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Effects of the loading rate and cyclic loading on the strength and deformation properties of a geosynthetic

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ABSTRACT

The paper describes monotonic and cyclic load-extension tensile tests performed on a geocomposite used as soil reinforcement material. The effects of the loading rate and cyclic loading on the geocomposite behaviour are important to improve numerical codes. This study showed that the damping ratio tends to decrease, while the stiffness tends to increase, with the loading cycles. The unload and reload stiffness are not very sensitive to the loading frequency, for the range of values analysed. The damping ratio tends to decrease with frequency of loading. Previous cyclic loading did not induce significant reduction of the geosynthetic tensile strength.

KEYWORDS: Polymeric material; Geosynthetics; Tensile load tests; Cyclic loading; Load-Strain; Stiffness; Damping

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NOTATION

The following symbols are used in this paper:

D - damping ratio (dimensionless)

f - loading frequency (Hz)

J - geosynthetic axial stiffness (kN/m)

J_0 - initial tangent stiffness (kN/m)

J_1 - stiffness of the primary loading (kN/m)

$J_{5\%}$ - secant stiffness at strain of 5% (kN/m)

J_{reload} - reload stiffness (kN/m)

J_{Tmax} - secant stiffness at ε_{Tmax} (kN/m)

J_{unload} - unload stiffness (kN/m)

T - load per unit width (kN/m)

T_{max} – geosynthetic tensile strength or maximum tensile force (kN/m)

$T_{max,cyc}$- geosynthetic tensile strength after cyclic loading (kN/m)

T_{nom} – nominal tensile strength of geosynthetic (value declared by the producer) (kN/m)

Greek letters

ε - geosynthetic strain (dimensionless)

$\dot{\varepsilon}$ - strain rate (%/min)

ε_{cum} - cumulative strain (dimensionless)

$\varepsilon_{max,cyc}$ - maximum strain recorded during cyclic loading (dimensionless)

ε_p - plastic strain (dimensionless)

ε_{Tmax} - geosynthetic strain for T_{max} (dimensionless)

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1 INTRODUCTION

Geosynthetics are polymeric materials that are specially fabricated to be used in geotechnical, geoenvironmental, hydraulic and transportation engineering applications. Geosynthetics can be classified into categories based on method of manufacture as geotextiles, geogrids, geomembranes, geonets, geocomposites, geosynthetic clay liners, geocells, geopipes and geofoams. The present paper refers to a geocomposite that combines the functions of reinforcement and drainage, being suitable to reinforced soil structures constructed with cohesive fills and road or railway applications.

When a geosynthetic is used to reinforce a geotechnical structure, its main function is to resist tensile stress not supported by the soil and, simultaneously, to reduce deformations. The use of geosynthetics as reinforcement elements of granular backfills has been widely used. However the use of fine grained soils, often referred as marginal fills, is not recommended by international guidelines and standards [1] since they are susceptible to reduction in strength due to pore water pressure generation.

The use of locally available soils has cost benefits and sustainable gains. Some studies [2], [3] have shown that in many cases excess pore water pressure is not generated and when the fill is compacted close to the optimum moisture content, the reinforced structure contains significant suctions (negative pore water pressures). The research shows that, in order to utilise wet cohesive fills, there is a need for a geosynthetic that provides both drainage and reinforcement functions [4]. The geocomposite selected for the present study meets this requirement.

Geosynthetic reinforced soil structures are being used in a wide range of applications such as retaining structures and infrastructures. These structures are subjected to various loading conditions including repeated or cyclic loads. The geosynthetic properties used for the design of reinforced soil structures under dynamic or seismic loading are typically based on the results of monotonic load-extension tests or creep tests. According to several authors [5], [6], [7], [8] the strength and stiffness of polymeric materials are sensitive to strain rate, so it should be expected that the behaviour of these materials under repeated loads could be more complex.

The standard tests used typically for load-extension geosynthetics characterization (EN ISO 10319 [9], ASTM D 4595-11 [10]) do not describe the non-linear behaviour of these materials under cyclic loading conditions. Although the common approach in the analysis of geosynthetic reinforced structures under dynamic loads is to ignore the effects of the loading rate on reinforcement properties and to use pseudo-static limit equilibrium methods [11], [12], [13], it is important to characterize the cyclic behaviour of geosynthetics and to implement suitable hysteretic models in numerical codes.

Few studies have been conducted to investigate the tensile properties of geosynthetics under cyclic loadings [6], [7], [14], [15].These studies are mainly related to the behaviour of geogrids. This work aims to improve the knowledge related to the effects of the loading rate and cyclic loading on the strength and deformation properties of a geocomposite suitable for reinforcement of fine grained soils or marginal fills.

2 EXPERIMENTAL TESTING PROGRAM

The material used in this experimental program is a geocomposite reinforcement consisting of polypropylene continuous filament nonwoven geotextile reinforced with high strength polyester (PET) yarns, with nominal tensile strength of 50 kN/m (value declared by the producer of the material). The spacing of PET yarns is approximately 8.3mm, which corresponds to 120 yarns per meter of geotextile width (Figure 1). The geocomposite has a thickness of 2.1 mm and mass per unit area equal to 310 g/m^2.

The tensile strength of the nonwoven geotextile is negligible compared with the strength of PET yarns. This geocomposite combines the functions of reinforcement (PET yarns) and drainage (polypropylene nonwoven geotextile).

The monotonic tensile tests were carried out in accordance with the European Standard for geotextile wide-width tensile tests [9]. Each specimen (for monotonic and cyclic tests) was cut with dimensions 200 mm width × 340 mm length from the same roll. The distance between the jaws was adjusted to give a test specimen length of 100 mm. The reference points were fixed on the specimen 60 mm apart. A Video-Extensometer was used to measure the geocomposite strains. For the monotonic tensile tests five specimens were used and the cyclic tests were carried out on three specimens.

The monotonic tensile tests were performed with two rates of strain values: 20%/min (recommended by EN ISO 10319 [9]) and one tenth of that value, 2%/min.

The cyclic tensile tests were load controlled, divided in two categories: constant strain rate unload-reload tests (Figure 2a) and constant load rate unload-reload tests (Figure 2b).The constant strain rate tests were performed with rate of strain equal to 20%/min and 2%/min. The specimens were subjected to one unload-reload cycle at 10%, 20%, 40%, 60% and 80% of the geocomposite nominal tensile strength (Figure 2a).

The constant load rate tests were carried out with single load amplitude unload-reload cycles (with or without full cyclic unloading) and different loading frequencies. Each specimen was subjected to ten unload-reload cycles. This number of cycles was selected since it has been considered as a representative number of loading cycles for a typical strong earthquake [16]. Some tests were performed with loading amplitude equal to the maximum imposed load level (tests with full cyclic unloading) and other tests were carried out with amplitude equal to half of the maximum load level (as represented in

Figure 2b). Table 1 exhibits a summary of the cyclic constant load rate tests, as well as, the notation used.

At the end of the constant load rate tests, the specimens were totally unloaded and after a short period of time (approximately 5 minutes) they were subjected to a monotonic test with strain rate equal to 20%/min.

3 RESULTS AND DISCUSSION

3.1 General aspects

The discussion of the results of monotonic tensile tests is based on the values of the geosynthetic tensile strength, T_{max}, the geosynthetic strain for T_{max}, ε_{Tmax}, the initial tangent stiffness, J_0, the secant stiffness at strain of 5%, $J_{5\%}$, and the secant stiffness at ε_{Tmax}, J_{Tmax} (Figure 3a).

The results of cyclic tensile tests are presented and discussed using the values of the unload stiffness, J_{unload}, the reload stiffness, J_{reload}, the plastic strain, ε_p, the cumulative strain, ε_{cum}, and the damping ratio, D (Figure 3b) for each load cycle. The damping ratio, D, was obtained normalizing the energy dissipated in each cycle by the elastic strain energy. The strain accumulated from cyclic loading, ε_{cum}, was defined by the difference between the strain after the reload and the strain at the first unload cycle.

3.2 Effect of the loading strain rate on monotonic tensile tests

Figure 4 and Table 2 show the results of monotonic tensile tests performed with rate of strain equal to 20%/min as recommended by the European Standard [9]. The load-strain curves showed a slight concavity (S shaped curves) and the geocomposite presented a brittle failure (failure of PET yarns).

The average curve of the results is also plotted in Figure 4. The average curve was determined by fitting a fifth degree polynomial to the load-strain curve of each specimen. The calculation of the average curve of the tests is essential to make comparisons such as those related to the behaviour of different materials, the effect of strain rate or the effect of cyclic loading.

The values of the initial stiffness, the secant stiffness at 5% of strain and the secant stiffness for T_{max} (Figure 3a) were also included in Table 2. Table 2 shows that the average value of the geosynthetic tensile strength, obtained in the tensile tests, exceeded 10% its nominal strength (50 kN/m). The coefficient of variation either for the geosynthetic tensile strength or for the strain it was achieved, ε_{Tmax}, was around 4%. These coefficient of variation values are considered satisfactory indicating a slight variability in the test results.

The difference between the secant stiffness at strain of 5% and the secant stiffness at ε_{Tmax} was much smaller than the usual in other geosynthetic and it is justified by the almost linear shape of the load-strain curves (Figure 4). A small difference between the secant stiffness for small strains and the secant stiffness at failure was also reported by [17] for a polyester woven geotextile.

To appraise the effect of the strain rate on the load-extension behaviour of this geocomposite, a monotonic tensile test (5 specimens) with strain rate 10 times lower than the one specified by the EN ISO 10319 [9] was performed. The results are summarized in Table 3.

Figure 5 compares the average curves of tests carried out with strain rate of 20%/min and 2% /min. When the loading strain rate decreases, the same value of the tensile force is achieved for greater values of strain. For the lowest strain rate (2% /min), the geocomposite tensile strength slightly increased (2.2%) and the variability of the results for the 5 specimens decreased (Table 3). Comparatively to the results obtained for loading rate of 20%/min, the initial stiffness and the secant stiffness at failure decreased on average 26% and 12%, respectively (Tables 2 and 3).

The stiffness values obtained in accordance with standard tensile tests [9], [10] are not intrinsic properties of the material. They are stiffness values estimated with respect to the results of a particular standard test. In practice since the materials are not loaded with a standard rate (of strain or load) it is important to know how they will respond to different loading rates closer to the real loading conditions.

3.3 Constant strain rate cyclic tests

The constant strain rate cyclic tests were performed with rate of strain equal to 20%/min and 2%/min. The specimens were subjected to one unload-reload cycle at 10%, 20%, 40%, 60% and 80% of nominal tensile strength of the geosynthetic, T_{nom}. Figure 6 presents the load-strain behaviour of the geosynthetic under constant strain rate cyclic load tests. The cyclic load curves are compared with the average curve of monotonic tensile tests carried out with intact specimens.

The results presented in Figure 6 show that unload-reload cycles performed at load levels smaller than the geocomposite tensile strength did not induce, on average, significant strength reduction. The load-strain curves for the cyclic tests are close to the average curve of monotonic tensile tests. This implies that, for a given value of strain, unload and reload stiffness are greater than the secant stiffness for the same strain under monotonic loading. This is an important conclusion for numerical simulation of the geocomposite behaviour on reinforced soil structures subjected to dynamic loads.

The effect of the strain rate on the evolution of the unload stiffness (J_{unload}), reload stiffness (J_{reload}) and damping ratio (D) with the strain level are presented in Figure 7. The figure shows that, independently of the strain rate, the unload and reload stiffness initially decreased and then increased almost as a linear function of the strain level. The damping ratio had an inverse tendency. To show clearly these tendencies, the best fit straight lines for the two value of strain rate (20%/min and 2%/min) are also plotted. The described evolution of the unload stiffness, reload stiffness and damping ratio with the strain level could be justified by the S-shape of the load-strain curves (Figure 6).

For monotonic loading tests, as mentioned in 3.2, when the rate of strain decreased, the geosynthetic strain increased and, as a result, the secant stiffness is smaller for lower strain rates. For cyclic loading tests, this relationship is valid for the unload stiffness (Figure 7a) but is not true for the reload stiffness (Figure 7b). After the break point of the best fit straight lines, the influence of the loading strain rate on the unload stiffness, reload stiffness and damping ratio is not particularly significant.

3.4 Constant load rate cyclic tests

3.4.1 Results from cyclic unload-reload tests

The effect of the loading frequency on the load-strain relationship for the unload-reload cycles performed at 80% of the nominal strength (*T80_80*) is shown in Figure 8. The figure was divided in three graphs to simplify the interpretation of the results. The effect of the loading frequency is visible mainly on the first unload-reload cycle. For the range of frequencies studied, the plastic strain, ε_p, and the cumulative strain, ε_{cum}, decreased with the loading frequency.

The effect of the loading frequency on cumulative strain, ε_{cum},is illustrated in Figure 9. Figure 9(a) shows the strain accumulated from cyclic loading in constant load rate cyclic tests with full unloading and amplitude equal to 80% of the nominal tensile strength (tests *T80_80*) and Figure 9(b) exhibits the results of tests *T40_40* (loading amplitude equal to 40% of the nominal tensile strength). Figure 9 corroborates that

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cumulative strain decreases with frequency and, as expected, increases with loading amplitude. Although the reduced number of cycles (representative number for a typical strong earthquake), the relationship between the strain accumulated and the loading cycles seems to be hyperbolic.

The effect of the loading frequency on the reload stiffness normalized by the stiffness of the primary loading and on the damping ratio for tests *T40_40* (Table 1) is shown in Figure 10. For the range of analysed loading frequencies, the reload stiffness, J_{reload}, increased with the number of loading cycles, however the effect decreased after 5 loading cycles. After 10 loading cycles the reload stiffness of this geosynthetic is approximately twice of the primary loading stiffness.

Figure 10(b) points out the reduction of the damping ratio, D, with the number of loading cycles. For the range of loading frequencies of the present study, the effect of loading frequency on the damping ratio was not particularly significant. Even so, the damping ratio slightly decreased with frequency.

To avoid the publication of similar figures, the graphs with the results of the constant load rate cyclic tests performed with loading amplitude equal to 80% of the geosynthetic nominal strength (*T80_80*) were not included in the paper. The conclusions related to the effects of the loading frequency and loading cycles were similar.

Figure 11 compares the geocomposite load-strain behaviour for cyclic tests carried out with loading amplitude of 40% and 80% of the nominal strength and loading frequency equal to 0.02Hz. The average curve of monotonic loading tests performed with rate of strain equal to 20%/min was also represented in Figure 11. This figure provides evidence that the normalized reload stiffness was not greatly influenced by the loading amplitude. Notwithstanding for the same loading frequency, the damping ratio for the first five loading cycles was smaller for the tests *T80_80*.

In order to isolate the effect of the loading amplitude, particularly the effect of the full or partial cyclic unloading, cyclic loading tests with equal load rate but different loading amplitude were performed. Notice that, since the loading amplitude is different, to achieve the same value of the load rate, the tests were performed with distinct loading frequencies.

The load-strain curves for the test *T40_20* performed with loading frequency of 0.02Hz and for the test *T40_40* carried out with loading frequency of 0.01Hz are illustrated in Figure 12. The geosynthetic showed greater unload and reload stiffness values when was submitted to partial unload during cycles. As a result, the residual strains at the end of loading cycles were smaller for tests *T40_20* (average value of 4.2% for test *T40_20* and 5.0% for test *T40_40*). As expected, the cumulative strains were higher when the geocomposite was submitted to full cyclic unloading.

3.4.2 Results from post-cyclic monotonic load tests

At the end of unload-reload cycles the specimens were totally unloaded and after approximately 5 minutes they were subjected to a monotonic tensile test with strain rate equal to 20%/min. Figure 13 presents the load-strain curves of three specimens previously subjected to the cyclic load test *T40_40* (f = 0.01Hz) and the average curve of the monotonic loading test performed with intact specimens.

The analysis of Figure 13 shows that when the specimens were previously subjected to cyclic loading, the geocomposite stiffness increased and, consequently, the strain at maximum load decreased. The geosynthetic strength does not seem to be largely affected by previous cyclic loading. Even so, the progressive failure of the polyester yarns due, possibly, to fatigue phenomena is visible in the three specimens (Figure 13).

The mean value of the maximum load reached in specimens previously submitted to cyclic loading, $T_{max,cyc}$, was normalized by the mean value of the maximum load achieved in intact specimens, T_{max}. Figure 14 presents the normalized tensile strength of the geocomposite as a function of the mean value of the maximum strain recorded during cyclic loading, $\varepsilon_{max,cyc}$. It can be observed that in some tests a slight loss of strength was recorded while in other tests a small increase of strength was reached. So it can be conclude that the cyclic loading did not induce a significant reduction of the geocomposite tensile strength.

4 CONCLUSIONS

To better understand the performance of the reinforced soil mass particularly under repeated loading, it is necessary to investigate in laboratory the geosynthetic response to simple loading conditions. Although the number of cycles (assumed as representative for a typical strong earthquake [16]) and the range of loading frequencies could be considered limited, the experimental work herein presented allows to draw some important conclusions:

- the tensile load-strain behaviour of the geocomposite during monotonic loading are rate-dependent. At faster strain rates the behaviour of the geocomposite was stiffer; this conclusion could be extended to the cyclic loading tests;
- the load-strain curves for the constant strain rate unload-reload tests are close to the average curve of the monotonic load tests. Thus, the unload stiffness and reload stiffness are greater than the secant stiffness for the same strain under monotonic loading;

- the damping ratio tended to decrease with the number of loading cycles and the stiffness of the geocomposite showed an inverse tendency: the geocomposite became stiffer with loading cycles;

- the stiffness increased and the damping ratio decreased with loading frequency;

- previous cyclic loading, performed at load levels smaller than the geocomposite tensile strength, did not induce significant strength reduction. In some cases, a small increase of strength was recorded.

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TABLES

Table 1. Summary of the cyclic constant load rate tests.

Test designation	Maximum load level (%T_{nom})	Amplitude of cycles (%T_{nom})	Frequency (Hz)	Number of cycles
T80_80	80	80	0.001, 0.005, 0.02	10
T40_40	40	40	0.005, 0.01, 0.02, 0.05	10
T40_20(*)	40	20	0.02	10

(*) schematically represented in Figure 2b

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Table 2. Summary of the results of monotonic tensile tests - strain rate = 20%/min.

	T_{max} (kN/m)	ε_{Tmax} (%)	J_o (kN/m)	$J_{5\%}$ (kN/m)	J_{Tmax} (kN/m)
Specimen 1	57.2	16.6	466	318	344
Specimen 2	52.2	15.4	464	310	340
Specimen 3	56.6	16.8	449	313	336
Specimen 4	57.2	16.3	479	317	351
Specimen 5	53.5	15.6	432	312	344
Mean value	55.3	16.1	458	314	343
Standard deviation	2.3	0.6	18	3	6
Coef. of variation (%)	4.2	4.0	3.9	1.1	1.7

Table 3. Summary of the results of monotonic tensile tests - strain rate = 2%/min.

	T_{max} (kN/m)	ε_{Tmax} (%)	J_o (kN/m)	$J_{5\%}$ (kN/m)	J_{Tmax} (kN/m)
Specimen 1	57.3	18.8	313	262	304
Specimen 2	57.3	19.1	324	259	299
Specimen 3	56.7	18.6	339	253	305
Specimen 4	55.3	18.2	310	259	304
Specimen 5	55.8	18.3	415	287	305
Mean value	56.5	18.6	340	264	303
Standard deviation	0.9	0.4	44	13	2
Coef. of variation (%)	1.6	2.0	12.8	4.9	0.8

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