COMBINED EFFECT OF DAMAGE DURING INSTALLATION AND LONG-TERM MECHANICAL BEHAVIOUR OF GEOSYNTHETICS

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Abstract: One of the main questions in using geosynthetics in civil works or ground applications is their durability, in particular, the mechanical actions to which they are subject during the installation processes and construction. Under these actions the geosynthetics can be damaged and the changes in their properties can compromise the performance of the constructions where these materials are used.

To contribute to the comprehension of the effect of damage during installation on long-term mechanical behaviour of geosynthetics, a research program was established. Two different geosynthetics have been studied: a woven PP-tape and a woven PE geogrid. These materials have been subjected to field damage tests, using two different soils and two compaction energies. To characterise the effect of the damage induced in the long-term mechanical behaviour, tensile creep tests and creep rupture tests were carried out, in accordance with the procedures described in EN ISO 13431. The results obtained are compared and discussed. The main conclusions of the study are presented.

Keywords: Durability, damage, creep, creep rupture, long-term behaviour.

INTRODUCTION

One of the main questions in using geosynthetics in civil works or ground applications is their durability, in particular, the mechanical actions to which they are subject during the installation processes and construction. Under these actions the geosynthetics can be damaged and the changes in their properties can compromise the performance of the constructions where these materials are used.

Therefore it is important to assess the effect of damage during installation (DDI) of geosynthetics on their properties. Traditionally the targets of this type of study are the mechanical properties of geosynthetics.

Then, to contribute to the evaluation of the effects of the installation damage of geosynthetics on their mechanical behaviour, a research program was established. A woven geotextile and a woven geogrid were submitted to field damage tests and the short and long-term mechanical behaviour of these materials was studied.

MATERIALS AND TEST PROGRAM

Geosynthetics

The research program implemented includes a larger number of geosynthetics (Pinho-Lopes *et al.* 2000, Pinho-Lopes *et al.* 2002 and Pinho-Lopes 2006). The results presented refer only to two geosynthetics (Table 1):

- a woven polypropylene geotextile (GTXt);
- a biaxial woven polyester geogrid (GGRt).

To allow the results to be compared, the geosynthetics were chosen with similar values for their nominal tensile strength, ranging from 55 to 65kN/m. This way, the effect of the type of geosynthetic on the properties studied can be analysed.

Table 1. Geosynthetics studied

Material		Nominal Strength (kN/m) MD*/CMD†
1	Woven polypropylene geotextile (GTXt)	65/65
2	Woven polyester geogrid (GGRt)	55/55

* MD – machine direction
† CMD – cross machine direction

Test program

The test program established consists of: 1) inducing the effects of the installation damage in field, under real conditions, on samples of geosynthetics; and 2) characterising the effects of the damaged induced on the mechanical behaviour of the geosynthetics in isolation. The mechanical response of the geosynthetics studied was the short-term behaviour (tensile tests, in accordance with EN ISO 10319) and the long-term behaviour (creep and creep rupture tests, in accordance with EN ISO 13431).

To carry out field damage tests, experimental embankments were built, using adequate construction procedures. More details can be found in Pinho-Lopes *et al.* (2002) and Pinho-Lopes (2006). After their installation, the geosynthetics were exhumed and recovered for testing. The geosynthetics were installed in contact with two different soils: Soil 1 is an aggregate used in road construction, while Soil 2 is a residual soil from granite (Table 2). To study the effect of the compaction energy in the damage induced, two different compaction energies were considered (CE1 – 90% of the normal Proctor and CE2 – 98% of the normal Proctor). Therefore, four different embankments were built.

Table 2. Results obtained from the laboratorial characterization of Soil 1 and Soil 2

Soil	% < 0,074mm	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	D_{max} (mm)	C_u	C_C
Soil 1	5.18	0.22	2.68	11.78	19.15	50.80	87.81	1.71
Soil 2	21.53	0.07	0.17	0.38	0.68	5.00	9.64	0.58

As mentioned before, the evaluation of the damage induced on the geosynthetics was carried out by submitting intact (reference) and damaged materials to the same index tests: wide-width tensile tests (EN ISO 10319), creep rupture tests and creep test (EN ISO 13431).

According with EN ISO 13431, for the creep tests the specimens are submitted to a static load for 1000 hours and the strain of the specimen is recorded. In this study, creep tests were carried out for load levels under 60% of the tensile strength of the materials.

For the creep rupture tests the static load is kept constant until the specimen ruptures and the time until rupture is registered. These tests were carried out for different load levels, ranging from 50% to 90% of the tensile strength of the materials studied. Three specimens were tested for each load level, in a total of 12 specimens for each type of sample considered.

ANALYSES AND RESULTS

Tensile tests

The results obtained from the wide-width tensile tests are presented in Table 3 in terms of the tensile strength, strain for rupture and the corresponding values of the coefficient of variation.

The same results are presented in Table 4 in terms of residual tensile strength and residual strain for the tensile strength of the different types of specimens tested. These quantities are defined by the following equation:

$$X_{residual} = X_{damaged} / X_{intact} \times 100 \text{ (in \%)}$$

Where $X_{residual}$ is the residual value of the property after damage during installation (DDI) (residual strength, $S_{residual}$, or residual strain, $\varepsilon_{Fmáx\ res}$), $X_{damaged}$ is the value of the property after DDI (tensile strength and the strain of the damaged material) and X_{intact} is the same parameter corresponding to reference (intact) samples.

Table 3. Results obtained from the tensile tests – tensile strength (S), coefficient of variation of the tensile strength (CV_S), strain for the tensile strength (ε) and coefficient of variation of the strain (CV_ε)

Geosynthetic	Quantity	Intact material	After DDI field tests			
			Soil 1		Soil 2	
			CE1	CE2	CE1	CE2
GTXt	S (kN/m)	77.5	43.7	26.4	*	70.4
	CV_s (%)	1.8	8.6	5.0	*	1.0
	ε (%)	13.0	8.9	7.1	*	11.7
	CV_ε (%)	4.8	13.1	7.9	*	5.6
GGRt	S (kN/m)	83.4	52.0	45.9	64.5	62.2
	CV_s (%)	2.4	8.8	8.7	6.0	6.3
	ε (%)	14.9	11.8	11.9	13.8	13.2
	CV_ε (%)	5.7	5.1	2.5	4.6	3.1

* It was not possible to obtain this result

Table 4. Results obtained from the tensile test – residual strength and residual strain for the tensile strength

Geosynthetic	Quantity (%)	Soil 1		Soil 2	
		CE1	CE2	CE1	CE2
GTXt	$S_{residual}$	56.4	34.0	*	90.6
	$\varepsilon_{Fmáx\ res}$	68.3	54.8	*	90.7
GGRt	$S_{residual}$	62.4	55.0	77.3	74.6
	$\varepsilon_{Fmáx\ res}$	79.2	79.9	92.6	88.6

* It was not possible to obtain this result

The residual strength for GTXt ranges between 34.0% and 90.6%; for GGRt, the extreme values for the residual strength are 55.0% and 74,6%. The lowest values of the residual strength refer to the samples obtained after DDI with Soil 1 and CE2.

The coefficient of variation of the tensile strength is under 2.5% for all the undamaged samples of geosynthetics, and for the damaged materials ranges between 1.0% and 8.8%. The highest value of the coefficient of variation of the tensile strength corresponds to the geosynthetics in contact with the Soil 1: about 9%. It is curious to note that the highest values of the coefficient of variation are associated with the lowest values for the residual strength, which indicates that the more severe observed damage was associated with large variability in that damage and its consequences.

The residual strain for the tensile strength of the geosynthetics studied ranges from 54.8% to 92.6%. In general, the reductions of this quantity follow the same trend of the residual tensile strength. Nevertheless, in most cases the reduction of strain after the damage induced is smaller than the one observed for the strength.

The coefficient of variation of the strain for the tensile strength of the undamaged samples is higher than the one for the corresponding tensile strength, 4.8% and 5.7% for GTXt and GGRt, respectively. After damage, a separate analysis has to be done. For the GTXt, the values obtained range from 5.6% to 13.1%, higher than for the undamaged material; however, for GGRt, these values range from 2.5% to 5.1%, always being lower than the ones obtained for the reference samples. This means that the damage induced on GGRt under the four the different conditions considered is less variable, in terms of the strain for the tensile strength, than the same quantity for the reference material.

Therefore, it can be concluded that, though the specimens were damaged and tested under the same conditions, there is some scatter of the results obtained.

To try to better understand the results obtained, analysis was attempted on the influence of several factors on the effects of the DDI induced on the geosynthetics. Among these factors were the structure and strength of the geosynthetic and the field damage tests type (type of soil and compaction energy used).

Regarding the type (or structure) of the geosynthetic, when damaged with Soil 1 the same trend was observed for the two geosynthetics: GGRt had lower strength and strain reductions for the two compactions energies considered. For the results referring to Soil 2, the opposite trend was observed. As mentioned before, Soil 1 induced more severe consequences. Therefore, for these conditions (i.e., the more aggressive soil) the response of the geogrid is better than that of the geotextile. This can be partially explained by the area of the geosynthetic in contact with the soil, which is greater for the geotextile, being more exposed to mechanical damage.

The strength of the two geosynthetics considered is quite similar, which allows the comparison of results and the evaluation of the influence of the type of structure of the geosynthetic. Therefore, this is not a parameter than can be analysed from the results presented in the present work. Nevertheless, it can be noted that GTXt has slightly higher strength and, for most cases, lower endurance for the DDI induced, in terms of residual strength. This can indicate that, for these materials and for the test conditions considered, the influence of the structure of the geosynthetic is greater than the strength of the materials.

As far as the field damage test conditions are concerned, the effect of the type of soil and of the compaction energy used should be analysed separately.

To assess the effect of the type of soil, results referring to the same compaction energy should be analysed. As it was not possible to study GTXt for Soil 2 and CE1, this analysis is referred to CE2. Then, the results obtained for CE1 are compared. From Tables 3 and 4 it is clear that the more aggressive soil is Soil 1, with values for the residual strength of GTXt and GGRt of 34% and 55% respectively (and of 91% and 75%, for Soil 2). These differences can be explained by the type of soil: Soil 1 (D_{50}=11.78mm), with grains larger than Soil 2 (D_{50}=0.38mm), is more “aggressive” to the geosynthetics inducing more severe consequences.

As expected, the compaction energy used in the field DDI tests influences the changes in the mechanical behaviour of the geosynthetics. Higher compaction energy (CE2) corresponds to lower values of the residual strength and strain.

After the damage during installation field tests it is possible to define values for the corresponding partial safety factors to be used in the design of the geosynthetics (Table 5) from the following equation:

$$\gamma_{DDI} = S_{intact} / S_{damaged}$$

Where γ_{DDI} is the partial safety factor for damage during installation, S_{intact} is the tensile strength of the undamaged material and the $S_{damaged}$ is the tensile strength of the damaged material.

Table 5. Partial safety factors for damage during installation

Geosynthetic	γ_{DDI}			
	Soil 1		Soil 2	
	CE1	CE2	CE1	CE2
GTXt	1.77	2.94	*	1.10
GGRt	1.60	1.84	1.29	1.34

* It was not possible to obtain this result

The values obtained for the partial safety factors for DDI reflect the influence of the factors referred before. These values range from 1.10 (for GTXt after DDI with Soil 2 CE2) to 2.94 (for GTXt after DDI with Soil 1 CE2).

Long-term tests

Results of creep rupture tests

In Figure 1 the results obtained from the creep rupture tests are presented, as well as the creep rupture curves and the lower confidence limit curves for 95% (LCL 95%) for the two geosynthetics studied and the different types of samples considered. Such results allow the prediction of the design life of the material, using extrapolations. However, such extrapolations should be done with extreme care and precaution. For this reason, the extrapolations have been done for lifetimes of 30 years only.

For all the types of samples tested, it is observed that the slopes of the creep rupture curves for damaged material are less than those of the corresponding undamaged material. In fact, the creep rupture curves for the damaged material would meet the line for the undamaged material beyond 10^6 hours.

It has to be noted that the scatter of results from the creep rupture tests of most of the damaged materials is large and the R^2 parameter for those data trend lines can be quite low (ranging from 0.37 to 0.86). These linear interpolations can be improved if some of the results are not considered. However, it was considered useful to keep all the results obtained in the graphs, as they help one to understand the dispersion of behaviour observed after DDI, particularly for the most affected samples (GTXt after DDI with Soil 1 and CE2). It is important to note that, for GGRt after DDI with Soil 1 and CE1 (with residual strength of 62.4%) the scatter observed for the creep rupture behaviour was higher than for GGRt after DDI with Soil 1 and CE2 (with residual strength of 55.0%). Therefore, in spite of suffering greater strength reductions with higher compaction energy, in terms of long-term behaviour, the response of this geogrid after DDI with Soil 1 (the more aggressive soil) and lower compaction energy is more consistent.

As a consequence, further results are needed before establishing any definitive conclusion.

Nevertheless, from the results available and for a lifetime of 30 years, it can be determined that the rupture of GTXt intact would occur for a load of 49.7% of the tensile strength of the material, while for GGRt the intact material would rupture for a load of 56.7% of the corresponding quantity. These values indicate that the long-term behaviour (after 30 years) of GTXt is more affected by the DDI induced than the one of GGRt.

The European approach to design uses partial reduction factors to represent the different agents that contribute to the reduction of strength of geosynthetics during their lifetime. Traditionally this is done by using different reduction factors and superimposing their effects. With the results obtained in this work, the values of the reduction factors for DDI and creep rupture were determined, by considering the synergy between these two mechanisms, using the methodology described by Pinho Lopes *et al.* (2000). More details are presented by Pinho Lopes (2006).

These reduction factors ($\gamma_{CREEP,DDI}$) were determine by using the following equation:

$$\gamma_{CREEP,DDI} = F_{1min,ref} / F_{30years,da}$$

Where $F_{1min,ref}$ is the load for rupture after 1 minute for the intact samples (reference) and $F_{30years,da}$ is the load for rupture after 30 years. The values obtained are presented in Table 6. Obviously, the values presented for the intact materials refer only to the effect of creep rupture (as no damage was induced) as can be designated by γ_{CREEP}.

Table 6. Partial safety factors for creep rupture and damage during installation – considering synergy

Geosynthetic	$\gamma_{CREEP,DDI}$				
	Intact	Soil 1		Soil 2	
		CE1	CE 2	CE 1	CE 2
GTXt	1.74	4.37	9.78	*	1.91
GGRt	1.47	2.14	*	1.91	*

* It was not possible to obtain this result

The values of these reduction factors range from 1.47 to 9.78. This last and highest value corresponds to GTXt after DDI with Soil 1 CE2, the material and type of sample most affected by the damage induced in the field trials.

In Table 7 the values for the reduction factors for creep rupture and DDI determined by the traditional approach (superimposition of the effects of creep rupture and DDI considered separately) are presented. These factors are determined by multiplying the partial reductions factors for DDI (γ_{DDI}) and for creep rupture (γ_{CREEP}).

$$\gamma_{CREEP,DDI,\ trad} = \gamma_{CREEP} \text{ x } \gamma_{DDI}$$

Table 7. Partial safety factors for creep rupture and damage during installation – traditional approach (superimposition of effects)

Geosynthetic	$\gamma_{CREEP,DDI,\ trad}$			
	Soil 1		Soil 2	
	CE1	CE2	CE1	CE2
GTXt	3.08	5.12	*	1.91
GGRt	2.35	2.07	1.90	1.97

* It was not possible to obtain this result

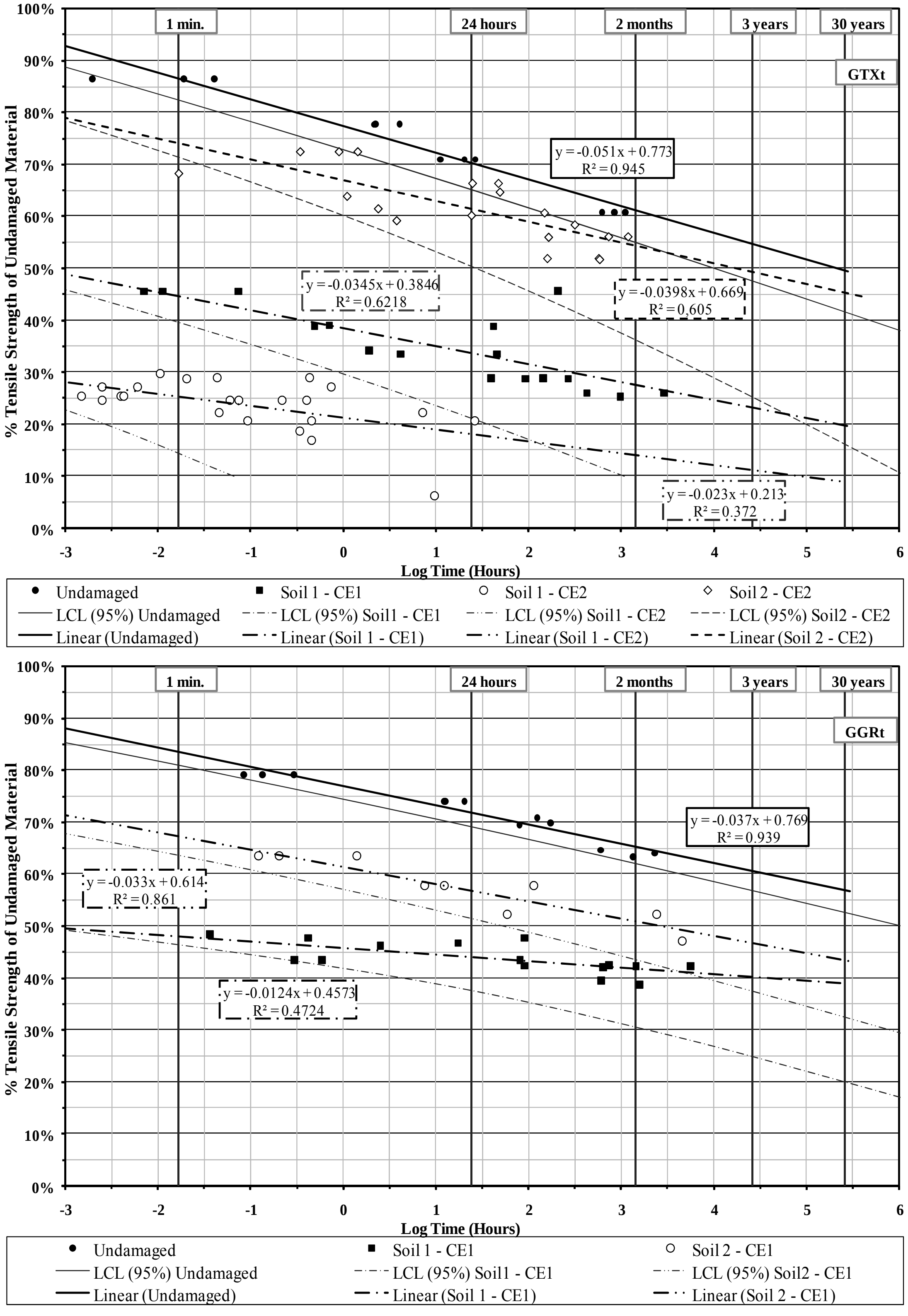

Figure 1. Creep rupture curves obtained for GTXt and for GGRt.

By comparing the values presented in Tables 6 and 7, it is possible to conclude that for Soil 2 the traditional approach gives a good estimate of the values obtained after inducing DDI and creep rupture of these two geosynthetics, as well as for GGRt after DDI with Soil 1 and CE1. However, for the values available for the materials damaged with Soil 1, in particular for GTXt, the traditional approach leads to unsafe values.

Results of creep tests

In this study, creep tests were carried out for load levels below 60% of the tensile strength of the materials.

In Figure 2, the results of the creep tests of the GTXt undamaged and damaged with Soil 1 and CE1 and Soil 2 and CE2 are presented. In Figure 3 the results of the creep tests of GGRt to undamaged and damaged with Soil 1 and CE1 and Soil 2 and CE1 are presented. The creep tests of both GTXt and GGRt damaged with Soil 1 and CE2 and GGRt damaged with Soil 2 and CE2 are not available because, at the time of preparation of this paper, the tests were still running.

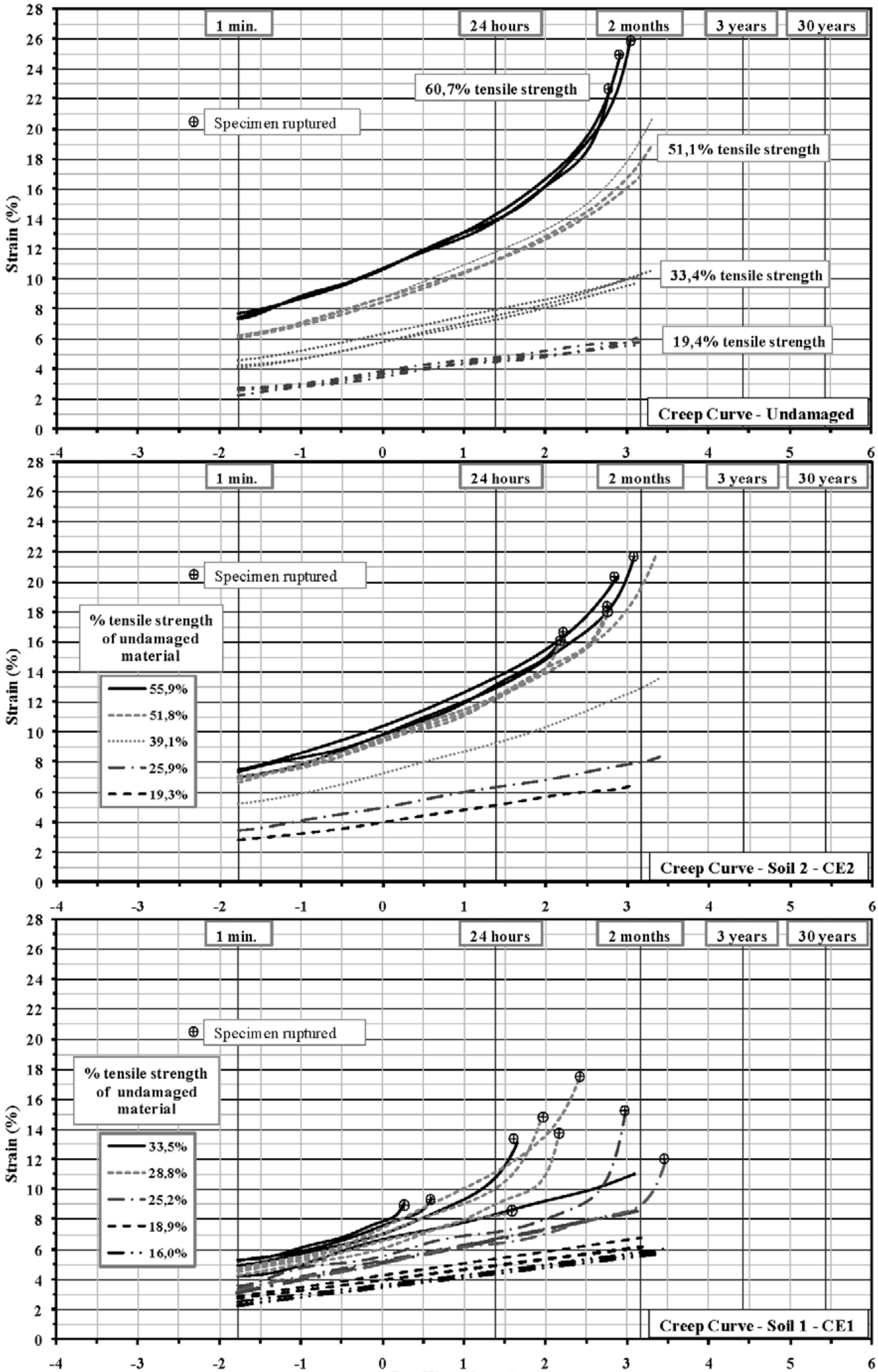

Figure 2. Creep curves of the GTXt (EN ISO 13431 1999)

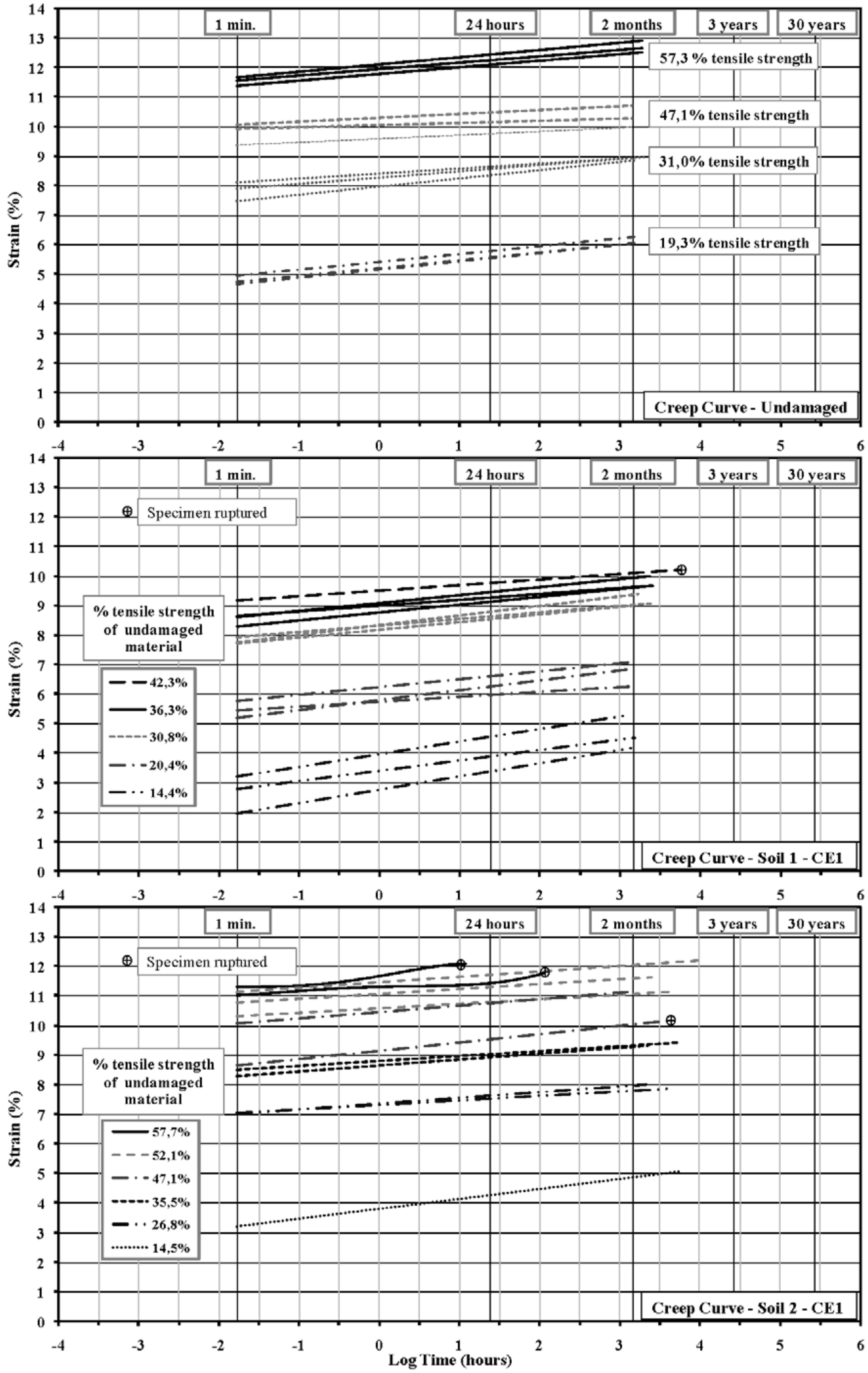

Figure 3. Creep curves of the GGRt (EN ISO 13431 1999)

The load levels applied to each specimen are indicated in Figures 2 and 3 as a percentage of the tensile strength of undamaged material. In some cases, for each percentage load, three specimens have been tested.

As expected, the strains obtained for the higher load levels applied to the geosynthetics are more important.

For GTXt, the undamaged specimens ruptured when loaded to 60.7% of their tensile strength. The tests on the other specimens, with lower imposed load levels, were stopped after 1440hours (about two months). Therefore, these results should be used with care, particularly when extrapolating values, as there could have been rupture of the specimens for longer durations.

Some specimens of GTXt after DDI also ruptured during the creep tests. For this geosynthetic it is evident that the strain ratio increases before rupture, which can be a good indicator that rupture is about to happen.

For the specimens loaded with smaller values of the static load, the strain ratio is constant in time (on a log scale).

As observed for the other tests results, after damage the scatter of results generally increases, particularly after DDI with Soil 1 and CE1 (for GTXt after DDI with Soil 1 and CE2 there is not enough information).

For undamaged specimens of GGRt there was no rupture before the creep tests were stopped after 1440hours. Therefore, the comments referred for GTXt are also relevant for this material.

There was rupture of some damaged specimens of GGRt. However, there was no increase in the strain ratio before rupture, which does not allow for the anticipation of rupture. In fact, for most of the specimens of GGRt tested, both intact and damaged, the strain ratio remains constant through the tests period in time (on a log scale).

As observed for the other tests results and for GTXt, after damage the scatter of results generally increases.

CONCLUSIONS

In this work the effect of installation damage on the short and long-term mechanical behaviour of a woven geotextile and of a woven geogrid was studied. Field damage tests were carried out using two different soils and two compaction energies. To characterize the mechanical behaviour of the materials, wide-width tensile tests, creep rupture and creep tests were carried out.

From and for the results presented it is possible to conclude:

- The effect of the type of geosynthetic on the short and long-term mechanical behaviour was shown. The values for the partial safety factors for DDI and creep rupture obtained for the geogrid were lower than for the geotextile. The geotextile is generally more sensitive to DDI than the geogrid, which may be caused by the larger area in contact with the soil.
- The effect of the type of soil and of the compaction energy on the short-term mechanical behaviour of the geosynthetics was also observed. The soil with larger particles was more aggressive (Soil 1) and higher compaction energy (CE2) led to greater reductions in the mechanical properties.
- As far as the creep rupture behaviour of the undamaged materials is concerned, the GTXt exhibits higher reduction of the load leading to rupture after the same lifetime (30 years) than GGRt, which indicates that GTXt is more affected by creep.
- The effect of the creep rupture on the damaged materials is shown. The scatter of results increases which leads to poorer trend lines.
- The partial safety factors for the combined and simultaneous effect of DDI and creep were analysed and compared with values for the traditional approach (superimposition of effects). In some cases (that correspond to the most severe conditions) the traditional approach leads to unsafe values. These results have to be confirmed by longer duration tests.
- For the creep tests, the strains increased with the load level applied to the specimens. For GTXt the increase in the strain ratio allows the anticipation of rupture. For GGRt there wass no such increase.
- The results of the creep tests of the damaged samples have some scatter, namely after DDI with Soil 1 (the most aggressive).

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