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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 (%);
$\Delta H_{cyc-perm}$	permanent variation of the length of the specimen during the cyclic phase;
ε_{ax}	axial strain (%);
$\varepsilon_{ax-failure}$	axial strain at failure (%);
$\varepsilon_{ax-perm}$	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.