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Effect of the binder content in a soft stabilized soil unreinforced and reinforced subjected to cyclic loading – energy evaluation

Effet de la teneur en liant dans un sol stabilisé mou non renforcé et renforcé soumis à une charge cyclique - évaluation énergétique

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ABSTRACT: When a soil is subjected to cyclic loading, there are changes in the behaviour of the material that need to be characterized for a safe design. To this end, a series of unconfined compressive strength (UCS) tests were performed, with and without the application of cyclic loading, to study the effect of the binder content on the behaviour of a soft soil stabilized under cyclic loading, unreinforced and reinforced with polypropylene fibres. The results were analysed in terms of the evolution of plastic deformation, and of the elastic and plastic energy. It was observed that plastic energy prevails in the first cycles but decreases with the increase in the number of loading cycles, and the increase of the binder content is associated with the decrease of the initial plastic energy. The accumulated plastic deformation occurring during the cyclic loading induces a strain hardening effect that is responsible for the increase in the undrained resilient modulus. The addition of polypropylene fibres prevents the development of some cementitious bonds and promotes an increase in the plastic deformation energy, leading to an increase in the accumulated plastic strains and to a reduction in the undrained resilient modulus during the cyclic loading stage.

RÉSUMÉ: Lorsqu'un sol est soumis à une charge cyclique, il y a des changements dans le comportement du matériau qui doivent être caractérisés pour une conception sûre. À cette fin, une série d'essais de résistance à la compression non confinée (UCS) a été réalisée, avec et sans application d'une charge cyclique, pour étudier l'effet de la teneur en liant sur le comportement d'un sol mou stabilisé sous charge cyclique, non renforcé et renforcé avec des fibres de polypropylène. Les résultats ont été analysés en termes d'évolution de la déformation plastique et de l'énergie élastique et plastique. Il a été observé que l'énergie plastique prédomine dans les premiers cycles mais diminue avec l'augmentation du nombre de cycles de chargement, et l'augmentation de la teneur en liant est associée à la diminution de l'énergie plastique initiale. La déformation plastique accumulée pendant le chargement cyclique induit un effet d'écrouissage qui est responsable de l'augmentation du module de résilience non drainé. L'ajout de fibres de polypropylène empêche le développement de certaines liaisons cimentaires et favorise une augmentation de l'énergie de déformation plastique, ce qui entraîne une augmentation des déformations plastiques accumulées et une réduction du module de résilience non drainé pendant la phase de chargement cyclique.

Keywords: Stabilized soil; reinforced soil; cyclic loading; energy.

1 INTRODUCTION

One of the techniques that has been applied to improve the geomechanically behaviour of soils is chemical stabilization, in which the natural soil is mixed in situ with chemical stabilizers such as Portland cement (Horpibulsuk et al. 2003; Lemos et al. 2021; Venda Oliveira et al. 2013). However, the composite material is in general characterized by brittle behaviour and poor tensile strength. In this context, the inclusion of randomly distributed fibres to the stabilized soil promotes the increase in the tensile strength as well as increases the ductility (Consoli et al. 2009; Correia et al. 2015; Tang et al. 2007).

When a cycling loading is applied to a fibre-reinforced stabilized soil there are changes in the material's behaviour that need to be characterized. So far, the knowledge acquired about such behaviour is still limited and sometimes inconsistent. Dall'Aqua et al. (2010); Venda Oliveira et al. (2017) presented an increase in the plastic deformations induced by cyclic loading, with the most significance during the first loading cycles. Instead, Chauhan et al. (2008)

observed an increase in the plastic deformations for a high number of loading cycles.

The application of the energy concept in geotechnical studies has focus on elucidating the behaviour of cohesionless soils subjected to dynamic loads in which the deformation of a material under cycling loading corresponds to the dissipation of energy (Lenart 2008; Sas et al. 2017). In cases of cyclic loading, stress-strain hysteresis loops provide a means to analyse the plastic energy, equivalent to the area enclosed by the hysteresis loop. Simultaneously, the elastic energy is determined by the area beneath the unloading curve (Sas et al. 2017). The energy concept has been applied to a limited number of fibre-reinforced stabilized soils subjected to cyclic loading. Narani et al. (2021) observed that the plastic energy is higher in initial cycles but decreases rapidly with the increase in the number of cycles and increases with cement content. Additionally, the addition of fibres induces a reduction in plastic energy, due to the absorption of deformation by the fibres, resulting in less energy transfer to the soil matrix.

Despite the existing research, the impact of the number of the loading cycle on the behaviour of a fibre-reinforced stabilized soft soil has not been adequately explored. So, this study aims to improve the knowledge regarding the cyclic loading behaviour of fibre-reinforced stabilized soft soil.

2 MATERIALS AND PROCEDURES

2.1 Characteristics of the materials

It was used a soft soil from Coimbra, Portugal. The geotechnical characterization revealed a grain size composition of 77% of silt, 12% of clay and 11% of sand, a liquid limit of 72%, a plastic limit of 45%, organic matter content of 9.5%, and a natural moisture content of 81%. The soil was classified as a high plasticity organic silt (OH) (ASTM-D2487, 1998) and presents a pH of 4.6 (Martins et al. 2023).

The binder chosen was Portland cement Type I 42.5 R (EN-197-1, 2000) characterized by a high composition of calcium oxide (CaO) 63% and silica oxide (SiO_2) 19%. It was used a binder content of 12, 21, 30 and 39% (dry weight ratio of binder to soil).

In the case of reinforced samples, polypropylene fibres were used as reinforcing elements. The fibres have a length of 12 mm and a diameter of 32 µm. The content of fibres added to the chemically stabilized soil was 1.2% (weight ratio of dry fibre to dry soil).

2.2 Experimental procedures

The samples used for this research were prepared based on the laboratory procedure described in Correia (2011); EuroSoilStab (2002); Martins et al. (2023): (i) the soil, in its natural water content, the cement and the fibres were mixed in a mechanical mixer at a speed of 142 rpm for four minutes; (ii) the paste was introduced into PVC moulds (37 mm diameter, 85 mm high) and compacted in three layers each (tapping the moulds against a wooden table twenty times by hand); (iii) the samples were cured under water in a room with temperature and humidity control (20±2°C and 95±5%, respectively) for 28 days; (iv) at the end of the curing period, the samples were removed from the moulds and the surfaces were cut to obtain 76 mm high samples.

A monotonic UCS test was carried out to define the mechanical characteristics under monotonic loading conditions, with a constant axial strain rate of 1% min (BSI-1377-7 (1990). The UCS cyclic loading tests were carried out for a deviatoric stress level of 50%; an amplitude of ±10% of the maximum unconfined compressive strength (defined in the monotonic UCS test), a frequency of 0.5 Hz and during 5,000 loading cycles.

3 RESULTS

3.1 Plastic deformation

The evolution of the accumulated plastic axial strain with the numbers of loading cycles is shown in Figure 1 for the different binder content in both unreinforced and fibre-reinforced stabilized soil.

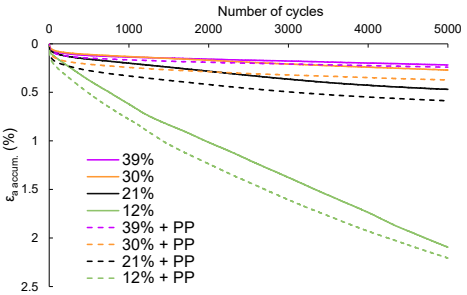

Figure 1. Evolution of the accumulated plastic axial strain with the number of loading cycles.

The analysis of the results reveals that the samples with binder content between 21 and 39% show a rapid increase in axial strain within the first 100 loading cycles, followed by a gradual, asymptotic approach to a constant value over subsequent cycles. Distinct behaviour is noted for samples stabilized with the lowest binder quantity, 12%, exhibiting a continuous

increase in accumulated permanent axial strain during all the cyclic stage. It is possible to observe a decreasing of accumulated plastic axial strain as the binder quantity increases. This trend aligns with the understanding that a higher binder quantity promotes the formation of cementitious bounds, resulting in a stronger and stiffer stabilized matrix, as seen in previous studies (Kaniraj and Havanagi 2001).

Furthermore, the results suggest that the addition of fibres may reduce the development of certain cementitious bonds within the stabilized matrix, leading to a composite material with lower strength and stiffness. Consequently, fibre-reinforced stabilized material experiences higher plastic axial strains during cyclic loading. The reduction of the impact of the fibre addition as the binder content increases is attributed to the constant amount of fibres added across all fibre-reinforced stabilized samples, resulting in a decrease in relative fibre importance.

3.2 Plastic and Elastic Energy

The plastic energy corresponds to the area enclosed by the hysteresis loop, while the elastic energy is calculated as the area beneath the unloading curve (Martins et al. 2023; Narani et al. 2021; Ostadan et al. 1996). These calculi were carried out utilizing the trapezoidal rule integration method in Matlab software, employing an in-house algorithm. The results are illustrated in Figures 2 and 3.

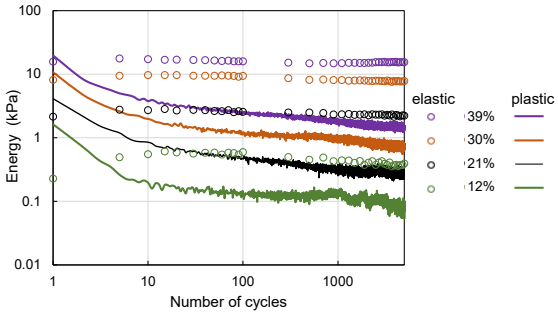

Figure 2. Evolution of plastic and elastic energy with the number of loading cycles – without fibres.

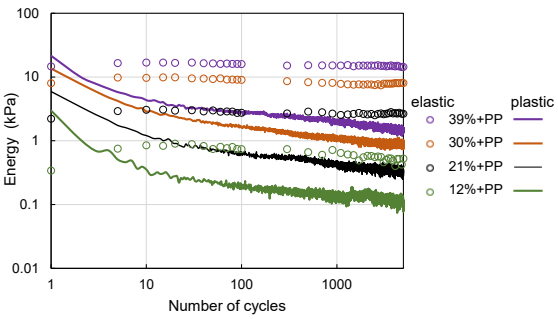

Figure 3. Evolution of plastic and elastic energy with the number of loading cycles – with fibres.

For both unreinforced and fibre-reinforced stabilized materials, the initial cycles reveal a dominance of plastic energy, which gradually reduce as the number of loading cycles increases. In contrary, elastic energy exhibits a progressive increase, particularly evident in the first 10 cycles. During the early loading cycles, the external cyclic load primarily dissipates energy as plastic, with some residual energy absorbed elastically by the composite material. However, this dynamic shifts rapidly as cycles progress, leading to a quasi-steady hysteretic response of the stabilized material, as observed from Figures 2 and 3.

Analysing the addition of fibres, it is possible to observe that the introduction of fibres amplifies the plastic energy and diminishes the elastic energy. This behaviour seems to be induced by the combined effects of the polypropylene fibres' high compressibility (Narani et al. 2020) and the presence of fibers potentially impeding the development of specific cementitious bonds.

For both unreinforced and fibre-reinforced stabilized materials, there is a noticeable transition of energy from plastic to elastic, particularly pronounced in the initial cycles.

4 CONCLUSIONS

The outcomes from the unconfined compressive strength tests conducted on both unreinforced and fibre-reinforced stabilized samples subjected to a cyclic loading stage. lead to the following conclusions:

i) The accumulated plastic axial strain decreases with the increase in binder content, attributed to a larger amount of cementitious bonds leading to a stronger and stiffer stabilized matrix.

ii) In the initial loading cycles, most of the energy applied by the external cyclic load is dissipated as plastic energy, with the remaining energy absorbed elastically by the composite material. This trend changes with the increase in the number of cycles. After a limited number of cycles (10 to 100). The results suggest the predominant dissipation mechanism involves the breakage of cementitious bonds, inducing plastic deformations in the solid skeleton, particularly intensified with lower binder content.

iii) The addition of fibres amplifies plastic energy, especially noticeable in the initial cycles. These results are coherent with a high accumulation of plastic axial strains in the first steps of cycling loading.

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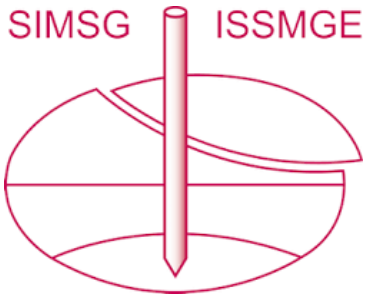

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