Journal of Building Technology, 2025, Volume 7, Issue 1
DOI: 10.32629/jbt.v7i1.3375
ISSN Online: 2717-5103
ISSN Print: 2705-1390

Influence of Key Parameters of Cyclic Loading on the Behaviour of Chemically Stabilized Soil Unreinforced and Reinforced with Fibres

Jorge A. Villarroel-Ortega[1, 2], Antonio A.S. Correia[2], Paulo J. Venda Oliveira[2], Luís J.L. Lemos[2]

1. Faculty of Engineering, University of Magallanes, Punta Arenas, Chile.
2. Department of Civil Engineering, University of Coimbra, Portugal.

Abstract: In this work, the effect of the number of cyclic loads on the mechanical behaviour of a chemically stabilized soft soil, reinforced with synthetic polypropylene fibres, and not reinforced, are analysed. This experimental study was carried out on a Portuguese soft soil collected in the Baixo Mondego area in the centre of the country. The laboratory work is based on the following tests: i) monotonic unconfined compression test (UCS), ii) cyclic unconfined compression test performed with different numbers of cycles (2500, 5000, 10000) and several frequencies (0.25, 0.5, 1.0, 2.0 Hz) for a load corresponding to 50% of the strength evaluated in the monotonic tests (UCS) and iii) monotonic UCS tests performed after the cyclic loading stag (UCS_{pc}). The analysis is complemented with the study of the accumulated permanent axial deformation developed during the cyclic stage. The results show that the accumulated permanent axial strain increases with the number of cycles, also the strength and stiffness after the cyclic loading stage increase their values.

Key words: chemical stabilization; soft soils; unconfined compression strength test; cyclic loading

1. Introduction

The behaviour of chemically stabilized fibre-reinforced soft soils under monotonic conditions has been studied by several authors (e.g. Correia et al., 2011; Venda Oliveira et al., 2015). The inclusion of fibres converts the mechanical behaviour of the stabilized soil from brittle to ductile (Tang et al., 2010; Venda Oliveira et al., 2018), although an increase in residual strength is commonly observed due to the mobilization of fibre tensile strength for higher strain levels (Tang et al., 2010; S Sukontasukkul and Jamsawang, 2012). However, this behaviour may change in the presence of repetitive or cyclic loading carried out by different types of actions, industrial machinery, vibrations in offshore structures, traffic loads carried out by trains or roads and earthquakes. As the number of loading cycles increases, a progressive degradation of the cementation bonds occurs, in tests carried out on stabilized soils (without fibers), generating an increase in the accumulated permanent deformations (Chauhan et al., 2008; Yang et al., 2008) and a decrease in stiffness (Subramaniam and Banerjee, 2014). Other parameters that also affect the unconfined compressive strength of the composite material are the binder content, the length/type of fibers and the type of test (Correia et al., 2015; Venda Oliveira et al., 2015). Some works on the use of fibre-reinforced stabilized soils subjected to cyclic loading have shown: i) an increase in permanent strains with increasing number of loading cycles (Chauhan et al., 2008; Dall'Aqua et al., 2010; Venda Oliveira et al., 2018); ii) the addition of fibres expressly increases the number of cycles and the magnitude of deformation required to cause failure (Maher and Ho, 1993); iii) an increase in unconfined compressive strength with the number of loading cycles (Venda Oliveira et al., 2018). In this work, the behaviour of a soft soil collected near Coimbra, Portugal, in the Baixo Mondego, which is stabilized with cement and reinforced with synthetic fibres, is studied. The laboratory work is based on the compressive behaviour evaluated by the following tests: i) monotonic unconfined compressive strength (UCS) tests, ii) cyclic UCS tests (CYC) varying the number of cycles (2500, 5000, 10000) and the applied frequencies for a load corresponding to 50% of the strength evaluated in the monotonic tests (UCS), and iii) monotonic unconfined compressive strength tests performed after the cyclic loading stage (UCS_{pc}). The study reports the accumulated permanent axial deformation (εax-perm) during the cyclic stage and the influence that the number of cycles and the frequency have on the compressive strength and stiffness.

2. Test Materials

This study was carried out with a Portuguese soft soil from the Baixo Mondego area, located in central Portugal on the banks of the Mondego River, and which has been characterized by many researchers (Coelho, 2000; Correia, 2011). The soil deposit was formed more than 20,000 years ago in a fluviomarine depositional environment and has a thickness of more than 20 m. In this work, a sample was used that was collected at a depth of 2.5 m. Table 1 summarizes the main physical and chemical properties of the soil under study. It can be observed that the soil has a mostly silty particle size distribution (71%), a low unit weight $\gamma = 14.6$ kN/m^3, a high void index $e > 2.0$, a high natural moisture content $w^{nat} = 80.6\%$ and a high organic matter content OM = 9.3%. Furthermore, these results have a great influence on the mechanical behavior, since it translates into a low undrained shear strength ($c\ u \approx 25$ kPa) and a high compressibility (Coelho, 2000). This organic clayey-silty soil with high plasticity was classified by the USCS as OH (ASTM D2487, 2017). The chemical composition of the soil exhibited a high content of silica (SiO_2 = 62%) and alumina (Al_2O_3 = 16%), which conferred pozzolanic properties to the soil.

Table 1. Physical characteristics and chemical composition of the soil used

Physical properties		Chemical composition	
w_{nat},%	80.87	pH (BS1377-3)	3.5
G_s	2.55	SiO_2,%	62.00
e_{nat}	2.03	Al_2O_3,%	16.00
γ, kN/m^3	14.6	Fe_2O_3, %	4.80
OM, %	9.3	CaO, %	0.74
Particle size distribution		MgO, %	1.10
Clay, %	10	Na_2O, %	0.90
Silt, %	71	K_2O, %	3.00
Sand, %	19	TiO_2, %	0.69
w_L, %	71		
w_p, %	43		
Plasticity index %	28		
Liquidity index %	1.35		
USCS	OH		

The soft soil was stabilized with a Portuguese Portland cement binder (Portland cement Type I 42.5 R, produced by CIMPOR), whose main chemical characteristics are presented in Table 2. Portland cement reacts immediately with water producing a large amount of short-term reaction products; over time, the physicochemical reactions develop at a slower rate, helping to produce more cementitious products responsible for improving the mechanical properties of the stabilized soil.

Table 2. Chemical characterization of Portland cement (manufacturer's data)

CaO, %	62.88
SiO_2, %	19.00
Al_2O_3, %	5.15
Fe_2O_3, %	3.19
SO_2, %	3.14
MgO, %	2.16
K_2O, %	1.29
Na_2O, %	0.10

The polypropylene fibres used in this study are 12 mm long, 32 mm in diameter and have high flexibility, a high specific surface area (134 m^2/kg), a density of 905 kg/m^3, a tensile strength of 250 N/mm^2 and a Young's modulus of 3500 - 3900 N/mm^2 (according to the product data sheet provided by the manufacturer BEKAERT).

2.1 Experimental procedure

The samples used in all tests were prepared with a binder quantity (dry weight of binder per cubic metre of soil) of 250 kg/m^3, a fibre quantity (weight of fibre per cubic metre of soil) of 10 kg/m3. The soil was mechanically mixed (142 rpm for 4 min) with the fibres and a binder slurry raising the water content to 115%. The homogeneous paste was compacted in a PVC cylindrical mould (37 mm diameter and 76 mm height) in three layers. Each layer was tapped 20 times against a rigid table, followed by top-setting; the surface of the layer was carefully lightly scarified before a new layer was introduced. The specimens were cured for 28 days in a room with controlled conditions of temperature of 20 ± 2°C and humidity of 95 ± 5%. After the curing time, the specimens were placed in the testing equipment and the electronic devices (load cell and displacement transducer) were set up and adjusted. Finally, the tests were performed and the data were recorded automatically. Unconfined compression tests, UCS, were performed at a constant strain rate of 1%/min (BS 1377-7, 1990). Cyclic loading tests (CYC) were performed for a stress level of 50% of the strength evaluated in the monotonic tests (0.50 $q_{u\text{-}max}$), a sinusoidal excitation of 0.5 Hz and an amplitude of ±10% (± 0.10 q u-max) by varying the number of loading cycles (2500, 5000, 10000) and in a second study stage, varying the frequency (0.25, 0.50, 1.00, 2.00 Hz) and maintaining the number of loading cycles at 5000. After the cyclic stage, a monotonic UCS test (UCS_{pc}) was carried out. To ensure the reliability of the procedure used, the tests were repeated at least twice.

3. Results

At the beginning of the experimental work, unconfined compression tests UCS were performed. The results obtained are shown in Figure 1. The materials present an unconfined compressive strength $q_{u\text{-}max}$ of 292 kPa associated with an axial extension $\varepsilon_{ax\text{-}rot}$ of 4.5% for the chemically stabilized and fiber-reinforced samples (FQ = 10 kg/m^3). In the other situation, the results showed that the unconfined strength $q_{u\text{-}max}$ is 276 kPa at an axial extension $\varepsilon_{ax\text{-}rot}$ of 2.3% for the case without fibers (FQ = 0 kg/m^3). In general, it can be observed that the inclusion of fibers induces a slight increase in the mechanical strength and a modification of the behavior from brittle to ductile, presenting a residual strength.

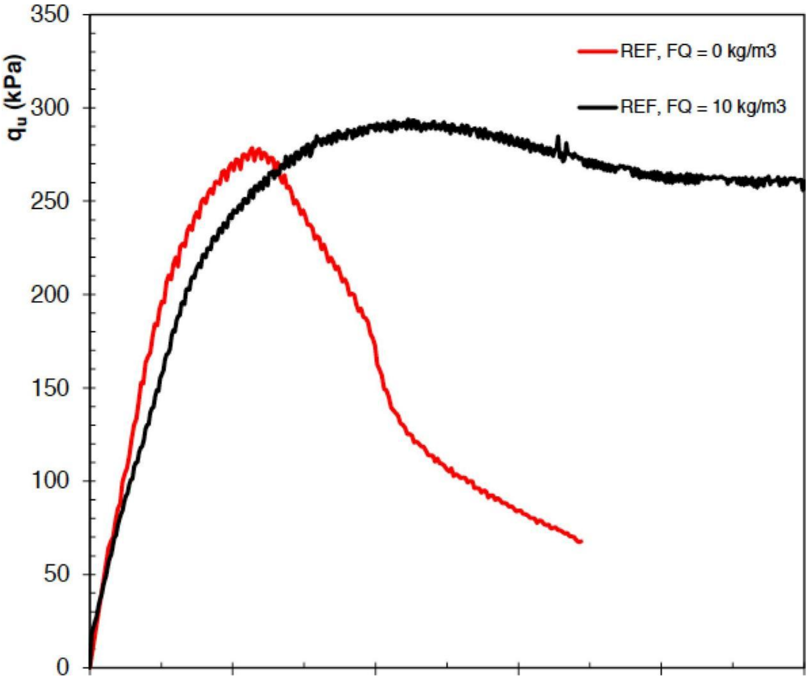

Figure 1. Stress-extension curve for the reference UCS tests.

The cyclic loading stage was carried out from a stress level of 50% of the reference values obtained (Figure 1) in the reference UCS monotonic tests. Maintaining this deviatoric stress level, the effect of the number of cycles and the applied frequency was studied. In the case of the effect of the number of cycles (2500, 5000, 10000), it was at a sinusoidal excitation of 0.5 Hz, with an amplitude of ±10% of $q_{u\text{-max}}$. On the other hand, for the study of the effect of frequency, this has been varied from 0.25, 0.50, 1.0 and 2.00 Hz, having kept the number of cycles constant at 5000. The comparison of the accumulated permanent axial deformation $\varepsilon_{ax\text{-perm}}$ during the cyclic stage for both studies, for the stabilized non-reinforced soils and those reinforced with fibers, is illustrated in Figures 2 and 3.

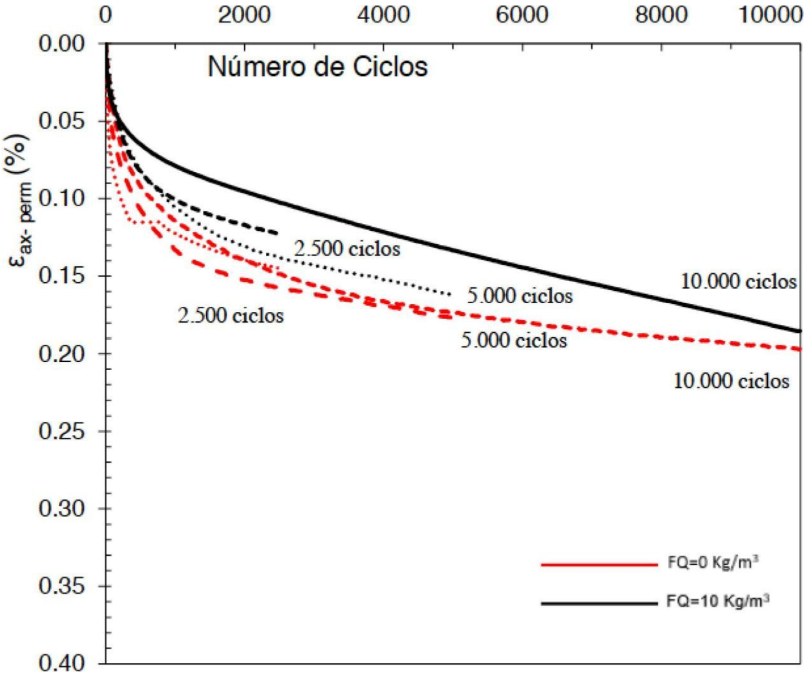

Figure 2. Evolution of the accumulated permanent axial deformation during the cyclic stage - effect of the number of cycles.

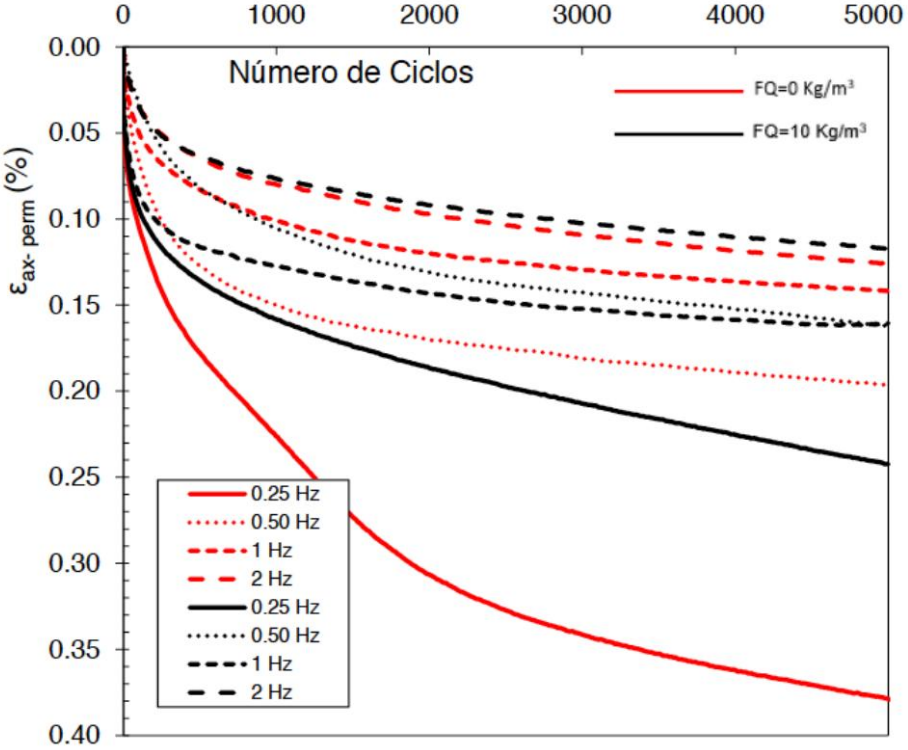

Figure 3. Evolution of the accumulated permanent axial deformation during the cyclic stage - effect of frequency.

3.1 Results of cyclic tests

During the cyclic stage, it is observed that the permanent axial deformation shows a strong increase at the beginning of the cyclic stage followed by a decrease in the deformation rate for both cases (unreinforced and fiber-reinforced). The same occurs in the study of the number of cycles and the applied frequency.

In terms of the effect of the cycles, a greater axial deformation is observed for the fiber-reinforced soils (Figure 1). However, Figure 2 shows the effect of the cycles in the cyclic stage. For the case without fibers, greater deformations are observed than for the fiber-reinforced composite material, where due to the level of deformations this tends to mobilize the fibers in tension and thus reduce the permanent deformation.

In the context of analyzing the variation in frequency, a clear reduction in the accumulated permanent axial deformation is observed with the increase in the frequency level (Figure 3).

The samples that were subjected to lower frequencies show greater axial deformations, because they were also tested for a longer time. The increase in their plastic deformations, which can be interpreted as a deterioration of the cementitious matrix, suggests that the higher frequencies are associated with a more significant portion of elastic deformations. The addition of fibers to the stabilized material leads to a progressive transfer of stresses to the fibers that contribute to a lower deterioration of the cementitious matrix, that is, a reduction in the accumulated permanent axial deformation.

3.2 Post-cyclic results

Figures 4 and 5 show the results of the UCS_{pc} tests carried out after the cyclic stage, both for the effect of the cycles and the effect of the frequency. It is observed that the resistances increase in relation to the reference tests (Figure 1).

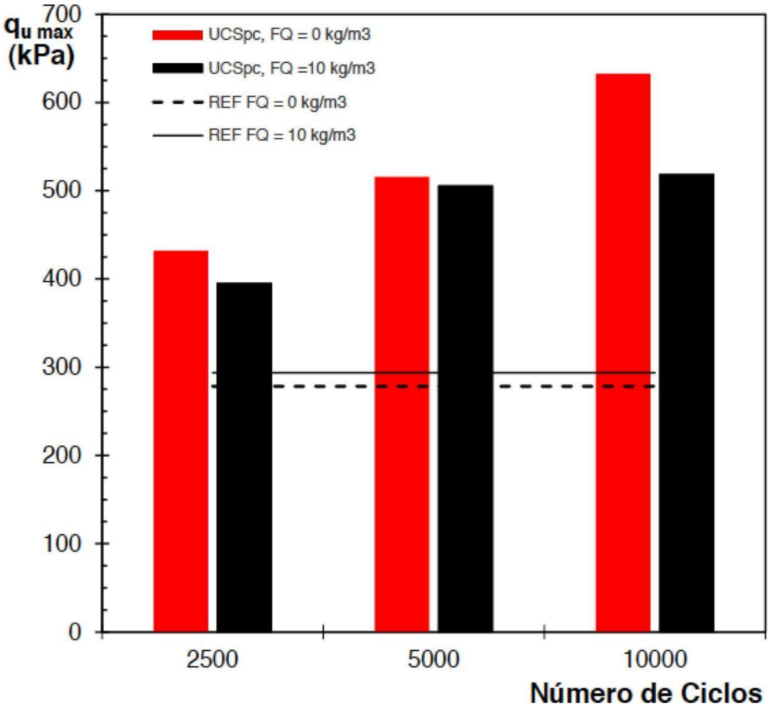

Figure 4. Maximum unconfined strength results for the case of the cycle effect.

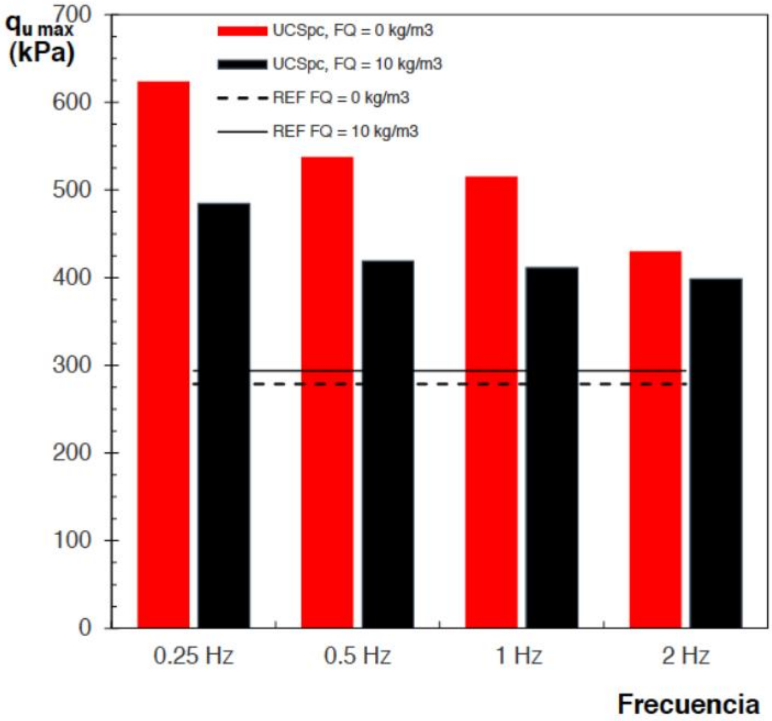

Figure 5. Maximum unconfined strength results for the case of frequency effect.

Figure 4 also shows that post-cyclic resistances show a noticeable increase with the cycles, and this is because, with greater permanent deformations during the cyclic stage, they generate greater unconfined resistance. Since it is understood that cementitious bonds tend to break and generate thicker particles in their granulometry, they give them greater resistance due to friction. It can also be understood that the samples, as they were in the tests for a longer time (with longer cycles), present greater resistance, since they could present a suction effect.

With what was mentioned above, it is understood that the suction phenomenon could also occur in the effect of frequency, giving the composite material greater resistance as they were in the test for a longer time, that is, lower frequency. Observing Figure 5, it is shown that the lower the frequency, the greater its resistance for both cases. In any case, it is possible to understand that considering greater axial deformations during the cyclic stage, a greater quantity of coarse particles could be obtained in the particle size of the composite material, and with this, frictional resistance could be generated and coincidentally, greater results of unconfined resistance could be obtained, as shown in Figure 5.

4. Conclusions

4.1 Effect of the number of cycles

The results of the tests for all stages (before cyclic loading, cyclic stage and UCS after the cyclic stage) lead to the following conclusions.

- In the case of monotonic behavior before the cyclic stage, the inclusion of fibers (FQ = 10 kg/m^3) induced a slight increase in the unconfined compressive strength and a change in behavior from brittle to ductile, presenting a residual strength.
- During the cyclic stage, it was observed that the permanent axial deformation shows a strong increase at the beginning of the cyclic stage followed by a decrease in the deformation rate for both cases. The evolution of the permanent axial deformation is greater for the case without fibers, which is related to the influence of the mobilization of the fibers in terms of the assistance it provides in the plastic axial deformations.
- After the cyclic phase, the unconfined compressive strength increases relative to the reference values for both unreinforced and fiber-reinforced cases.

4.2 Effect of frequency

From the monotonic UCS tests performed before cyclic loading (reference values) and after the cyclic stage (UCS_{pc}) for the fibre-reinforced and unreinforced stabilized soil, the following conclusions are drawn.

- During the cyclic stage, it is observed that the permanent axial strain shows a sharp increase at the beginning of the cyclic stage, followed by a decrease in the strain rate for both cases.
- As the frequency applied in the cyclic stage increases, the permanent axial strain decreases, indicating a lower deterioration of the cementitious matrix. This is explained by the fact that higher frequencies are associated with a more significant portion of the elastic deformation.
- After the cyclic stage, the mechanical behaviour of the reinforced and unreinforced stabilized soil becomes stronger than the reference values (monotonic UCS tests). Thus, an increase in maximum resistance is observed after the application of the cyclic stage, which is more significant for lower frequencies.

Acknowledgments

The authors would like to express their gratitude to CIMPOR and BIU International for providing the binders and fibers, and to the institutions that financially supported the research: CIEPQPF (UIDB/00102/2020), Portuguese Foundation for Science and Technology (project PTDC/ECI-CON/28382/2017), ISISE (UIDB/04029/2020), CONICYT PAI/INDUSTRIA 79090016, Universidad de Magallanes and ACIV.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] ASTM D2487 (2017). Standard practice for classification of soils for engineering purposes (unified soil classification system). West Conshohocken, PA, USA.

[2] BS 1377-3 (1990). Methods of test for soils for civil engineering purposes: chemical and electro-chemical testing. British Standards Institution BSI, Milton Keynes, UK.

[3] BS 1377-7 (1990). Methods of test for soils for civil engineering purposes: shear strength tests (total stress). British Standards Institution BSI, Milton Keynes, UK.

[4] Chauhan, M.S., Mittal, S. and Mohanty, B. (2008). Performance evaluation of silty sand subgrade reinforced with fly ash and fibre. Geotextiles and Geomembranes 26(5), 429-435.

[5] Coelho, P.A.L.F. (2000). Caracterização geotécnica de solos moles - estudo do local experimental da Quinta do Foja . Tesis de maestría, Universidad de Coimbra, Portugal.

[6] Consoli, N.C., Rosa, D.A., Cruz, R.C. and Rosa, A.D. (2011). Water content, porosity and cement content as parameters controlling strength of artificially cemented silty soil. Engineering Geology 122(3-4), 328-333.

[7] Correia, A.A.S. (2011). Aplicabilidade da t écnica de deep mixing aos solos moles do Baixo Mondego . Dissertação de doutoramento, Universidade de Coimbra, Portugal.

[8] Correia, A.A.S., Venda Oliveira, P.J. and Custódio, D.G. (2015). Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilized with binders. Geotextiles and Geomembranes 43(2), 97-106.

[9] Dall'Aqua, G.P., Ghataora, G.S. and Ling, U.K. (2010). Behaviour of fibre-reinforced and stabilized clayey soils subjected to cyclic loading. Studia Geotechnica et Mechanica 32(3), 3-16.

[10] Maher, M. and Ho, Y. (1993). Behavior of fiber-reinforced cemented sand under static and cyclic loads. Geotechnical Testing Journal 16(3), 330-338.

[11] Subramaniam, P. and Banerjee, S. (2014). Factors affecting shear modulus degradation of cement treated clay. Soil Dynamics and Earthquake Engineering 65, 181-188.

[12] Sukontasukkul, P. and Jamsawang, P. (2012). Use of steel and polypropylene fibers to improve flexural performance of deep soil–cement column. Construction and Building Materials 29, 201-205.

[13] Tang, C.-S., Shi, B. and Zhao, L.-Z. (2010). Interfacial shear strength of fiber reinforced soil. Geotextiles and Geomembranes 28(1), 54-62.

[14] Venda Oliveira, P.J., Correia, A.A.S., Teles, J.M.N.P.C. and Custodio, D.G. (2015). Effect of fibre type on the compressive and tensile strength of a soft soil chemically stabilized. Geosynthetics International 23(3), 171-182.

[15] Venda Oliveira, P.J., Correia, A.A.S. and Cajada, J.C.A. (2018). Effect of the type of soil on the cyclic behaviour of chemically stabilized soils unreinforced and reinforced with polypropylene fibres. Soil Dynamics and Earthquake Engineering 115, 336-343.

[16] Yang, C., Cui, Y.J., Pereira, J.M. and Huang, M.S. (2008). A constitutive model for unsaturated cemented soils under cyclic loading. Computers and Geotechnics 35(6), 853-859.