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Effect of cyclic loading on the behaviour of fiber-reinforced stabilized soils

Effet du chargement cyclique sur le comportement des sols stabilisés et renforcés avec fibres

P.J. Venda Oliveira
ISISE, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal

J. C. A. Cajada, A. A. S. Correia*, L. J. L. Lemos, J. A. V. Ortega
Department of Civil Engineering, University of Coimbra, Coimbra, Portugal
**CIEPQPF, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal*

ABSTRACT: This work examines the effect of cyclic loading on the mechanical characteristics of three stabilised soils reinforced with polypropylene fibres, by comparing the results of unconfined compression strength tests carried out before and after the cyclic loading. The analysis is based on 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 (UCS_{pc}). The inclusion of fibres in the mixture induces a decrease in the permanent axial strain obtained in the cyclic stage. The experimental results also show that the cyclic stage induces an increase in the unconfined compressive strength and stiffness.

RÉSUMÉ: Cet travail examine l'effet du chargement cyclique sur les caractéristiques mécaniques des trois sols stabilisés et renforcés avec fibres de polypropylène, comparant les résultats des essais de résistance de compression simple réalisées avant et après le chargement cyclique. L'analyse est basée sur les suivants essais: *(i)* essais monotones de compression simple (UCS); *(ii)* essais UCS cycliques (Cyc) ; *(iii)* et des essais monotones de compression simple effectués après le chargement cyclique (UCS_{pc}). L'inclusion des fibres dans la mixture provoque la diminution de la déformation axiale permanente dans la phase cyclique. Les résultats expérimentaux montrent aussi que la phase cyclique induit une augmentation de la résistance en compression simple et de la rigidité.

Keywords: stabilised soil; reinforced soil; cyclic loading; polypropylene fibres; UCS test.

1 INTRODUCTION

The behaviour of stabilized soils reinforced with synthetic fibres under monotonic conditions has been studied by several authors (Sukontasukkul and Jamsawang, 2012; Correia et al., 2015; Consoli et al., 2011, Olgun, 2013; Venda Oliveira et al., 2015). Although, in general the results with the use of synthetic fibres show a decrease in brittleness and an increase in the post-peak strength of the soil-binder-water mixture, 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 (Correia et al., 2015; Venda Oliveira et al., 2015).

Considering that some structures are frequently subjected to cyclic loading (such as: earthquakes, wind, traffic loads, industrial machinery, waves on offshore structures and vibrations due to the use of explosives) it is important to know the effect of cyclic loading on their behaviour, namely when these structures are supported by artificially stabilized soils.

The few 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., 2017); *(ii)* the inclusion of fibres promotes a slight increase in the shear strength (evaluated by cyclic simple shear tests) mainly for higher cyclic strain levels (Festugato et al., 2013); *(iii)* indirect tensile cyclic load tests showed a significant increase in the tensile strength with the inclusion of the fibres in the mixture and this increase was more significant for higher fibre contents (Khattak and Alrashidi, 2006); *(iv)* the addition of fibres significantly increases the number of cycles and the magnitude of strain required to cause failure (Maher and Ho, 1993); *(v)* an increase in the unconfined compressive strength with the number of load cycles, which is more significant at the beginning of the cyclic stage followed by a progressive decrease in the strength rate (Venda Oliveira et al., 2017, 2018).

Considering the few works published about this theme, the aim of the present work is to complement this subject with a study of the effect of the cyclic loading on the behaviour of fibre-reinforced stabilised soils. Thus, this work examines the behaviour of three different fibre-reinforced stabilized soils after being subjected to cyclic loading, based on their compressive behaviour, which is obtained from 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 (UCS_{pc}). This study addresses the permanent axial strain developed during the cyclic stage and the influence of the cyclic loading on compressive strength and stiffness.

2 MATERIALS

Table 1 shows the characteristics of the three Portuguese soils (A, B and C) used in this work. The three soils are inorganic. Soils A and B are sandy soils with a decrease in the content of sand particles from 100% (soil A) to 65% (soil B); thus, soil A is classified as poorly graded sand (SP) whereas soil B is a silty sand (SM). Soil C presents a high content of clay/silt particles (56%) and is classified as a low plasticity silty soil (ML).

Table 1. Properties of the soils (based on Venda Oliveira et al., 2018)

Property	**Soil**		
	A	**B**	**C**
Grain size distribution:			
Clay (%)	0	13	4
Silt (%)	0	22	52
Sand (%)	100	65	44
Specific gravity, G	2.68	2.70	2.73
Dry unit weight (kN/m^3)	16.9	17.7	15.8
Plasticity index, PI (%)	NP(**)	NP(**)	NP(**)
Soil classification, USCS(*)	SP	SM	ML

(*) Unified Soil Classification System (ASTM D2487, 1998);
(**) Non plastic;

The binder used to stabilize the three soils is Portland cement Type I 42.5 R (EN 197-1, 2000), which is composed by 45% of cement particles smaller than 45μm and shows a high content of calcium oxide (CaO = 63.0%), which promotes the spontaneous reaction with water. The polypropylene (Pp) fibres used to reinforced the water-binder-soil mixture have a length of 12 mm, diameter of 32μm, tensile strength of 250 N/mm^2 and an elasticity modulus of 3500-3900 N/mm^2.

3 SPECIMEN PREPARATION

The samples used in all the tests were prepared with a binder quantity (dry weight of binder per cubic meter of soil) of 175 kg/m^3, a fiber quantity (weight of fiber per cubic meter of soil) of 10 kg/m^3 (cement-fiber ratio of 17.5), and a water-binder ratio of 5.3.

To reduce the heterogeneity and variability of the soils used in the experiments, these were previously homogenised and prepared based on the procedures defined by EuroSoilStab (2001) and Correia (2011). Thus, the methodology employed involved the following steps (Venda Oliveira et al., 2018): *(i)* the cement, the water and the polypropylene fibers were mixed with the soils (using a mechanical mixer at a speed of 142 rpm for 4 min) producing a slurry; *(ii)* the homogeneous paste was compacted into a cylindrical PVC mold (70 mm in diameter and 140 mm in height) in three layers; *(iii)* each layer was submitted to the following steps: tapped 10 times against the floor, a circular wooden disc was pressed down on the top layer, application of a steel bar near the inner surface of the mold, new adjustment of the top of the layer, and new tapping (10 times), the surface of the layer was lightly scarified before the introduction of a new layer; *(iv)* the specimens were cured for 28 days inside a room with a controlled temperature (20±2ºC) and humidity (95±5%); *(v)* after the curing time the specimens were placed on a universal testing machine (for the UCS tests) or cyclic loading equipment and the electronic devices (load cell and strain gauge transducer) were set up and adjusted; *(vi)* finally, the tests were performed and the data were automatically recorded.

The UCS tests were carried out with a constant strain rate of 0.25%/min (BS 1377-7, 1990).

The cyclic loading tests were carried out with a dynamic load frame for a deviatoric stress level of 55% ($q_u = 0.55 \times q_{u\text{-}max}$), a sinusoidal excitation of 0.25 Hz and an amplitude of ±7.5% ($\Delta q_u = \pm 0.075 \times q_{u\text{-}max}$) up to 3000 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.

4 RESULTS AND DISCUSSION

4.1 Cyclic behaviour

The comparison of the accumulated permanent axial strain during the cyclic stage obtained for the unreinforced and reinforced (F= 10 kg/m^3) stabilized soils is illustrated in Figure 1. The behaviour observed is in line with that observed in other works (Dall'Aqua et al., 2010; Venda Oliveira et al., 2017, 2018), which is described by 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.

For the three soils tested, the results show that the inclusion of the fibres decreases the $\varepsilon_{ax\text{-}perm}$, mainly for a number of load cycles higher than 300-500 cycles. The results suggest that the strain level imposed by a high number of cycles is enough to mobilize the tensile strength of the fibres, which support part of the load applied, therefore the expected damage of the matrix of the soil is reduced.

Soil C, when compared with soils A and B, shows a higher $\varepsilon_{ax\text{-}perm}$, probably due to the detrimental effect of the increase of the clay/silt fraction, which induces a weaker cementation matrix (see Figure 2c) and a less effective anchorage of the fibres.

4.2 Mechanical behaviour

The effect of the cyclic loading on the stress-strain behaviour of the three fibre-reinforced stabilized soils is shown in Figure 2. Independently of whether the specimens were subjected or not to cyclic loading, the reinforced soils studied show a ductile behaviour, with a reduced loss of strength after the peak. This behaviour is linked 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. These results agree with other works (Correia et al., 2015; Venda Oliveira et al., 2015; Olgun, 2013).

Analysing the stabilized soils A to C, it may be seen that the increase in the silt/clay fraction induces a decrease in the peak strength and a tendency for the loss of strength to decrease after the peak (see from soil A to soil B)

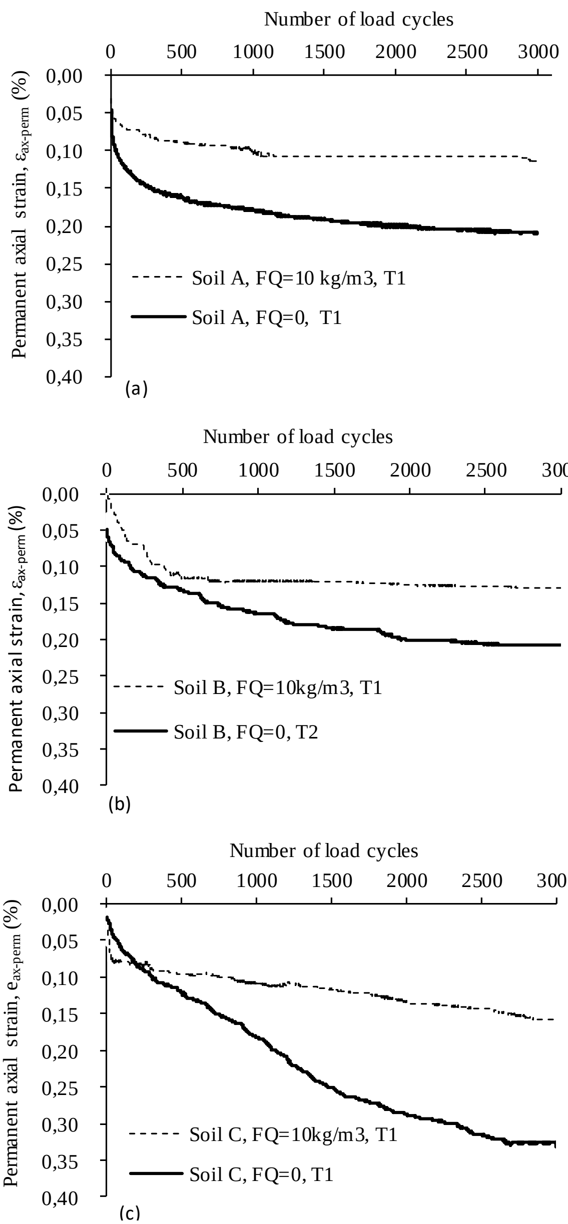

Figure 1. Accumulated permanent axial strain during the cyclic loading: a) Soil A; b) Soil B; c) Soil C.

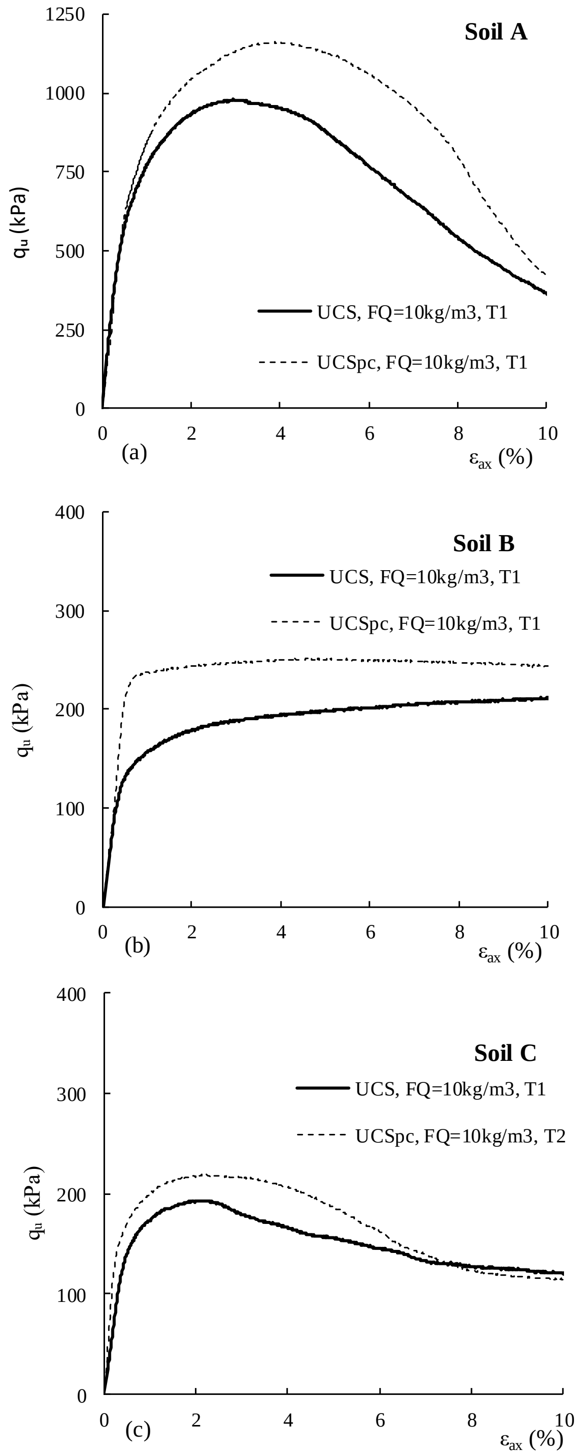

Figure 2. Stress-strain curves of the UCS tests carried out before (UCS) and after (UCS_{pc}) the cyclic loading: a) Soil A; b) Soil B; c) Soil C.

Figure 3 highlights the effect of the cyclic stage on the peak unconfined compressive strength (q_u), and Young's modulus evaluated at 50% of the peak compressive strength (E_{u50}). Figures 2 and 3 show that the specimens previously subjected to a cyclic stage display an improvement in the mechanical properties (q_u and E_{u50}) in comparison with the specimens not subjected to cyclic loading. The results also show that this effect is more significant for E_{u50} than q_u: the increase of q_u is between 15-17% while the increase of E_{u50} changes from 28% (soil A) to 91% (soil C).

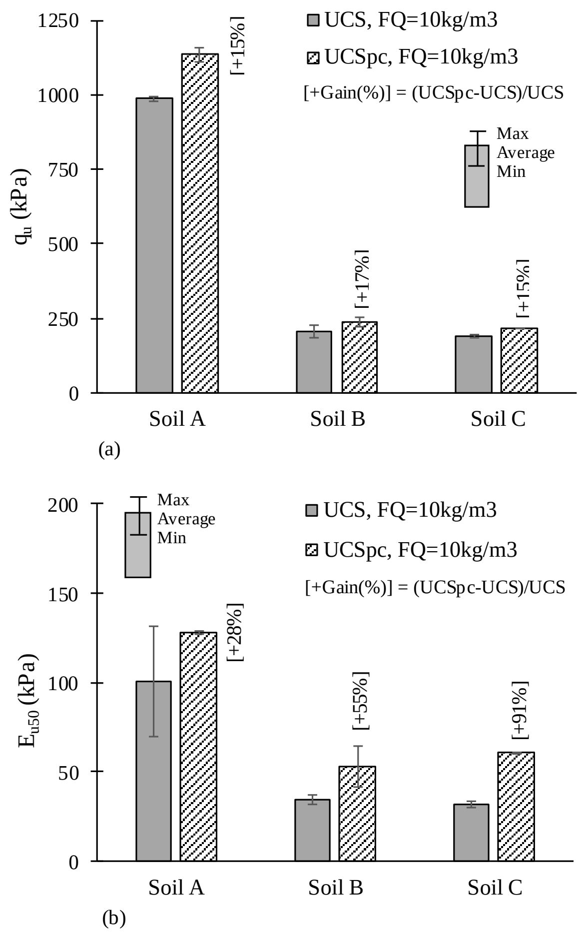

Figure 3. Results of the UCS tests carried out before (UCS) and after (UCS_{pc}) the cyclic loading: a) Effect on the peak compressive strength; b) Effect on Young's modulus.

Although these results are in line with other works (Festugato et al., 2013; Khattak and Alrashidi, 2006; Venda Oliveira et al., 2017), they do not reflect the expected breakage of the cementation bonds during the cyclic stage, and the consequent deterioration of the mechanical properties. In fact, these results seem to indicate that the beneficial effect due to the partial mobilization of the tensile strength of the fibres during the cyclic stage is sufficient to compensates the detrimental effect induced by the destruction of the soil-binder-water matrix during this stage, consequently, the cyclic loading promotes the increases in q_u and E_{u50}.

5 CONCLUSIONS

Considering the results of the monotonic UCS tests performed with and without a cyclic loading stage on three fibre-reinforced stabilized soils, the following conclusions are drawn:

i) The evolution of the permanent cumulative axial strain during the cyclic stage shows a sharp increase at the beginning of the cyclic stage followed by a decrease in the strain rate.

ii) The fibre-reinforcement has a beneficial effect on the cyclic behaviour, inducing a decrease in the permanent cumulative axial strains in relation to unreinforced soil.

iii) The increase of the silt/clay fraction induces higher permanent cumulative axial strains during the cyclic stage and a weaker cementation matrix.

iv) The cyclic stage induces an increase in the mechanical characteristics (more significant for the stiffness than strength) of the composite material. Indeed, the deterioration of the solid skeleton that occurs during the cyclic stage is partially compensated for by the mobilization of the tensile strength of the fibres.

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