Journal of Civil Engineering and Architecture 20 (2026) 232-237
doi: 10.17265/1934-7359/2026.06.004

Influence of Frequency on the Mechanical Behaviour of a Soft Soil Reinforced with Fibres

Jorge Villarroel-Ortega[1,2], Antonio Alberto S. Correia[3], Paulo J. Venda Oliveira[4], and Luis J. L. Lemos[5]

1. Department of Civil Engineering, University of Coimbra, Coimbra 3030-788, Portugal

2. Department of Construction Engineer, University of Magallanes, Punta Arenas 6200000, Chile

3. CIEPQPF, Department of Civil Engineering, University of Coimbra, Coimbra 3030-788, Portugal

4. ISISE, Department of Civil Engineering, University of Coimbra, Coimbra 3030-788, Portugal

5. CGEO, Department of Civil Engineering, University of Coimbra, Coimbra 3030-788, Portugal

Abstract: The chemical stabilization of soils has been applied worldwide with success to improve the mechanical properties of soils. However, it is known that chemical stabilization of soils induces poor tensile and flexural strength and a brittle behaviour which prevents its application in seismic areas and where is subjected to horizontal displacements. Reinforce the composite material with fibres. This work aims to study the influence of the frequency in cyclic loading on the mechanical behaviour of a soft soil chemically stabilized unreinforced and reinforced with synthetic fibres is one of the solutions. Unconfined compressive strength tests were carried out before and after the cyclic loading, changing the frequency of the cyclic loading (0.25, 0.5, 1, and 2 Hz). The laboratory work was complemented with the study of the permanent axial strain during the cyclic stage. The results indicate that the addition of synthetic fibres decreases the brittleness of the composite material inducing a residual strength to the material. Furthermore, the strength decreases with the increment of the frequency, more than on the unreinforced material. Moreover, the permanent axial strain observed during the cyclic stage show a deterioration of the mechanical behaviour as the frequency applied increases.

Key words: Chemical stabilization, soft soils, unconfined compression strength test, cyclic loading, frequency.

1. Introduction

Over the last decades, chemical stabilisation of problematic soils has become widely spread around the world and can be applied in many different areas such as foundations of structures and embankments, stability of slopes, liquefaction, mitigation of the effects of vibrations of high-speed trains, etc. [1]. One of the methods usually employed in chemical stabilisation of soils is the deep mixing technique, which involves the modification of the mechanical properties of problematic soils, such as soft soils (characterised by low strength and high compressibility) [2].

One of the main limitations associated with the chemical stabilisation of soils is the low tensile and flexural strength due to their brittle behaviour, particularly important in structures subject to horizontal loads and displacements induced by earth pressures, cyclic actions, among others. These limitations can be minimised by the introduction of fibres, which generate modifications in the mechanical behaviour of the composite material. The behaviour of stabilized soils unreinforced and reinforced with fibres under monotonic conditions has been studied by several authors [3, 4]. The presence of the fibres modifies the mechanical behaviour of the stabilised soil from brittle to ductile [5, 6], while an increase of the residual strength is generally observed due to the mobilisation of the tensile strength of the fibres for higher strain levels [5, 7]. However, this behaviour may change in the presence of cyclic loading induced by different types of actions, such as traffic loads, industrial machinery, vibrations on offshore

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Corresponding author: Jorge Villarroel-Ortega, Ph.D., research field: geotechnical engineering.

structures and even earthquakes.

The results of cyclic loading tests performed on stabilized soil samples (without fibres) have showed that an increase in the number of load cycles causes a progressive degradation of the cementation bonds, inducing an increase in the accumulated permanent deformations [8] and a decrease in stiffness [9]. When the stabilised soil is reinforced with synthetic fibres the results have showed a decrease in brittleness and an increase in the post-peak strength of the composite material. Moreover, it has been observed: (i) an increase in the permanent deformations with the increment of the number of load cycles; (ii) the addition of fibres significantly increases the number of cycles and the magnitude of strain required to cause failure [10]; (iii) an increase in the unconfined compressive strength with the number of load cycles [11]. The effects on the strength depend on the binder content, the length/type of fibre and even the type of test used to evaluate the compressive and/or tensile strength [12]. This work studies the behaviour of a soft soil collected near to Coimbra, Portugal, and stabilized with Portland cement reinforced or not with synthetic fibres under cyclic loading. The laboratory work is focused on the influence of frequency of cyclic loading on the compressive behaviour evaluated by the following tests: i) monotonic unconfined compressive strength (UCS) tests; (ii) cyclic UCS (Cyc) tests performed for different frequencies (0.25, 0.5, 1, and 2 Hz); (iii) and monotonic unconfined compressive strength tests performed immediately after the cyclic loading stage (UCSpc).

2. Laboratory Tests

2.1 Materials

The soil was collected from countryside near to Coimbra, Portugal, in the banks of the Mondego river, and has been characterised by many researchers [13]. The soil deposit was formed more than 20,000 years ago in a fluvio-marine depositional environment and shows a thickness higher than 20 metres. For this study it was used a sample that was collected at a depth of 2.5 m. Tables 1 and 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 (80.9%) and a high organic matter content (9.3%).

Indeed, those results have a high influence in the mechanical behaviour, resulting in a low undrained shear strength (≈ 25 kPa) and in high compressibility [13]. This clayey-silt organic soil with high plasticity was classified by USCS as OH [14]. The

Table 1 Physical Properties of the soils [15].

Descriptions	Values
w_{nat} (%)	80.87
Gs	2.55
e_{nat}	2.03
γ (kN/m^3)	14.56
OM (%)	9.3
Grain size distribution	
Clay (%)	10
Silt (%)	71
Sand (%)	19
w_L (%)	71
w_P (%)	43
PI (%)	28
LI (%)	1.35
USCS (ASTM) D2487)	OH

Table 2 Chemical characterisation of the soils [15].

Descriptions	Values
pH (BS1377-3)	3.5
SiO2 (%)	62
Al2O3 (%)	16
Fe2O3 (%)	4.8
CaO (%)	0.74
MgO (%)	1.1
Na2O (%)	0.9
K2O (%)	3
TiO2 (%)	0.69
MnO (%)	< 0.3
P2O5 (%)	< 0.5
TOC (%)	2.79
CTC (emol+/kg)	11

chemical composition of the soil revealed a high silica (SiO_2 = 62%) and alumina contents (Al_2O_3 = 16%), conferring pozzolanic properties to the soil. The soft soil was stabilised with a Portland cement binder (Portland cement Type I 42.5 R, manufactured by CIMPOR), which main characteristics are presented in Table 3. The Portland cement reacts spontaneously with water producing a high quantity of reaction products in the short term; with time, the physic-chemical reactions develop at a lower rate, promoting the production of more cementitious products responsible for the enhancement of the mechanical properties of the stabilised material.

The synthetic fibres selected to reinforce the stabilised soil are polypropylene type (manufactured by BEKAERT) with a length of 12 mm, diameter of 32 μm, tensile strength of 250 N/mm^2 and an elasticity modulus of 3,500-3,900 N/mm^2 (Table 4).

Table 3 Chemical characterization of Portland cement (manufacturer data).

Descriptions	Values
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

* Manufacturer data

Table 4 Properties of Polypropylene fibres (manufacturer data).

Descriptions	Values
Length, L (mm)	12
Diameter, D (μm)	32
Aspect ratio (L/D)	375
Tensile strength (N/mm^2)	250
Elasticity modulus (N/mm^2)	3.5-3.9
Roughness	Lower
Biodegradability	Not
Density (g/cm^3)	0.905

2.2 Test Procedure

The samples used in all the tests were prepared with a binder quantity (dry weight of binder per cubic meter of soil) of 250 kg/m^3, and fibre quantity (weight of fibre per cubic meter of soil) of 10 kg/m^3. The soil was mechanically mixed (142 rpm, 4 min) with the fibres and a binder slurry which raises the water content to 115%. The homogeneous paste was compacted into a cylindrical PVC mould (37 mm in diameter and 76 mm in height) in three layers. Each layer was tapped 20 times against a rigid table followed by an adjustment of the top and tapped 10 times more, the surface of the layer was lightly scarified with care before the introduction of a new layer. The specimens were cured for 28 days in a temperature (20 ± 2 °C) and humidity (95 ± 5%) controlled room; after the curing time the specimens were placed on 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 automatically recorded. The UCS tests were carried out with a constant strain rate of 1%/min (BS 1377-7, 1990). The cyclic loading tests were carried out for a deviatoric stress level of 50% of $q_{u\text{-}max}$ of the reference value obtained in the monotonic UCS tests, a sinusoidal excitation of 0.25, 0.5, 1 and 2 Hz and amplitude of ±10% ($\pm 0.10 \times q_{u\text{-}max}$) up to 5,000 load cycles. After the cyclic stage, a monotonic UCS test was carried out. To guarantee the reliability of the procedure used the tests were repeated twice.

3. Test Results and Discussion

3.1 Monotonic Results

Fig. 1 shows the results of the monotonic unconfined compressive strength (UCS) tests done on the stabilised reinforced and unreinforced samples. As it can be seen, the unconfined compression strengths ($q_{u\ max}$) of both materials are of the same order but the material with fibres exhibits a ductile behaviour characterised with a peak strength at a higher strain (4.3%) and a high residual strength.

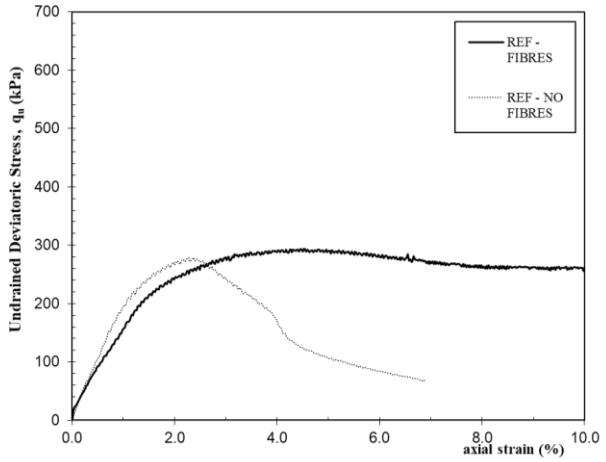

Fig. 1 Stress-strain behaviour for stabilised soils without and with fibres

3.2 Cyclic loading

As previously write, the cyclic loading stage was carried out for a deviatoric stress level of 50% of the reference values obtained in the monotonic UCS tests, i.e., ±300 kPa, Fig. 1. Maintaining that deviatoric stress level, a sinusoidal excitation of 0.25, 0.5, 1 and 2 Hz, with an amplitude of 10% of $q_{u\text{-}max}$ of references values, was imposed on the samples. Fig. 2 shows the evolution of the accumulated permanent axial strain with the number of load cycles for the frequencies studied and for the case of the unreinforced stabilized material. During the 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 all frequencies. It may be seen a clear reduction of the accumulated permanent axial strain with the increase of the frequency level: the strains for 5,000 cycles are around of 0.35 % for 0.25 Hz and 0.10% for 2 Hz.

When comparing the materials without fibres with the samples with fibres (Fig. 3), it is possible to observe a slight decrease in their permanent axial deformation. The results with fibres also confirm the decrease of the accumulated permanent axial deformations when the frequency level increases: the deformations for 5,000 cycles are around 0.20% for 0.25 Hz and 0.08% for 2 Hz.

In Figs. 2 and 3, it is clearly observed that with increasing frequency applied in the cyclic stage, there is a decrease in its plastic deformations, which can be interpreted as deterioration of the cemented matrix, suggesting that higher frequencies are associated with a more significant portion of elastic deformations. The addition of fibres to the stabilised material results in a progressive transfer of stresses to the fibres that contribute to less deterioration of the cemented matrix (i.e., a reduction of the accumulated permanent axial strain), effect more evident for higher frequencies.

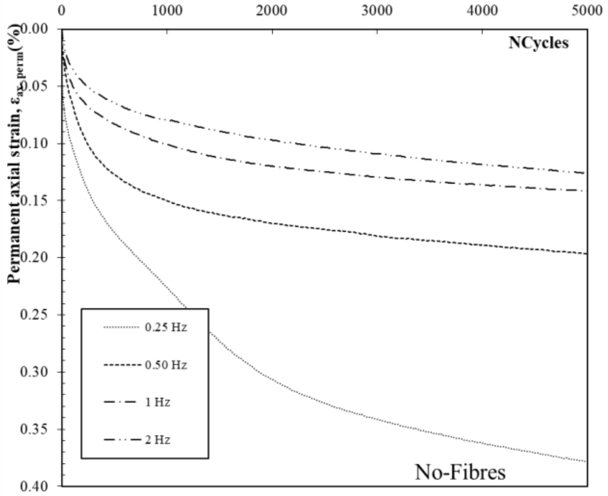

Fig. 2 Effect of the frequency on the accumulated permanent axial strain with the number of load cycles for the unreinforced stabilized material.

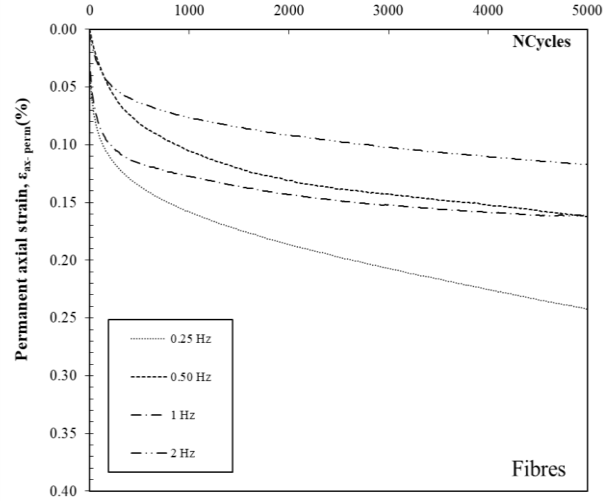

Fig. 3 Effect of the frequency on the accumulated permanent axial strain with the number of load cycles for the reinforced stabilized material.

3.3 Post Cyclic Behaviour

The post cyclic stage was carried out after cyclic loading. Fig. 4 shows the evolution of the stress-strain curves of the UCS tests performed after the cyclic stage for the unreinforced samples. Fig. 5 depicts the results of the behaviour of the samples with the addition of the fibres to the stabilised material, which changes the behaviour from brittle (unreinforced material), to more ductile (reinforced with PP).

The effect of the cyclic loading on the compressive mechanical behaviour of a stabilized material reinforced with fibres seems to be correlated with the plastic axial strain developed during the cyclic stage.

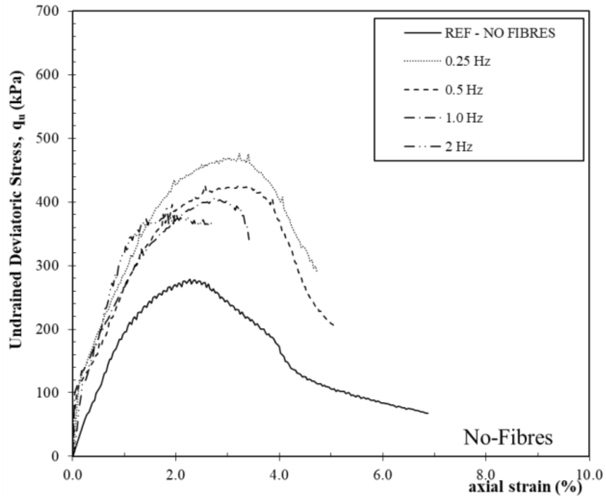

Fig. 4 Stress-strain behaviour for stabilised soils without fibres.

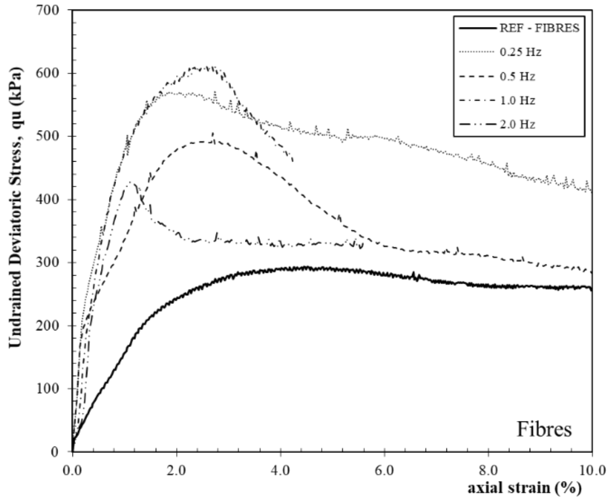

Fig. 5 Stress-strain behaviour for stabilised soils reinforced with fibres.

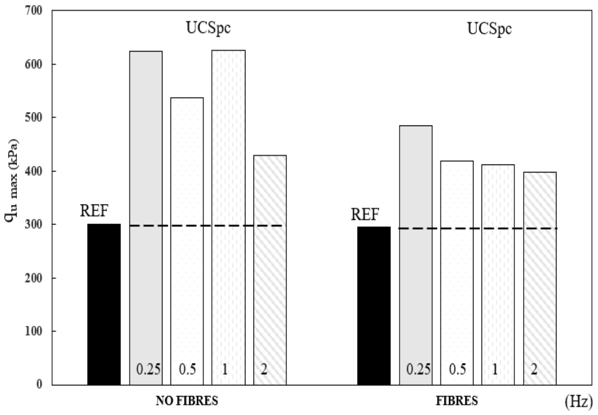

Fig. 6 Effect of the frequency on the unconfined compressive strength (q_u) evaluated through tests carried out after (UCSpc) the cyclic stage for stabilized soils reinforced and unreinforced with fibres.

In general, it is observed that subjecting the samples to cyclic loading induced an increase in mechanical strength and a slight modification of the behaviour from brittle to ductile, with residual strength. The frequency of cyclic loading on the unconfined compressive strength of the fibre-reinforced and unreinforced stabilised soil is shown in Fig. 6, which confirms a significant increase in the maximum strength after the application of the cyclic stage. This effect is more significant for lower frequencies and in the case of the stabilised soil without fibres compared to the reinforced soil with fibres.

4. Conclusions

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

In the case of monotonic behaviour before the cyclic stage, the inclusion of fibres induced a slight modification of the behaviour from a fragile to a ductile, exhibiting a residual strength.

During the 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 unreinforced and reinforced with fibres samples.

As the frequency applied on the cyclic stage increases the permanent axial strain decreases, which indicates a lower deterioration of the cemented matrix. This is explained by the fact that higher frequencies are associated with a more significant portion of elastic strain.

After the cyclic stage, the mechanical behaviour of the stabilised soil reinforced and unreinforced becomes stronger and stiffer than the reference values (monotonic tests). Thus, an increase in the maximum strength after the application of the cyclic stage is observed, which is more significant for lower frequencies and in the case of the stabilised soil without fibres compared to the reinforced soil with fibres.

Acknowledgements

The authors would like to express thanks to CIMPOR and to Biu International for supplying the binders and the fibres, 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 (UID/ECI/04029/2013), CONICYT PAI/INDUSTRIA 79090016; Universidad de Magallanes and ACIV.

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