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Effect of cyclic loading on the behaviour of a chemically stabilised soft soil reinforced with steel fibres

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ABSTRACT

This work studies the effect of cyclic loading on the behaviour of a soft soil chemically stabilized with Portland cement and blast furnace granulated slag (proportion 75/25) and reinforced with steel fibres. The influence on accumulated permanent axial strain and on the unconfined compressive strength and stiffness, determined by unconfined compression strength tests, is evaluated for different numbers of load cycles applied initially to the samples. For the conditions tested, the results of the cyclic stage indicate there is a number of load cycles below which the accumulated permanent axial strain increases with the number of cycles, whereas above it, it remains almost constant. The results of the UCS tests show an increase in strength with the number of cycles, which is more pronounced in the tests performed with a low number of cycles. It was also observed an increase in stiffness until 2500 cycles were reached, while for higher number of cycles the opposite occurs.

1. Introduction

One of the methods employed to overcome the brittle behaviour, the poor tensile and flexural strength exhibited by soil-binder-water mixtures [1,2] is the inclusion of short fibres into the mixture. The monotonic behaviour of fibre-reinforced stabilized soils has been studied by several authors, which used mostly synthetic fibres [1–7] and also steel fibres [1,7,8]. In general, the use of synthetic or steel fibres decreases the brittleness and increases the post peak strength of the soil-binder-water mixture. However, the effects on the strength depend on the binder content, the type of fibre and even the type of test used to evaluate the compressive and/or tensile strength [2,7].

During their lifetime some structures are often subjected to cyclic loading induced by different types of actions, such as earthquakes, traffic loads, industrial machinery and waves on offshore structures. When these structures are supported by artificially cemented soils it is essential to know the effect of the cyclic loading on their behaviour. The cyclic behaviour of artificially cemented soils without fibre-reinforcement show that an increase in the number of load cycles promotes a progressive degradation of the cementation bonds, increasing the accumulated permanent deformations [9–11], reducing the stiffness [12,13] and decreasing the yield stress [12].

Cyclic simple shear tests showed that the inclusion of fibres in the mixture promotes a slight increase in the shear strength for higher strain levels [14]. As for the plastic deformations, the results are contradictory, with an increase in Nottingham Asphalt Tests (NAT) [15] and a decrease observed in cyclic triaxial tests [9] and indirect tensile cyclic load tests [16]. The results also showed that there is an increase in the permanent deformations with the increase in the number of load cycles, regardless of the type of test [9,15]. However, some differences are observed in the general trend, with the cyclic triaxial tests [9] presenting a moderate increase at the beginning of the cyclic stage followed by a sharp increase, while the NAT [15] shows exactly the opposite, i.e. a sharp increase at the beginning of the cyclic stage, followed by a plateau.

Considering the limited number of works published about this theme, their contradictory results and the fact that they only used synthetic fibres, it is very pertinent to study the effect of cyclic loading on the behaviour of a soft soil chemically stabilised with a high-binder content and reinforced with steel fibres. Based on the results of UCS tests, the influence of the number of load cycles on the permanent deformations, unconfined compressive strength and stiffness of the composite material are analysed.

2. Description of the experimental work

2.1. Characteristics of the soft soil

The soft soil used in this study was collected in the “Baixo Mondego” area, located near Coimbra, Portugal. The natural soil has

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Nomenclature

The following symbols are used in this paper (basic SI units are given in parentheses):

E_{u50}	secant Young's modulus for 0.5 qu (Pa);
n_{cycles}	number of load cycles;
q_u	maximum unconfined compressive strength (Pa);
UCS	unconfined compressive strength;
w_L	Atterberg liquid limit (%);
w_P	Atterberg plastic limit (%);
ε_{ax}	axial strain (%);
$\varepsilon_{ax\text{-}perm}$	permanent cumulative axial strain (%);

a predominantly silty particle size distribution (sand=14%; silt=61%; clay=25%), a specific gravity of 2.61, a low unit weight (14.6 kN/m^3), a high void ratio (> 2.0), a high natural moisture content (80.9%) and a high organic matter content (13.1%). This clayey-silt organic soil has high plasticity (w_L=68.0%; w_P=41.9%) and is classified as OH [17]. The soil presents low undrained shear strength (< 25 kPa) and high compressibility [7,18,19]. The chemical composition revealed a high silica content, (SiO_2=62%) followed by alumina (Al_2O_3=16%).

2.2. Characteristics of the binders and fibres

The soft soil was chemically stabilised with a binder mixture composed of Portland cement Type I 42.5R [20] and blast furnace granulated slag, in a dry weight proportion of 75/25, which was defined based on a laboratory optimization study [19]. The cement and the blast furnace granulated slag particles specific gravity are 3.18 and 2.89, respectively. The grain size distribution shows that 45% of cement particles and 3% of slag particles are less than 45 µm. In terms of chemical composition, the cement has a predominant content of calcium oxide (CaO=63.0%, SiO_2=19.7%; Al_2O_3=5.2%). The slag, besides a high calcium oxide content, also presents a high silica content (CaO=37.0%, SiO_2=38.7%; Al_2O_3=11.6%).

The steel fibres used have a wire-hooked end to maximize their anchorage capacity, a length of 30 mm and a diameter of 0.55 mm. According to the manufacturer, the fibres present a tensile strength higher than 1345 N/mm^2 and an elasticity modulus of 200×10^3 N/mm^2.

2.3. Specimen preparation and testing

To reduce the variability and heterogeneity of the samples, the soft soil was homogenised previously. The remoulded samples of stabilized soil with the inclusion of fibres were prepared having as a reference the methodology proposed by EuroSoilStab [21] and the procedures defined by Correia [19]. The complete methodology employed involved the following steps: *(i)* the binder was mixed with the natural soil and with the quantity of distilled water necessary to increase the final moisture content of the samples to 113%, producing a slurry (this water content was established to ensure the best compromise between the strength and the quality of the samples [19]); *(ii)* the soft soil, the slurry and fibres were mixed thoroughly using a mechanical mixer at a speed of 142 rpm for 4 min; *(iii)* this homogeneous paste was introduced and compacted directly into a cylindrical PVC mould (100 mm in diameter and 200 mm in height) in three layers ; *(iv)* after the deposition of each layer the mixture was lightly tapped by hand, subjected to vibrations by the application of a hand drill with a steel bar near the inner surface of the mould, and compacted with 100 kPa for 10 s; *(v)* the surface of the mixture was then lightly scarified before the deposition of another layer; *(vi)* subsequently the samples were cured for 28 days inside a room with temperature (20 ± 2 °C) and humidity (95 ± 5%) controlled; *(vii)* after the curing period the samples were placed on the pedestal of a universal cyclic loading machine (Servosis MUF 400) and the electronic devices (load cell and strain gauge transducer) were set up and adjusted; *(viii)* finally, the tests were performed and the data was recorded using an automatic data acquisition system.

Each cyclic test comprised two stages, a cyclic loading stage followed by a UCS test. The cyclic loading stage was carried out for a deviatoric stress level of 55% [7] of the failure value obtained in the monotonic UCS tests (q_{cyclic}=0.55×q_u ≈450 kPa). Maintaining that deviatoric stress level a sinusoidal excitation of 0.5 Hz, with an amplitude (q_{max}−q_{min}) of 7% of q_{cyclic} (≈31.5 kPa), was imposed on the samples. These conditions were defined so that a minimum safety factor of 1.5 was assured during the test. After the required number of load cycles (n_{cycles}) was applied, a monotonic UCS test [22] was performed at a constant strain rate of 0.25%/min. All tests were

Table 1
Summary of the tests and the main results.

Test	Property	No cycles		Number of cycles									
				625		1250		2500		5000		10,000	
		T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
Cyclic phase	Permanent cumulative axial strain, $\varepsilon_{ax\text{-}perm}$ (%)	– [–]	–	0.027 [0.034]	0.041	0.016 [0.029]	0.042	0.049 [0.045]	0.041	0.060 [0.054]	0.049	0.043 [0.045]	0.047
UCS	Unconfined comp. strength, q_u (kPa)	891.6 [819.7]	747.9	1323.7 [1221.0]	1118.2	1168.0 [1191.4]	1214.8	1067.4 [1086.4]	1105.4	1323.5 [1346.4]	1369.2	1413.0 [1377.0]	1341.0
	Axial strain at failure, $\varepsilon_{ax\text{-}failure}$ (%)	0.847 [0.871]	0.895	0.894 [1.012]	1.130	0.754 [0.778]	0.801	0.742 [0.795]	0.848	0.924 [1.051]	1.178	1.356 [1.288]	1.221
	Young's modulus for 0.5q_u, E_{u50} (MPa)	180.4 [158.9]	137.4	356.9 [233.0]	109.0	297.1 [305.8]	314.4	364.8 [383.7]	402.6	261.5 [211.5]	161.4	146.5 [155.5]	164.5

[...] – Average value; T_i – Test