The Effect of Cyclic Loading on the Behaviour of a Soft Soil Chemically Stabilised Reinforced and Unreinforced with Polypropylene Fibres

Jorge Villarroel Ortega, Antonio Alberto Santos Correia, Luis Lemos and Paulo da Venda Oliveira

July 16, 2022

THE EFFECT OF CYCLIC LOADING ON THE BEHAVIOUR OF A SOFT SOIL CHEMICALLY STABILISED REINFORCED AND UNREINFORCED WITH POLYPROPYLENE FIBRES

INFLUÊNCIA DA SOLICITAÇÃO CÍCLICA NO COMPORTAMENTO DE UM SOLO MOLE ESTABILIZADO QUIMICAMENTE E REFORÇADO E NÃO REFORÇADO COM FIBRAS DE POLIPROPILENO

Villarroel-Ortega. J., University of Magallanes, Chile and University of Coimbra, Portugal, jorge.ortega@uc.pt
Correia. A.A.S, CIEPQPF, University of Coimbra, Portugal, aalberto@dec.uc.pt
Lemos. L.J.L, CGEO, University of Coimbra, Portugal, llemos@dec.uc.pt
Venda Oliveira. P.J, ISISE, University of Coimbra, Portugal, pjvo@dec.uc.pt

ABSTRACT

This paper aims to identify the effect of cycling loading on the behaviour of a soft soil chemically stabilised reinforced (SSRF) and unreinforced (SSCS) with polypropylene fibres. The soil under study is a Portuguese soft soil collected in Baixo Mondego area. The laboratory work is based on the following tests: (i) monotonic Unconfined Compressive Strength (UCS) test (reference values); (ii) cyclic UCS test performed in different number of cycles (1.000; 2.500; 5.000; 10.000), and (iii) monotonic UCS tests developed after the cyclic loading stage (UCSpc). The analysis is complemented with the study of the accumulated permanent axial strain developed during the cyclic stage. The results show the accumulated permanent axial strain increases with the number of cycles, as well as the strength and stiffness after cycling loading stage.

RESUMO

Este trabalho visa analisar o efeito da aplicação de carregamento cíclico no comportamento de um solo mole quimicamente estabilizado (SSRF) reforçado e não reforçado (SSCS) com fibras de polipropileno. O solo analisado é um solo mole português proveniente na área de Baixo Mondego. O trabalho de laboratório baseia-se nos seguintes testes: (i) ensaio monotónico de compressão não confinada (UCS) (valores de referência); (ii) ensaios UCS cíclico realizado com diferentes números de ciclos (1.000; 2.500; 5.000; 10.000); e (iii) ensaios UCS monotónicos realizados após a fase de carregamento cíclico (UCSpc). A análise é complementada com o estudo da deformação axial permanente acumulada desenvolvida durante a fase cíclica. Os resultados mostram que a tensão axial permanente acumulada aumenta com o número de ciclos, bem como a resistência e a rigidez após os provetes terem sido submetidos a carregamento cíclico.

1. INTRODUCTION

The behaviour of soft soils chemically stabilised with or without reinforced with fibres under monotonic conditions has been studied by several authors (Correia et al., 2015; Consoli et al., 2011; Venda Oliveira et al., 2015). The inclusion of fibres in the stabilised soil changes its stress-strain behaviour from brittle to ductile (Tang et al. 2010; Venda Oliveira et al, 2018), consequently an increase of the residual strength is commonly observed due to the mobilisation of the tensile strength of the fibres for higher strain levels (Tang et al. 2010; Sukontasukkul and Jamsawang 2012). Nevertheless, this behaviour may change in the presence of cyclic loading made by different types of actions, industrial machinery, vibrations on offshore structures, traffics loads made by trains or highways and earthquakes.

When the number of load cycles increases a progressive degradation of the cementation bonds is observed on tests performed on stabilized soils (without fibres), inducing an increase in the accumulated permanent deformations (Chauhan et al., 2008; Yang et al., 2008) and a decrease in stiffness (Subramaniam and Banerjee, 2014). Therefore, when stabilised soil is reinforced with synthetic fibres the results show a decrease in brittleness and an increase in the post-peak strength of the composite material (Venda Oliveira et al., 2015). Other parameters also affect the behaviour, such as the binder content, the length/type of the fibres and the type of test carried out (Correia et al., 2015; Venda Oliveira et al., 2015). Some works about the use of fibre-reinforced stabilized soils subjected to cyclic loading have showed:
(i) an increase in the permanent deformations with the increment of the number of load cycles (Chauhan et al., 2008; Dall'Aqua et al., 2010; Venda Oliveira et al., 2018);
(ii) the addition of fibres increases the number of cycles and the magnitude of strain required to cause failure (Maher and Ho, 1993);
(iii) an increase in the unconfined compressive strength with the number of load cycles (Venda Oliveira et al., 2018).

This work studies the behaviour of a stabilized soft soil under two different conditions, reinforced with synthetic fibres and unreinforced. The laboratory work is focused on the compressive behaviour evaluated by the following tests:
(i) monotonic unconfined compressive strength (UCS) tests;
(ii) cyclic (CYC) UCS tests;
(iii) and monotonic unconfined compressive strength tests performed after the cyclic loading stage (UCSpc).

The study reports the accumulated permanent axial strain ($\varepsilon_{ax\text{-}perm\ \%}$) obtained during the cyclic stage and the influence of the number of cycles on the unconfined compressive strength and the stiffness.

2. MATERIALS

This study was carried out using a Portuguese soft soil, from the "Baixo Mondego" area, located in the centre of Portugal near the Mondego river, which has been characterised by many researchers Coelho, 2000; Correia, 2011; Teles et al., 2014. The soil deposit was formed more than 20.000 years ago in a fluviomarine depositional environment and shows a thickness higher than 20 metres. On this work it was used a sample that was collected at a depth of 2.5 meters. Table 1 summarizes the main physical and chemical properties. It may be seen that the soil has a largely silty grain size distribution (71%) a low unit weight (14.6 kN/m^3), a high void ratio (> 2.0), a high natural water content (80.6%) and a higher organic matter (OM) content (9.3%). Also, those results have a high influence in the mechanical behaviour, inducing a low undrained shear strength ($c_u \approx 25$ kPa) and a high compressibility (Coelho, 2000). This clayey-silt organic soil with high plasticity was classified as OH (ASTM D2487). The chemical composition of the soil shows a high silica content (SiO_2=62%) and an alumina (Al_2O_3) content of 16%, which conferred pozzolanic properties to the soil.

Table 1: Coimbra soft soil main characteristics (average values) (Villarroel-Ortega, 2018, Coelho, 2000)

Physical Properties		Chemical composition	
w_{nat} (%)	80.6	pH (BS1377-33)	3.5
G_s	2.55	SiO_2 (%)	62
e_{nat}	2.03	Al_2O_3 (%)	16
γ (kN/m^3)	14.6	Fe_2O_3 (%)	4.8
OM (%)	9.3	CaO (%)	0.74
Grain size		MgO (%)	1.1
Clay (%)	10	Na_2O (%)	0.9
Silt (%)	71	K_2O (%)	3
Sand (%)	19	TiO_2 (%)	0.69
w_L (%)	71	MnO (%)	<
w_p (%)	43	P_2O_5 (%)	<
PI (%)	28	TOC (%)	2.79
LI (%)	1.35	CTC (cmol+/kg)	11
USCS (ASTM)	OH		

The soft soil was stabilised with a Portuguese Portland cement binder (Portland cement Type I 42.5 R, produced by CIMPOR), which main chemical characteristics are presented in Table 2. Portland cement reacts immediately with water producing a high quantity of reaction products in the short terms; with time, the physico-chemical reactions (pozzolanic reactions) develop at a lower rate, helping the production of more cementitious products responsible for the enhancement of the mechanical properties of the stabilised soil.

Table 2: Chemical characterisation of the Portland cement (average values; data from manufacturer)

SiO_2 (%)	19.3
Al_2O_3 (%)	5.09
Fe_2O_3 (%)	3.15
CaO Total (%)	63.87
MgO (%)	1.91
SO_3 (%)	3.15
K_2O (%)	1.13
Na_2O (%)	0.1
CaO Free (%)	2.19
Loss on ignition (%)	1.26

The polypropylene fibres used in this study are 12 mm in length, 32 mm in diameter and exhibit a great flexibility, a high specific surface (134 m2/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 (in accordance with the product datasheet supplied by the manufacturer BEKAERT).

3. RESULTS AND DISCUSSION

At the beginning were done Unconfined Compressive Strength (UCS) tests, which results are shown in Figure 1 and Table 3. The results of stabilized soil reinforced with fibres (FQ=10 kg/m^3) show an average unconfined compressive strength ($q_{u\ max}$) of 296.7 kPa at an axial strain at peak-failure ($\varepsilon_{ax\text{-}rot}$) of 4.03%, while without fibres (FQ=0 kg/m^3) the $q_{u\ max}$ is 183.59 kPa at $\varepsilon_{ax\text{-}rot}$ of 1.26 % for the case. In general, it may be seen that the inclusion of the fibres induced an increase on the unconfined compressive strength and a significant modification of the stress-strain behaviour from a brittle to a ductile, exhibiting a residual strength (Venda Oliveira et al., 2015).

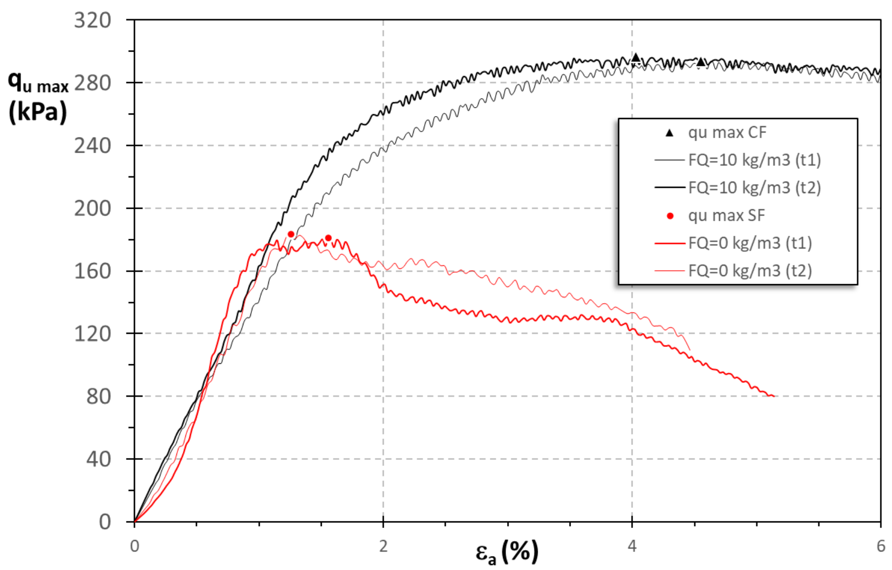

Figure 1: Stress – Strain plot from UCS tests monotonics (references values)

Table 3: references UCS values

		$q_{u\ max}$ (kPa)	E_{U50} (MPa)	$\varepsilon_{ax\text{-}rot}$ (%)	$0{,}5q_u$ (kPa)	$\varepsilon_{ax}\text{-}0.5q_u$ (%)
FQ=10kg/m^3	T1	293.87	14.32	4.55	145.38	1.01
FQ=10kg/m^3	T2	296.65	16.10	4.03	145.51	0.90
FQ=0kg/m^3	T1	181.12	15.09	1.56	86.90	0.58
FQ=0kg/m^3	T2	183.59	14.61	1.26	90.59	0.62

The cyclic loading stage were carried out from a deviatoric stress level of 50% of the reference values obtained in the monotonic UCS tests. Maintaining that deviatoric stress level, a sinusoidal excitation of 0.5 Hz, with an amplitude of 10% of q_{cyclic} was applied on the samples. The comparison of the accumulated permanent axial strain ($\varepsilon_{ax\text{-}perm}$) during the cyclic stage obtained for the unreinforced and reinforced stabilized specimens is illustrated in Figure 2.

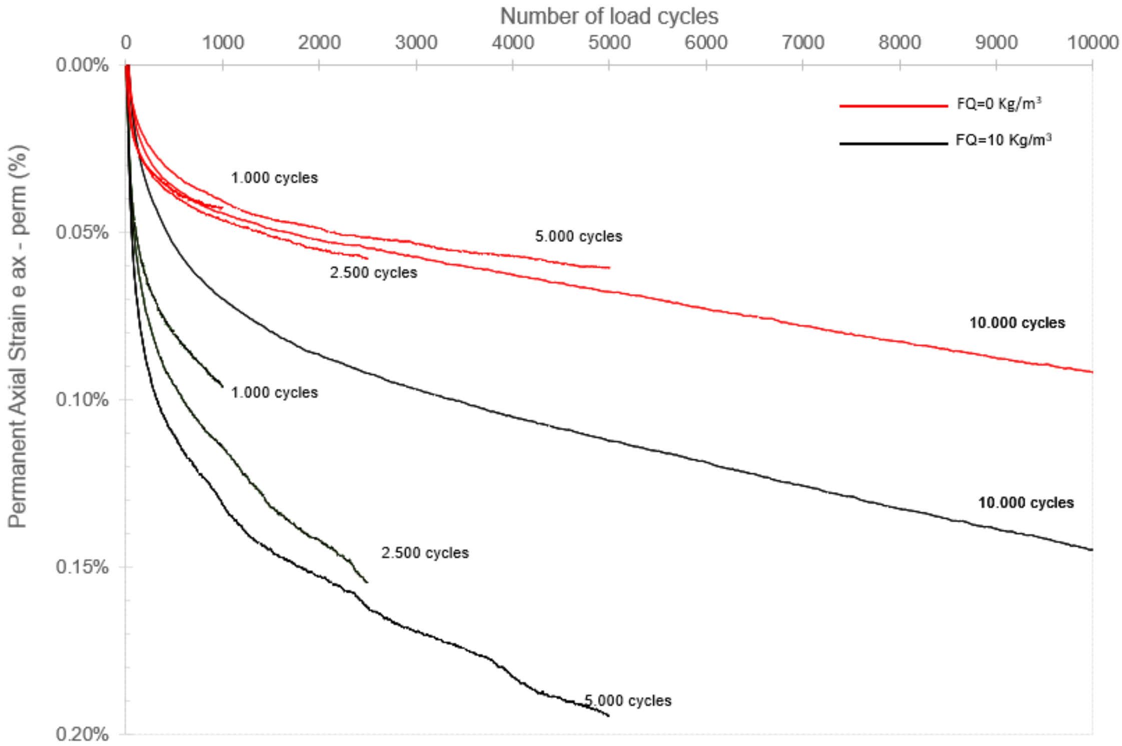

Figure 2: Accumulated Permanent Axial Strain during Cyclic Loading

As observed by Dall ‘Aqua et al. (2010) and Venda Oliveira et al. (2018) the results show a sharp increase in the $\varepsilon_{ax\text{-}perm}$ at the beginning of the cyclic stage, followed by a decrease in the permanent strain rate with the increment of load cycles, phenomena that occurs in both of cases (with and without fibres) represented in Figure 2. Some local breakage of the cement bonds and the consequent transfer of stresses from the cement matrix to the fibres, have small stiffness influence in case of stabilised soil reinforced with fibres because is also noticed that the $\varepsilon_{ax\text{-}perm}$ are higher comparing with the one without fibres.

The effect of the cyclic loading stage on the stress-strain behaviour of the stabilised soil reinforced with fibres is shown in Figure 4. From the figure it is possible to see that the inclusion of the fibres gives a ductile behaviour to the composite material in accordance with Venda Oliveira et al., 2018, showing a reduced loss of strength after the peak in comparison with the case without fibres (Figure 3). The behaviour associated to the presence of the fibres is related to the high strain levels that occur at failure which allow the mobilization of the tensile strength of the fibres and, consequently, the loss of strength after the peak decreases significantly. Results agree with other works Correia et al., 2015; Venda Oliveira et al., 2018.

The effect of the cyclic loading on the mechanical behaviour in both cases show an increase of the strength ($q_{u\ max}$) and stiffness (E_u) obtained in UCSpc (Figure 3 and Figure 4) when compared with the reference values, however for the case without fibres (Figure 4) these effects are stronger. For the case with fibres, results show that the effect of the mobilization of the tensile strength of the fibres largely compensates the degradation of the material matrix associated to the breakage of cementation bonds (Venda Oliveira et al., 2018), justifying the improvement of the mechanical behaviour. Figure 5 summarizes the strength results.

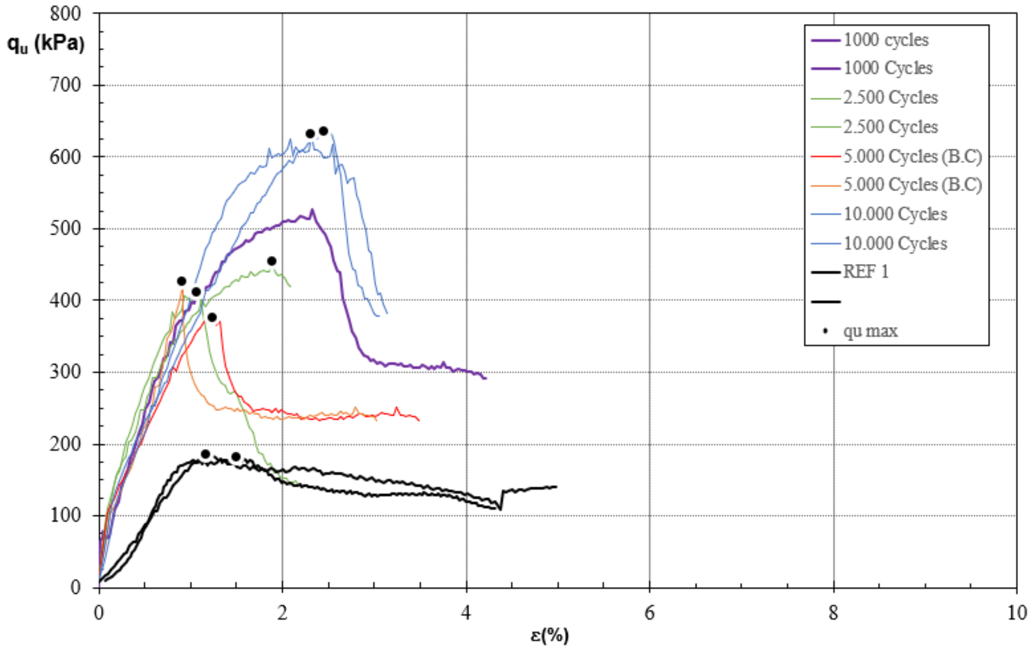

Figure 3: Stress - Strain plot made by UCS after several cycles under frequency of 0.5 Hz

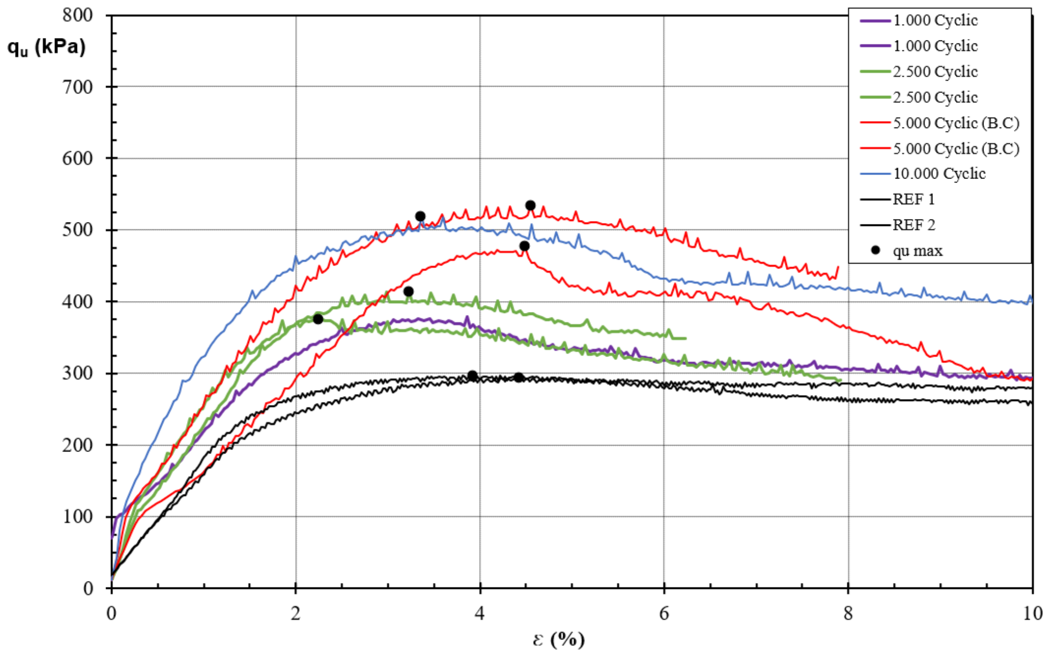

Figure 4: Stress - Strain plot made by UCS after several cycles under frequency of 0.5 Hz

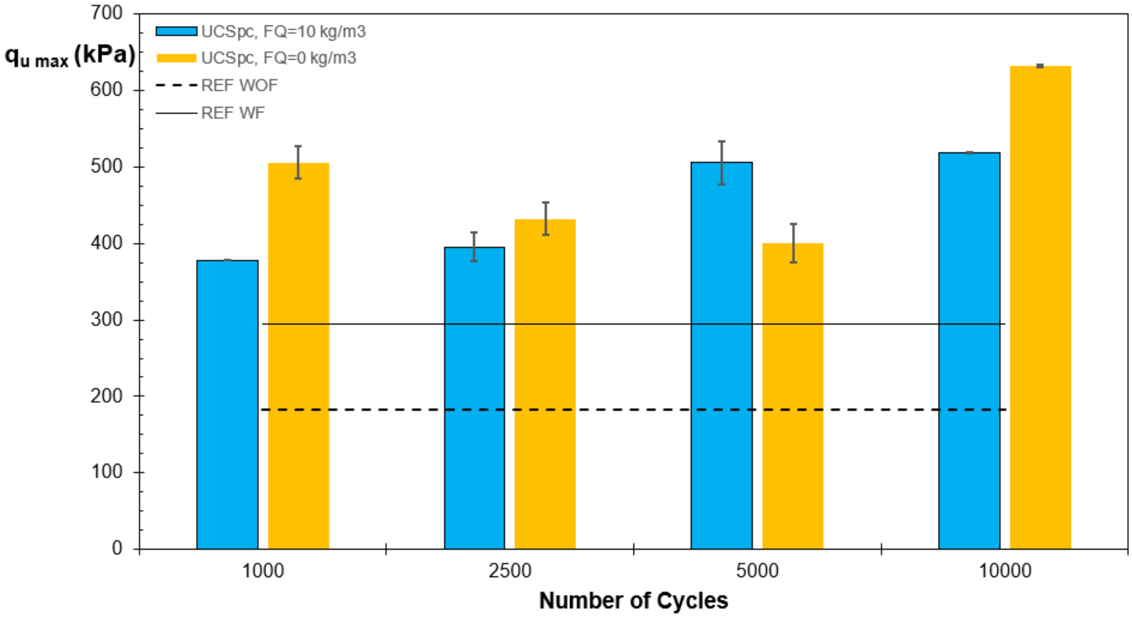

Figure 5: Box Plot ilustrative of $q_{u\ max}$ of monotonic test after cyclic loading (UCSpc)

4. CONCLUSIONS

Results from tests concerning all stages (before cyclic loading, cycling stage and post cyclic UCS) delivering the following conclusions:

i) In the case of monotonic behaviour before the cyclic stage, the inclusion of fibres (FQ=10 kg/m^3) induced an increase on the unconfined compressive strength and a modification of the behaviour from a fragile to a ductile, exhibiting a residual strength.

ii) During cyclic stage it was 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. The evolution of the permanent axial strain is higher for the case with fibres which may be linked to some local breakage of the cement bonds and the consequent transfer of stresses from the cement matrix to the fibres, which are characterised by a small axial stiffness.

iii) After the cyclic stage, the unconfined compressive strength increases in relation to the reference values for both cases, unreinforced and reinforced fibres.

AKNOWLEDGEMENTS

The authors appreciate the support of CIMPOR and to BEKAERT for supplying the binder and the fibres, and to the institutions that financially supported the research: IEPQPF(Pest/C/EQB/UI0102/2013), ISISE (project UID/ECI/04029/2013), FCT (POCI-01-0145-FEDER-028382), ACIV, University of Magallanes, Punta Arenas, Chile and CONICYT PAI/INDUSTRIA 79090016.

REFERENCES

Aqua, G. P. D., Ghataora, G. S. & Ling, U. K. (2010) Behaviour Of Fibre-Reinforced And Stabilized Clayey Soils Subjected To Cyclic Loading. *Studia Geotechnica et Mechanica*, **32**.

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

Coelho, P. A. L. F. (2000) *Caracterização Geotécnica de Solos Moles*. University of Coimbra, Coimbra.

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

Correia, A. A. S. (2011) *Aplicabilidade da Técnica de Deep Mixing aos Solos Moles do Baixo Mondego*. Dissertação de Doutoramento. Universidade de Coimbra, Coimbra.

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

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

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

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

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

Teles, J. M. N. P. C., Correia, A. A. S. & Venda Oliveira, P. J. (2014) Mechanical Characterization Of A Chemically Stabilized Soft Soil Reinforced With Fibers When Subjected To Tensile Solicitations.

Venda Oliveira, P. J., Correia, A. A. S., Teles, J. M. N. P. C. & Custodio, D. G. (2015) Effect of fibre type on the compressive and tensile strength of a soft soil chemically stabilised. *Geosynthetics International*.

Venda Oliveira, P. J., Correia, A. A. S., Lemos, L. & Cajada, J. (2018) Effect Of Cycling Loading On The Strength Of Chemically Stabilized Soils.

Villarroel-Ortega, Correia, A. A. S. & p.j (2018) Soft soil chemically stabilised – influence of key parameters. In: *X Congreso Chileno de Geotecnia, 2018, Valparaíso, Chile*. (in Spanish).

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