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Effect of cyclic loading stress level and amplitude on the behaviour of a soft soil chemically stabilized unreinforced and fibre-reinforced

Effet du niveau et de l'amplitude des contraintes de chargement cycliques sur le comportement d'un sol meuble chimiquement stabilisé, non renforcé et renforcé de fibres

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ABSTRACT: This works aims to characterise the effect ofin cyclic loading stress level and amplitude, on the behaviour of a soft soil chemically stabilized and reinforced with polypropylene fibres by comparing the results of unconfined compressive strength (UCS) and split tensile strength (STS) tests (STS) carried out before and after a cyclic loading stage. The laboratory work is based on the following tests: i) monotonic UCS and STS test (reference values); (ii) cyclic UCS and STS tests and (iii) monotonic UCS and STS tests performed after the cyclic loading stage (UCSpc and STSpc). From the results it is observed that the permanent deformations show a sharp increase at the beginning of the cyclic stage followed by a decrease in the strain rate for unreinforced and fibre-reinforced samples. In terms of cyclic loading stress level and amplitude, Ffor levels of stress and amplitudes of up to 50% of the maximum strength/load, the samples exhibit lower permanent strains but become stronger and stiffer than the reference values (monotonic tests). These observations are valid for both stabilised materials (unreinforced and fibre-reinforced).

RÉSUMÉ: Ce travail vise à caractériser l'effet du niveau de contrainte et de l'amplitude de la charge cyclique sur le comportement d'un sol meuble chimiquement stabilisé et renforcé avec des fibres de polypropylène en comparant les résultats des essais de résistance à la compression non confinée (UCS) et de résistance à la traction par flexion (STS) réalisés avant et après une étape de chargement cyclique. Le travail en laboratoire est basé sur les tests suivants: i) essai monotone de l'UCS et de la STS (valeurs de référence); ii) essais cycliques de l'UCS et de la STS; et iii) essais monotones de l'UCS et de la STS réalisés après l'étape de chargement cyclique (UCSpc et STSpc). Les résultats montrent que les déformations permanentes augmentent brusquement au début de la phase cyclique, suivies d'une diminution du taux de déformation pour les échantillons non renforcés et renforcés de fibres. En ce qui concerne le niveau de contrainte et l'amplitude de la charge cyclique, pour des niveaux de contrainte et d'amplitudes allant jusqu'à 50% de la résistance/charge maximale, les échantillons présentent des déformations permanentes plus faibles mais deviennent plus résistants et plus rigides que les valeurs de référence (essais monotones). Ces observations sont valables pour les matériaux stabilisés, qu'ils soient renforcés de fibres ou non.

Keywords: Ground improvement; unconfined compressive strength; split tensile strength; monotonic and cyclic loading; stabilisation of soft soils.

1 INTRODUCTION

When infrastructures such as bridge foundations or embankments are built on soft soil deposits, these soils tend to exhibit deformation over long periods due to consolidation and creep phenomena. Such behaviour of soft soils is a consequence of their weak geotechnical characteristics (low strength and excessive deformability) fundamentally due to the high-water content, high specific surface of the particles (clays, silts) and high organic matter (OM) content. Therefore, it is essential to ensure stability and to control/minimise the deformations during the construction stage and structure life (Kitazume and Terashi, 2013). It is important to mention that in the past construction on soft soil deposits was avoided (Venda Oliveira et al., 2018) due to the above-mentioned stability and deformation problems. However, due to the population growth, development of societies and expansion of urban and industrial areas, the pressure to build on these soft soils has increased, which poses challenges in terms of geotechnical engineering. There are two main geotechnical solutions to solve these types of problems: add reinforcement elements to the ground, or improve the soil's properties by mechanical, physical or chemical methods (Kitazume & Terashi, 2013). The presence of the fibres attenuates the brittle behaviour of the composite material, and improves its tensile strength (Sukontasukkul and Jamsawang, 2012; Correia et al., 2015). The field of application of this technique is vast, for example: embankments on soft soils, stabilisation of slopes, stabilisation of contaminated soils, mitigation of vibrations induced by high-speed trains, retaining walls, etc. (Correia, 2011; Kitazume and Terashi, 2013). Some geotechnical structures are often subjected to cyclical loadings induced by different types of actions, such as wind, earthquakes, traffic loads, heavy machinery, sea waves on offshore structures and even vibrations due to explosives. It is very important to assess the repercussions of cyclical loadings on the mechanical behaviour of chemically stabilised, fibre-reinforced soft soils (Venda Oliveira et al., 2018). Despite the research to date, the impact of the cyclic loading stress level and the amplitude on the compressive strength and tensile behaviour of a stabilized soft soil reinforced with fibres has not been properly studied.

The main goal of this research is to analyze the effect of the cyclic loading in stress level and amplitude on the compressive and tensile and post-cyclic behaviour of a stabilized soft soil, unreinforced and reinforced with polypropylene fibres. The permanents strains or displacement developed during the cyclic stage and the stress-strain, and the load-displacement curves will be used to assess the effect of the parameters studies on the cyclic loading in both materials. To achieve such goals, the following experimental testing program was designed: (i) monotonic unconfined compressive strength (UCS) splitting tensile strength (STS) tests performed with samples not subjected to cyclic loading; (ii) cyclic (Cyc) UCS - STS tests; (iii) and post-cyclic UCS and STS tests (UCSpc - STSpc). Table 1 summarizes the experimental testing plan.

Table 1. Summarize test.

Mix	**Qty**	**M^a**	**Cyclic Stage Loading Stress^b (%)**			**Cyclic Stage Amplitude (%)**		
			10	50	70	5	10	20
U	2	2	1	2	1	2	2	1
R	2	2	2	2	1	1	2	1

U= Unreinforced; R=Reinforced samples

$^{a)}$ Monotonic Test; $^{b)}$ Stress level = q_u/q_{uref}; $^{b)}$ amplitude = q_u/q_{uref}=50% varying amplitude

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 2 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.

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 3. 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. Coimbra soft soil main characteristics (average values) (Coelho, 2000 and Correia, 2011).

Physical Properties		Chemical composition	
w_{nat} (%)	80.67	pH (BS1377-	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 (%)	48
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 (%)	< 0.3
w_p (%)	43	P_2O_5 (%)	< 0.5
PI (%)	28	TOC (%)	2.79
LI (%)	1.35	CTC	11
USCS (ASTM) D2487)	OH		

Table 3. Chemical characterisation of the Portland cement (average values; data from manufacturer).

Nomenclature	Value
SiO_2 (%)	19.30
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 (%)	0.10
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 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 (in accordance with the product datasheet supplied by the manufacturer BEKAERT).

3 SAMPLE PREPARATION AND TESTING

The procedures and methodologies described below are based on the recommendations from EuroSoilStab (2001) and Correia (2011), though with slight differences. First, the soil was manually mixed to obtain a uniform paste. Then, a specified amount of cement (250 kg/m^3) was mixed with the required volume of water to increase the natural soil's water content from 80.67% to 115%. This paste was then mixed with the natural soil using a mechanical mixer at 142 rpm for 4 minutes. The soil-cement-water mixture was layered into cylindrical PVC molds (37 mm in diameter and 78 mm in height). After introducing each layer, the mold was lightly tapped by hand (20 times), and then it was lightly scarified before the next layer was added (each sample was divided into three equal layers). The samples were cured for 28 days in a controlled environment with a temperature of 20 ± 2 °C and humidity of 95 ± 5%. Subsequently, the samples were carefully removed from the PVC molds. Both surfaces were accurately ground to maintain parallelism, resulting in specimens measuring 37 mm in diameter and 76 mm in height. The remaining material was used to determine the moisture content of each sample. The specimens were then placed in the compression machine, and electronic devices (load cell and displacement transducer) were configured and adjusted. Unconfined compression strength (UCS) tests were conducted at a constant strain rate of 1% per minute (BS 1377-7, 1990). Cyclic loading tests were performed at 5.000 cycles, varying deviatoric stress level from 10%, 25%, and 70% ($0.50\times q_{u\text{-}max}$), with sinusoidal excitation at 0.5 Hz and an varying amplitude of ±5, ±10, ±20 ($\pm\ 0.10\times q_{u\text{-}max}$). After the cyclic stage, a monotonic UCS test (UCSpc) was carried out. To ensure the reliability of the procedure used, the tests were repeated at least twice.

4 ANALYSIS OF THE RESULTS

4.1 Effect of cyclic loading stress level

In Table 4, will be show the results of permanent strain resulted from the cyclic loading stress and the postcyclic test, strength parameters ($q_{u\ max}$, and strain). Is observed that concerning a higher stress level the strength starting to lose and the sample became fragile. On the case of the reinforced with fibres samples, the results show an improve of the behaviour on 50% of $q_{u\ max}$ of the level of stress. On the other side, is affected to higher stress level, taking the samples more brittle and losing strength.

In contrast, the split tensile test, STS and post cyclic stage and (STSpc), the higher forces applied, the sample became fragile however with less strength. In the case of reinforced occurs similarity effects (Table 5).

Table 4. STS test – effect of level of cyclic loading stress level.

Type	Stress level (%)	Test N°	Cyclic stage	UCSpc	
			$\varepsilon_{ax\text{-}perm}$ (%)	$\varepsilon_{ax\text{-}failure}$ (%)	$q_{u\ max}$ (kPa)
without Fiber	10	T1	0.16	3.53	506.6
		T2	-	-	-
	50	T1	0.22	1.73	543.2
		T2	0.24	1.89	581.3
	70	T1	0.25	1.84	462.3
		T2	0.55	1.42	237.9
reinforced	10	T1	0.07	2.82	425.5
	50	T1	0.16	1.98	571.5
		T2	0.16	2.7	504.7
	70	T1	0.75	8.34	448.4
		T2	1.00	10.36	465.0

Table 5. STS test – effect of level of cyclic loading stress level.

Type	Stress level (%)	Test N°	Cyclic stage	STSpc	
			$\delta_{v\text{-}perm}$ (mm)	$\delta_{v\text{-}failure}$ (mm)	F_{max} (N)
unreinforced	10	T1	0.17	0.76	1877.9
		T2	-	-	-
	50	T1	0.22	0.89	1862.9
		T2	0.21	1	1755.3
	70	T1	0.23	0.59	1400.5
		T2	-	-	-
reinforced	10	T1	0.07	3.92	2030.8
		T2	0.19	2.78	2093.9
	50	T1	0.2	4.53	2123.4
		T2	0.2	2.43	2022.2
	70	T1	0.75	5.33	1841.7

In Figure 1 and 2 shown a pronounced increase in permanent axial strain on samples but is more showed in samples reinforced with PP fibres. This shown that the structural matrix of the soft soil became more affected by the cyclic loading when they have more force/strength applied due the mobilization of fibres inside of the solid skeleton of the sample.

The results suggest that applying different levels of stress leads to an increase in the strength and load-bearing capacity of the fiber-reinforced material when compared to the standard monotonic tests. However, it's worth noting that for higher stress levels, there is a decrease in strength and load-bearing capacity.

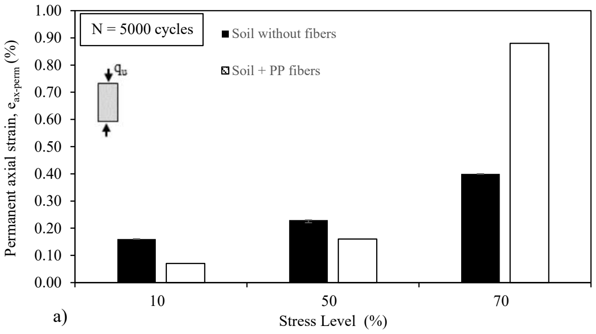

Figure 1. Effect of cyclic loading stress level on UCS$_{pc}$ tests.

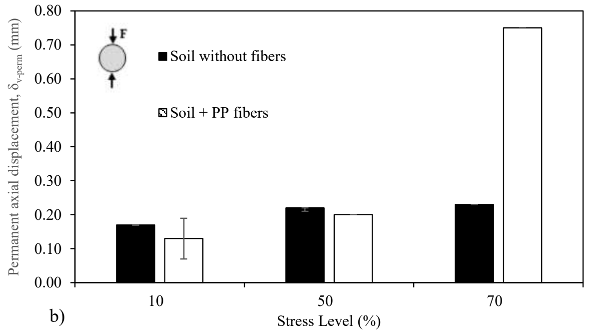

Figure 2. Evolution of permanent axial strain during the cyclic stage with cyclic loading stress level for STS$_{pc}$ test.

These results seem to imply that, during the cyclic stage, the tensile strength of the fibres couldn't fully compensate for the deterioration of the cementitious matrix caused by the cyclic stage. Additionally, the presence of fibres impedes the development of certain cementitious bonds, leading to a loss in unconfined compressive strength and stiffness. Comparing unreinforced and reinforced samples, it becomes evident that permanent deformation is similar in both cases for stress amplitudes ranging from 5% to 10%. However, for a 20% stress amplitude, the reinforced samples subjected to UCS tests exhibit lower permanent deformation. This suggests that as material deformation increases, the fibres progressively engage, helping to reduce permanent axial strain (UCScyc tests) compared to their unreinforced counterparts.

4.2 Effect of cyclic loading amplitude

In case of the effect of cyclic loading amplitude, the results shown similar behaviour in contrast with stress level. Comparing unreinforced and reinforced samples, it becomes evident that permanent deformation is similar in both cases for stress amplitudes ranging from 5% to 10%. However, for a 20% stress amplitude, the reinforced samples subjected to UCS tests exhibit lower permanent deformation. This suggests that as material deformation increases, the fibres progressively engage, helping to reduce permanent axial strain (UCScyc tests) compared to their unreinforced counterparts. Tables 6 and 7, as well as Figures 3 and 4, provide a summary of the results obtained during post-cyclic UCS and STS tests immediately after altering the cyclic stage's stress amplitude for the stabilized samples reinforced with polypropylene fibres. These results demonstrate an increase in the strength and load-bearing capacity of the stabilized fiber-reinforced material in comparison to the reference monotonic tests, albeit with a reduction as stress amplitude increases, which is linked to greater degradation of the cementitious matrix during the cyclic stage.

Table 6. UCS test – effect of cyclic loading amplitude.

Type	Amp	Test	Cyclic stage	UCS$_{pc}$		
	(%)	N°	$\varepsilon_{ax\text{-}perm}$ (%)	$\varepsilon_{ax\text{-}failure}$ (%)	$q_{u\ max}$ (kPa)	E_{u50} (MPa)
unreinforced	5	T1	0.13	1.79	473.3	92.1
		T2	0.08	1.77	608.6	48.3
	10	T1	0.22	1.73	543.2	71.2
		T2	0.24	1.89	581.3	72.7
	20	T1	0.3	1.21	321.8	80.5
reinforced	5	T1	0.15	3.1	631.7	38.9
	10	T1	0.16	1.98	571.5	69.2
		T2	0.16	2.7	504.7	52.8
	20	T1	0.38	1.62	371.1	82.7

Table 7. STS test – effect of cyclic loading amplitude.

Type	Amp	Test	Cyclic stage	STS$_{pc}$	
	(%)	N°	$\delta_{v\text{-}perm}$ (mm)	$\delta_{v\text{-}failure}$ (mm)	F_{max} (N)
unreinforced	5	T1	0.18	0.48	1120.4
		T2	0.21	1.45	2422.6
	10	T1	0.22	0.87	1862.9
		T2	0.22	1.00	1755.3
	20	T1	0.37	0.60	1052.9
reinforced	5	T1	0.19	2.47	2082.0
	10	T1	0.20	4.53	2123.4
		T2	0.20	2.43	2022.2
	20	T1	0.38	2.39	1816.9

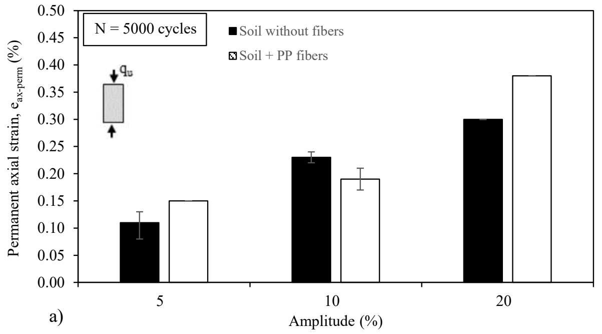

Figure 3. Effect of amplitude for UCS$_{pc}$ tests.

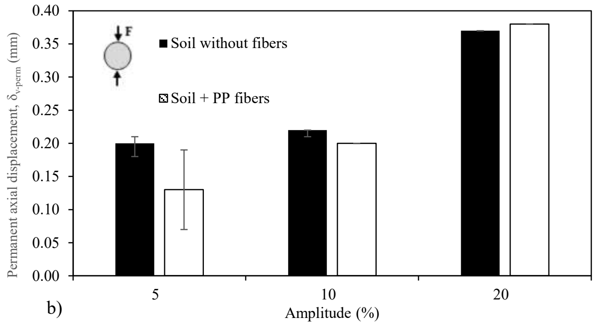

Figure 4. Effect of amplitude for STS$_{pc}$ tests.

5 CONCLUSIONS

From the monotonic UCS and STS tests performed before cyclic loading (references values) and after cyclic loading stage (UCSpc and STSpc) for the stabilized soil reinforced with fibres and not reinforced are drawn:

a. As other works shown that could be observed that the permanent strains show a sharp increase at the beginning of the cyclic stage followed by a decrease in the strain rate for unreinforced and fibre-reinforced samples. In this work results are not shown, mainly for the highly effect on the detriment of the cementitios matrix due the load/stress applied above 50% of the $q_{u\text{-}max}$.

b. Addition of fibres promotes a reduction in the permanent axial strains for the UCS cyclic tests, the opposite effect could be observed for the STS cyclic tests, explained by the different failure mechanisms associated with each test.

c. Up to stress levels and amplitudes of 50% of the maximum strength/load, the samples display reduced permanent deformations and also demonstrate increased strength and stiffness when compared to the reference values from the monotonic tests. These findings hold true for both stabilized materials, whether they are unreinforced or fiber reinforced.

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