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Influence of cyclic loading amplitude and stress level on a soft soil chemically stabilised and reinforced with fibres.

Influencia de la amplitud y nivel de tensión sometido a cargas cíclicas en un suelo blando químicamente estabilizado y reforzado con fibras.

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ABSTRACT: The purpose of this research is to characterize the effect of cyclic loading stress level and amplitude on the behavior of a soft soil chemically stabilised and reinforced with polypropylene fibres by comparing the results of unconfined compressive strength (UCS) and split tensile strength (STS) tests performed before and after a cyclic loading stage. The following tests are used in the laboratory: i) monotonic UCS and STS tests (reference values); ii) cyclic UCS and STS tests; and iii) monotonic UCS and STS tests following cyclic loading (UCSpc and STSpc). According to the findings, permanent deformations show a significant increase at the start of the cyclic period, followed by a decrease in strain rate for unreinforced and fibre-reinforced materials. In terms of cyclic loading stress level and amplitude, For levels of stress and amplitudes of up to 50% of the maximum strength/load, the samples exhibit lower permanent strains but become stronger and stiffer than the reference values (monotonic tests). These observations are valid for both stabilised materials (unreinforced and fibre-reinforced).

KEYWORDS: stabilised soil; reinforced soil; cyclic loading; unconfined compressive strength test; split tensile strength test

1 INTRODUCTION.

Various authors (Correia et al., 2015; Consoli et al., 2011; Venda Oliveira et al., 2016) have investigated the behavior of soft soils that are chemically stabilised, with or without reinforcement by fibres, under monotonic conditions.

The introduction of fibres into the stabilised soil alters its stress-strain characteristics from brittle to ductile (Tang et al., 2010). Consequently, an increase in residual strength is commonly observed due to the activation of the tensile strength of the fibres at higher strain levels (Tang et al., 2010; Sukontasukkul and Jamsawang, 2012). However, this behavior can change when subjected to cyclic loading from various sources such as industrial machinery, vibrations in offshore structures, traffic loads from trains or highways, and earthquakes.

As the number of load cycles increases, tests on stabilised soils (without fibres) show a gradual degradation of cementation bonds, leading to an increase in accumulated permanent deformations (Chauhan et al., 2008; Yang et al., 2008) and a decrease in stiffness (Subramaniam and Banerjee, 2014). Consequently, when stabilised soil is reinforced with synthetic fibres, there is a reduction in brittleness and an increase in the post-peak strength of the composite material (Venda Oliveira et al., 2016). Several factors, including binder content, fibre length/type, and test type, also influence the behavior (Correia et al., 2015; Venda Oliveira et al., 2016). Previous studies on fibre-reinforced stabilised soils subjected to cyclic loading have indicated: (i) an increase in permanent deformations with an increase in the number of load cycles (Chauhan et al., 2008; Dall'Aqua et al., 2010; Venda Oliveira et al., 2018); (ii) the addition of fibres increases the number of cycles and the magnitude of strain required to cause failure (Maher and Ho, 1993); (iii) an increase in unconfined compressive strength with the number of load cycles (Venda Oliveira et al., 2018).

This research aims to better understand the behavior of stabilised soils under two types of conditions: reinforced with fibres and unstabilised soils. The laboratory work involves

unconfined compression tests (UCS) and Split Tensile Strength (STS) tests, considering a cyclic stage.

Finally, a post-cyclic stage is conducted to observe the effects of the cyclic stage varying the stress level and amplitude keeping constant the number of cycles and frequncy. The study presents the accumulated permanent axial strain (Ɛax-perm %) and accumulated permanent vertical displacement during the cyclic stage, and discusses the influence of the cyclic loading on unconfined compressive strength (UCS) and indirect tensile strength (STS).

2 MATERIALS

This investigation was conducted using a soft soil from the "Baixo Mondego" region in central Portugal, near the Mondego River. The area has been studied by various researchers such as Coelho (2000), Correia (2011), and Villarroel-Ortega (2022). The soil deposit originated over 20,000 years ago in a fluviomarine depositional environment and has a thickness exceeding 20 meters.

The sample utilized in this study was collected at a depth of 2.5 meters. Table 1 provides a summary of the primary physical and chemical properties.

The soil exhibits predominantly silty grain size distribution (71%), a low unit weight (14.6 kN/m3), a high void ratio (> 2.0), elevated natural water content (80.6%), and a notable organic matter (OM) content (9.3%). These characteristics significantly influence its mechanical behavior, resulting in a low undrained shear strength (cu ≈ 25 kPa) and high compressibility (Coelho, 2000). This clayey-silt organic soil with high plasticity is classified as OH (ASTM D2487). The chemical composition reveals a substantial silica content (SiO2=62%) and 16% alumina (Al2O3), granting pozzolanic properties to the soil.

Table 1: Coimbra soft soil main characteristics (average values) (Villarroel-Ortega, 2018, Coelho, 2000)

Physical Properties		Chemical composition	
w_{nat} (%)	80.67	pH (BS1377-33)	3.5
G_s	2.55	SiO_2 (%)	62
e_{nat}	2.03	Al_2O_3 (%)	16
γ (kN/m^3)	14.6	Fe_2O_3 (%)	4.8
OM (%)	9.3	CaO (%)	0.74
Grain size distribution		MgO (%)	1.1
Clay (%)	10	Na_2O (%)	0.9
Silt (%)	71	K_2O (%)	3
Sand (%)	19	TiO_2 (%)	0.69
w_L (%)	71	MnO (%)	< 0.3
w_p (%)	43	P_2O_5 (%)	< 0.5
PI (%)	28	TOC (%)	2.79
LI (%)	1.35	CTC (cmol+/kg)	11
USCS (ASTM D2487)	OH		

The soft soil was treated with a binder consisting of Portug uese Portland cement (Portland cement Type I 42.5 R, manu factured by CIMPOR), and its key chemical characteristics a re outlined in Table 2. Upon contact with water, Portland ce ment undergoes rapid reactions, yielding a substantial quantit y of reaction products in the short term. Over time, physico -chemical reactions, particularly pozzolanic reactions, occur a t a slower pace, contributing to the generation of additional cementitious products. These products play a crucial role in improving the mechanical properties of the stabilised soil.

Table 2: Chemical characterisation of the Portland cement (average values; data from manufacturer)

SiO_2 (%)	19.3
Al_2O_3 (%)	5.09
Fe_2O_3 (%)	3.15
CaO Total (%)	63.87
MgO (%)	1.91
SO_3 (%)	3.15
K_2O (%)	1.13
Na_2O (%)	0.1
CaO Free (%)	2.19
Loss on ignition (%)	1.26

The polypropylene fibres used in this study are 12 mm in length, 32 mm in diameter and exhibit a great flexibility, a high specific surface (134 m2/kg), a density of 905 kg/m3, a tensile strength of 250 N/mm2 and a Young's modulus of 3500 - 3900 N/mm2 (in accordance with the product datasheet supplied by the manufacturer BEKAERT).

3 SAMPLE PREPARATION AND TESTING

The procedures and methodologies outlined below are based on recommendations from EuroSoilStab (2001) and Correia (2011), albeit with slight variations. Initially, the soil was manually mixed to achieve a uniform paste. Subsequently, a specified quantity of cement (250 kg/m3) was mixed with the necessary volume of water to raise the natural soil's water content from 80.67% to 115%. This paste was then combined with the natural soil using a mechanical mixer operating at 142 rpm for 4 minutes.

The soil-cement-water mixture was layered into cylindrical PVC molds (37 mm in diameter and 78 mm in height). Following the addition of each layer, the mold underwent a light manual tapping (20 times), and it was gently scarified before the subsequent layer was added (each sample was divided into three equal layers). The samples underwent a 28-day curing period in a controlled environment with a temperature of 20 ± 2 °C and humidity of 95 ± 5%. Subsequently, the samples were carefully extracted from the PVC molds, and both surfaces were precisely ground to maintain parallelism, resulting in specimens measuring 37 mm in diameter and 76 mm in height. The remaining material was utilized to determine the moisture content of each sample.

The samples were then placed in the compression machine, and electronic devices (load cell and displacement transducer) were configured and adjusted. Unconfined Compression Strength (UCS)

tests were conducted at a constant strain rate of 1% per minute (BS 1377-7, 1990).

Cyclic loading tests were performed for 5,000 cycles, with a variation in deviatoric stress levels from 10%, 25%, and 70% (0.50×qu-max), employing sinusoidal excitation at 0.5 Hz and a varying amplitude of ±5, ±10, ±20 (± 0.10×qu-max). Following the cyclic stage, a monotonic UCS test (UCSpc) was carried out. To ensure the reliability of the procedure, the tests were repeated at least twice.

4 DISCUSSION OF THE RESULTS

Stress level

Figures 1 and 2 depict a notable rise in permanent axial strain in the samples, particularly evident in those reinforced with Polyprilene fibers. This suggests that the structural matrix of the soft soil is significantly impacted by cyclic loading, especially when subjected to higher forces or strength levels, as the fibers within the solid framework of the sample become mobilized.

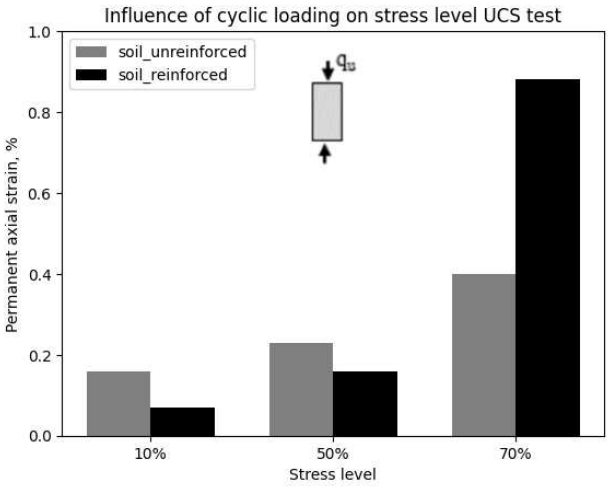

Figure 1: effect of the cyclic loading on stress level in UCS test

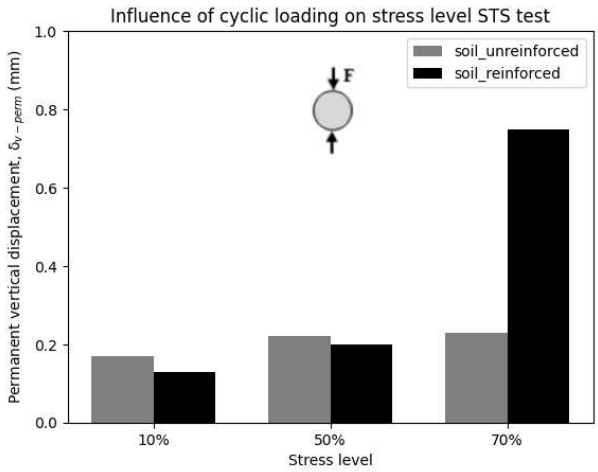

Figure 2: effect of the cyclic loading on stress level in STS test

In Figures 3 and 4, the findings indicate that varying stress levels result in enhanced strength and load-bearing capabilities of the fiber-reinforced material compared to conventional monotonic tests. However, it is noteworthy that at higher stress levels, there is a decline in both strength and load-bearing capacity.

Regarding samples reinforced with fibres, the results demonstrate an improvement in behavior up to 50% of the maximum stress level. Conversely, at higher stress levels, the samples become more brittle and experience a loss of strength.

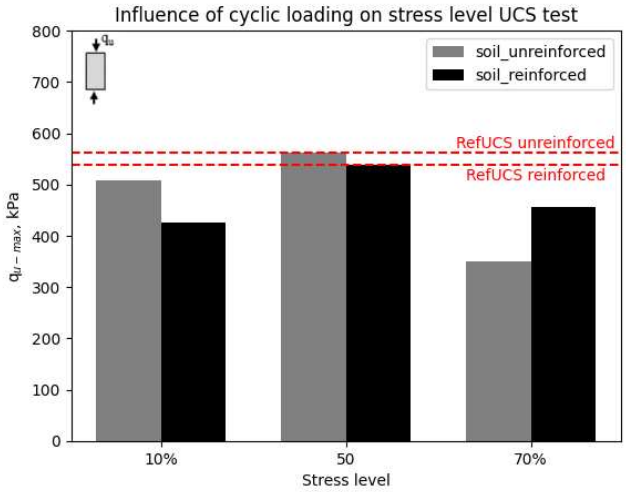

Figure 3: effect of the cyclic loading on stress level in UCSpc test

On the contrary, in the split tensile test (STS) and the post-cyclic stage (STSpc), it was observed that as higher loadings were applied, the samples became more fragile, albeit with reduced stre ngth. Similar effects were noted in the reinforced samples, as depi cted in Figure 4.

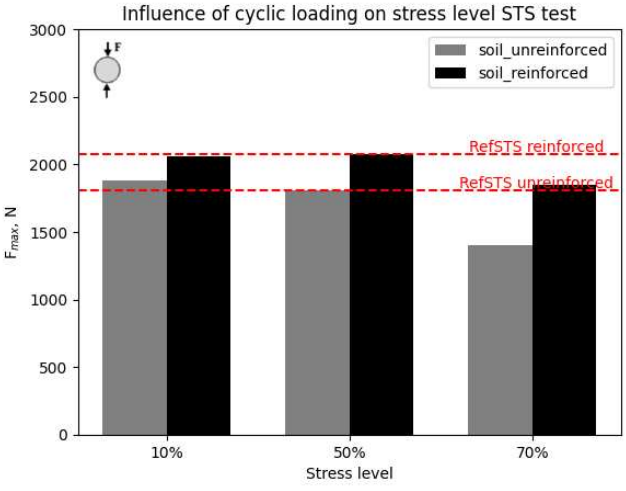

Figure 4: effect of the cyclic loading on stress level and stress level in STS_{pc} test

The analysis should consider the failure mechanism observed in the STS test, characterized by a sudden breakage of cementitious bonds, occurring with minimal vertical displacements.

The presence of fibers physically hinders the formation of certain cementitious bonds within the composite matrix, leading to a reduction in stiffness. Consequently, the fiber-reinforced material will undergo greater deformations due to its lower stiffness compared to the unreinforced material. The small vertical displacements induced in the STScyc tests are insufficient for effective fiber mobilization.

However, applying a stress level of 75% during the cyclic stage had an adverse impact on post-cyclic strength compared to monotonic tests. This behavior appears to stem from significant damage to the composite material during the cyclic stage, resulting from substantial accumulated permanent deformations.

Amplitude

When considering the effect of cyclic loading amplitude, the results reveal similar behavior compared to stress level.

When comparing unreinforced and reinforced samples, it becomes apparent that permanent deformation is comparable in both cases for stress amplitudes ranging from 5% to 10%. However, for a 20% stress amplitude, the reinforced samples tested in UCS exhibit lower permanent deformation. This indicates that as material deformation increases, the fibers progressively engage, assisting in reducing permanent axial strain (UCScyc tests) compared to their unreinforced counterparts.

Figures 5 and 6, offer a summary of the results obtained during post-cyclic UCS and STS tests immediately after altering the stress amplitude of the cyclic stage for the stabilized samples reinforced with polypropylene fibres.

These findings demonstrate an enhancement in the strength and load-bearing capacity of the stabilized fiber-reinforced material compared to the reference monotonic tests, albeit with a reduction as stress amplitude increases, which is associated with greater degradation of the cementitious matrix during the cyclic stage.

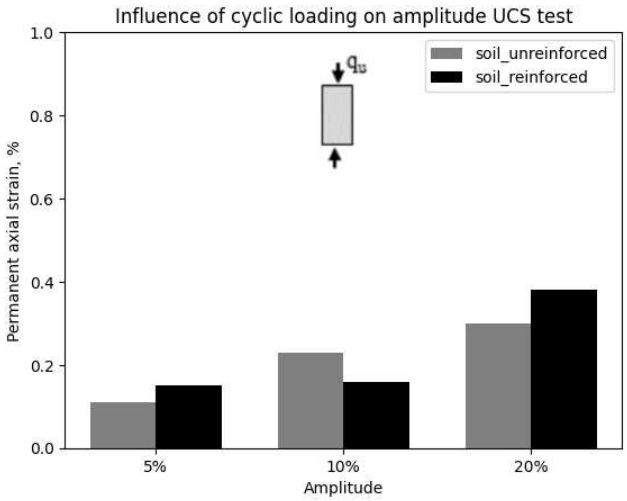

Figure 5: effect of the cyclic loading on amplitude in UCS test

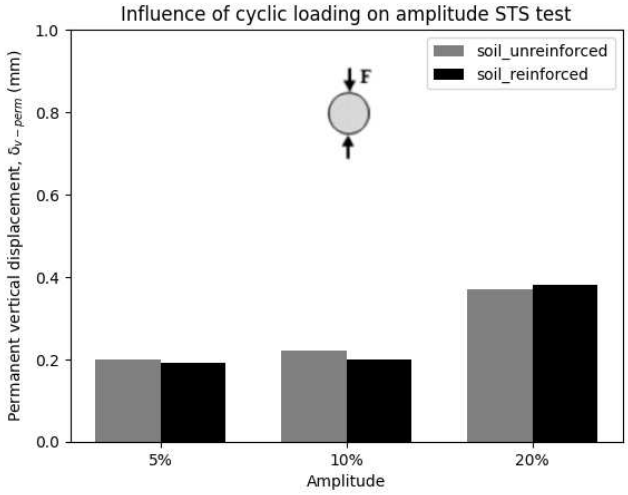

Figure 6: effect of the cyclic loading on amplitude in UCS test

The results clearly indicate that when the amplitude falls within the range of 5 – 10%, the strength/load of the composite material surpasses that of the reference monotonic tests. The observed breakage of cementitious bonds during the cyclic stage might lead to a coarser apparent grain size, resulting in greater strength during this stage.

Furthermore, the findings show that an increase in amplitude leads to a decrease in strength/load, consistent with the progressive damage of the composite material during the cyclic stage, characterized by higher permanent deformations.

Comparing unreinforced and reinforced samples, it's evident that permanent deformations are similar in both cases for amplitudes ranging from 5 to 10%. However, for an amplitude of 20%, the reinforced samples subjected to UCS tests exhibit lower permanent deformation. This suggests that as a material experiences higher deformation, the fibres become increasingly mobilized, aiding in reducing permanent axial strain (UCScyc tests) compared to the corresponding unreinforced sample.

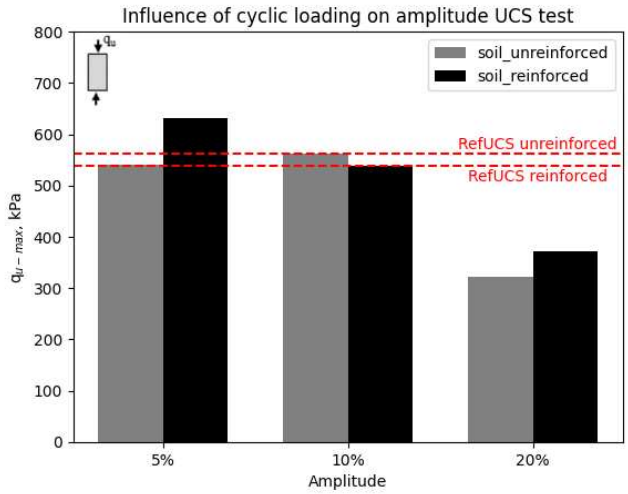

Figure 7: effect of the cyclic loading on amplitude in UCSpc test

Overall, the results indicate an enhancement in the strength/load of the stabilized fiber-reinforced material compared to the reference monotonic tests. However, there's a reduction with increasing amplitude, attributed to greater degradation of the cementitious matrix during the cyclic stage.

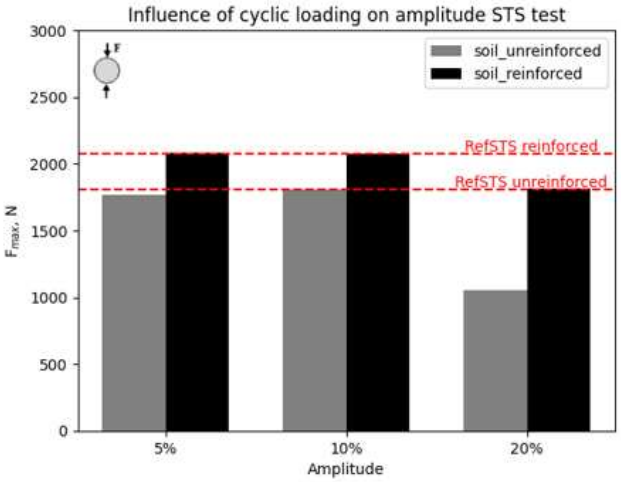

Figure 8: effect of the cyclic loading on amplitude in STSpc test

5 CONCLUSIONS

In this section, the three most important conclusions of this work will be discussed.

a. Similar to findings in other studies, it could be observed that the permanent strains initially exhibit a sharp increase at the onset of the cyclic stage, followed by a decrease in the strain rate for both unreinforced and fiber-reinforced samples. However, in this study, these results are not presented prominently, primarily due to the significant detrimental impact on the cementitious matrix caused by loads/stresses exceeding 50% of the $q_{u\text{-}max}$.

b. The addition of fibers leads to a reduction in permanent axial strains in UCS cyclic tests, whereas the opposite effect is observed in STS cyclic tests. This discrepancy can be attributed to the different failure mechanisms associated with each test.

c. For stress levels and amplitudes up to 50% of the maximum strength/load, the samples exhibit reduced permanent deformations and demonstrate increased strength and stiffness compared to the reference values obtained from monotonic tests. These findings hold true for both stabilized materials, whether they are unreinforced or fiber reinforced.

6 ACKNOWLEDGEMENTS

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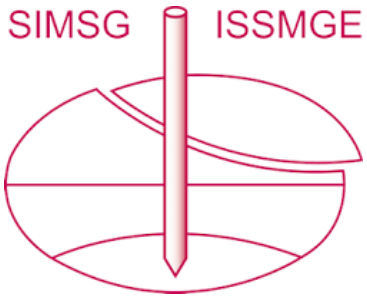

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