPa and close to 0.8 mm for the vertical stress of 200 kPa. It is noteworthy that the curves have a tendency to increase vertical displacements, in agreement with the tendency of increasing shear stresses observed in the curves of Figure 13, which evidence the fact that the samples did not reach rupture until the end of the tests.

Figure 17 shows the Vertical Displacement versus Horizontal Displacement curves of sample A in the remolded condition.

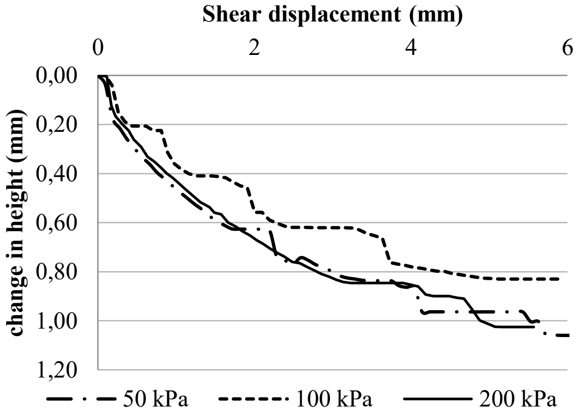

Fig. 17. Vertical Displacement (mm) x Horizontal Displacement (mm) curves of sample A in remolded condition.

From the presented results, it is possible to state that the restructuring did not change the original contractile tendency of the material. The order of magnitude of the vertical deformations, when compared to those observed in the undisturbed sample, remained similar, except in the case of the test with 200 kPa of applied vertical stress, for which greater compression was recorded. For remolded samples, vertical deformations tend to stabilize at the end of the tests, unlike what was observed for undisturbed samples.

Figure 18 shows the Stress versus Horizontal Displacement curves of sample B in the undisturbed condition.

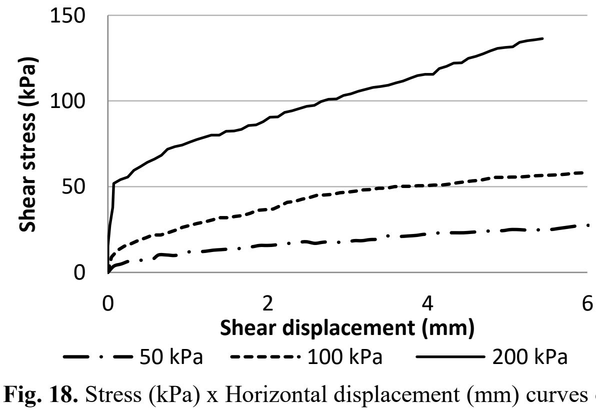

Fig. 18. Stress (kPa) x Horizontal displacement (mm) curves of sample B in undisturbed condition.

According to the curves presented, the samples tested regardless of the vertical stress applied did not show strength peaks. The maximum values of stress to the shear strength were observed for values above 5mm of displacement. As observed for sample A (Figure 13), for the results shown in Figure 18 it is highlighted that samples did not reach rupture at the end of the test, as indicated by the growth trend of the curves presented.

As in the case of sample A, in the results of sample B, the absence of evident peaks is noted, indicating a behavior similar to that of soft sand or normally densified clay, without cementation and with low or no influence of the microstructure on the strength behavior.

Figure 19 shows the Stress versus Horizontal Displacement curves of sample B in the disturbed condition.

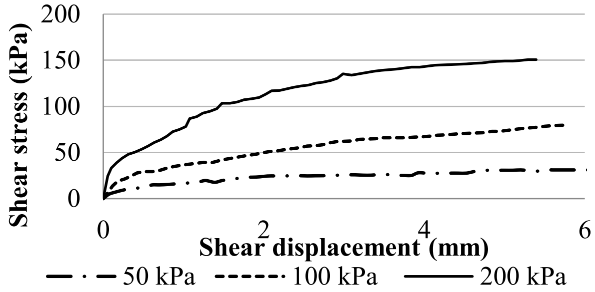

Fig. 19 Stress (kPa) x Horizontal displacement (mm) curves of sample B in disturbed condition.

Similar to what was observed for sample A, it is possible to notice in sample B the similarity between the curves presented for undisturbed and disturbed conditions. Thus, the material's destructuring did not change its behavior regarding its shear strength. Similar to that observed for sample A (Figure 14), there is a tendency to stabilize the shear stress strengths, indicating that the samples in the remolded condition approached the rupture condition at the end of the test.

As in the undisturbed condition, the curves obtained in the remolded condition do not have peaks, thus remaining close to the expected behavior for a soft sand or normally densified clay, with little or no cementation.

Comparing the results of the tests carried out for the samples in the undisturbed and remolded conditions, it is observed that the remolded samples presented values of maximum strength superior to those of the undisturbed samples, with increases of 13.8%, 27.4% and 10.0% for the vertical stresses of 50, 100 and 200 kPa, respectively. The registered increase can be explained by the fact that the undisturbed samples had not yet shown a tendency to rupture when the tests were completed.

Figure 20 shows the Strength Envelops of sample B.

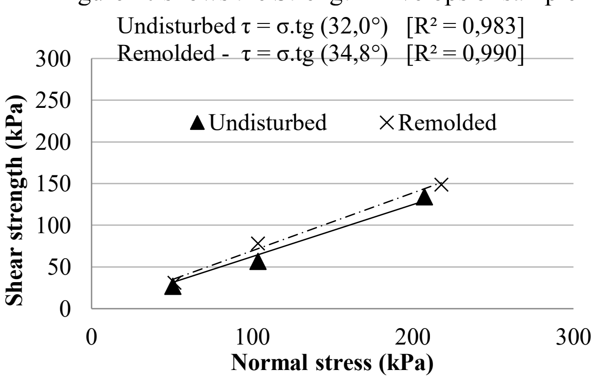

Fig. 20. Strength Envelops of sample B.

As observed for sample A, the strength envelopes obtained for the undisturbed and remolded conditions for sample B are similar. The cohesive intercept is null and for the undisturbed and remolded conditions the effective friction angles obtained were equal to 32º and 34.8º, respectively. Correlation coefficients of 0.983 were found for the sample in its undisturbed condition and 0.990 for the remolded condition. Both values point to a low dispersion between the test results regarding the ploted envelopes. A small increase in the effective friction angle of the material was recorded when in the remolded condition, in the order of 3º.

In the same way as for sample A, the destructuring of sample B was not harmful to its shear strength, which was mainly dependent on its void ratio and the vertical stress to which it is submitted.

Figure 21 shows the Vertical Displacement versus Horizontal Displacement curves of sample B in the undisturbed condition.

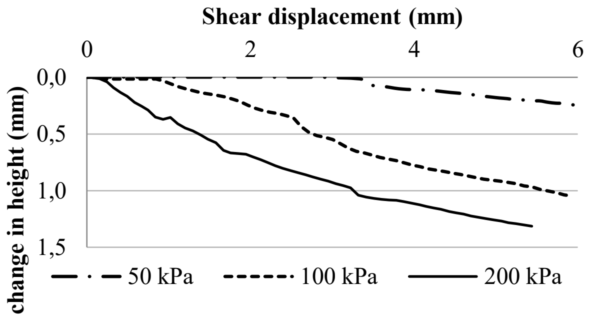

Fig. 21. Vertical displacement (mm) x Horizontal displacement (mm) curves of sample B in undisturbed condition.

Analyzing the results shown in Figure 21, we notice the contractile tendency of the material, which is consistent with the absence of peaks in the Shear Stress versus Horizontal Displacement curves represented in Figure 18. It is possible to perceive a trend of greater vertical deformations due to the increase of vertical stresses. There is a considerable increase in vertical displacements as the vertical stress applied increases, with the maximum vertical displacement being close to 0.25 mm for an applied stress of 50 kPa, close to 1.05 mm for the stress of 100 kPa and close to 1.30 mm to 200 kPa. In line with the observed for shear stresses (Figure 18), even at the end of the tests, the upward displacement trend continued, indicating that the samples had not yet reached rupture.

Figure 22 shows the Vertical Displacement versus Horizontal Displacement curves of sample B in the condition of remolded sample.

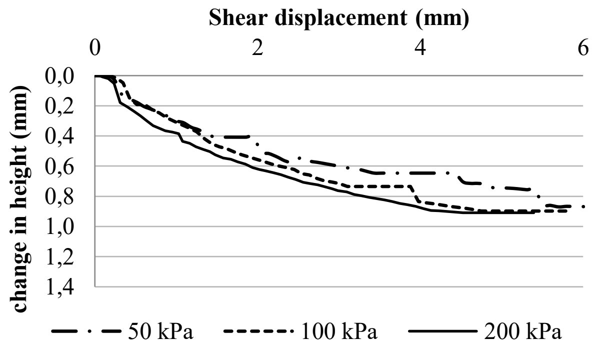

Fig. 22. Vertical Displacement (mm) x Horizontal Displacement (mm) curves of sample B in remolded condition.

Analyzing the results presented in Figure 22, it can be seen that the contractile characteristic of the material was not affected by the destructuring, and similarly to the undisturbed situation, it agrees with the Shear Stress versus Horizontal Displacement curves shown in Figure 19. The maximum vertical displacements observed were all in the order of magnitude of 0.9 mm, regardless of the vertical stress applied. Vertical displacements tended to stabilize at the end of the tests, differently from what was observed for undisturbed samples.

Still, it is verified that the vertical displacements obtained are significant for all stresses, and the reduction in the compression of the material only occurs for tests performed with vertical stresses applied of 100 kPa and 200 kPa.

4 Conclusions

In this study, the influence of the microstructure on the collapse potential and on the shear strength of two samples of residual soils from the municipality of Salgueiro, located in the semiarid region of the state of Pernambuco, Brazil, was analyzed. Oedometric tests were carried out with inundating in the stress stages corresponding to the vertical stresses of 12.5 kPa, 25 kPa, 50 kPa, 100 kPa and 200 kPa, and direct shear tests were carried out with inundated samples and vertical stresses of 50 kPa, 100 kPa and 200 kPa. Specimens carved directly from undisturbed blocks and specimens remolded with the same physical indexes as undisturbed samples were used.

It was found that the two soil samples in undisturbed condition are subject to the occurrence of collapse with magnitudes capable of generating severe to very severe problems in buildings, according to the classification proposed by Jennings and Knight (1975). The destructuring of the material was able to reduce the collapse potential of samples A and B by 69.0% and 43.0%, respectively, although it was not able to eliminate its occurrence. The modification of the soil microstructure, however, did not significantly influence their respective shear strengths, preserving or even increasing the parameters obtained.

For certain tests, there was a reduction in the compressibility of the reconstituted material, demonstrating the influence of the microstructure also in this aspect. However, there was no clear correlation between the observed reductions and the variation in inundation stresses.

In general, it was concluded that the microstructure has a preponderant role in the collapsibility of the studied samples, so that the consideration of only parameters such as the void ratio and the dry density in preliminary analyzes of collapsible potential may not accurately reflect the soil behavior.

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