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Damage induced by recycled Construction and Demolition Wastes on the short-term tensile behaviour of two geosynthetics, Transportation Geotechnics, Vol.4, pp. 64-75, DOI: 10.1016/j.trgeo.2015.07.002

Degradation induced by recycled Construction and Demolition Wastes on the short-term tensile behaviour of two geosynthetics

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ABSTRACT

Geosynthetics have been used as a reinforcement material in roadways and railways construction. Notwithstanding, one of the main questions of using is their durability. The damage caused by the mechanical actions during installation and the chemical and biological degradation are important issues to consider in the physical, mechanical and hydraulic behaviour of geosynthetics. The change in their properties induced by these degradation processes can compromise the performance of these materials. In order to study the chemical and environmental degradation induced by a recycled Construction

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and Demolition Waste (C&DW) on the short-term tensile behaviour of two geosynthetics (a uniaxial HDPE geogrid and a nonwoven PP geotextile reinforced with PET yarns) used commonly as reinforcement material, a damage trial embankment (2m x 3m in plant) was constructed. This paper presents and discusses the effects produced by the recycled C&DW on geosynthetic samples exhumed after 6 months of the embankment construction. The constituents and the leaching behaviour of the recycled C&DW are presented. Wide width tensile tests were performed on exhumed and intact (as-received) geosynthetics and their tensile behaviour is compared. Scanning electron microscope (SEM) images of intact and exhumed specimens are also presented. As expected the degradation induced by the recycled C&DW after 6 months of exposure is not very expressive. On the HDPE geogrid the recycled C&DW induced a small decrease on the tensile strength and the reduction of the tensile stiffness modulus. The geocomposite experienced some reduction on the tensile strength (16% on average) but the effects on tensile stiffness and shape of the load-strain curves were not significant.

KEYWORDS: Construction and Demolitions materials; Recycled aggregates; Geosynthetics; Environmental degradation; Damage trial embankment

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NOTATION

J - geosynthetic axial stiffness (kN/m)

$J_{2\%}$ - secant stiffness modulus at strain of 2% (kN/m)

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

RF_{ID} - installation damage reduction factor (dimensionless)

RF_{CR} - creep reduction factor (dimensionless)

RF_{D} - durability reduction factor (dimensionless)

RF_{W} - reduction factor for weathering (dimensionless)

RF_{CH} - reduction factor for chemical/environmental effects (dimensionless)

R_{T} - retained tensile strength (dimensionless)

R_{ε} - retained peak strain (dimensionless)

$R_{J2\%}$ - retained secant modulus at 2% of strain (dimensionless)

T - load per unit width (kN/m)

T_{al} - available long-term tensile strength (kN/m)

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

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

T_{ult} - ultimate tensile strength (kN/m)

ε - geosynthetic strain (dimensionless)

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

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1. INTRODUCTION

Granular materials are commonly used in civil engineering applications, such as embankments, retaining walls, road bases and railway ballast. In addition, over the last years the environmental sustainability has been demanding a progressive increase in the waste recycling in general and in the waste valorisation in construction industry, in particular. Some studies and applications of recycled Construction and Demolition materials have been performed in recent years, mainly related to the production of aggregates for use in concrete and in base and sub-base layers of transportation infrastructures (Jiménez et al. 2012; Arulrajah et al. 2013a; Rahman et al. 2013; Rahman et al. 2015).

Construction and Demolition materials have been found to be viable alternative materials in applications such as pavement sub-bases and other road construction applications (Arulrajah et al. 2013a). However, the properties of these alternative materials is not fully understood compared to natural quarried materials, and, hence, their usage continues to face many barriers (Arulrajah et al. 2013b).

Geosynthetics, particularly geogrids and high strength geotextiles, are used as a reinforcement material in various geotechnical engineering applications such as roads and railway embankments. Consequently, the assessment of their behaviour during and after exposition to recycled C&DW is an important research issue to overcome the barriers on the usage of recycled aggregates.

The durability is one of the main questions on the use of geosynthetics in ground applications. The damage caused by mechanical actions during the installation and the chemical and the biological degradation are important issues to be considered in the behaviour of these materials. The changes in their physical, mechanical and hydraulic properties, induced by these degradation processes, can compromise the performance of the structures where these materials are used.

The available long-term tensile strength of a geosynthetic (AASHTO, 2012; FHWA, 2010), T_{al}, or the design strength for the ultimate limit state (BS 8006, 2010), can be estimated as:

$$T_{al} = \frac{T_{ult}}{RF_{ID} \times RF_{CR} \times RF_{D}} \qquad (1)$$

where T_{ult} is the ultimate tensile strength (per unit width) determined according to the standards (ASTM D6637 - 11; ASTM D 4595; EN ISO 10319), RF_{ID} is the installation damage reduction factor (that accounts for the damaging effects of placement and compaction of soil or aggregate over the geosynthetic during installation), RF_{CR} is the creep reduction factor (that accounts for the effect of creep resulting from long-term sustained tensile load applied to the geosynthetic) and RF_{D} is the durability reduction factor (that accounts for the strength loss caused by chemical and biological degradation of the polymers used in the geosynthetic). Instead of the durability reduction factor, RF_{D}, the British Standard (BS 8006, 2010) considers two reduction factors: a reduction factor for weathering, RF_{W}, and a reduction factor for chemical/environmental effects, RF_{CH}.

Over the last years several field studies regarding the installation damage of geosynthetics have been performed (Hufenus et al., 2005; Lim and McCartney, 2013; Pinho-Lopes and Lopes, 2014; Troost and Ploeg, 1990; Watts and Brady, 1990, 1994). They have shown that the type of geosynthetic, the weight, type and number of passes of the compaction material, the gradation and angularity of the fill influence the level of damage. The results presented by Watts and Brady (1990) revealed that the tensile strength and the elongation at break were both substantially reduced by the damage during installation but the Young's modulus was largely unaffected. Troost and Ploeg (1990) also found that the shape of the load-strain curve remains almost identical after installation damage, provided that not too many yarns were broken. More recently, the results reported by Hufenus et al. (2005) have also shown that the slope of the load-strain curve was not largely affected by the installation damage even when the maximum tensile strength and elongation at break decreased.

Based on data from controlled installation damage trials reported in the literature, Allen and Bathurst (1994) concluded that the initial modulus of the load-strain curves may or may not be shifted and the modulus of some materials does not change and in some cases appears to be slightly greater after exhumation.

Chemical and biological degradation has been studied mainly on geosynthetics used in landfill barrier systems. A review on the degradation and field long-term of HDPE geomembranes was presented by Rowe and Sangam (2002). Based on examination of both laboratory and field data, Rowe and Sangam (2002) have concluded that the projected service lives of HDPE geomembranes may range from many centuries to less than a decade, depending on the material and exposure conditions.

The oxidation degradation of geosynthetic in field conditions is affected by the temperature, oxygen partial pressure and chemical constituents of the surround media (pH, transition metal ions, etc.) (Hsuan et al., 2008). Temperature plays the most critical role of all physical and chemical processes. The oxidation mechanism is governed by the transport processes of oxygen which are all strongly temperature dependent. The available oxygen concentration in the environment surrounding the geosynthetic is essential to the degradation by oxidation. Different oxidation reactions can take place based on the available oxygen, however the reaction rate at ambient temperature is very slow (Hsuan et al., 2008). The oxidation of polyolefins (like polypropylene) can be accelerated by the presence of transition metal ions such as cobalt manganese, copper, and iron while the oxidation degradation of a polypropylene geotextile can be accelerated by the presence of rusting steel wires (Hsuan et al., 2008).

The resistance of a non-woven polypropylene needle punched geotextile against some degradation agents, such as liquids, thermo-oxidation and artificial weathering, and the existence of synergisms between them was studied by Carneiro et al. (2014) through laboratory tests. These authors found that the thermo-oxidative resistance was affected by sodium hydroxide and iron nitrate.

According to Koerner et al. (2007) biological degradation of geosynthetics is generally not a factor of concern unless biologically sensitive additives (such as low-molecular-weight plasticizers) are included in the polymer formulation.

In order to study the chemical and biological degradation induced by recycled C&DW on two geosynthetics, a damage trial embankment (2m x 3m in plant) was constructed. This trial damage embankment intends to simulate the potential degradation induced by recycled C&DW on the tensile behaviour of two geosynthetics with different structure and base polymers. Its construction method and dimensions are not adequate for other purposes, namely the analysis of the embankment behaviour. It was predicted the exhumation of geosynthetic samples from the embankment after 6, 12 and 24 months of its construction. The results herein presented are related to the samples exhumed after 6 months of construction.

Notwithstanding the fact that the period of time between the installation and the exhumation of the geosynthetic specimens are not equivalent or comparable to the service life of the structures, the construction of this trial embankment will allow us to have an estimate of the degradation level, induced by the environmental conditions in which the geosynthetics were inserted, on their short-term tensile behaviour.

2. MATERIALS AND METHODS

2.1. Geosynthetics

Two commercial available geosynthetics frequently used as reinforcement were used in this study: an extruded uniaxial high density polyethylene (HDPE) geogrid (Figure 1a) and a high-strength composite geotextile consisting of polypropylene continuous-filament needle-punched nonwoven and high-strength polyester yarns (unidirectional geocomposite reinforcement) (Figure 1b). Table 1summarizes the main properties of the geosynthetics provided by the manufacturers.

To analyse the effects of recycled C&DW on the short-term tensile behaviour of these geosynthetics, intact (as supplied by the manufacturers) and exhumed specimens were taken from the same roll and they were tested using the same methods and equipments.

The tensile tests were carried out in accordance with the European Standard EN ISO 10319 (2008) on five specimens (intact or exhumed) and with strain rate of 20%/min.

The preparation of the geocomposite specimens to perform tensile tests needs some previous work, namely the use of a particular nitrile based adhesive to glue the polyester yarns in the portion of geotextile located inside the clamps and the placement of steel rods of small diameter to avoid the sliding of the geotextile during the tests (Figure 2).

Each geocomposite specimen was cut with dimensions 200 mm width × 340 mm length. The distance between the jaws was adjusted to give a test specimen length of 100 mm. The reference points were fixed on the specimens 60 mm apart. A video-extensometer was used to measure the geosynthetic strains.

The geogrid specimens were cut with a width of 200 mm (9 longitudinal bars) and length of 470 mm. The distance between the clamps was adjusted to give a test specimen length of 395 mm approximately, to ensure fixing the geogrid on the transversal bars. The reference points for the video-extensometer were fixed on the specimens 200 mm apart.

2.2. Recycled C&DW

The trial damage embankment was constructed using a fine grain recycled C&DW, coming mainly from the demolition of single-family houses and cleaning of lands with illegal deposition of C&DW, provided by a Portuguese Recycling plant located in Centre region. The constituents of the C&DW determined in accordance with the European Standard EN 933-11 (2009) are listed in Table 2. The predominant materials of this recycled C&DW are concrete, mortar, unbound aggregates and natural stones. A significant amount of soils was also identified. The volume of floating particles exceeds the desirable value (< 5cm^3/kg), meaning that some wood and polystyrene is present in the recycled material.

The gradation of the recycled C&DW was determined following the European Standard EN 933-1 (2009) for aggregates. It was observed that the oven drying at 110ºC caused the melting and merging of some particles, so it was necessary to use the procedure described in Annex B of the Standard to determine the initial weight of the sample. The particle size distribution, obtained by sieving, is represented in Figure 3.

The environmental concerns regarding the potential contamination of the groundwater, as well as, the possible presence of substances that could induce geosynthetics degradation, impose the evaluation of the leaching behaviour of the recycled waste. Thus, laboratory leaching tests were carried out in accordance with the European Standard EN 12457-4 (2002).

Table 3 presents the leaching test results and the acceptance criteria for leached maximum concentration for inert landfill, define by the European Council Decision 2003/33/EC (2003).

From the analysis of the results presented in Table 3 it can be concluded that only the value of sulphate exceeds the maximum value established by the European legislation, notwithstanding the Directive 2003/33/EC (Council Decision 2003/33/EC) states that "*if the waste does not meet these values for sulphate, it may still be considered as complying with the acceptance criteria if the leaching does not exceed 6000 mg/kg at L/S = 10 l/kg, determined either by a batch leaching test or by a percolation test under conditions approaching local equilibrium.*"

The alkaline pH value can induce some chemical degradation on the geosynthetics, however since the pH is within the range 3 – 9 (and the maximum dimension does not exceed 19mm), the fill material could be classified, in accordance with AASHTO, (2012), as non-aggressive.

2.3. Embankment construction

The damage trial embankment was constructed with dimensions in plant of 2m × 3m and height of 0.45 m. Inside the embankment, 8 geogrid samples (0.45 m × 1.5m) and 8 geocomposite samples (0.47 × 1.5m) were distributed in 2 levels, vertically spaced of 0.20 m.

After cleaning the foundation from the existing vegetation (Figure 4a), a 0.05m high layer was placed and compacted. Eight geosynthetic samples (4 geogrid samples and 4 geocomposite samples) were carefully positioned without overlapping. Geosynthetic samples were covered with a first layer of C&DW placed manually to prevent mechanical damage (Figure 4b). Then additional quantities of C&DW were disposed, evenly spread and compacted to reach a lift with final thickness of 0.20 m.

The compaction was performed with a forward compaction plate with weight of 94 kg, plate dimensions of 450 mm x 696 mm, static pressure of 382 kg/m^2 and optimum vibration force of 16.5kN at 92Hz (Figure 4c).

A second layer of geosynthetic samples (4 geogrid samples and 4 geocomposite samples) was positioned and the same steps were repeated to reach a lift with final thickness of 0.20 m.

The lateral slopes of the embankment were also compacted with the forward compaction plate and aggregates from recycled C&DW were deposited to prevent erosion by rain water (Figure 4d).

A lightweight compaction process was adopted in order to minimize the installation damage of the geosynthetics. Field evaluations performed by Richardson (1998) have shown that installation damage can be minimized by using a minimum 250 mm initial lift over the geosynthetic and by limiting the maximum stone size to less than 25% of the lift thickness. In this trial embankment the final thickness of the layers placed over the geosynthetics is equal to 0.20 m, but the maximum particle size of the recycled C&DW is 18 mm, significantly lower than 25% of the lift thickness.

2.4. Specimens exhumation

After 6 months of the trial embankment construction, the first samples were carefully exhumed to prevent additional damage. Four geosynthetic samples (2 geogrid samples and 2 geocomposite samples) were exhumed from the upper layer.

The exhumation begun with the removal of the aggregates placed on the lateral slopes of the embankment, as well as, the vegetation that grew up over the embankment (Figure 5a). Then the fill material was manually removed with hoes and shovels until reaching the geosynthetics (Figure 5b), being the material just above the geosynthetics removed carefully with the hands (Figure 5c).

From the visual inspection, the geogrid did not show significant damages (visible to the naked eye). Geocomposite samples were damaged by plant roots that crossed the geotextile, some of them with a few millimetres in diameter (Figure 5d). The exhumed samples were put into plastic bags and transported to the laboratory where they remained at 20ºC until be tested.

After the exhumation of the samples, the recycled C&DW was replaced and compacted by similar process used in the construction, so that resembling conditions for the remained samples were maintained.

3. RESULTS AND DISCUSSION

3.1. SEM images

As mentioned in 2.4, the preliminary visual inspection of the exhumed samples did not reveal significant damages, apart from the plant roots that crossed the base geotextile of the geocomposite. In order to evaluate the damages with more detail, Scanning Electron Microscope (SEM) analyses were carried out.

The SEM analyses were performed using a High resolution Environmental Scanning Electron Microscope with X-Ray Microanalysis and Electron Backscattered Diffraction analysis (Quanta 400 FEG ESEM / EDAX Genesis X4M) from the Materials Centre of University of Porto.

Figure 6 shows SEM images (at ×500 magnification) of the longitudinal bars of the geogrid took from an intact specimen and an exhumed specimen. Only very small cavities and grooves were detected, appearing to be provoked by hard particles of the recycled C&DW.

SEM images of intact and exhumed specimens of geocomposite are illustrated in Figure 7. Figure 7(b) shows that fibres fixing the PET yarns to the base geotextile are still present even if they seem to be unrolled. Figure 7(c) and 7(d) show amplified images of the base nonwoven geotextile. Since the holes provoked by the plant roots are local damages visible to the naked eye, the specimens for SEM analyses (with diameter of 25 mm) were cut from a more representative area.

It is possible to see that some fibres of the geotextile are damaged in the exhumed specimen (Figure 7d). Images from PET yarns (Figure 7e and 7f) did not reveal significant damage on exhumed specimens. Very small particles are held to the yarns.

The images presented in Figure 6 and Figure 7 allow us to conclude that, as intended, the installation damage (induced by the construction process) was not very significant.

3.2. Tensile tests

Figure 8 presents load-strain curves of intact geogrid and exhumed geogrid specimens subjected to tensile tests carried out according to EN ISO 10319 (2008). It would be expected that the variability of the results for exhumed specimens would be greater than that of intact specimens, due to the different mechanisms that could contribute to the geosynthetics damage. However the results presented in Figure 8 and summarised in Table 4 and Table 5 contradict this assumption. In fact tensile tests carried out with intact geogrid specimens have shown great variability, even so the coefficient of variation for the tensile strength was smaller than 4.2%. This variability is usual and it might be attributed to the production process.

Table 4 and Table 5 present the maximum tensile strength (T_{max}), the geosynthetic strain for T_{max} (ε_{Tmax}), the secant stiffness modulus at strain of 2% ($J_{2\%}$) and the secant stiffness modulus at ε_{Tmax} (J_{Tmax}) for intact and exhumed geogrid specimens, respectively. The mean values of these parameters and the 95% confidence intervals assuming a Student's t-distribution were also included. The Student's t-distribution was assumed since the population standard deviation is unknown and the number of specimens is lower than 30.

The mean value of the tensile strength for exhumed specimens is outside the confidence interval of this parameter for intact specimens. Even if the lowest value of the tensile strength achieved in an intact specimen (Table 4) is coincident to the highest value recorded in exhumed specimens (Table 5), one can conclude that the C&DW induced the decrease of the geogrid tensile strength and stiffness modulus and the increase of peak strain (ε_{Tmax}).

Figure 9 compares the mean load-strain curve for intact specimens with the mean load-strain curve for the exhumed specimens. The shape of the curves for intact and exhumed specimens are similar but the coordinates at failure were shifted. The geogrid stiffness for very small strains (initial stiffness) did not change significantly but the secant modulus reduced. One can conclude that the recycled C&DW induced a small decrease on the geogrid tensile strength (5.9% on average) and the reduction of the geogrid stiffness.

Load-strain curves for intact and exhumed geocomposite (high strength geotextile) specimens are presented in Figure 10. As expected, the scattering of the results is more pronounced in exhumed specimens. The behaviour of Specimen 4 can be partly explained by local damage induced by plant roots (Figure 5d). Table 6 and Table 7 summarise the results of tensile tests carried out on intact and exhumed geocomposite specimens, respectively. The 95% confidence intervals assuming a Student's t-distribution are also presented.

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The recycled C&DW induced the reduction of the geocomposite tensile strength (16% on average) but the effect on the geocomposite tensile stiffness is not significant (Figure 11). The decrease on the secant stiffness modulus at ε_{Tmax} (J_{Tmax}) is obvious since the geocomposite fails for smaller strains. The shape of curves for intact and exhumed specimens are quite similar.

The high tensile stiffness of this geocomposite (when compared to other geotextiles) results mainly from the high modulus of polyester (PET) yarns. Visual inspection and SEM images (Figure 7f) did not reveal significant damage in PET yarns, although some damage produced by plant roots (Figure 5d) and other installation damage mechanisms (Figure 7d) on nonwoven geotextile could be identified. The degradation of the nonwoven geotextile (base of the geocomposite) could explain the reduction of the geocomposite tensile strength without significant change of the geocomposite stiffness modulus until failure (Figure 11).

The retained values of relevant parameters to characterise the load-strain behaviour, such as the tensile strength, the strain at maximum load or the secant stiffness modulus, are frequently used to quantify the damage on geosynthetics. The retained value of a generic parameter, X, is defined as:

$$R_X = \frac{X_{dam}}{X_{intact}} \qquad (2)$$

where X_{dam} is the value of parameter X for damaged (or exhumed) specimens and X_{intact} is the value for intact specimens. By definition, the mean value of R_X is not simply the ratio of the mean of populations X_{dam} and X_{intact}, as is typically presented in the literature (Mood et al., 1974). The mean value of R_X is the mean value of the

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quantities R_X estimated by equation (1). In this paper, the retained tensile strength, R_T, the retained peak strain, R_ε, and the retained secant modulus at 2% of strain, $R_{J2\%}$, were estimated to characterise the damage induced by recycled C&DW on the geosynthetics under analysis.

Table 8 summarises the mean values of R_T, R_ε, and $R_{J2\%}$ estimated as the ratio between the mean value of the parameter (tensile strength, peak strain or secant modulus) for exhumed specimens and the corresponding mean value for intact specimens ($\bar{X}_{dam}/\bar{X}_{intact}$), as well as, as the mean value of the 25 possible combinations to estimate R_X by equation (2) ($\overline{X_{dam}/X_{intact}}$). The values were presented with three decimal digits to demonstrate the reduced differences between the values estimated by the two approaches. In fact, the error is small if R_X is estimated as the ratio of the mean values. This finding can be justified by the low variability of the results.

The data indicates that the effect of the C&DW on the short-term tensile behaviour of the geosynthetics depends on the structure and base polymer of the material. The loss of strength was more pronounced in the geocomposite, notwithstanding no reduction in the secant modulus was recorded for this material. In the geogrid, the loss of strength on exhumed specimens was similar to the loss of stiffness at 2% of strain. The peak strain increased resulting in a more pronounced loss of stiffness at failure (retained secant stiffness modulus of 0.89).

The lack of change in the stiffness modulus observed in the geocomposite was also reported by Allen and Bathurst (1994) and Watts and Brady (1990) in installation

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damage trials for structurally simple geosynthetics (woven geotextiles and geogrids). Allen and Bathurst (1994) have justified this evidence by local defects induced in the geosynthetic that causes premature failure in the fibers/yarns at reduced strains.

The unchanged tensile stiffness modulus observed on the geocomposite suggests that after 6 months of exposure the damage induced in the polyester yarns could be neglected, even if some damaged was observed in the base geotextile (Figure 5d and Figure 7d).

4. CONCLUSIONS

The main objective of this paper is the characterisation of the changes in load-strain behaviour of two geosynthetics used as reinforcement material (a uniaxial high density polyethylene geogrid and a high-strength composite geotextile) due to the potential degradation induced by a recycled C&DW.

SEM images allow us to conclude that the installation damage (induced by the construction process) was not very significant. Visual inspection and SEM images did not reveal significant damage in PET yarns of the geocomposite, although some damage produced by plant roots on the nonwoven geotextile (base of the geocomposite) could be identified.

The results of tensile tests carried out on intact and exhumed specimens indicate that the effects of the C&DW on the short-term load-strain behaviour of the geosynthetics depend on the structure and base polymer of the material. On the HDPE geogrid the recycled C&DW induced a small decrease on the geogrid tensile strength and the reduction of the geogrid tensile stiffness. The recycled C&DW induced the reduction of

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the geocomposite tensile strength (16% on average) but the effect on the geocomposite tensile stiffness is not significant. The shape of the load-strain curves for intact and exhumed specimens are, on average, quite similar.

It should be pointed out that the results and conclusions herein presented are preliminary results, since they are related to the exhumation of the specimens after 6 months of the trial embankment construction. Broadening conclusions will be reached when possible the exhumation of specimens submitted to longer periods of exposure.

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REFERENCES

AASHTO, 2012. LRFD Bridge Design Specifications, 3rd Edition, Washington DC.

Allen, A.M., Bathurst, R.J., 1994. Characterization of geosynthetic load-strain behaviour after installation damage. Geosynthetics International 1, 181-199.

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Arulrajah, A., Piratheepan, J., Disfani, M.M., Bo, M.W., 2013a. Geotechnical and Geoenvironmental Properties of Recycled Construction and Demolition Materials in Pavement Subbase Applications. Journal of Materials in Civil Engineering 28, 1077-1088.

Arulrajah, A., Rahman, M.A., Piratheepan, J., Bo, M.W., Imteaz, M.A., 2013b. Interface Shear Strength Testing of Geogrid-Reinforced Construction and Demolition Materials. Advances in Civil Engineering Materials 2, 189 - 200.

ASTM D 4595, 2011. Standard test method for tensile properties of geotextiles by the wide-width strip method, American Society for Testing Materials, USA.

ASTM D6637 - 11, 2011. Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method, American Society for Testing Materials, USA.

BS 8006, 2010. Code of practice for strengthened/reinforced soils and other fills, British Standard Institution.

Carneiro, J.R., Almeida, P.J., Lopes, M.L., 2014. Some synergisms in the laboratory degradation of a polypropylene geotextile. Construction and Building Materials 73, 586–591.

Council Decision 2003/33/EC, 2003. Council Decision establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC. Official Journal of European Union L11/27.

EN 12457-4, 2002. Characterisation of waste - Leaching - Compliance test for leaching of granular waste materials and sludges - Part 4: One stage batch test at liquid

This manuscript is the accepted version of the paper:
Damage induced by recycled Construction and Demolition Wastes on the short-term tensile behaviour of two geosynthetics, Transportation Geotechnics, Vol.4, pp. 64-75, [DOI: 10.1016/j.trgeo.2015.07.002](https://doi.org/10.1016/j.trgeo.2015.07.002)

to solid ratio of 10l/kg for materials with particle size below 10 mm (without or with size reduction), CEN.

EN 933-1, 2009. Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. CEN.

EN 933-11, 2009. Tests for geometrical properties of aggregates - Part 11: Classification test for the constituents of coarse recycled aggregate. CEN.

EN ISO 10319, 2008. Geosynthetics - Wide width tensile test, International Organization for Standardization, TC 221.

FHWA, 2010. Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, in: Berg, R.R., Christopher, B.R., Samtani, N.C. (Eds.), FHWA-NHI-10-024 Washington D.C.

Hsuan, Y.G., Schroeder, H.F., Rowe, K., Müller, W., Greenwood, J., Cazzuffi, D., Koerner, R.M., 2008. Long-term performance and lifetime prediction of geosynthetics, Proc. 4th European Geosynthetics Conference, Edinburgh, September 2008, Keynote Paper.

Hufenus, R., Ruegger, R., Flum, D., Sterba, I.J., 2005. Strength reduction factors due to installation damage of reinforcing geosynthetics. Geotextiles and Geomembranes 23, 401–424.

Jiménez, J. R., Ayuso, J., Agrela, F., López, M., & Galvín, A. P. (2012). Utilisation of unbound recycled aggregates from selected CDW in unpaved rural roads. Resources, Conservation and Recycling, 58(0), 88-97.

This manuscript is the accepted version of the paper:

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Koerner, G.R., Hsuan, Y.G., Koerner, R.M., 2007. The durability of geosynthetics, in: Sarsby, R.W. (Ed.), Geosynthetics in Civil Engineering. Woodhead publishing Limited and CRC Press.

Lim, S.Y., McCartney, J.S., 2013. Evaluation of effect of backfill particle size on installation damage reduction factors for geogrids. Geosynthetics International 20, 62–72.

Mood, A.M., Graybill, F.A., Boes, D.C., 1974. Introduction to the Theory of Statistics, 3rd Edition. McGraw-Hill, New York.

Pinho-Lopes, M., Lopes, M.L., 2014. Tensile properties of geosynthetics after installation damage. Environmental Geotechnics 1, 161-178.

Rahman, M. A., Arulrajah, A., Piratheepan, J., Bo, M. W., & Imteaz, M. A. (2013). Resilient Modulus and Permanent Deformation Responses of Geogrid-Reinforced Construction and Demolition Materials. Journal of Materials in Civil Engineering.

Rahman, M. A., Imteaz, M. A., Arulrajah, A., Piratheepan, J., & Disfani, M. M. (2015). Recycled Construction and Demolition materials in permeable pavement systems: Geotechnical and hydraulic characteristics. Journal of Cleaner Production, 90, 183-194.

Richardson, G.N., 1998. Field evaluation of geosynthetic survivability in aggregate road base. Geotechnical Fabrics Report, September.

Rowe, R.K., Sangam, H.P., 2002. Durability of HDPE geomembranes. Geotextiles and Geomembranes 20, 77–95.

Troost, G.H., Ploeg, N.A., 1990. Influence of weaving structure and coating on the degree of mechanical damage of reinforcing mats and woven goegrids caused by

This manuscript is the accepted version of the paper:

Damage induced by recycled Construction and Demolition Wastes on the short-term tensile behaviour of two geosynthetics, Transportation Geotechnics, Vol.4, pp. 64-75, DOI: 10.1016/j.trgeo.2015.07.002

different fills during installation, Fourth International Conference on Geotextiles, Geomembranes and Related Products, Den Haag, pp. 609-614.

Watts, G.R.A., Brady, K.C., 1990. Site damage trials on geotextiles, Fourth International Conference on Geotextiles, Geomembranes and Related Products, Den Haag, pp. 603-607.

Watts, G.R.A., Brady, K.C., 1994. Geosynthetics - installation damage and the measurement of tensile strength, Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore, pp. 1159-1164.

This manuscript is the accepted version of the paper:

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TABLES

Table 1. Properties of the geosynthetics provided by manufacturers.

	Geogrid	Geotextile
Raw material	HDPE	PP & PET
Unit weight (g/m^2)	450	340
Aperture dimensions (mm)	16×219	-
Mean value of the tensile strength (kN/m)	68	75/14[#]
Elongation at maximum load (%)	11±3	10

[#] Machine direction / Cross direction.

Table 2. Classification of recycled C&DW constituents.

Constituents	
Concrete, concrete products, mortar, concrete masonry units, R_c (%)	36.8
Unbound aggregate, natural stone, hydraulically bound aggregate, R_u (%)	33.7
Clay masonry units, calcium silicate masonry units, aerated non-floating concrete, R_b (%)	10.8
Bituminous materials, R_a (%)	0.5
Glass, R_g (%)	1.0
Soils, R_s (%)	17.1
Other materials, X (%)	0.1
Floating particles, FL (cm^3/kg)	7.80

Table 3. Leaching test results.

Parameter	Value (mg/kg)	Acceptance criteria for leached concentrations – Inert landfill
Arsenic, As	0.013	0.5
Lead, Pb	< 0.01	0.5
Cadmium, Cd	< 0.003	0.04
Chromium, Cr	< 0.01	0.5
Copper, Cu	0.029	2
Nickel, Ni	0.01	0.4
Mercury, Hg	< 0.002	0.01
Zinc, Zn	< 0.1	4
Barium, Ba	0.069	20
Molybdenum, Mo	0.036	0.5
Antimony, Sb	0.011	0.06
Selenium, Se	< 0.02	0.1
Chloride, Cl	19	800
Fluoride, F	< 1.5	10
Sulphate, SO_4	2100	1000
Dissolved Organic Carbon, DOC	25	500
Dissolved Solids, DS	3030	4000
pH	8.3	-

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Table 4. Summary of results of tensile tests carried out on intact geogrid specimens.

	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{2\%}$ (kN/m)	J_{Tmax} (kN/m)
Specimen 1	63.6	10.4	1144	612
Specimen 2	57.8	9.8	1074	593
Specimen 3	58.8	10.4	1063	564
Specimen 4	62.2	9.8	1149	638
Specimen 5	58.9	10.2	996	578
Mean value	60.3	10.1	1085	597
Confidence interval of 95%	60.3 ± 3.1	10.1 ± 0.4	1085 ± 79	597 ± 36

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Table 5. Summary of results of tensile tests carried out on exhumed geogrid specimens.

	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{2\%}$ (kN/m)	J_{Tmax} (kN/m)
Specimen 1	55.5	10.3	988	539
Specimen 2	57.0	10.9	1008	524
Specimen 3	57.4	10.7	1026	538
Specimen 4	55.8	10.7	1015	522
Specimen 5	57.8	10.6	1024	544
Mean value	56.7	10.6	1012	534
Confidence interval of 95%	56.7 ± 1.2	10.6 ± 0.3	1012 ± 19	534 ± 12

Table 6. Summary of results of tensile tests carried out on intact geocomposite specimens.

	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{2\%}$ (kN/m)	J_{Tmax} (kN/m)
Specimen 1	70.1	9.2	693	765
Specimen 2	67.6	10.0	605	676
Specimen 3	73.7	10.7	648	691
Specimen 4	69.0	9.7	742	714
Specimen 5	72.7	9.2	549	793
Mean value	70.6	9.7	647	728
Confidence interval of 95%	70.6 ± 3.2	9.7 ± 0.8	647 ± 93	728 ± 62

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Table 7. Summary of results of tensile tests carried out on exhumed geocomposite specimens.

	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{2\%}$ (kN/m)	J_{Tmax} (kN/m)
Specimen 1	65.8	9.3	673	704
Specimen 2	60.5	8.3	844	726
Specimen 3	57.5	8.5	604	673
Specimen 4	51.3	9.4	442	548
Specimen 5	61.3	9.0	647	684
Mean value	59.3	8.9	642	667
Confidence interval of 95%	59.3 ± 6.7	8.9 ± 0.6	642 ± 126	667 ± 61

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Table 8. Mean values of retained tensile strength, R_T, retained peak strain, R_ε, and retained secant modulus, $R_{J2\%}$.

	Geogrid			Geocomposite		
	R_T	R_ε	$R_{J2\%}$	R_T	R_ε	$R_{J2\%}$
Estimated as $\overline{X}_{dam}/\overline{X}_{intact}$	0.941	1.052	0.933	0.839	0.915	0.992
Estimated as $\overline{X_{dam}/X_{intact}}$	0.942	1.053	0.936	0.840	0.918	1.003

LIST OF FIGURES

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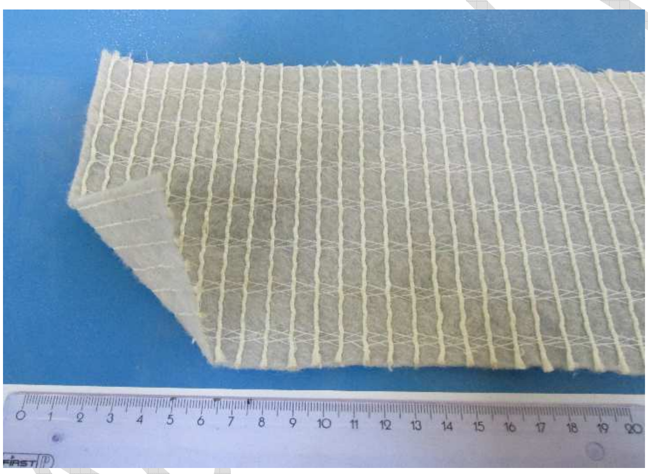
FIGURES

(a)



(b)

Figure 1 – Visual aspect of intact geosynthetics (ruler in centimetres): a) uniaxial HDPE geogrid; b) high-strength composite geotextile (geocomposite).

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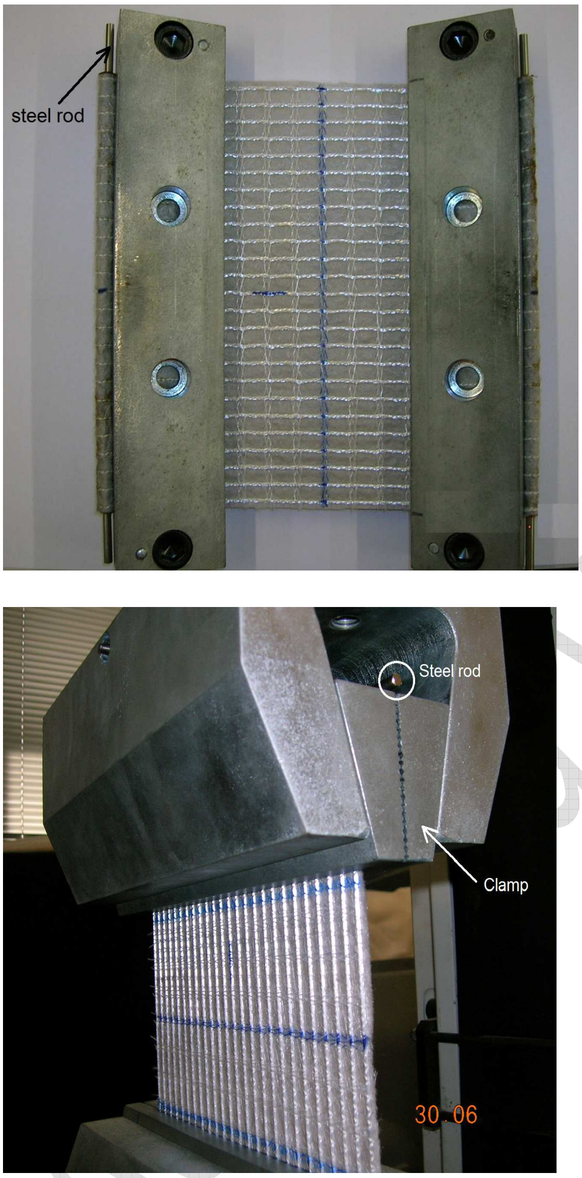

Figure 2 - Some stages of geocomposite specimens preparation for tensile tests.

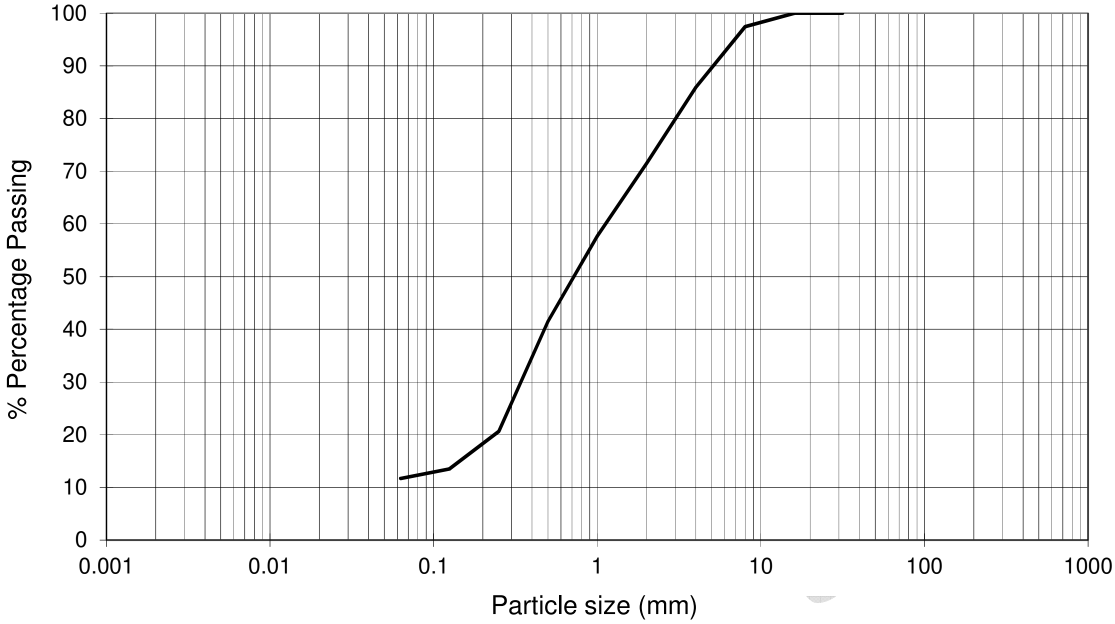

Figure 3 - Particle size distribution of the Recycled C&DW used in the trial embankment.

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(a)

(b)

(c)

(d)

Figure 4 - Trial embankment construction: a) cleaning of the foundation; b) manual placement of the C&DW over the geosynthetics; c) compaction of the final layer; d) lateral protection of the slopes with aggregates from C&DW.

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(a)

(b)

(c)

(d)

Figure 5 - Specimens exhumation: a) removal of vegetation and lateral aggregates; b) geogrid appearing during exhumation; c) careful exhumation of the specimens; d) plant roots crossing the geotextile.

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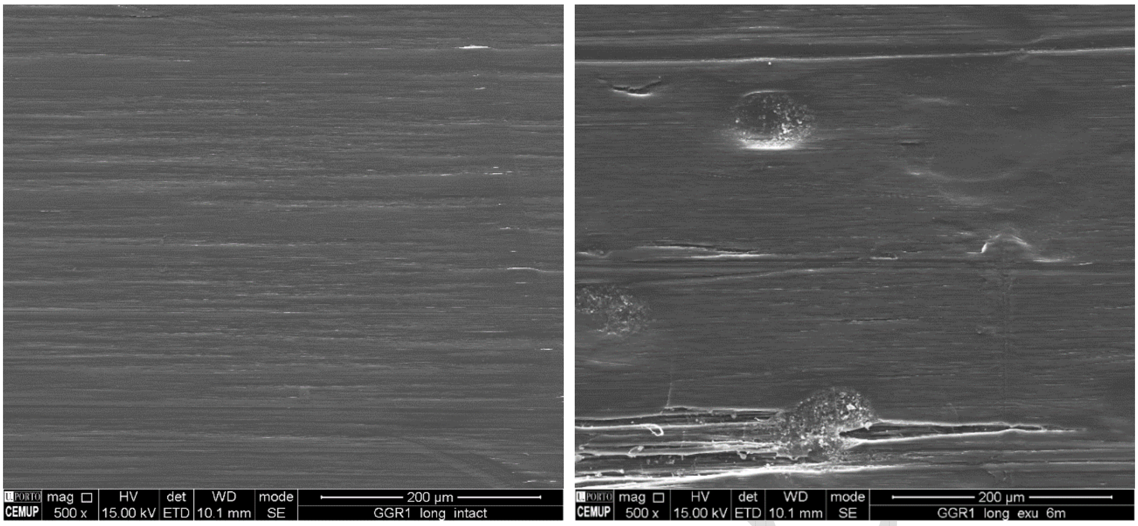

(a) (b)

Figure 6 – SEM images of the longitudinal bars of the geogrid (×500): a) intact specimen; b) exhumed specimen after 6 months.

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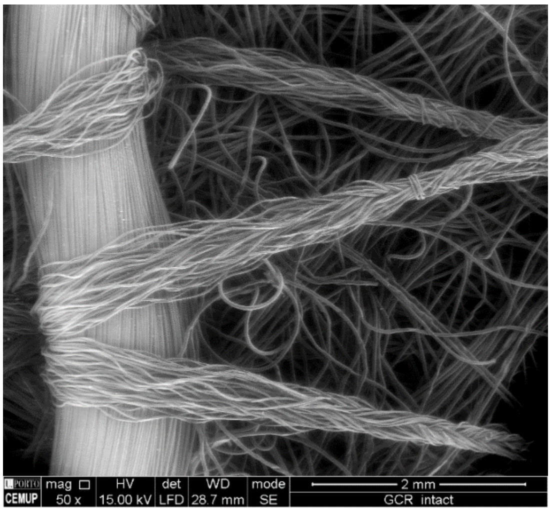
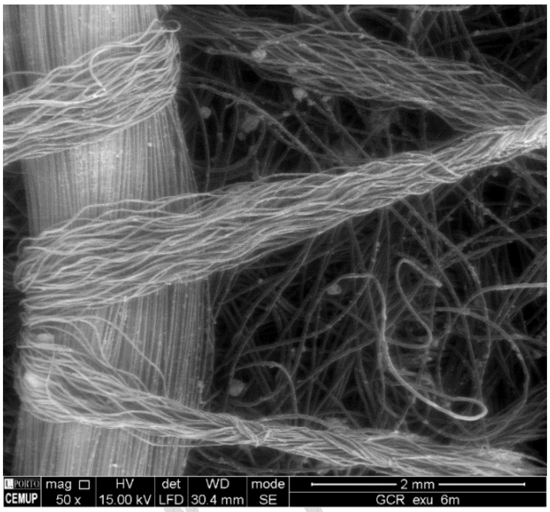
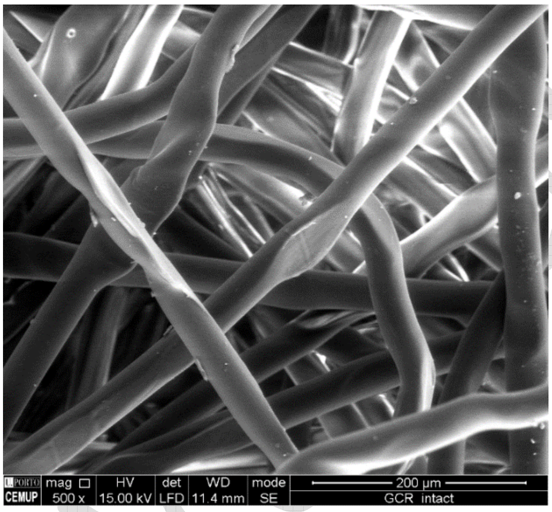


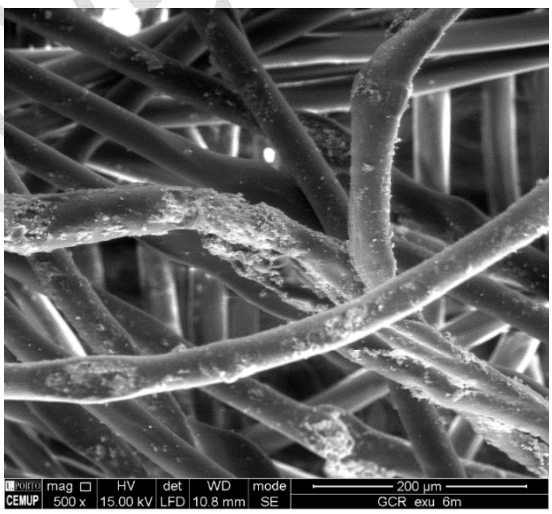
(a)



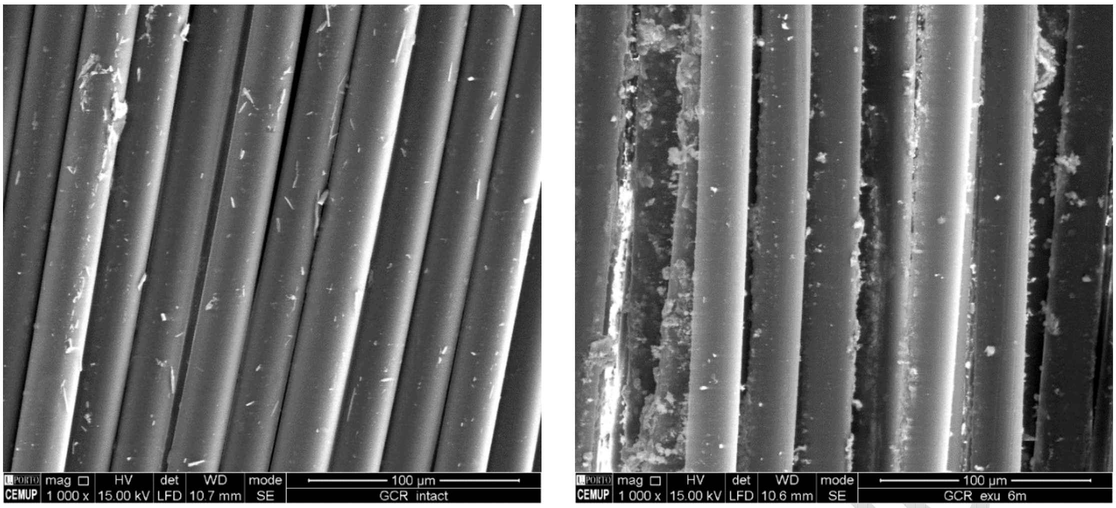
(b)



(c)



(d)



(e) (f)

Figure 7 – SEM images of geocmoposite specimens: a) intact (×50); b) exhumed specimen (×50); c) intact (×500); d) exhumed specimen (×500); e) intact (×1000); f) exhumed specimen (×1000).

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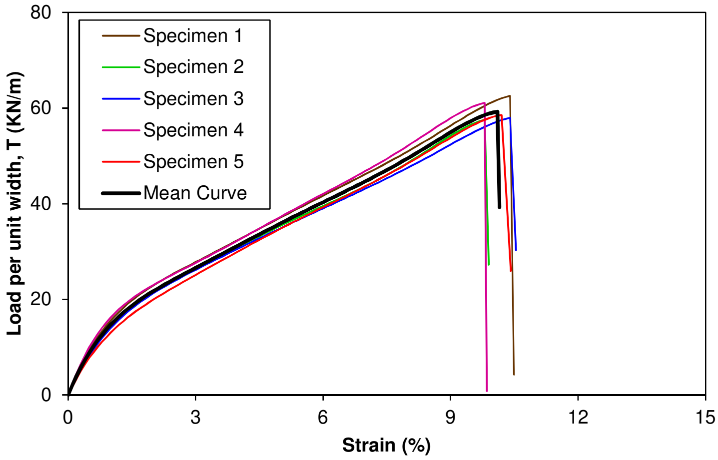
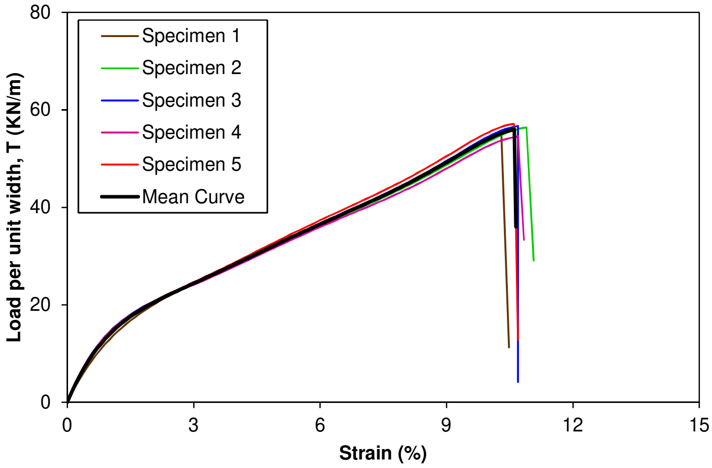


(a)



(b)

Figure 8 – Load-strain curves of tensile tests performed on: a) intact geogrid specimens; b) exhumed geogrid specimens.

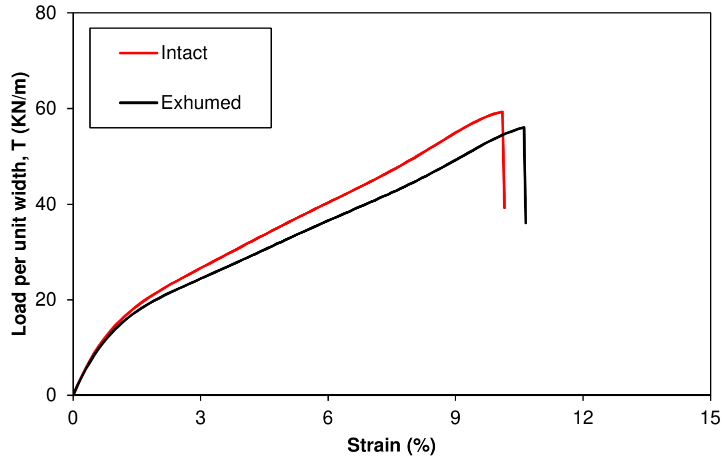


Figure 9 – Comparison of load-strain curves of intact and exhumed geogrid specimens.

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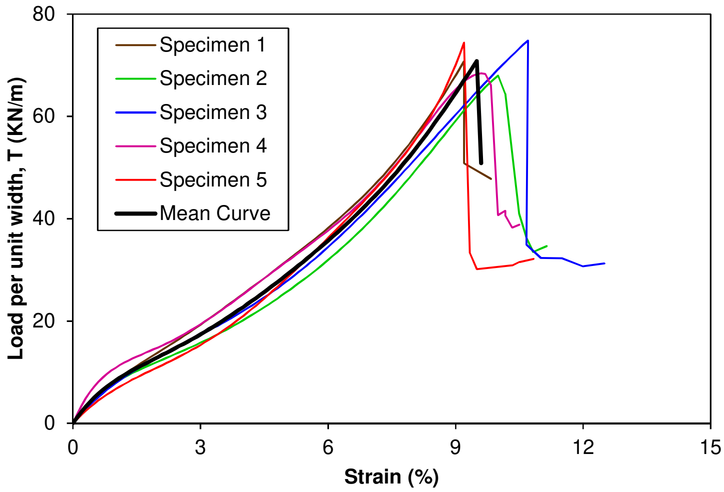
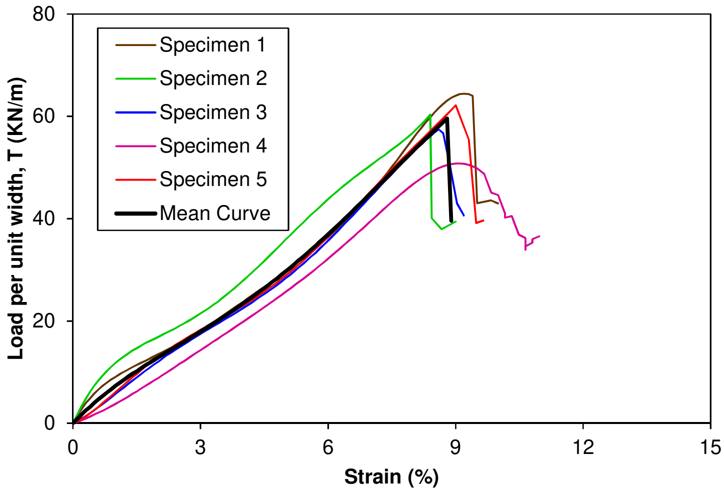


(a)



(b)

Figure 10 – Load-strain curves of tensile tests performed on: a) intact geocomposite specimens; b) exhumed geocomposite specimens.

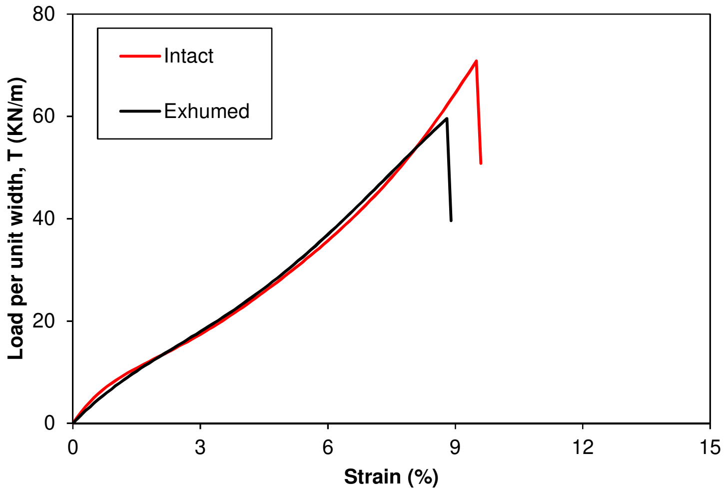


Figure 11 – Comparison of load-strain curves of intact and exhumed geocomposite specimens.