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Effect of the type of soil on the cyclic behaviour of chemically stabilised soils unreinforced and reinforced with polypropylene fibres

Paulo J. Venda Oliveira[a,*], António A.S. Correia[b], João C.A. Cajada[c]

[a] ISISE, Department of Civil Engineering, University of Coimbra, R. Luís Reis Santos, 3030-788 Coimbra, Portugal
[b] CIEPQPF, Department of Civil Engineering, University of Coimbra, R. Luís Reis Santos, 3030-788 Coimbra, Portugal
[c] Department of Civil Engineering, University of Coimbra, R. Luís Reis Santos, 3030-788 Coimbra, Portugal

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ABSTRACT

This work examines the effect of cyclic loading on the behaviour of five different soils chemically stabilized with Portland cement that were both non-reinforced and reinforced with polypropylene fibres. The inclusion of fibres in the composite material has a positive effect on the cyclic behaviour, decreasing the accumulated permanent axial strain, while the increase in the amount of clay/silt particles and the organic matter content has a detrimental effect. The effect of the cyclic stage on the mechanical characteristics is evaluated comparing the results of unconfined compression strength tests carried out without and after the cyclic loading. The experimental results show that the cyclic stage induces an increase in the unconfined compressive strength and stiffness and this effect is greater for the unreinforced stabilized soils. The inclusion of fibres in the stabilized soil tends to increase the strength for materials with a low level of stabilization, having the opposite effect for stiffer materials.

1. Introduction

During the last few years several studies have been carried out concerning the inclusion of short synthetic and steel fibres [1–17] in soil-binder-water mixtures to improve the mechanical characteristics of stabilized soils, mainly to increase the ductility and to confer some tensile and flexural strength. In general the works published about this issue, based on the results of monotonic tests, show that the use of short fibres promotes a decrease in the brittleness and increases the post peak strength of the composite materials. In terms of the effects of the fibre-reinforcement on the strength, the results are not totally convergent, since they seem to depend on the type of fibre, the binder content and even the type of test used to evaluate the compressive and/or tensile strength [1–3].

The works published about the cyclic behaviour of soils chemically stabilized with cement but without the use of fibres, although few in number, demonstrate an increase in the accumulated permanent deformations [18–20] and decreases in the stiffness [21,22] and the yield stress [21], as a consequence of the progressive breakage of the cemented matrix structure with the increase in the number of loading cycles.

The study of the cyclic behaviour of fibre-reinforced stabilized soils has been practically neglected by the scientific community. This lack of scientific knowledge restricts the use of these materials in contexts where they are subjected to cyclic actions, such as wind, earthquakes, traffic loads, heavy machinery, sea waves on offshore structures and even vibrations due to the use of explosives. The few works concerning the cyclic behaviour of fibre-reinforced stabilized soils [18,23–27] publish results that are not entirely convergent. Thus, in terms of permanent deformations the generality of the cyclic tests, regardless of the type, showed their increase with the increment of the number of load cycles [18,24,26], while, in a distinctly different way: the results obtained in Nottingham asphalt tests and in cyclic UCS tests [26] show a sharp increase at the beginning of the cyclic stage followed by a plateau [24], while the results of cyclic triaxial tests [18] present (in log scale) a behaviour described by a slight increase at the beginning of the cyclic stage followed by a sharp increase for a higher number of load cycles. In terms of strength, the results of water-binder-soil mixtures reinforced with polypropylene fibres subjected to cyclic simple shear tests [23] and indirect tensile cyclic load tests [25] are in line with each other; thus, in the former, the inclusion of fibres promotes a slight increase in the shear strength mainly for higher cyclic strain levels [23], while the results of the second test 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 [25]. The results of the cyclic axial compression tests carried out with a fibre-reinforced

* Corresponding author.
E-mail addresses: pjvo@dec.uc.pt (P.J. Venda Oliveira), aalberto@dec.uc.pt (A.A.S. Correia).

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Notation

FQ	fibre quantity (kg/m^3);
a_w	binder content (%) [weight ratio of dry binder to dry soil];
BQ	binder quantity (kg/m^3) [dry weight of binder per cubic metre of soil];
Cyc	cyclic stage;
E_{u50}	secant Young's modulus for 0.5qu (Pa);
f	water content (%)
FQ	fibre quantity (kg/m^3) [weight of fibres per cubic metre of soil];
f_w	fibre content (%) [weight ratio of fibres to dry soil];
H_0	length initial of the specimen;
I_B	brittleness index;
OM	organic matter content (%);
PI	plasticity index (%);
Pp	polypropylene fibre.
q_u	maximum unconfined compressive strength (Pa);
UCS	unconfined compressive strength test;
UCSpc	post-cyclic unconfined compressive strength test;
w_L	Atterberg liquid limit (%);
w_P	Atterberg plastic limit (%);
$\Delta H_{cyc\text{-}perm}$	permanent variation of the length of the specimen during the cyclic phase;
ε_{ax}	axial strain (%);
$\varepsilon_{ax\text{-}failure}$	axial strain at failure (%);
$\varepsilon_{ax\text{-}perm}$	permanent cumulative axial strain (%);

stabilized soil confirm this type of behaviour: Venda Oliveira et al. [26] observed an increase in the unconfined 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 [26], whereas the results Maher and Ho [27] obtained were that the addition of fibres significantly increases the number of cycles and the magnitude of strain required to cause failure.

Considering the limited scientific knowledge about this theme and some contradictory results, it is very pertinent to complement this subject with the study of the effect of the cyclic loading on the behaviour of stabilised soils, both unreinforced and reinforced with polypropylene fibres, which is the main novelty of this research. This work contributes for a possible practical application of these types of composite materials on foundation of structures subjected to different types of cyclic loading (vibrations induced by traffic loads, industrial machines, earthquakes, wind loads and sea waves). This work examines the behaviour of five different 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 (UCSpc). This study addresses the effect of the soil type and the fibre-reinforcement on the accumulated axial strain developed during the cyclic stage and, additionally, the influence of the cyclic loading on compressive strength, stiffness and brittleness index. Table 1 presents the testing programme carried out in this work.

2. Description of the experimental work

2.1. Characteristics of the soils studied

The main characteristics of the five soils (A, B, C, D and E) studied in this work are shown in Table 2. Soils A, C and E are natural Portuguese soils from Coimbra area, while soils B and D were produced artificially. Thus, soil B was obtained by mixing soils A and C, while soil D was produced by mixing soil C with soil E after a treatment to destroy the majority of the organic matter (loss on ignition at 400 °C).

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). Soils C, D and E are soils with a high content of clay/silt particles, 56% for soil C, 64% for soil D and 73% for soil E; additionally soil E displays a high organic matter (OM) content of 10.3%. These characteristics affect the plasticity of these soils, consequently soil C is non-plastic, soil D shows low plasticity (PI = 2%; wL = 44.0%; wP = 42.0%) and both are classified as a low plasticity silty soil (ML); while soil E presents high plasticity characteristics (PI = 23.2%; wL = 72.0%; wP = 48.8%) and is classified as a high plasticity organic soil (OH).

2.2. Characteristics of the binders and fibres

The five soils used in this study were chemically stabilised with Portland cement Type I 42.5 R [29], which is composed by particles with a specific gravity of 3.18 and a grain size distribution with 45% of cement particles smaller than 45 μm. The chemical composition of the cement shows a main content of calcium oxide (CaO = 63.0%, SiO_2 = 19.7%, Al_2O_3 = 5.2%), which confers hydraulic properties, promoting spontaneous reaction with water.

The polypropylene (Pp) fibres used in this work have a length of 12 mm and a diameter of 32 μm. According to the manufacturer's data, the fibres present a great flexibility, high specific surface (110 m^2/kg), density of 905 kg/m^3, tensile strength of 250 N/mm^2 and an elasticity modulus of 3500–3900 N/mm^2.

2.3. Specimen preparation and testing

In order to compare the results and evaluate the influence of the soil type and the reinforcement with polypropylene fibres accurately, all tests were carried out using a binder quantity (dry weight of binder per cubic metre of soil) of 175 kg/m^3, a quantity of water correspondent to a water-binder ratio of 5.3 and a fibre quantity (weight of fibre per cubic metre of soil) of 0 (non-reinforced specimens) and 10 kg/m^3 (reinforced specimens), which corresponds, in the latter case, to a cement-fibre ratio of 17.5. These parameters were established considering the results of previous studies [1–3].

The soils used were homogenised previously in order to mitigate the heterogeneity and variability usually seen in natural soils. The samples of the stabilized soils with or without the inclusion of fibres were prepared based on the procedures defined by EuroSoilStab [30] and Correia [31]. Thus, the procedure employed comprises the following steps:

(i) The required quantity of cement was mixed with the different types of soils for a specific quantity of distilled water producing a slurry.
(ii) In the case of the reinforced specimens, the slurry and the

Table 1
Testing program. Number of tests (UCS, Cyc, UCSpc) carried out.

Type of test	Soil									
	A		B		C		D		E	
	UR	R	UR	R	UR	R	UR	R	UR	R
UCS without cyclic stage - UCS	2	2	2	2	2	2	2	2	2	2
Cyclic stage - Cyc	2	2	2	2	2	2	2	2	2	2
UCS after cyclic stage - UCSpc	2	2	2	2	2	2	2	2	2	2

UR: Unreinforced stabilized soil; R: Stabilized soil reinforced with 10 kg/m^3 of polypropylene fibres.

Table 2
Main characteristics of the soils (based on Cajada [33]).

Property	Soil				
	A	B	C	D	E
Grain size distribution:					
Clay (%)	0	13	4	6	16
Silt (%)	0	22	52	58	57
Sand (%)	100	65	44	36	27
Specific gravity, G	2.68	2.70	2.73	2.77	2.60
Dry unit weight (kN/m^3)	16.9	17.7	15.8	9.9	8.1
Liquid limit, w_L (%)	NP[b]	NP[b]	NP[b]	44.0	72,0
Plastic limit, w_P (%)	NP[b]	NP[b]	NP[b]	42.0	48.8
Plasticity index, PI (%)	NP[b]	NP[b]	NP[b]	2.0	23.2
Organic matter content, OM (%)	0	0	0	2.1	10.3
Soil classification, USCS[a] [28]	SP	SM	ML	ML	OH

[a] Unified Soil Classification System.
[b] Non plastic.

required quantity of polypropylene fibres were mixed thoroughly using a mechanical mixer at a speed of 142 rpm for 4 min

(iii) The resulting homogeneous paste was introduced and compacted directly into a cylindrical PVC mould (70 mm in diameter and 140 mm in height) in three layers.
(iv) Each layer was subjected to the following moulding procedure: (1) the mould was tapped 10 times against the floor, (2) a circular wooden disc was pressed down on the top layer, (3) followed by the application of a steel bar near the inner surface of the mould, (4) new adjustment of the top of the layer, (5) and new tapping (10 times).
(v) The surface of each layer of the mixture was then lightly scarified before the introduction of a new layer.
(vi) The specimens were cured for 28 days inside a room with a temperature control of 20 ± 2 °C and humidity (95 ± 5%) controlled.
(vii) After the curing period the specimens were placed on the pedestal of a universal UCS or cyclic loading equipment and the electronic devices (load cell and strain gauge transducer) were set up and adjusted.
(viii) Finally, the tests were performed and the data were recorded using an automatic data acquisition system.

The UCS tests were carried out with a universal testing machine (Wykeham Farrance Tristar 5000 kg), without cyclic loading, in order to define the mechanical characteristics under monotonic conditions [32]. The cyclic loading tests were carried out with a dynamic load frame (Servosis ME-402/20), for a deviatoric stress level of 55% [33] of the failure value (q_{u-max}), which was defined in the monotonic UCS tests. Maintaining the deviatoric stress level, a sinusoidal excitation of 0.25 Hz with an amplitude (q_{max}-q_{min}) of ± 7.5% of q_{u-max} up to 3000 load cycles was imposed on the specimens. A safety factor of at least 1.6 (q_u / [(0.55 + 0.075) × q_u]) for the stabilized soils was assured during the cyclic loading tests with these conditions. After the cyclic stage, a monotonic UCS test was carried out in order to analyse the repercussions of the cyclic stage on the mechanical properties of the specimens studied. All the UCS tests were performed by imposing a constant strain rate of 0.25%/min in accordance with BS 1377-7 [32]. All tests were repeated at least twice in order to assure the reliability of the methodology.

3. Results and discussion

A summary of the main results obtained from the three sets of tests (UCS, Cyc and UCSpc) is presented in Tables 3 and 4 for the unreinforced and fibre-reinforced stabilized soils, respectively. As expected, the results show some disparity between the results of the two specimens tested for the same conditions, which reflects a slight heterogeneity induced mainly by the difficulty in spreading the fibres in a homogeneous manner. However, in the generality of the cases the differences between the maximum/minimum and the average value are not significant and are in line with other experimental results obtained with similar materials [1–3].

Table 3
Summary of the tests and main results for the stabilized soils without fibres (based on Cajada [33]).

Test	Property	Soil									
		A		B		C		D		E	
		T1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
	Binder quantity, BQ (kg/m^3)	175		175		175		175		175	
	Binder content, a_w (%)	10.2		9.7		10.8		17.4		21.3	
	Water-binder ratio	5.3		5.3		5.3		5.3		5.3	
	Initial water content, w_i (%)	53.9		51.5		57.4		92.3		113.0	
UCS without cyclic stage	Unconfined comp. strength, q_u (kPa)	891.2	904.2	170.5	172.0	163.9	133.1	1309.2	1446.6	323.4	325.5
		[897.7]		*[171.3]*		*[148.5]*		*[1377.9]*		*[324.4]*	
	Axial strain at failure, $\varepsilon_{ax\text{-}failure}$ (%)	0.73	0.73	0.92	0.97	2.36	1.99	0.81	0.83	2.27	3.17
		[0.73]		*[0.94]*		*[2.18]*		*[0.82]*		*[2.72]*	
	Young's modulus for $0.5q_u$, E_{u50} (MPa)	130.9	169.1	38.9	29.9	23.8	23.9	203.5	234.4	39.9	38.1
		[150.0]		*[34.4]*		*[23.9]*		*[218.9]*		*[39.0]*	
	Final water content,w_f (%)	12.2	12.7	37.4	36.6	43.4	41.6	73.8	73.3	85.7	86.2
		[12.5]		*[37.0]*		*[42.5]*		*[73.5]*		*[85.9]*	
Cyclic stage	Permanent cumulative axial strain for 3000 cycles, $\varepsilon_{ax\text{-}perm}$ (%)	0.11	0.22	0.23	0.21	0.34	0.18	0.10	0.11	0.62	0.65
		[0.17]		*[0.22]*		*[0.26]*		*[0.10]*		*[0.64]*	
UCS after cyclic stage	Unconfined comp. strength, q_u (kPa)	1426,6	1203.6	268.1	271.5	188.6	249.8	1610.4	1646.8	416.0	384.8
		[1315.1]		*[269.8]*		*[219.2]*		*[1628.6]*		*[400.4]*	
	Axial strain at failure, $\varepsilon_{ax\text{-}failure}$ (%)	0.76	0.78	1.63	1.50	2.73	2.28	1.32	1.56	3.27	2.24
		[0.77]		*[1.57]*		*[2.50]*		*[1.44]*		*[2.76]*	
	Young's modulus for 0.5qu, E_{u50} (MPa)	263.4	188.7	99.1	101.8	54.8	43.4	310.8	268.6	97.0	81.5
		[226.1]		*[100.5]*		*[49.1]*		*[289.7]*		*[89.2]*	
	Final water content, w_f (%)	9.0	12.1	34.3	34.3	41.3	41.8	69.2	68.6	82.7	82.5
		[10.5]		*[34.3]*		*[41.6]*		*[68.9]*		*[82.6]*	

[…] – Average value; T_i – Test number i.

Table 4
Summary of the tests and main results for the stabilized soils and reinforced with fibres (based on Cajada [33]).

Test	Property	Soil A T1	Soil A T_2	Soil B T_1	Soil B T_2	Soil C T_1	Soil C T_2	Soil D T_1	Soil D T_2	Soil E T_1	Soil E T_2
	Binder quantity, BQ (kg/m^3)	175		175		175		175		175	
	Binder content, a_w (%)	10.2		9.7		10.8		17.4		21.3	
	Water-binder ratio	5.3		5.3		5.3		5.3		5.3	
	Initial water content, w_i (%)	53.9		51.5		57.4		92.3		53.9	
	Fibre quantity, FQ (kg/m^3)	10		10		10		10		10	
	Fibre content, f_w (%)	0.58		0.56		0.62		1.00		1.22	
UCS without cyclic stage	Unconfined comp. strength, q_u (kPa)	978.6 *[987.2]*	995.8	218.5 *[203.0]*	187.4	193.2 *[189.9]*	186.6	1359.6 *[1324.5]*	1289.4	414.9 *[404.7]*	394.5
	Axial strain at failure, $\varepsilon_{ax\text{-}failure}$ (%)	2.95 *[3.69]*	4.43	12.3 *[8.25]*	4.18	1.99 *[2.37]*	2.75	0.88 *[0.83]*	0.78	5.21 *[5.00]*	4.78
	Young's modulus for $0.5q_u$, E_{u50} (MPa)	131.4 *[100.4]*	69.4	31.6 *[34.3]*	37.0	33.6 *[31.7]*	29.8	195.6 *[223.7]*	251.8	45.6 *[44.7]*	43.8
	Final water content, w_f (%)	14.1 *[15.2]*	16.2	37.5 *[37.4]*	37.3	44.4 *[44.7]*	45.0	70.6 *[70.1]*	69.7	82.8 *[82.2]*	81.7
Cyclic stage	Permanent cumulative axial strain, $\varepsilon_{ax\text{-}perm}$ (%)	0.11 *[0.13]*	0.14	0.14 *[0.11]*	0.09	0.16 *[0.15]*	0.14	0.07 *[0.09]*	0.11	0.66 *[0.57]*	0.48
UCS after cyclic stage	Unconfined comp. strength, q_u (kPa)	1160.4 *[1135.4]*	1110.4	251.5 *[237.1]*	222.6	217.1 *[218.0]*	218.8	1381.8 *[1340.2]*	1298.6	442.9 *[462.4]*	481.9
	Axial strain at failure, $\varepsilon_{ax\text{-}failure}$ (%)	3.88 *[4.16]*	4.44	4.84 *[6.99]*	9.13	2.14 *[2.13]*	2.12	0.73 *[0.82]*	0.88	3.60 *[3.33]*	3.06
	Young's modulus for 0.5qu, E_{u50} (MPa)	127.4 *[128.0]*	128.6	41.3 *[53.0]*	64.7	59.9 *[60.4]*	60.8	364.5 *[317.6]*	270.7	90.3 *[89.7]*	89.0
	Final water content, w_f (%)	13.7 *[13.9]*	14.0	33.4 *[34.0]*	34.6	45.1 *[44.4]*	43.7	68.4 *[67.4]*	66.4	78.2 *[78.7]*	79.3

[…] – Average value; T_i – Test number i.

3.1. Cyclic behaviour

Fig. 1 depicts the evolution of the accumulated permanent axial strain ($\varepsilon_{ax\text{-}perm} = \Delta H_{cyc\text{-}perm}/H_0$) with the number of load cycles for the five soils unreinforced and reinforced with a fibre content of 10 kg/m^3. 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 in the number of load cycles; this behaviour agrees with that observed in other works [24,26].

Regardless of the soil type, the results show a positive effect for the inclusion of the fibres in the water-binder-soil mixture, inducing a decrease in the $\varepsilon_{ax\text{-}perm}$ with a greater impact for a high number of load cycles (higher than 1000 cycles). Indeed, for a higher number of load cycles, the level of strain imposed is enough to mobilize the tensile strength of the fibres, consequently the cyclic load applied is partially supported by the fibres, mitigating the expected destructuration of the matrix of the stabilised soil. Curiously, the two more deformable soils (C and E) show, at the beginning of the cyclic stage, a slightly negative impact of the inclusion of the fibres, i.e., in these soils, for a low number of cycle loads, the loss of cementation bonds due to the presence of the fibres is not yet compensated for by the mobilization of the tensile strength of the fibres in consequence of the reduced strain level imposed. For the soils with a stronger cementation matrix (soils A, B and D) the mobilization of the tensile strength of the fibres tends to be earlier, probably in consequence of a more effective anchorage of the fibres.

Comparing the cyclic behaviour of the three sandy soils (A, B and C), soil C exhibits the most significant increase of the $\varepsilon_{ax\text{-}perm}$ (Fig. 1c), which reflects the higher content of clay/silt particles. The results of soils D and E clearly illustrate the detrimental effect of the organic matter content (associated with high plasticity), inducing much higher permanent axial deformations in soil E (OM = 10.3%), than in soil D (OM = 2.1%).

The effect of the previously analysed cyclic stage is highlighted in Fig. 2 and Tables 3 and 4, where the $\varepsilon_{ax\text{-}perm}$ for 3000 load cycles obtained for the five soils with and without fibres are compared. Although with some scattering, the results seems to indicate a beneficial effect of fibre-reinforcement (soils A to E) in terms of the decreasing of $\varepsilon_{ax\text{-}perm}$ and the detrimental effect of the increase in the amount of clay/silt particles (from soil A to C) and the organic matter content (from soil D to E).

3.2. Stress-strain behaviour

The effect of the fibre-reinforcement on the stress-strain behaviour is illustrated in Fig. 3 for the five soils studied. For all soils, and independently of whether the specimens were subjected or not to cyclic loading, the results clearly show that the inclusion of a fibre quantity (FQ) of 10 kg/m^3 induces a change in the behaviour of the composite material, from a brittle (unreinforced stabilized soils) to a ductile behaviour (fibre-reinforced stabilized soils). Thus, with the inclusion of fibres, mainly due to the mobilization of the tensile strength of the fibres for higher strain levels, the total strain at failure tends to occur for higher strain levels (Tables 3 and 4) and the loss of strength after the peak decreases significantly, i.e., there is a mobilization of a significant residual strength. These results are in agreement with other results published in the literature [1,2,12].

Analysing the stabilized soils A to C (without fibres), it is seen that the total strain at failure increases with the silt/clay fraction of the soil. This tendency is also observed from soil D to soil E, but in this case the cause is fundamentally due to the increase in the organic matter content, associated with the increase in the plasticity index.

In general, Fig. 3 also reveals that the cyclic stage improves the mechanical characteristics of the stabilized soils, inducing an increase in the peak strength and stiffness. These results do not reflect the expected breakage of the cementation bonds induced by the cyclic loading

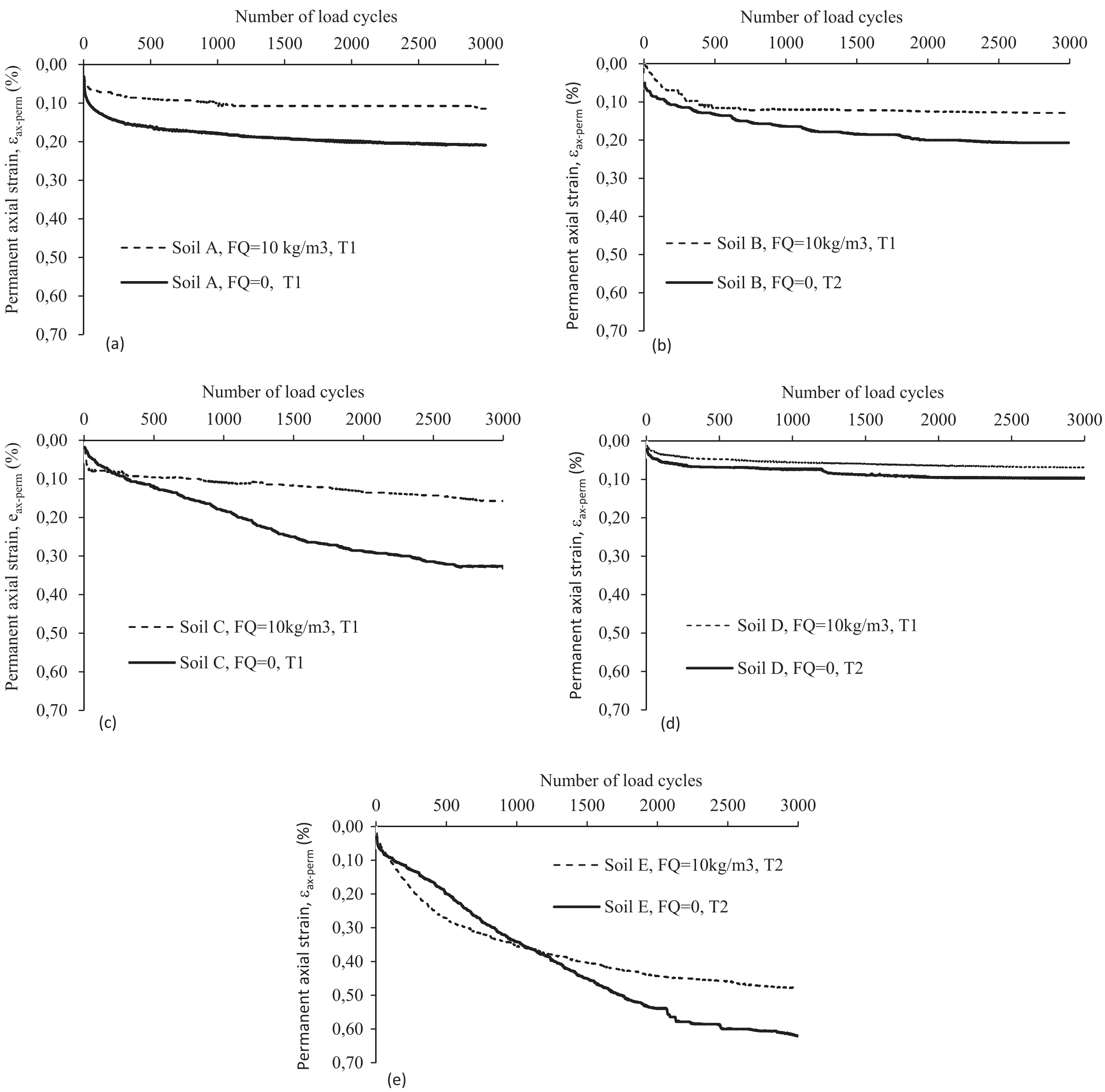

Fig. 1. Effect of soil type and reinforcement with Pp fibres on the accumulated permanent axial strain with the number of load cycles. a) Soil A; b) Soil B; c) Soil C; d) Soil D; e) Soil E.

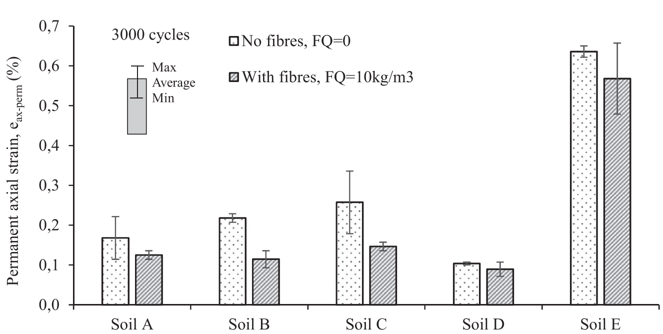

Fig. 2. Effect of soil type on the accumulated permanent axial strain for 3000 load cycles.

with the consequent deterioration of the mechanical properties.

The brittleness/ductility of the composite material is examined additionally through the brittleness index (I_B), defined by Eq. (1) [2]:

$$I_B = 1 - \frac{q_{(\varepsilon/\varepsilon_f=2)}}{q_u} \tag{1}$$

where q_u and $q_{(\varepsilon/\varepsilon f\ =2)}$ are the compressive failure strength and the compressive strength for a strain double of the strain at failure (ε_f), respectively. A brittle behaviour with a total loss of strength after the peak failure corresponds to an I_B equal to one and a lower value of I_B means a more ductile material. Fig. 4 depicts the I_B of the various soils tested without and after the cyclic stage, with and without the inclusion of the fibres. Notwithstanding some scatter, the values of the I_B are in agreement with the analysis performed in term of stress-strain behaviour, namely the ductility increases (I_B decreases) with the inclusion of the fibres. The effect of the cycling stage on the I_B changes with the type of soil; thus, in the coarser soils (A and B) the cyclic stage increases the value of I_B slightly (the brittleness increases), while the increase in OM (soils D and E) promotes a slight decrease in the value of I_B (i.e., the ductility increases).

3.3. Mechanical characteristics

Figs. 5 and 6 emphasize the repercussions of the cyclic stage and the fibre-reinforcement on the mechanical characteristics in terms of the peak unconfined compressive strength (q_u), and Young's modulus evaluated at 50% of the peak compressive strength (E_{u50}), respectively.

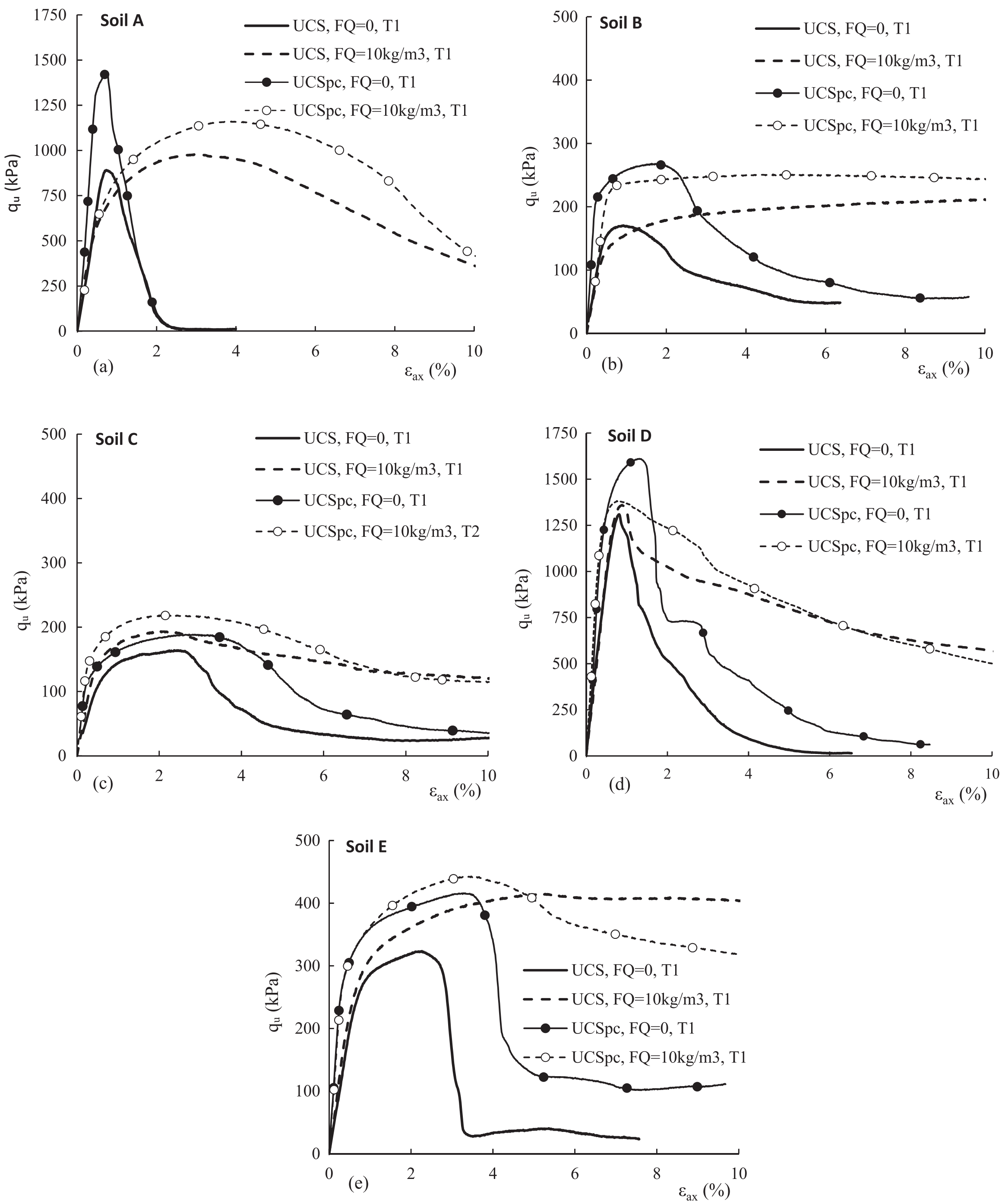

Fig. 3. Effect of soil type and reinforcement with Pp fibres on the stress-strain curves of the UCS tests carried out before (UCS) and after the cyclic stage (UCSpc). a) Soil A; b) Soil B; c) Soil C; d) Soil D; e) Soil E.

The results of the specimens not subjected to cyclic loading show that the inclusion of 10 kg/m^3 of polypropylene fibres in soils A, B, C and E promotes a slight increases of q_u, which corroborates the results of other works performed with low fibre and binder content [12,14,16,17]. On the other hand, the behaviour of soil D, which exhibits the highest level of cementation, differs from the remaining soils and is in line with the results of other authors obtained with high binder and fibre contents [1,2]. In terms of the E_{u50} (with the exception of soil A) the effect of the fibre-reinforcement is negligible, which agrees with other experimental results for low binder content [1]. These results seem to reveal that the fibre-reinforcement tends to have a positive effect for soils with a low cementation level and to be less effective, or even to have a negative effect, for stiffer composite materials.

The effect of the fibre-reinforcement may be due to the combination of the two following factors, the presence of fibres in the composite matrix that restricts the development of cementation bonds between the soil particles and the mobilization of the tensile strength of the fibres, which is associated with the strain level imposed on the specimen. Thus, as a stiff material exhibits low strain at failure, which is not sufficient for the total mobilization of the tensile strength of the fibres, the cementation bonds that are prevented due to the presence of the fibres are not totally compensated for by the increment in strength induced by the tensile strength of the fibres, therefore the presence of fibres has a detrimental effect. On the other hand, a material with a low

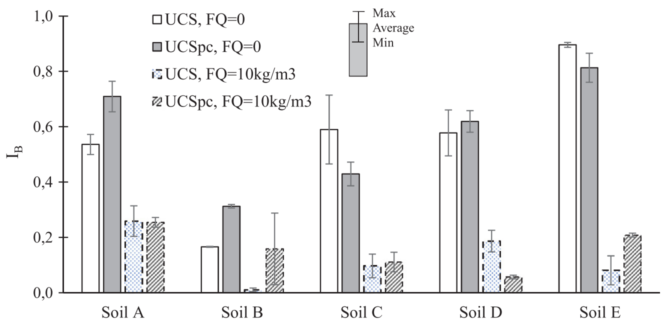

Fig. 4. Effect of soil type and polypropylene fibres reinforcement on the brittleness index (I_B) evaluated through UCS tests carried out before (UCS) and after (UCSpc) the cyclic stage.

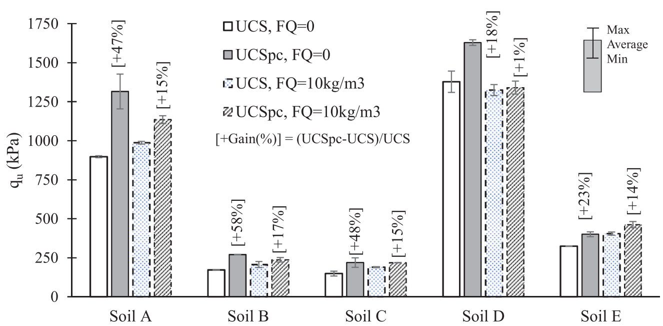

Fig. 5. Results of the UCS tests carried out before (UCS) and after (UCSpc) the load cyclic stage. Effect of soil type and the reinforcement with Pp fibres on the peak compressive strength.

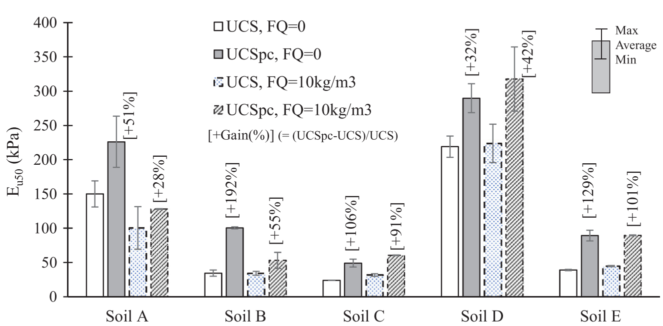

Fig. 6. Effect of soil type and polypropylene fibres reinforcement on Young's modulus (E_{u50}) evaluated through UCS tests carried out before (UCS) and after (UCSpc) the cyclic stage).

cementation level fails at a high strain level, which allows the mobilization of the tensile strength of the fibres to occur, consequently the balance between the loss of strength due to the decrease in the cementation bonds and the mobilization of the tensile strength of the fibres is positive.

For all the soils tested and regardless of the inclusion or not of the fibres in the soil-binder-water mixture, Figs. 5 and 6 also 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. It is worth mentioning that this effect is higher for unreinforced soils than for fibre-reinforced soils and is more significant for E_{u50} than q_u; thus for unreinforced stabilized soils, the increase of q_u ranges from 18% (soil D) to 58% (soil B), while the increase of E_{u50} changes from 32% (soil D) to 192% (soil B). In fact soils B and D show respectively the greater and the lesser increment in the mechanical properties in terms of percentage, this fact is related to the absolute values of the monotonic mechanical properties (not subjected to cyclic loading) of the soils. Although the increase in the mechanical characteristics induced by cyclic loading is in line with the results of similar research works [23,25–27], they do not reflect the deterioration in the soil-binder-water matrix during the cyclic stage, confirmed in Fig. 1 by the increase of $\varepsilon_{ax\text{-}perm}$ with the number of load cycles. This behaviour, although unexpected, may be explained by the partial mobilization of the tensile strength of the fibres during the cyclic stage as a consequence of the increase in the internal strains of the specimens promoted by the breakage of some cementation bonds. Indeed, the results seem to indicate that after the cyclic stage the beneficial effect of the mobilization of the tensile strength of the fibres is higher than the detrimental effect induced by the destruction of the soil-binder-water matrix, consequently, the cyclic loading promotes the increases in q_u and E_{u50}.

4. Conclusions

Considering the results of the monotonic UCS tests performed without and after the cyclic loading tests (average deviatoric stress level of $0.55xq_{u\text{-}failure}$, frequency of 0.25 Hz, amplitude of $\pm$ 7.5% × $q_{u\text{-}max}$ up to 3000 load cycles) carried out on five different soils stabilized with a Portland cement (Type I 42.5 R) and unreinforced or reinforced with polypropylene fibres, the following observations can be made and conclusions drawn:

i) The evolution of the permanent cumulative axial strain shows a sharp increase at the beginning of the cyclic stage followed by a decrease in the strain rate with the increment of the number of load cycles. This behaviour is a symptom of the progressive destructuration of the-soil-binder-water matrix.
ii) Regardless of the soil type, the fibre-reinforcement has a beneficial effect on the cyclic behaviour of stabilized soils, namely for a higher number of load cycles, inducing a decrease in the permanent cumulative axial strains in relation to unreinforced soil. In fact, this behaviour is due to the mobilization of the tensile strength of the fibres, which occurs for the strain level imposed during the cyclic stage.
iii) An increase in the content of silt/clay particles, and the organic matter content of a soil, has a detrimental effect on the cyclic behaviour, inducing higher permanent cumulative axial strains.
iv) The inclusion of fibres in the composite material changes the stress-strain behaviour from a brittle (unreinforced soil) to a ductile behaviour (fibre-reinforced soil), with a significant decrease in the loss of strength after the peak strength, which is well reflected in the brittleness index which decreases with the inclusion of fibres.
v) The effect of the cyclic stage on the brittleness depends on the soil type, thus, coarser soils show an increase in the brittleness while an increase in the organic matter content promotes a slight increase in the ductility.
vi) The inclusion of the fibres in the soil-binder-water mixture promotes an increase in the unconfined strength for stabilized soils with a low cementation level. The effect of fibre-reinforcement is small or even negative for stiffer soils, since the strain level at failure is not enough to mobilize the tensile strength of the fibres.
vii) The cyclic stage induces an increase in the mechanical characteristics (strength and stiffness) of the composite material; indeed, the deterioration of the solid skeleton during the cyclic stage is partially compensated for by the mobilization of the tensile strength of the fibres due to the strain level imposed by the cyclic loading. The improvement of the stabilised materials due to the cyclic stage is higher for unreinforced soils than for fibre-reinforced soils and is more significant for the stiffness than unconfined strength.

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