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Indirect verification of suction in cyclic UCS tests of a chemically stabilized soil

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ABSTRACT

The present study aims to indirectly evaluate the occurrence of suction and its effects in laboratory tests of a chemically stabilized soft soil. To achieve these goals, a series of unconfined compressive strength (UCS) and triaxial tests were performed, with and without the application of cyclic loading and with and without membrane during the cyclic loading stage, to evaluate the occurrence of suction and its effect on the mechanical behavior of a chemically stabilized soft soil. The results show that during the cyclic loading stage there is an occurrence of suction which influences both the permanent axial strain during the cyclic loading and the maximum strength of the stabilized soil. During the cyclic loading stage, the occurrence of suction promoted the increase of the plastic deformation. In terms of strength, it is observed an occurrence of suction in the stabilized soil which may be related with the increase of the strength. It is observed that suction can be avoided by saturation of the sample, verified in triaxial tests, or by using a membrane during the cyclic UCS test.

Keywords: Stabilized soil; axial permanent strain; suction; UCS test; triaxial test.

1. Introduction

The construction of embankments on highly compressible soils is usually associated with problems of stability and displacements of high magnitude, both vertical and horizontal. One of the techniques that has been successfully applied to reduce the magnitude of settlements and increase stability is to improve the mechanical properties of the foundation soil by adding binders (such as Portland cement, quicklime, fly ash, slag), a process called chemical stabilization (Abdullah et al., 2020; Åhnberg, 2006; Basha et al., 2005; Consoli et al., 2007; Consoli et al., 2011; Corrêa-Silva et al., 2020; Correia, 2011; Correia et al., 2019; Horpibulsuk, 2001; Horpibulsuk et al., 2003, 2005; Kamruzzaman et al., 2009; Kitazume and Terashi, 2013; Lorenzo and Bergado, 2004, 2006; Rios et al., 2016; Venda Oliveira et al., 2013; Venda Oliveira et al., 2014).

When a dynamic loading induced by earthquakes, explosives, vibrations from industrial equipment, the action of wind or sea waves, in the vicinity of high-speed railroads, among others, is applied to a stabilized soil there are changes in the material's behavior that need to be characterized and understood. So far, the knowledge acquired about the behavior of soils under cyclic loading is still limited (mainly focused on granular materials) and sometimes the results are inconsistent.

Sharma and Fahey (2003), using cyclic triaxial tests, analysed the degradation of a cemented reconstituted limestone and found that the increase in the number of cycles reduces the stiffness of the material due to the progressive degradation of the cemented matrix. The same authors also observed a reduction in the yield stress-strain due to the same reason. The results of cyclic triaxial tests performed by Subramaniam and Banerjee (2014) in a cement stabilized marine clay corroborated the results obtained by the previous authors verifying a loss of stiffness under cyclic loading, being that the lower the frequency applied, the greater the stiffness degradation is.

Varkuti (2015) using a clay soil stabilized with cement and lime obtained increases of up to 10% of the unconfined compressive strength (UCS) after cyclic loading. Such increase was also observed by Venda Oliveira et al. (2017) who analysed the post cyclic strength with different numbers of cycles (650 - 10000 cycles) verifying that in all cases there was an increase in strength after the cyclic stage, with no significative variation with the number of cycles. Venda Oliveira et al. (2018) studied different types of cement stabilized soils, with and without fiber addition, and independently of the soil type it was observed the same behavior, i.e., an increase in strength after cyclic loading.

Chae et al. (2010) affirm that an unconfined compression strength test is a commonly used method to evaluate undrained shear strength. However, variations in the undrained shear strength can be observed due to sampling disturbances during the extraction, transport, storage, and test process. One of the problems that could happen is a variation in the sample moisture content and the occurrence of suction. In this sense, several authors have stated that soils with smaller pore diameters could have higher suction (Fredlund et al., 2011).

Despite the knowledge acquire on suction effects in terms of the mechanical behavior of soils, few studies on chemically stabilized soils have been done. Thus, this study aims to evaluate indirectly through post cyclic UCS tests with and without membrane complemented with post cyclic triaxial tests the occurrence of suction and its influence on the results in terms of deformation and compressive strength.

2. Materials and procedures

2.1. Characteristics of the soil

It was used for this research an organic soft soil from "Baixo Mondego", a place near the city of Coimbra Portugal.

The mineralogical composition, which is very important to the choice of the binder, reveals, quartz, muscovite, albite, microcline, kaolinite, ilite and chlorite (Martins, 2021). The chemical composition of the soil exhibits a high silica (SiO2), 59%, and alumina (Al2O3) 17% content, and a pH of 4.6.

The geotechnical characterization revealed a grain size composition characterized by 77% of silt, 12% of clay and 11% of sand, a liquid limit of 72%, a plastic limit of 45%, organic matter content of 9.5%, and a moisture content of 81%.

The soil was classified as an high plasticity organic silt (OH) based on the Unified Soil Classification System (ASTM-D2487, 1998).

2.2. Characteristics of the binder

Based on the soil's characteristics the binder chosen for this research was Portland cement Type I 42.5 R (EN-197-1, 2000), i.e., due to the soil's pH, silica and alumina content, it is expected that the soil reacts satisfactorily with Portland cement (Janz and Johansson, 2002). The Portland cement is characterized by a high composition of calcium oxide (CaO) 63% and silica oxide (SiO2) 19%. It was used a quantity of 175 kg/m^3 equivalent to a binder quantity of 21% of dry weight ratio of binder to soil.

2.3. Procedures

2.3.1. Sample preparation

The samples of the chemically stabilized soil used for this research were prepared based on the laboratory procedure described in EuroSoilStab (2002) and Correia (2011) comprising the following steps:

i – the soil in its natural moisture content and the cement were weighed;

ii – the materials were mixed in a mechanical mixer at a speed of 142 rpm for four minutes;

iii – the paste was introduced into PVC molds (37 mm diameter, 85 mm high) and compacted in three layers each (tapping the molds against a wooden table twenty times by hand) in a time inferior to 20 min after the start of the mixture;

iv - the stabilized samples were cured under water in a room with temperature and humidity control (20±2°C and 95±5%, respectively) for 28 days;

v – at the end of the curing period, the samples were removed from the molds and the surfaces were trimmed to obtain 76 mm high samples.

vi - a monotonic UCS test was used to define the mechanical characteristics under monotonic loading conditions, with a constant axial strain rate of 1%min, in accordance with the standard BSI-1377-7 (1990).

2.3.2. UCS cyclic test

All the cyclic loading tests were carried out in the GDS Dynamic Triaxial apparatus for an initial deviatoric stress level of 50% of the maximum unconfined compressive strength evaluated in the monotonic UCS test, an amplitude of ± 10% of the maximum unconfined compressive strength, a frequency of 0.5 Hz and it was applied 5,000 loading cycles. For suction analysis, tests were performed with and without membrane during the cyclic loading stage.

Once the cyclic loading stage ended, the equipment was unloaded and a monotonic UCS post cyclic test or a triaxial test was carried out to analyse the effect of the suction on the mechanical behavior of the composite material.

2.3.3. Triaxial test

Triaxial compression tests were performed in drained (CID) condition in a stress-path cell with a confining stress level of 250 kPa. The tests were performed in three different stages: saturation, consolidation, and drained shear. The saturation stage took approximately 2 days and was controlled by the Skempton's B parameter, which should be greater than 95%. Once saturation is completed, an initial effective stress state (consolidation stage) begins, where the sample was allowed to drain until present constant volume. This stage has lasted approximately 7 hours. The last stage, drained shear, was performed under constant axial strain rate (0.209 mm/h). This stage ended when an axial strain of 25% was reached (to achieve the material's critical state).

In the case of post-cyclic triaxial tests, the samples were previously subjected to cyclic loading before being inserted into the triaxial cell.

3. Results

3.1. Cyclic loading stage – accumulated plastic axial strain

Fig. 1 shows the evolution of the accumulated plastic axial strain with the number of loading cycles for the stabilized materials both without membrane and with membrane. From the results it is possible to observe a reduction in the accumulated plastic axial strain when the sample is involved by a membrane. The presence of the membrane does not allow the reduction of the moisture content of the samples during the cyclic loading stage, therefore minimizes suction effects. Indeed, the development of suction promotes the increase of the effective stress which increases the accumulated plastic axial strain.

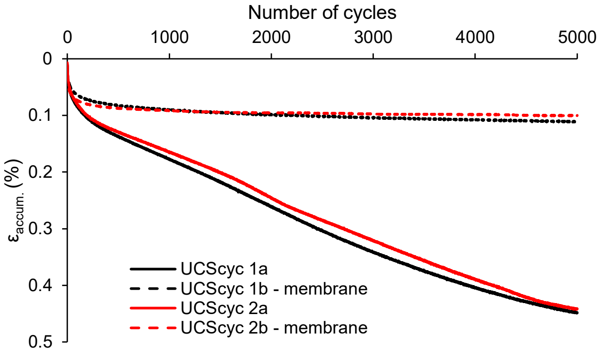
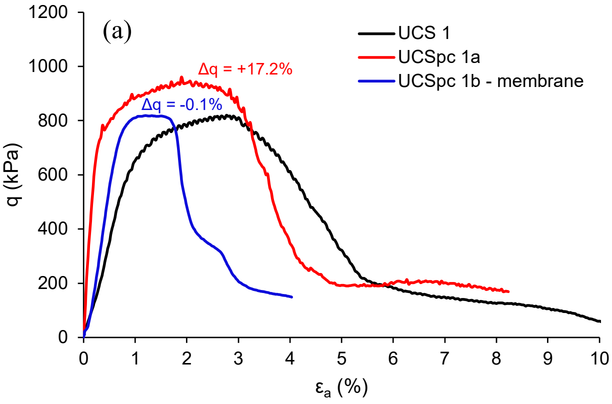


Figure 1. Evolution of the accumulated plastic axial strain with the number of loading cycles for samples tested with and without membrane.

3.2. Stress-strain behavior

Fig. 2a shows the stress-strain behavior from the unconfined compression strength tests (UCS 1), unconfined compression strength tests after the cyclic loading stage without membrane (UCSpc 1a) and with membrane (UCSpc 1b- membrane). Fig. 2b presents the stress-stain behavior from the monotonic triaxial test (Triax 2), triaxial test after cyclic loading stage without membrane (Triaxpc 2a) and with membrane (Triaxpc 2b-membrane). From the analyses of the results, it is possible to verify that the post cyclic UCS test without membrane shows an increase of 17.2% of the strength compared to the monotonic test while the test with membrane shows a similar strength result of the monotonic UCS test, with a deviation less than 10%.

Analysing the triaxial tests it is possible to observe that the samples tested after cyclic loading without and with membrane present a similar strength result of the monotonic triaxial test, with a deviation less than 10%.



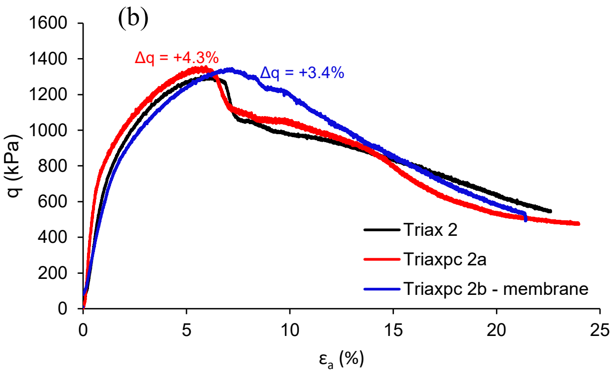


Figure 2. Stress-strain behavior of samples tested before and after the cyclic loading stage: a) UCS tests b) Triaxial tests.

Table 1 summarizes the results of the moisture content measured immediately after the end of the UCS and triaxial tests without and with a cyclic loading stage.

Table 1. Moisture content at the end of testing

	Monotonic test	**Post-cyclic test without membrane**	**Post-cyclic test with membrane**
UCS	59.4%	57.1%	59.6%
Triaxial	59.3%	59.1%	59.3%

It is possible to observe that the post cyclic UCS test without membrane present a moisture content reduction of more than 2% during the cyclic loading when compared with the monotonic UCS test. The same behavior was not observed in the tests with membrane, where the moisture content is almost equal to the monotonic UCS test. So, the increase of the strength in post cyclic UCS test seems to be explained by the reduction of the moisture content occurred during the cyclic loading stage which promotes the development of suction effects.

For the triaxial tests is observed that the final moisture content of the samples in all conditions is almost equal, fact that was expected since the saturation stage tends to uniform the moisture content. Since the effect of the suction was avoided with the saturation of the sample the strength was not impacted.

3.3. Yield loci

Fig. 3 shows the stress-path (q-p') and the yield loci (p'$_{yield}$) based on ε_a-p' and ε_v-p' criteria, where the p'$_{yield}$ is the average of the yield points, while Fig. 4 shows the yield locus based on q/p'-dilatancy criterion. From the analysis of the results, it is possible to observe that the yield loci for both cases with and without membrane, after the cyclic loading is the same. Analyzing the results of the monotonic and post cyclic triaxial tests it is possible to observe that after the samples being subjected to a cyclic loading stage the yield happened earlier. Such behavior can be justified by the degradation of the cementitious matrix during the cyclic loading stage which is not enough to reduce the strength but is enough to promote a degradation of the material's stiffness, i.e., the yield happened earlier.

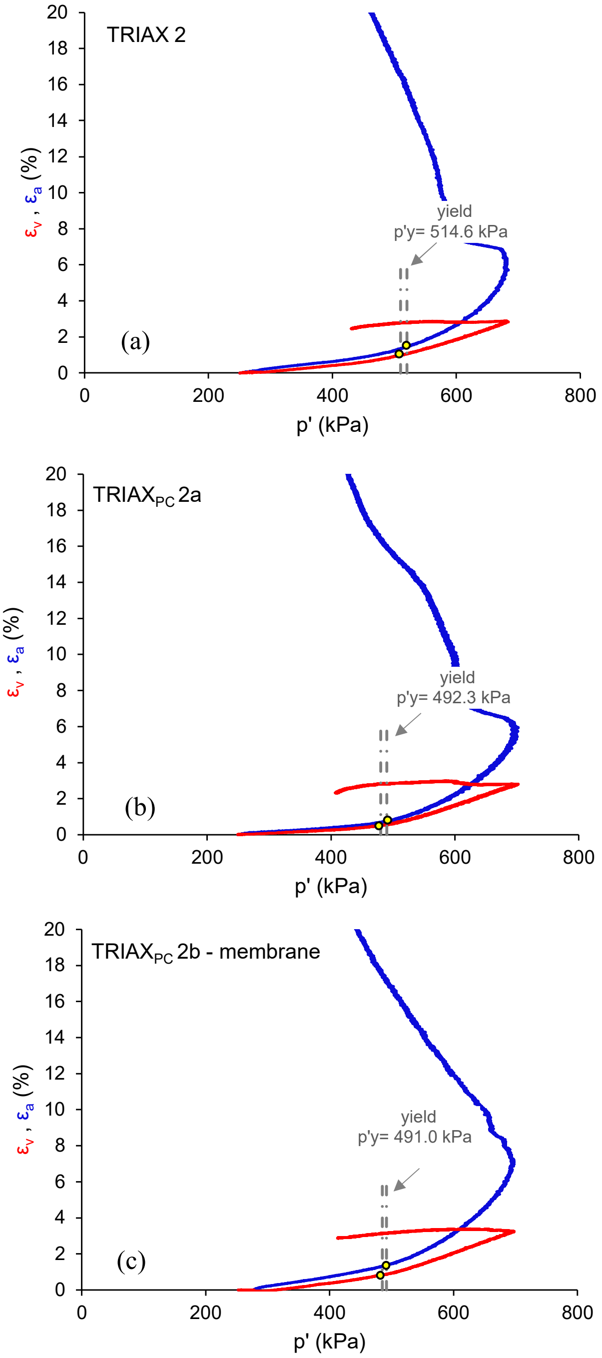


Figure 3. Development of the volumetric strain and axial strain with p' for the CID tests performed with the identification of the yield loci; a) monotonic b) without membrane c) with membrane.

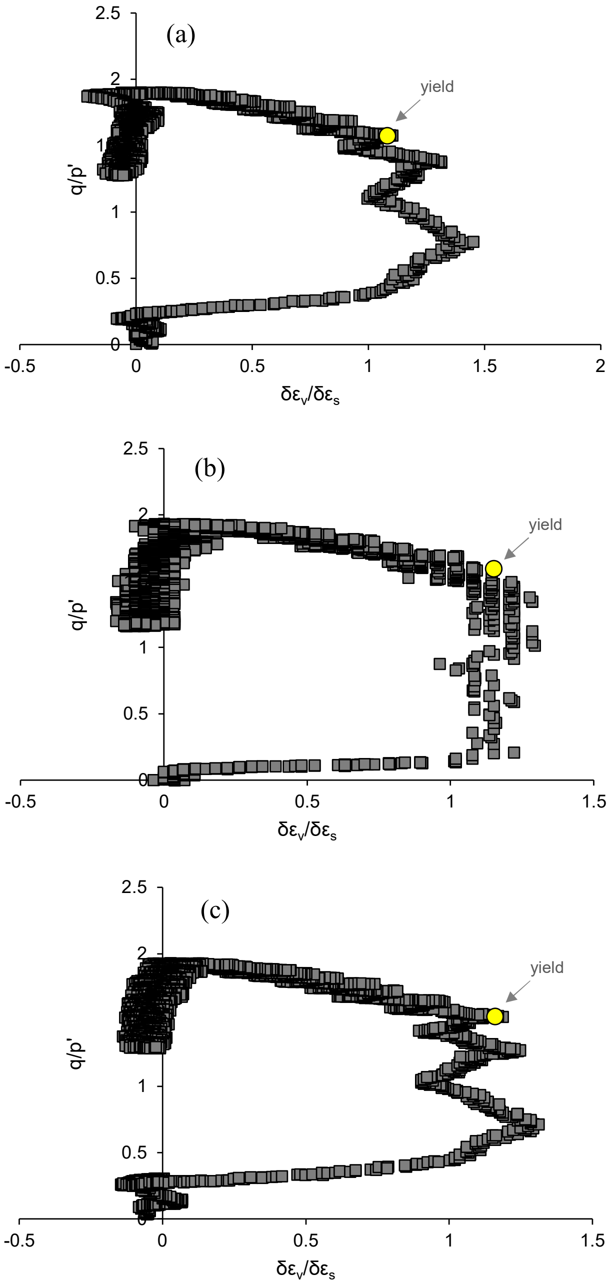


Figure 4. Development of q/p' with the dilatancy for the CID tests performed with the identification of the yield locus; a) monotonic b) without membrane c) with membrane.

4. Conclusions

The results of the unconfined compressive strength and triaxial tests performed on stabilized samples subjected or not to a prior cyclic loading stage (50 ± 10% of $q_{u\ max}$, applied with a frequency of 0.5 Hz and during 5,000 loading cycles), allow the authors to reach the following conclusions:

1. Cyclic UCS tests produce suction if there is no way to avoid it, such as using a membrane or ensuring saturation.
2. In laboratory tests the presence of suction results in an increase in permanent axial strain during cyclic loading.

3. Analysing the compressive strength, it is very important to avoid suction during the cyclic UCS tests, since the occurrence of suction results in a considerable increase in the strength obtained in the post-cyclic UCS test. In the triaxial tests, saturation of the sample nullifies suction generated during the cyclic stage.
4. Analysing the yielding of the studied material it is important to emphasize that the cyclic loading decreases the yield locus, i.e., reduces the elastic zone of the chemically stabilized soil.
5. In the test performed suction is a parameter that affects both plastic deformation and strength of the material, so it is extremely important that the effect of suction is mitigated either by using a membrane during the UCS cyclic tests or by ensuring that the samples are saturated in triaxial tests.

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