Title: Synergisms between laboratory mechanical and abrasion damage on mechanical and hydraulic properties of geosynthetics

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Highlights

- Laboratory damage tests were performed on a geotextile, a geogrid and a geocomposite.
- Abrasion damage was the most important mechanism for the tensile response.
- Mechanical damage was the most important mechanism for the hydraulic properties.
- Positive synergy between mechanical and abrasion damage for the tensile properties.
- Traditional approach for estimating hydraulic properties is likely unsafe.

Abstract:

This paper analyses the existence of synergisms between some endurance durability agents of geosynthetics – mechanical damage (usually associated with installation) and abrasion damage (often associated with cyclic actions, for example due to contact with ballast). Three geosynthetics (geotextile, geogrid and geocomposite) were submitted to mechanical damage and abrasion damage using index laboratory tests. The geosynthetics were exposed first individually to each agent (single exposure) and then sequentially to the two agents (multiple exposures). To ensure the results were statistical representative, each set of tests was performed three times. The consequences of the damage induced were visible (naked eye). Abrasion damage was found the most critical damage mechanism for the tensile properties, particularly for the geogrid and geocomposite tested. The connections between their components created potential fragility points in the abrasion test. Due to its structure, combined with high mass per unit area and thickness, the geotextile tested survived well the damage induced. A positive

synergy between the mechanical and the abrasion damage induced was found for the tensile properties of the geosynthetics most affected by damage, more important for their tensile strength than for their secant stiffness. The mechanical damage was the most critical mechanism for the permittivity of the geotextile and the geocomposite, likely due to clogging of their pores. For the permittivity and the characteristic opening size of these geosynthetics, negative synergy between mechanical and abrasion damage was found; the traditional approach was found likely to result in unsafe estimates of these properties.

Keywords:

Geosynthetics, mechanical damage, abrasion damage, mechanical properties, hydraulic properties

1 INTRODUCTION

Geosynthetics are often used in transportation engineering applications, replacing traditional construction materials or enhancing them and increasing the sustainability of engineering works. The functions of geosynthetics are drainage, filtration, protection, reinforcement, separation, surface erosion control, barrier and stress relief (EN ISO 10318-1). Although it is common to identify a primary function, in many cases geosynthetics perform two or more functions simultaneously. Geosynthetics are designed for all those functions, considering their hierarchy. Durability of geosynthetics is one of the key issues affecting their performance and includes (Koerner, 2005): degradation (oxidation, ultra-violet radiation, hydrolysis and chemical and biological agents) and endurance (installation damage, creep, stress relaxation, abrasion and compressive creep). Several studies have focused on the beneficial effect of using geosynthetics in transportation engineering (for example, Hussaini et al., 2015, Chen et al., 2014, Indraratna et al., 2014, Indraratna et al., 2013, Chen et al., 2012). Examples of such favourable effects include: providing additional lateral confinement of aggregates, reducing settlements, increasing stiffness, reducing rutting, providing drainage and filtering fine particles. However, during service the geosynthetics properties may differ significantly from their initial values. Therefore, understanding how functional properties of geosynthetics are affected by the endurance durability agents and mechanisms is essential to achieve realistic and economic designs.

This paper focus on two endurance durability factors: mechanical damage and abrasion damage. Mechanical damage resulting from installation procedures (which encompass handling

and placing the geosynthetics and compaction actions associated with the placement of fill material) can considerably affect the performance of geosynthetics. Such damage is relevant to most applications of geosynthetics and its effects on relevant functional properties of geosynthetics (mechanical and hydraulic) need to be quantified. For some applications, where there is cyclic relative motion (friction) between the geosynthetic and contact soil during service, abrasion is relevant. The synergy between mechanical and abrasion damage on properties of geosynthetics are yet to be studied extensively. Some authors (e.g., Greenwood et al., 2012) point out the high scatter associated with relevant properties of geosynthetics after damage (usually after one mechanism only) and the need to increase the number of specimens tested.

The mechanical damage associated with installation depends on the geosynthetic (its structure and nature of the constituent polymer; Hufenus et al., 2005), fill material (grain size, angularity, thickness of layers), procedures and construction equipment and climatic conditions (Want and Chew, 2002). Adequate selection of the material and control of the installation conditions can minimise the mechanical damage induced during installation. Nevertheless, often such damage cannot be avoided.

The consequences of installation damage on the mechanical properties of geosynthetics have been studied using field damage tests (Pinho-Lopes and Lopes, 2013, Lim and McCartney, 2013, Bathurst et al., 2011, Hufenus et al., 2005, Bräü, 1998, Allen and Bathurst, 1994); mechanical damage due to installation has been simulated using laboratory tests (ENV ISO 10722-1 or EN ISO 10722); correlations between those two types of tests have also been attempted (Pinho-Lopes and Lopes, 2013 and Huang and Wang, 2007). According to Huang and Wang (2007), using an aggregate similar to that of the project and changing the cyclic load intensity, the standard laboratory test ENV ISO 10722-1 could properly simulate field installation damage. Pinho-Lopes and Lopes (2013) concluded that, for the set of materials and conditions considered, the laboratory damage tests was more severe than the field trials.

Mechanical damage due to installation can cause strength reductions and changes in the hydraulic properties of geosynthetics (Greenwood et al., 2012), as installation in coarse aggregates and severe handling of materials results in cuts and holes (visible), and poor placing can create folds and local stresses, enabling initiation of other forms of degradation. Often strength reductions can be quantified directly. For some applications, strength reductions during service are neglected, assuming that the mechanical loads in service are much lower than those induced during the short installation period and that the damage they cause is insignificant. For other applications (railways and roads), further damage can be caused by continuous dynamic

loading. Thus, in such cases the lifetime of geosynthetics will be governed by abrasion and fatigue (Greenwood et al., 2012).

Abrasion damage of geosynthetics has been studied less extensively than mechanical damage. Van Dine et al. (1982) reported an assessment of abrasion processes on geotextiles, identifying peeling, splitting and cutting for woven geotextiles and peeling, flattening, clumping and cutting for non-woven geotextiles. The mass per unit area of geosynthetics and the volume of traffic were linked with losses of tensile strength of geotextiles due to abrasion in railways (Hausmann et al., 1990). Focusing on seashore and river bank protection structures, Huang et al. (2007) and Huang (2008) tried to link potential in-field abrasion damage of a geotextile to that obtained in laboratory index tests as in EN ISO 13427. Although the abrasion index test is valid for all geosynthetics, it has been evaluated mostly for geotextiles (Perkins 2007). Perkins (2007) pointed out the need to make available a larger database of results for other materials, which the present paper also tries to address.

Rosete et al. (2013) studied the effect of mechanical damage and abrasion damage (in isolation and combined, sequentially) on mechanical and hydraulic properties of six geosynthetics, using index laboratory tests, accompanied by visual inspections. Woven materials with a sheet structure were found more sensitive to damage, particularly due to abrasion. A positive synergy between mechanical damage and abrasion damage was observed for most geosynthetics. In some cases, the variability of results after damage was important.

In real conditions, mechanical damage and abrasion damage do not act in isolation. Thus, identifying and quantifying synergisms between them may contribute to better understating the response of geosynthetics. Identifying the interactions between these agents can help understanding the durability of geosynthetics and their effects on different functional properties that geosynthetics have to attain simultaneously, such as in transportation engineering applications.

2 GEOSYNTHETICS

Three geosynthetics were studied (same nominal tensile strength and different structures):

- a nonwoven geotextile (GTX), with continuous mechanically bonded polypropylene (PP) filaments;
- a woven geogrid (GGR), comprising high modulus polyester (PET) fibres knitted in a flat orientation and covered with a protective polymeric coating;
- an uniaxial geocomposite (GCR) constituted by high modulus PET fibres (yarns) attached to a nonwoven continuous filament geotextile backing.

Table 1 summarises some of their (nominal) properties (from their technical datasheets): peak tensile strength, T_{nom} , and strain at break, ε_{nom} , at machine direction (EN ISO 10319); permittivity, ψ_{nom} (EN ISO 11058); characteristic opening size, $O_{90\ nom}$ (EN ISO 12956); mass per unit area, μ_{nom} of the products containing a geotextile (EN ISO 9864); thickness, t_{nom} (EN ISO 9863-1); and grid spacing of the geogrid (equal for machine and cross machine direction).

3 EXPERIMENTAL PROGRAM

3.1 Test program

The experimental programme consisted of performing laboratory index tests to: 1) do single and multiple exposures of the geosynthetics to mechanical damage under cyclic loading and to abrasion damage; 2) characterise the consequences of the damage induced on several properties of the geosynthetics. The multiple exposures to damage were achieved by sequentially inducing the effects of mechanical damage and abrasion damage.

A visual observation of the damaged geosynthetics was performed, to identify relevant damage mechanisms. To assess the tensile properties of the samples wide-width tensile tests were performed (EN ISO 10319). For characterising the hydraulic properties (permittivity and characteristic opening size) the test standards used were EN ISO 11058 and EN ISO 12956, respectively. Each test was performed three times (Table 2).

3.2 Laboratory damage

Index damage tests (using standardised procedures) were chosen, to enable similar test conditions, ensuring repeatability and minimising the heterogeneity of responses after damage. Thus, it is expected the mechanisms of damage were similar for all specimens tested under the same conditions.

The damage laboratory tests do not intend simulating realistic conditions, but only to enable comparisons between materials tested under the same conditions, for example for CE marking (where CE stands for *Conformité Européenne*, in French). CE marking represents the declaration that a product conforms to all applicable European legislation and is mandatory for a product to be placed legally on the market in any European member state.

The mechanical damage test equipment consists of a frame to apply cyclic loads and a container (EN ISO 10722). For the test, a geosynthetic specimen is placed between two layers of a synthetic aggregate (Figure 1). The aggregate is a sintered aluminium oxide (corundum)

with grain sizes between 5 mm and 10 mm. During the test, cyclic loading (10 kPa to 500 kPa) is applied at a frequency of 1 Hz for 200 loading cycles. After the loading (Figure 1b), the specimen is removed carefully and subjected to a characterisation test (usually to assess mechanical or, sometimes, hydraulic properties). If necessary the aggregate should be wet sieved on a 5 mm aperture sieve after every three uses, discarding any material passing the sieve. After 20 uses the material should be completely discarded (EN ISO 10722).

For simulating abrasion damage (EN ISO 13427) a specimen is placed on a stationary platform (upper plate) and rubbed by an abrasive film (P100) placed on the lower plate (Figure 2a). During the test the lower plate is moved along a horizontal axis, under controlled pressure conditions and abrasive action. The specimen-abrasive contact area is 220 mm wide and 300 mm long. After securing the specimen and the abrasive film to the respective plates, the top plate is loaded to enable a pressure of 6 kPa at the geosynthetic (Figure 2b). The test ends after 750 cycles (1 cycle = 1 double pass); the specimen is removed carefully and subjected to a characterisation test. For geotextile GTX the test setup was slightly changed (Rosete et al., 2013).

3.3 Characterisation of the geosynthetics

To assess the type and the severity of the damage induced (naked eye) visual inspections were done. A photographic record was performed, using rulers as a scale reference.

In the tensile tests (EN ISO 10319), a specimen (200 mm wide and 100 mm long) is submitted to an increasing tensile force at a strain rate of 20% per minute, until rupture. The jaws used were capstan jaws for geogrid GGR and wedge jaws for geotextile GTX and geocomposite GCR. The strains were measured with a video-extensometer. For each test a minimum of five valid specimens should be used.

The water permeability of the geosynthetics normal to their plane was determined (EN ISO 11058) by submitting specimens to a unidirectional flow of water normal to their plane under a range of constant head losses. A minimum of five specimens should be used per sample.

To determine the characteristic opening size of geosynthetics (EN ISO 12956) a granular material is washed through each specimen (used as sieve), without load. The characteristic opening size of the specimen (O_{90} , μm) is equal to the d_{90} of the particle size distribution curve (particle size for which 90% of the mass fraction is smaller than the mass of measured particles). A minimum of three specimens should be used per sample.

The mean values of the properties were accompanied by the corresponding 95% confidence intervals (CI). The latter were estimated assuming that the variables studied were

normally distributed and, therefore, the confidence intervals for the corresponding means could be determined using the t-Student distribution (Zar, 2009). The 100(1- α) percent confidence interval for the population mean, $\bar{x}$, was given by Equation 1 (σ , standard deviation; n, size of the sample; α , level of significance, taken as 0.05, for a 95% confidence interval; $t_{1-(\frac{\alpha}{2})}$, t-Student distribution).

$$CI = \bar{x} \pm t_{1-(\frac{\alpha}{2})} \frac{\sigma}{\sqrt{n}} \quad (1)$$

To quantify the changes due to the damage induced residual values of relevant properties were determined. R_Y is the residual value (in %) after damage of the property Y, determined as the ratio between the mean value of Y for the damaged sample (Y_{dam}) and the corresponding mean value for the undamaged sample (Y_{und}).

Reduction factors (RF) representing the effects of single exposures to mechanical damage and to abrasion damage and the successive exposures to mechanical and abrasion damage were determined (Equation 2) for tensile strength, secant tensile stiffness modulus at 2% of strain, permittivity and characteristic opening size.

$$RF = \frac{1}{R_Y} \quad (2)$$

The presence of synergy between mechanical and abrasion damage was assessed by comparing the reduction factor for multiple (successive) exposures to damage with the traditional one (obtained by multiplying the reduction factors for the corresponding single exposures to damage). The traditional approach is based on the assumption that the different agents affecting the endurance of geosynthetics are independent and that their combined effect is equal to that resulting from their superposition. Positive synergy occurs when the consequences of multiple (successive) exposures to damage are less severe than those estimated using the traditional approach, while negative synergy corresponds to the opposite situation.

The reduction factors determined can be used for comparative purposes but should not be used for design, as they result from laboratory simulations of damage.

4 RESULTS AND DISCUSSION

4.1 Visual inspections

After abrasion geotextile GTX (Figure 3) exhibited partial disaggregation of its superficial layer (peeling) and preferential reorientation of filaments (clumping). After mechanical damage, it was possible to observe some incrustation of fine particles resulting from corundum fragmentation and some puncturing. Multiple exposures to damage GTX resulted in superficial disaggregation, superficial filament cutting and filament reorientation, originating a perpendicular accumulation of fibres in the machine direction of the geotextile GTX (which coincided with the direction of the abrasive action). This indicates that the mechanical damage (previously induced) enabled the detachment and superficial disaggregation of filaments, causing fibres to further accumulate perpendicularly to the machine direction (clumping).

The surface of geogrid GGR was affected significantly by the damage induced (Figure 4). After abrasion, there was detachment of the protective polymeric coating, disaggregation and cut of transversal ribs and splitting of longitudinal ribs. After mechanical damage, besides the incrustation of fine particles, some fibre cutting and localised damage of the coating were observed. The multiple exposures to damage enhanced the effects observed for a single exposure to abrasion damage.

After abrasion, geocomposite GCR (Figure 5a) suffered partial detachment and damage of its yarns and clumping perpendicular to the machine direction. A single exposure to mechanical damage (Figure 5b) led to incrustation of fines in the geotextile backing and localised puncturing; some yarns were cut and detached from the geotextile backing. The multiple exposures of geocomposite GCR to damage (Figure 5c) resulted in detachment and superficial disaggregation of the yarns, filament cutting and clumping. After abrasion damage the specimens of geocomposite GCR suffered lateral contraction.

The visual inspections indicated that after the mechanical damage tests all materials exhibited accumulation of fine particles on their surface and some puncturing particularly bellow the load plate. These are in good agreement (qualitatively) with changes reported after installation field trials by Pinho-Lopes and Lopes (2013). Apparently, the abrasion damage was the most important and was aggravated by multiple exposures to damage. The main consequences observed for geotextile GTX and geocomposite GCR after abrasion (single and multiple exposures) were peeling and clumping, which were in good agreement with those reported by Van Dine et al. (1982) for exhumed geotextiles.

4.2 Tensile tests

4.2.1 Summary of results

Table 3 summarises mean values of tensile strength ($T_{\max}$, kN/m), strain at break (ϵ_f , %) and secant tensile stiffness modulus at 2% of strain ($J_{\text{sec } 2\%}$, kN/m) and the corresponding 95% confidence intervals (CI)

Figure 6 summarises the residual values of the tensile strength, peak strain and secant tensile stiffness modulus at 2% of strain after single and multiple exposures to mechanical and abrasion damage. Figure 7 illustrates the 95% confidence intervals for the different types of samples studied, normalised to the corresponding mean value. For each sample (fifteen valid specimens), a mean load–strain curve was obtained (Figure 8).

4.2.2 Tensile strength and peak strain

The tensile strength of geotextile GTX was little affected by exposures to mechanical and abrasion (single or multiple), as the corresponding residual tensile strength (Figure 6) was always higher than 94%. The tensile strength of geogrid GGR and geocomposite GCR were severely reduced, particularly after abrasion damage (single exposure and multiple exposures), with residual tensile strength of 22% (abrasion damage) and 25% (mechanical and abrasion damage), for geogrid GGR, and 23% (abrasion damage) and 22% (multiple exposures damage), for geocomposite GCR.

The different structures of these geosynthetics played an important role on the responses observed. Geotextile GTX is manufactured by needlepunching continuous filaments, which then become entangled (and thus mechanically bonded). Due to its high mass per unit area and thickness, the damage induced is not likely to affect geotextile GTX over all its thickness; for example, the peeling observed was mostly superficial. Therefore, during the tensile test, around damaged areas it is very likely that there are several other elements able to sustain tensile loads.

The fibres of geogrid GGR are knitted into a grid structure and covered with a protective coating. However, the damage (particularly abrasion) significantly affected both coating and fibres (Figure 4). If the smaller surface area of geogrid GGR may reduce the possible contacts with the damage elements (aggregate and abrasive film), when damage occurs (such as the cut and splitting of ribs), it also reduces the number of elements around which loads can arch during the tensile test.

Mostly the high tenacity yarns provide the tensile strength of geocomposite GCR. These are knitted to the geotextile backing and, therefore, such connections are quite sensitive to contact with sharp-edged materials, such as corundum (or the particles resulting from its fragmentation). Additionally, the abrasive action induced (in single and multiple exposures) also promoted cutting and detachment of the yarns. The mass per unit area and the thickness of

geocomposite GCR are small, increasing the likelihood of the damage to propagate over all its cross section.

Abrasion damage was the most critical mechanism for the tensile strength, particularly for geogrid GGR and geocomposite GCR. The different structure of these materials likely caused the differences: the connections between components (possible weaker points) increase their sensitivity to abrasion and do not allow for arching around damaged areas (and, thus, enable propagation of localised effects of damage).

Although the structure of the geosynthetics is likely to be one of the principal factors affecting their survivability when submitted to mechanical and abrasion damage, additional considerations are necessary. The setup of the abrasion damage test is likely to affect the results. For example, abrasion is particularly relevant in railway applications, due to the movement of ballast in contact with geosynthetics. Although it depends on both the compaction state of the ballast and on the rearrangement of particles due to loading, the contact area between the geosynthetics and the ballast particles is likely to be smaller than the surface area of the geosynthetics, thus reducing the importance of the abrasion. Nevertheless, the number of loading cycles in railway applications is much larger than that of the index test and currently there is no correlation between them.

The peak strain of the geosynthetics was less affected by the damage induced than their tensile strength, single and multiple exposures to mechanical and abrasion damage (Figure 6). For most samples, the residual peak strain is higher than 78%. The exception is geocomposite GCR, as its peak strain was reduced significantly, particularly after abrasion damage (single or multiple exposures). The corresponding residual peak strain measured was 41% after abrasion damage and 40% after successive mechanical and abrasion damage.

After abrasion damage (single and multiple exposures) geogrid GGR had the largest variability of results (Figure 7). This can be attributed to the smaller number of specimens tested. The normalised 95% confidence intervals for geogrid GGR and geocomposite GCR were wider for damaged samples than for the corresponding reference samples (Figure 7). Such difference was more important after abrasion damage (single and multiple exposures). A possible explanation for the scatter of results associated with the abrasion of geocomposite GCR relates to how the damage affected its structure. The degree to which the reinforcing yarns and their connections to the backing geotextile were partially destroyed during abrasion had a significant impact on the tensile response of the specimens tested, thus resulting in a large scatter of results. For geotextile GTX the scatter of results after single exposure to mechanical damage and multiple exposures to damage was lower than that of the undamaged samples,

while after a single exposure to abrasion damage the opposite occurred. This may indicate that the abrasion damage is likely to introduce some heterogeneity on geotextile GTX.

4.2.3 Secant stiffness

The secant stiffness modulus has been identified as a more rational quantity to represent the resistance to damage of some geosynthetics, particularly when defined for low strain levels (Pinho-Lopes and Lopes, 2013, Allen and Bathurst, 1994).

The load-strain curves of geogrid GGR (Figure 8b) and geocomposite GCR (Figure 8c) after a single exposure to mechanical damage were very close to those of the corresponding undamaged sample. The reductions of stiffness for 2% of strain measured after single exposure to mechanical damage were 0.3% for geogrid GGR and 4.5% for geocomposite GCR; after abrasion damage (single and multiple exposure) such reductions ranged between 39% and 47%. This means that the abrasion damage induced (if representative or related to that in relevant applications) could affect not only the strength of these geosynthetics but also their performance in service.

Although the nominal peak strain of geotextile GTX is very high ($\epsilon_{nom}=105\%$), for most applications such strains are never achieved. The load-strain curves of geotextile GTX were not affected significantly by the damage induced, particularly for lower strains (Figure 8a). The stiffness for 2% of strain (Table 3) decreased after damage: 13% and 2%, after a single exposure to abrasion and to mechanical damage, respectively, and 17% after multiple exposures to mechanical and abrasion damage.

4.2.4 Reduction factors for damage

Table 4 summarises the reduction factors for single and multiple exposures to mechanical and abrasion damage obtained from the tensile tests results: tensile strength, RF_{Tmax} ; and secant tensile stiffness modulus at 2% of strain ($RF_{Jsec2\%}$). The minimum value for these reduction factors is 1.0. It is important to reemphasise that these reduction factors can be used for comparative purposes but should not be used for design, as they result from laboratory index tests.

For geogrid GGR and geocomposite GCR the reduction factor for the tensile strength, RF_{Tmax} , for multiple exposures to mechanical and abrasion damage was smaller than that estimated using the traditional approach. These results indicate a significant positive synergy between mechanical and abrasion damage of geogrid GGR and geocomposite GCR. For these geosynthetics, abrasion damage was the most conditioning mechanism. When combined with abrasion, the effects of mechanical damage on the reduction factor for the tensile strength of

GGR and GCR were very small. Data for $RF_{Jsec2\%}$ confirmed the positive synergy, though less important. This indicates that using the peak parameters to represent the effects of damage can be too conservative, particularly considering that the strain levels in geosynthetics are usually limited.

For geotextile GTX the traditional approach (assuming mechanical and abrasion damage as independent) can be slightly unsafe, as the corresponding reduction factor ($RF_{Tmax}=1.05$) was smaller than the reduction factor obtained from multiple exposures ($RF_{Tmax}=1.06$). A similar trend was found for the secant tensile stiffness modulus as the $RF_{Jsec2\%}$ was 1.17 for the traditional approach and 1.21 considering multiple exposures to mechanical and abrasion damage. These results indicate that using the tensile strength to represent the effect of damage of geotextile GTX can be unsafe, as the stiffness reductions observed were most important.

The results showed a positive synergy between mechanical and abrasion damaged induced for the two geosynthetics most affected by such damage (geogrid GGR and geocomposite GCR).

4.3 Hydraulic tests

4.3.1 Summary of results

The hydraulic tests results are summarised in Table 5: mean values of permittivity (ψ , s^{-1}) and characteristic opening size (O_{90} , μm), and corresponding 95% confidence intervals (CI).

Figure 9 summarises the residual values of the permittivity (ψ_{res}) and characteristic opening size (O_{90res}) after single and multiple exposures to mechanical and abrasion damage. Figure 10 illustrates the 95% confidence intervals for the different types of samples studied, normalised to the corresponding mean value.

Figure 11 represents the relationships obtained from the hydraulic tests between head loss and flow velocity at 20°C for GTX and GCR before and after laboratory damage tests. The data and the fitted quadratic regression curve plotted according to EN ISO 11058 correspond to the mean curve for each sample.

The damage induced can have contradicting effects on the permittivity of geosynthetics. On the one hand, if there are holes or openings in the materials or if their thickness is reduced (decreasing the number of constraints to the flow of water normal to the geosynthetics) the permittivity is likely to increase after damage. On the other hand, if aggregate particles become trapped in the geosynthetics or if the surface abrasion leads to obstruction of superficial pores,

then the permittivity is likely to decrease. In some cases, a mixed behaviour may be found. The characteristic opening size is expected to have an opposite evolution.

4.3.2 Permittivity and characteristic opening size

The permittivity (Table 5, Figure 9) of geotextile GTX and geocomposite GCR increased slightly after abrasion (4% and 1%, respectively), whereas the characteristic opening size (O_{90}) increased about 18% for GTX and 21% for GCR. After mechanical damage the permittivity of GTX and GCR decreased 10% and 3%, respectively, when compared with the undamaged sample; O_{90} increased about 13% for GTX, while for GCR it decreased 7%. After multiple exposures to damage the permittivity of GTX and GCR decreased about 13% and 14%, respectively, whereas for the O_{90} values there was an increase (about 22% and 25%, respectively, for geotextile GTX and geocomposite GCR).

The variability of the results, represented by the normalised 95% confidence intervals (Figure 10), was acceptable (always lower than 9%). For the undamaged sample, they ranged between 4.2% (permittivity of GTX) and 2.7% (characteristic opening size of GCR). If these values were representative of the inherent variability of the materials, it would be expected that they would increase after damage. This was observed for the permittivity of both geotextile GTX and geocomposite GCR. The variability of the characteristic opening size reduced after a single exposure to mechanical damage of GTX and after a single exposure to abrasion damage of GTX and GCR.

Figure 11 shows that, as expected, the flow velocity at 20°C increased with the increasing of head loss. For both GTX (Figure 11a) and GCR (Figure 11b) the curves for undamaged samples and after a single exposure to abrasion damage were very close to each other, compared to the curves for the mechanical damage (single and multiple exposures). The mechanical damage induced in single and multiple exposures reduced the mean permittivity of both geosynthetics. This indicates that, for the permittivity, the mechanical damage was the most conditioning damage.

After mechanical damage there are two opposite consequences affecting the hydraulic properties of the geosynthetics: on the one hand, the aggregate in contact with the geosynthetics induces puncturing, likely to create small cuts and openings on their surface, and, on the other hand, the aggregate fragments and small particles are trapped in the geosynthetics. These effects were confirmed by visual observations. Submitting geocomposite GCR to a single exposure to mechanical damage decreased both the permittivity and the characteristic opening size, compared to the undamaged sample. This is likely to indicate that the second phenomenon

(clogging) is prevalent relatively to the first (cuts and openings). As the thickness of geocomposite GCR is small (2.1 mm), this geosynthetic is likely to be more affected by the damage than geotextile GTX. For geotextile GTX the permittivity decrease indicated the prevalence of clogging, while the characteristic opening size increase indicated the prevalence of cuts and openings. Rosete et al. (2013) found similar trend, which were likely to be a consequence of the different test procedures used in the tests.

A single exposure to abrasion damage changed the superficial layer of the geosynthetics, likely decreasing the number of constrictions to the passage of water. This explains the slight increase of permittivity observed for both geotextile GTX and geocomposite GCR, compared to the undamaged samples.

The results obtained for samples submitted to multiple exposures to damage showed the permittivity increased and the characteristic opening size decreased when compared to those of the corresponding undamaged samples. Again, likely to be a consequence of the different test procedures used in the tests.

The comparisons between geotextile GTX and geocomposite GCR have to be contextualised, as these materials have different nominal hydraulic properties: they are not alternative solutions to be used as a filter, for example.

4.3.3 Reduction factors for damage

Table 6 summarises the reductions factors for single and multiple exposures to mechanical and abrasion damage using results from the hydraulic tests for permittivity (RF_{ψ}) and characteristic opening size (RF_{O90}). These reduction factors can be used for comparative purposes. For a conservative design, lower values of the permittivity and higher values of the characteristic opening size should be considered.

When the permittivity and the characteristic opening size of geosynthetics tend to increase after damage the corresponding reduction factors will be smaller than 1.0. Thus, they need to be carefully analysed. Nevertheless, for coherence, the same formulation (Equation 1) was used for all the properties analysed.

In terms of permittivity, for both geotextile GTX and geocomposite GCR, the multiple exposures to mechanical and abrasion damage were more severe than the estimates from the traditional approach (Table 6). This indicates the existence of synergy between mechanical and abrasion damage and that the traditional approach is likely to result in unsafe values for the permittivity.

For geotextile GTX the traditional approach represented a decrease of the characteristic opening size (compare to that for the multiple exposures), while for geocomposite GCR it led to an increase of the characteristic opening size obtained considering synergy, on the safe side for design. Again, for geotextile GTX the traditional approach is likely to result in unsafe values.

These conclusions, if confirmed for real conditions, indicate that, where relevant, the multiple effect of these damage mechanisms should be considered (particularly for geotextile GTX), other than their traditional superposition (considering them as independent).

4.4 Number of tests

Each characterisation tests was performed three times to ensure the data obtained was statistically representative. On the one hand, the inherent variability of geosynthetics and their properties is less likely to affect the results and the conclusions from the tests. On the other hand, the heterogeneity of the damage induced is less important.

For the mechanical damage test the number of particles in contact with the surface of the geosynthetics and the fragmentation of the aggregate play a crucial role on the damage induced. Therefore, by repeating the tests their variability is reduced significantly. The low normalised 95% confidence intervals for the properties analysed (Figures 7 and 10) confirmed it. As mentioned before, most likely the exceptions observed for the mechanical properties of geogrid GGR after abrasion damage (single and multiple exposures) were related to using a smaller number of specimens.

5 CONCLUSIONS

In this paper three geosynthetics were subjected to laboratory index tests of mechanical and abrasion damage (using single and multiple exposures) to assess the existence of synergisms between the two types of damage, typical for geosynthetics in transportation engineering applications. Laboratory tests were carried out to determine mechanical and hydraulic properties of the geosynthetics. To ensure the results were statistical significant each test was performed three times. From the results the main conclusions are:

- The consequences of the damage induced were visible (naked eye). The mechanical damage induced was (qualitatively) in good agreement with reports from installation field trials. For the materials with a geotextile the observations after laboratory damage tests were in good agreement with those for geotextiles exhumed from railways.

- Visual inspections indicated that the abrasion damage was the most important and was aggravated by multiple exposures to damage. The abrasion damage laboratory test (single and multiple exposures) was found very severe for the geocomposite and geogrid tested, as the connections between their components create potential fragility points in the abrasion test (laboratory index test). Further research is necessary, to assess whether this is representative of or can be related to the damage mechanisms resulting from abrasion due to cyclic loading of aggregates in contact with geosynthetics.
- Due to its structure, combined with high mass per unit area and thickness, the geotextile tested survived well to the damage induced, maintaining high residual values for all properties assessed (tensile strength, strain at break, secant stiffness, permittivity and characteristic opening size).
- A positive synergy between mechanical and abrasion damaged induced was found for the tensile properties of the two geosynthetics most affected by such damage (geogrid GGR and geocomposite GCR). This was more important for their tensile strength than their secant stiffness. This indicates that, if the damage mechanisms in the laboratory tests are proved to be representative of those in field, more economic and realistic designs can be achieved by considering the combined effect of mechanical and abrasion damage (multiple exposures).
- For the permittivity of geotextile GTX and geocomposite GCR the mechanical damage was the most conditioning damage, due to clogging of their pores. The abrasion damage likely decreased the number of constrictions to the passage of water, with a slight increase of permittivity, compared to the undamaged samples.
- The different trends observed for the characteristic opening size and the permittivity of the geosynthetics may be caused by differences in the corresponding test set-ups.
- Negative synergy between mechanical and abrasion damage was found for the permittivity of the geotextile and the geocomposite and for the characteristic opening size of the geotextile; the traditional approach was found likely to result in unsafe estimates of these properties.

NOTATION

Basic SI units are given in parentheses.

d_{90}	particle size for which 90% of the mass fraction is smaller than the mass of measured particles (m)
$J_{\text{sec } 2\%}$	secant tensile stiffness modulus at 2% of strain (N/m)

$J_{\text{sec } 2\% \text{ res}}$	residual secant tensile stiffness modulus at 2% of strain (dimensionless)
n	size of the sample
O_{90}	characteristic opening size (m)
$O_{90 \text{ nom}}$	nominal characteristic opening size (m)
$O_{90 \text{ res}}$	residual characteristic opening size (dimensionless)
RF	reduction factor (dimensionless)
$RF_{J_{\text{sec } 2\%}}$	reduction factor for the secant tensile stiffness modulus at 2% of strain (dimensionless)
$RF_{O_{90}}$	reduction factor for the characteristic opening size (dimensionless)
RF_{ψ}	reduction factor for the permittivity (dimensionless)
$RF_{T_{\text{max}}}$	reduction factor for the tensile strength (dimensionless)
R_Y	residual value of property Y (%)
$t_{1-(\frac{\alpha}{2})}$	t-Student distribution
t_{nom}	nominal thickness (m)
T_{nom}	nominal peak tensile strength (N/m)
T_{max}	maximum tensile strength (N/m)
T_{res}	residual tensile strength (dimensionless)
VI_{H50}	water flow velocity for a head loss of 50 mm (m/s)
Y_{dam}	mean value of property Y for the damaged sample
Y_{und}	mean value of property Y for the undamaged sample
$\bar{x}$	population mean
α	level of significance
ϵ_{nom}	nominal strain at break (dimensionless)
ϵ_f	strain at break (dimensionless)
ϵ_{res}	residual strain at break (dimensionless)
σ	standard deviation
ψ	permittivity (s^{-1})
ψ_{nom}	nominal permittivity (s^{-1})
ψ_{res}	residual permittivity (dimensionless)
μ_{nom}	nominal mass per unit area (kg/m^2)

512 ABBREVIATIONS

CI	confidence intervals
GCR	geocomposite
GGR	geogrid
GTX	geotextile
PET	polyester
PP	Polypropylene

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590

TABLES

Table 1 - Properties of the geosynthetics studied.

Geosynthetic			GGR	GTX	GCR
Structure			Woven geogrid	Nonwoven geotextile	Non-woven geotextile, high tenacity yarns
Constituent polymer			PET	PP	PET
Tensile strength ¹	T _{nom}	kN/m	55	55	55
Strain at break ¹	ε _{nom}	(%)	10.5	105.0	10.0
Permittivity ²	ψ _{nom}	(s ⁻¹)	-	0.16	1.40
Characteristic opening size ³	O _{90 nom}	(μm)	-	75	95
Mass per unit area ⁴	μ _{nom}	(g/m ²)	-	1000	321
Thickness ⁵	t _{nom}	(mm)	1.7	7.2	2.1
Grid spacing		(mm)	25	-	-

¹ Determined according to EN ISO 10319

² Determined according to EN ISO 11058

³ Determined according to EN ISO 12956

⁴ Determined according to EN ISO 9864

⁵ Determined according to EN ISO 9863-1

Table 2 – Test program implemented and number of specimens tested.

Geosynthetic	Tensile properties EN ISO 10319			Permittivity EN ISO 11058		Characteristic opening size EN ISO 12956	
	GGR	GTX	GCR	GTX	GCR	GTX	GCR
Undamaged	15	15	15	15	15	9	9
Abrasion damage	8*	15	15	15	15	9	9
Mechanical damage	15	15	15	15	15	9	9
Mechanical + Abrasion damage	10*	15	15	15	15	9	9

* The number of valid results available was lower

Table 3 – Mean values of tensile tests results, with 95% confidence interval.

Geosynthetic	Sample	T _{max} (kN/m)	CI (kN/m)	ε _f (%)	CI (%)	J _{sec 2%} (kN/m)	CI (kN/m)
GGR	Undamaged	47.5	± 1.7	8.6	± 0.3	516.7	± 17.0
	Abrasion damage	10.2*	± 1.6	7.8*	± 1.9	273.0*	± 17.5
	Mechanical damage	40.2	± 2.1	8.2	± 0.4	515.2	± 15.0
	Mechanical + Abrasion damage	11.9*	± 1.5	6.7*	± 1.2	315.9*	± 27.1
GTX	Undamaged	68.4	± 2.5	99.5	± 5.1	229.0	± 15.2
	Abrasion damage	66.1	± 3.0	104.0	± 4.9	198.9	± 16.3
	Mechanical damage	67.5	± 2.0	95.7	± 5.6	224.4	± 20.9
	Mechanical + Abrasion damage	64.3	± 1.2	98.2	± 3.8	189.4	± 14.6
GCR	Undamaged	44.5	± 1.3	15.9	± 0.8	457.0	± 32.6
	Abrasion damage	10.2	± 0.7	6.5	± 0.6	241.2	± 25.3
	Mechanical damage	31.2	± 1.3	12.6	± 1.1	436.5	± 45.2
	Mechanical + Abrasion damage	9.6	± 0.7	6.3	± 0.4	242.0	± 21.4

* The number of valid results available was lower (Table 2)

Table 4 – Reduction factors for the tensile strength (RF_{Tmax}) and for the secant tensile stiffness modulus for 2% strain ($RF_{Jsec2\%}$).

Geosynthetic	Sample	RF_{Tmax}	$RF_{Jsec2\%}$
GGR	Abrasion damage	4.66	1.89
	Mechanical damage	1.18	1.00
	Mechanical + abrasion damage	4.00	1.64
	Mechanical damage X abrasion damage (traditional)	5.51	1.90
GTX	Abrasion damage	1.03	1.15
	Mechanical damage	1.01	1.02
	Mechanical + abrasion damage	1.06	1.21
	Mechanical damage X abrasion damage (traditional)	1.05	1.17
GCR	Abrasion damage	4.37	1.89
	Mechanical damage	1.43	1.05
	Mechanical + abrasion damage	4.64	1.89
	Mechanical damage X abrasion damage (traditional)	6.23	1.98

Table 5 – Mean values of permittivity (ψ) and characteristic opening size (O_{90}), with 95% confidence interval.

Geosynthetic	Sample	ψ (s ⁻¹)	CI (s ⁻¹)	O_{90} (μ m)	CI (μ m)
GTX	Undamaged	0.27	± 0.01	176.5	± 6.4
	Abrasion damage	0.28	± 0.02	207.5	± 4.3
	Mechanical damage	0.24	± 0.01	199.4	± 5.0
	Mechanical + Abrasion damage	0.24	± 0.02	215.2	± 9.8
GCR	Undamaged	1.31	± 0.05	167.0	± 4.4
	Abrasion damage	1.33	± 0.08	202.0	± 3.9
	Mechanical damage	1.27	± 0.07	155.2	± 7.0
	Mechanical + Abrasion damage	1.13	± 0.08	208.5	± 8.6

Table 6 – Reduction factors for the permittivity (RF_{ψ}) and for characteristic opening size (RF_{O90}).

Geosynthetic	Sample	RF_{ψ}	RF_{O90}
GTX	Abrasion damage	0.96	0.85
	Mechanical damage	1.11	0.88
	Mechanical + abrasion damage	1.15	0.82
	Mechanical damage X abrasion damage (traditional)	1.07	0.75
GCR	Abrasion damage	0.99	0.83
	Mechanical damage	1.03	1.08
	Mechanical + abrasion damage	1.16	0.80
	Mechanical damage X abrasion damage (traditional)	1.02	0.89

FIGURES

Figure 1 – Equipment used for the mechanical damage laboratory tests: a) lower box with the first sublayer of aggregate; b) container in the test frame after a mechanical damage test.

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621

622 **Figure 2 – Equipment used for the abrasion damage laboratory tests: a) abrasive film on the lower plate**
623 **(220 mm wide and 385 mm long); b) test equipment assembled.**

624

625

a)

b)

c)

626 **Figure 3 – Visual effects on geotextile GTX after: a) single exposure to abrasion damage; b) single exposure**
 627 **to mechanical damage; c) multiple exposures to mechanical and abrasion damage.**

a)

b)

628 **Figure 4 – Visual effects on geogrid GGR after: a) single exposure to mechanical damage; b) multiple**
 629 **exposures to mechanical and abrasion damage.**

a)

b)

c)

Figure 5 – Visual effects on geocomposite GCR after: a) single exposure to abrasion damage; b) single exposure to mechanical damage; c) multiple exposures to mechanical and abrasion damage.

Figure 6 – Residual values of the tensile strength (T_{res}), peak strain (ϵ_{res}) and secant stiffness for 2% strain ($J_{sec2\% res}$) after single and multiple exposures to mechanical and abrasion damage.

638

639 **Figure 7 – Normalised 95% confidence intervals for the tensile strength (T_{max}), peak strain (ϵ_f) and secant**
 640 **stiffness for 2% strain ($J_{sec\ 2\%}$).**

641

642

a)

b)

c)

Figure 8 – Mean load–strain curves after the laboratory damage tests: a) geotextile GTX; b) geogrid GGR; c) geocomposite GCR.

Figure 9 – Residual values of the permittivity (Ψ_{res}) and characteristic opening size ($O_{90\ res}$) after single and multiple exposures to mechanical and abrasion damage.

650

651

652 **Figure 10 – Normalised 95% confidence intervals for the permittivity (ψ) and characteristic opening size**
 653 **(O_{90}).**

654

a)

b)

655 **Figure 11 – Water flow velocity at a temperature of 20°C for different head losses after laboratory tests**
 656 **(mean curves): a) GTX; b) GCR.**