This manuscript is the accepted version of the paper:
Short-term tensile behaviour of three geosynthetics after exposure to Recycled Construction and Demolition materials, Construction and Building Materials, 273, 122031
DOI: 10.1016/j.conbuildmat.2020.122031

Short-term tensile behaviour of three geosynthetics after exposure to recycled Construction and Demolition materials

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ABSTRACT

Designing and building structures and infrastructures with alternative and environmentally friendly materials is, nowadays, an important step towards a more sustainable society. Recycled Construction and Demolition (C&D) materials have been considered as alternative materials in different civil engineering applications, such as unbound pavement layers and structural embankments, in which geosynthetics are also frequently applied. If the durability of geosynthetics is an important issue when conventional materials are used, it becomes more relevant when utilising alternative materials. This paper presents and discusses the chemical and environmental degradation induced by a recycled C&D material on the short-term tensile behaviour of three geosynthetics used typically as reinforcement material (two geogrids and a high-strength geotextile), after 24 months of exposure. For comparison purposes, geosynthetics samples were also exposed to a natural soil. The physical and environmental characterization of the recycled C&D material are presented and the tensile behaviour of intact (as-received) samples, immediately exhumed samples and exhumed samples after 24 months of exposure are characterized and discussed. To evaluate the potential damage in more detail, Scanning Electron Microscope (SEM) analyses were carried out. Regardless of the geosynthetic type and exposure condition, the geosynthetic's tensile strength decreased after 24-month exposure. This loss of tensile strength was insignificant for the high density polyethylene geogrid and higher for the geotextile. The effect of exposing the geosynthetics to the recycled C&D material for 24 months had some relevance only for geotextile. For both geogrids, the loss of strength for the specimens immediately exhumed and exposed through 24 months is comparable. In general, the exposure to the recycled C&D material or to the soil induced similar effects.

KEYWORDS: Geosynthetics; Construction and demolition waste; Recycled aggregates; Geosynthetics degradation; Tensile behaviour.

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NOTATION

ε - geosynthetic strain (dimensionless)

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

D_{max} - maximum soil or aggregate size

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)

R_{ε} - retained peak strain (dimensionless)

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

R_T - retained tensile strength (dimensionless)

T - load per unit width (kN/m)

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

1. INTRODUCTION

Recycled Construction and Demolition (C&D) aggregates have been considered as alternative materials in several civil engineering applications, such as unbound pavement layers [1-4], as cement stabilized or geopolymer-stabilized material in pavement base/subbase applications [5-8], as backfill material for geosynthetic reinforced structures [9-13], as pipe backfilling material [14, 15] and as aggregates for concrete production [16-18]. In some of those applications, geosynthetics, particularly geogrids and high strength geotextiles, are used as reinforcement elements of the recycled materials. Thus, it is of utmost importance evaluating the potential degradation caused by these alternative materials on the geosyntethics short- and long-term tensile behaviour.

One of the main issues on the use of geosynthetics pointed out by some construction industry stakeholders is their durability. In fact, the damage caused by the mechanical actions during installation and the chemical and biological degradation are key aspects to be thought over in geosynthetics behaviour.

When assessing the design value of a geosynthetic's long-term tensile strength, reduction factors to account for the damage during installation, the effect of creep and the effects caused by chemical and biological degradation of the polymers are usually considered.

Laboratory and field studies concerning the mechanical damage of geosynthetics caused by the compaction procedures have been reported for many years [19-25]. More recently, the installation damage induced by recycled C&D materials has also been simulated through laboratory tests [26, 27] and field tests [28].

The oxidation degradation of geosynthetics in field conditions is affected by chemical constituents of the surround media (pH, transition metal ions, etc.), the temperature and the available oxygen concentration [29]. The presence of transition metal ions such as cobalt, manganese, copper and iron can accelerate the oxidation of polyolefins. However, since all geosynthetics made from polyolefins contain antioxidants, it is expected that the oxidation of the polymer does not begin until nearly all of the antioxidants have been consumed [29].

The hydrolytic susceptibility of polyester (PET) geosynthetics has also been assessed. A pH of 9 is considered the upper limit for using PET geosynthetics for critical applications, while a lower limit of about 4 is assumed [29]. The Federal Highway Administration (United States) defines a lower limit of pH of 3 for polyolefin (high density polyethylene and polypropylene) and polyester geosynthetics [30].

The biological degradation has often been mentioned as a concern, but according to [31, 32], unless biologically sensitive additives (such as low-molecular-weight plasticizers) are included in the polymer formulation, geosynthetic resins are not sensitive to bacteria and fungi.

Geosynthetics have been exhumed after decades of service with marginal losses on their property values [32]. However, it is of great significance understanding the effects of the use of alternative fill materials, such as recycled aggregates coming from C&D waste, on geosynthetics short and long term behaviour.

In order to study the chemical and environmental degradation induced by a recycled C&D material on the short-term tensile behaviour of three geosynthetics (two geogrids and one geotextile), damage trial embankments were constructed. For comparison purposes, an embankment with a clayey sand was also built.

It should be pointed out that the construction of these damage trial embankments intended to simulate the potential degradation (chemical and environmental) induced by a recycled C&D material on the geosynthetics and not the damage during installation due to the compaction procedures. Secondly, the construction method and the dimensions of these small trial embankments are not suitable for other purposes, namely the study of the embankments behaviour.

Geosynthetic samples were exhumed from the embankments after 6, 12 and 24 months of their construction. The effects induced on two geosynthetics (the HDPE geogrid and the geotextile) after 6 months of exposure to the recycled C&D material was presented and discussed in a previous publication [33]. Vieira [10] reported the effects provoked by the recycled C&D material on the geosynthetic samples exhumed after 12 months of the embankment construction. This paper refers to geosynthetic samples exhumed after 24 months of exposure and also includes a comparative analysis with the effects induced by a soil.

Although the period of exposure of the geosynthetics to the recycled C&D material (2 years) is not comparable to the service life of a real structure, this study will provide information on the degradation induced by an alternative fill material on the tensile behaviour of three geosynthetics with different structure and base polymers and also allows the comparison with the effects caused by a conventional material (a natural soil).

2. MATERIALS AND METHODS

2.1. Geosynthetics

The study was carried out on three commercial geosynthetics used commonly as reinforcement (Figure 1). A uniaxial high density polyethylene (HDPE) geogrid, referred to as Geogrid 1 (Figure 1a), a uniaxial geogrid manufactured of extruded polyester (PET) bars with welded rigid junctions, referred to as Geogrid 2 (Figure 1b) and a high-strength composite geotextile consisting of polypropylene (PP) continuousfilament needle-punched nonwoven and high-strength PET yarns, referred to as Geotextile (Figure 1c). Table 1 summarizes the main properties of these geosynthetics.

2.2. Filling materials

To study the chemical and environmental degradation induced by a recycled C&D material on the short-term tensile behaviour of the geosynthetics, three damage trial embankments were constructed. A fourth embankment was constructed using a clayey sand for comparison purpose.

The recycled C&D aggregate is a fine grain material, coming mainly from maintenance and demolition works of residential buildings and removal of C&D waste from illegal waste disposal sites. This recycled material was provided by a Portuguese recycling plant and results from an initial sorting process (to remove contaminating materials such as steel, plastic, wood, …), followed by crushing and grain size separation. The resulting materials are mixed recycled aggregates, consisting of concrete, mortar, bricks, stones and others. The constituents of the C&D material were determined in accordance with the European Standard [34], following a manual sorting process of the particles larger than 4 mm (Figure 2). Table 2 presents the constituents of the recycled C&D material (only for particles above 4mm). It is mostly composed of concrete, mortar, unbound aggregates and soil. It should be noted that the volume of floating particles exceeds the desirable value (< 5cm^3/kg of dry matter according to [35]), meaning that some wood and polystyrene are still present in the recycled material.

Figure 3 presents the particle size distribution of the recycled C&D material and clayey sand. It should be noted that the sand used in this study was not ideal since it is finer than the C&D material and presents a high fine content, but it was not possible to find in due time a more suitable material.

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The evaluation of the leaching behaviour of recycled C&D materials is of utmost importance due to environmental concerns regarding the potential contamination of groundwater and the possible presence of chemical substances that could induce geosynthetics degradation. Laboratory leaching tests were carried out in accordance with the European Standard [36] on recycled C&D material before the construction of the trial embankments and on material collected after 24 months of construction. Results of leaching tests will be presented and discussed in Section 3.1.

2.3. Construction of the trial embankments

Three damage trial embankments were constructed using recycled C&D material. "Embankment 1" and "Embankment 1S" are similar and were constructed to allow the exhumation of geosynthetic samples after 6, 12 and 24 months of exposure. "Embankment 2" is a smaller embankment also constructed using recycled C&D material but with the purpose of exhuming the geosynthetic samples immediately after the installation.

It should be highlighted that the main purpose of the construction of the damage trial embankments was evaluating the chemical and environmental degradation induced by the exposure of the geosynthetics to a recycled C&D material and not the damage during installation. Therefore, to separate the effect of these two factors (exposure to an alternative material and damage during installation), it was constructed the "Embankment 2" under the same conditions of the other two embankments. Thus, it is possible to separate the damage during installation, from the degradation induced by the exposure to recycled C&D material. Additionally, and having in mind that the main purpose of this study is not the damage during installation, a lightweight compaction process was adopted.

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For comparison purposes, a fourth embankment ("Embankment 3") was constructed using a clayey sand.

Embankments 1, 1S and 3 were constructed with dimensions in plant of 2m × 3m and height of 0.45 m. Embankment 2 had dimensions 1.5 m × 1.5 m× 0.45 m.

Inside the embankments the geosynthetic samples (aprox. 0.45 m × 1.5m) were distributed in 2 levels vertically spaced of 0.20 m. After cleaning the foundation from the existing vegetation, a 5 cm-thick layer was placed and compacted and the geosynthetic samples of the first level were carefully positioned without overlapping. Geosynthetic samples were then covered with a first layer of C&D material (soil in Embankment 3) placed manually to prevent mechanical damage (Figure 4a). Additional quantities of filling material were disposed, evenly spread and compacted to reach a lift with final thickness of approximately 0.20 m. The second layer of geosynthetic samples was positioned and the compaction process was repeated.

The lateral slopes of the embankments were also compacted (Figure 4b) and coarse recycled C&D aggregates were disposed to prevent erosion by rain water (Figure 4c).

As previously mentioned a lightweight compaction process was adopted. The compaction was carried out 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. The compaction was only carried out to make easier the construction and to prevent wind and rain erosion.

More details on embankments construction can be found on a previous publication [33] referring to the exhumation after 6 months of exposure to recycled C&D material.

2.4. Exhumation of the specimens

To prevent additional damage, the exhumation of the geosynthetic samples was carefully carried out. It begun with the removal of the coarse aggregates placed on the lateral slopes, as well as the vegetation that grew up over the embankments. Fill materials were manually removed with hoes and shovels, being the material just above the geosynthetics removed gently with the hands (Figure 5a and 5b).

From visual inspection after exhumation, the geogrids did not show damage visible to the naked eye. Geotextile samples were crossed by plant roots, either in the Embankment 1 (recycled C&D material) or in the Embankment 3 (clayey sand), some of them with a few millimetres in diameter (Figure 5c).

Exhumed geosynthetic samples were put into plastic bags and transported to the laboratory where they remained at 20ºC until be tested.

2.5. SEM images

Apart from the plant roots that crossed the geotextile and C&D material (or soil) particles and fine roots stuck to the geosynthetics, the preliminary visual inspection of the exhumed samples did not reveal significant damage. Nonetheless, in order to evaluate the damage in 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.

The samples were coated with an Au/Pd thin film for 120 seconds, by sputtering, using the SPI Module Sputter Coater equipment.

2.6. Tensile strength tests

The tensile behaviour of the geosynthetics was characterized through tensile strength tests carried out on virgin and exhumed geosynthetic samples. The tensile strength tests were performed in a Universal Testing Machine on five specimens for each condition (intact or exhumed), following the European Standard [37], with strain rate of 20%/min. A video-extensometer was used to measure the geosynthetics strain.

In order to characterise the tensile behaviour of the geosynthetics, for each geosynthetic specimen the maximum tensile force, T_{max}, the geosynthetic tensile 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}, were evaluated. The average value of each parameter for the 5 specimens and the 95% confidence intervals assuming a Student's t-distribution were then computed. The Student's t-distribution was assumed since the population standard deviation is unknown and the number of specimens is lower than 30.

The specimens of Geogrid 1 were cut with a width of 200 mm (9 longitudinal bars) and length of 470 mm. To ensure fixing the geogrid on the transversal bars, the distance between the clamps was adjusted to give a test specimen length of 395 mm approximately. The reference points for the video-extensometer were fixed on the specimens 200 mm apart.

The specimens of Geogrid 2 were cut with a width of 200 mm (5 longitudinal bars) and length of 380 mm. The distance between the clamps was approximately 200 mm and the reference points for the video-extensometer were fixed on the specimens spaced approximately 100 mm apart.

Tensile strength tests of the high strength geotextile need some previous preparation to avoid the sliding of the polyester yarns, namely the use of a particular nitrile based adhesive to glue the geotextile positioned inside the clamps and the use of steel rods of small diameter in the area of geotextile folding (Figure 6).

The geotextile specimens were cut with dimensions 200 mm width × 340 mm length to allow the procedure of gluing and folding above-mentioned. The distance between jaws was adjusted to give a test specimen length of 100 mm and the reference points were fixed on the specimens 60 mm apart.

In order to quantify the damage on geosynthetics due to their exposure to recycled C&D materials or to the soil, 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 and compared. The retained value of a generic parameter, *X*, is typically defined as:

$$R_X = X_{exhu}/X_{virg} \tag{1}$$

where X_{exhu} is the value of parameter *X* for exhumed specimens and X_{virg} is the value for virgin specimens (as provided by the manufacturer).

The mean value of R_X is not simply the ratio of the mean of populations X_{exhu} and X_{virg}, as is usually presented in the literature, but the mean value of the quantities R_X estimated by equation (1) [38]. However, there are studies [33] showing that the values obtained by the two approaches are very similar and hence the mean value of R_X was evaluated as the ratio of the mean values of the parameter X_{exhu} and X_{virg}.

3. RESULTS AND DISCUSSION

3.1. Leaching behaviour of the recycled C&D material

Table 3 presents the results of the laboratory leaching test carried out on the recycled C&D material used in the construction of the trial embankments at the initial stage and after 24 months exposed to weather conditions. The acceptance criteria for leached maximum concentration for inert landfill, defined by the European Council Decision 2003/33/EC (2003), were also included in last column of Table 3.

From the analysis of the results included in Table 3 it can be concluded that only the value of sulphate of the initial C&D material (highlighted in bold) exceeds the maximum value established by the European legislation for inert landfill. All the other pollutants are well below the limits. However, it should be pointed out that above-mentioned Directive [39] makes an exception to the limit for sulphates, noting that if the waste does not meet the limit 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 (liquid/solid).

High sulphate values have also been reported by other authors in mixed recycled aggregates [40-42]. The source of the sulphates in recycled aggregates is often associated with gypsum drywall, also known as wallboard or sheetrock, a very common component of mixed recycled aggregates [40]. There are, however, some research studies [41] showing that the correlation between the percentage of gypsum and the amount of sulphates leached is not clear, being the sulphates in leaching processes also related to other compounds of recycled aggregates such as concrete and mortar, natural aggregates and ceramic particles.

The recycled C&D material collected from the embankments (24 months of exposure) exhibited a significant decrease of the value of sulphate and dissolved solids. These changes can be explained by the decrease in leachate concentration over time as a result of rainwater.

The pH value also decreased from alkaline to neutral (slightly acidic). It is worth mentioning that the pH values of recycled aggregates are generally within the range of natural aggregates, which varies from 7 to 13 [43]. Recycled concrete aggregates (RCA) are commonly more alkaline than recycled mixed aggregates (RMA). While typical pH range for RCA is 10–13, for RMA the pH value usually varies between 9 and 10 [43]. Moreover, lower pH values have been reported in the finer fractions of recycled aggregates [10, 44, 45]

In accordance with the FHWA [30] and regarding the electrochemical properties, the reinforced fill soils are qualified for use in mechanically stabilized earth using geosynthetics, if their pH is within the range 3 – 9 for polyester materials and if pH is higher than 3 for polyolefin base materials (PP & HDPE). The recycled C&D material fulfils both specifications.

3.2. Geogrid 1

The results of tensile strength tests carried out on Geogrid 1 are summarised in Table 4. The mean values of the maximum tensile force, T_{max}, geosynthetic tensile strain for T_{max}, ε_{Tmax}, secant stiffness modulus at strain of 2%, $J_{2\%}$, and secant stiffness modulus at ε_{Tmax}, J_{Tmax}, are presented. Table 4 also presents the 95% confidence intervals assuming a Student's t-distribution for virgin specimens and

geogrid specimens subjected to the different damage processes: construction of the embankment using recycled C&D material immediately followed by their exhumation; construction of the embankment using recycled C&D material and exhumation after 24 months of exposure; construction of the embankment with a clayey sand and exhumation after 24 months of exposure.

Analysing the results presented in Table 4 one can conclude that, regardless the damage condition, the mean value of the tensile strength of the exhumed specimens is inside the confidence interval of this parameter for virgin specimens. A similar conclusion can be drawn for the other parameters with the exception of the geosynthetic tensile strain for T_{max} and secant stiffness modulus at ε_{Tmax} for the specimens exposed to the clayey sand. Indeed, high variability of T_{max} was observed for this condition.

Specimens immediately exhumed and specimens exposed to soil have experienced a small decrease in tensile strength (decrease of around 2% and values inside the confidence interval for virgin samples). This shows that, as expected, the construction of the embankments did not induce damage and the effect of the geogrid exposure to soil is negligible. The exposure of this geogrid to recycled C&D material for 24 months lead to a slight decrease of its tensile strength (around 4% but remaining inside the confidence interval).

Figure 7 compares the mean load-strain curves for virgin and exhumed specimens. The graph reveals only a small decrease of the geogrid's tensile stiffness, particularly for strain greater than 2%. Although related to full-scale field installation tests, the slight change of the load-strain curves for small geosynthetics strains was also reported by [20]. Hufenus et al. [20]have concluded that, even when the maximum tensile strength and elongation at break decreased, the slope of the load-strain curve was not largely affected by the installation damage.

The absence of significant damage was also proven by SEM images. Figure 8 and Figure 9 exhibit SEM images with 500 times magnification for longitudinal and transversal bars of the geogrid, respectively. There is no visible damage, only appearing microscopic particles that remained gummed to the geogrid after exhumation.

3.3. Geogrid 2

The results of tensile tests performed on virgin and exhumed samples of the PET geogrid (Geogrid 2) are summarised in Table 5.

The tensile strength reached in laboratory tests of virgin specimens exceeded the mean value provided by the manufacturer (Table 1) however, high variability of results was observed. It should also be noted that the maximum tensile force is achieved for a low value of strain (5.6%), meaning that it is a geogrid of high tensile stiffness (around 1900 kN/m for 2% of strain).

Regardless the damage condition, as observed for Geogrid 1, the mean value of the tensile strength of exhumed specimens is inside the confidence interval of this parameter for virgin specimens. There was a small decrease in the mean value of the tensile strength, partly due to the high value of T_{max} achieved in virgin specimens, however this decrease is quite similar for the three damage conditions.

Comparing the tensile strength of the specimens immediately exhumed with that of specimens exposed to recycled C&D material, one can conclude that the effects of exposure to this alternative material is negligible. There are slight changes in terms of tensile stiffness (exposed specimens exhibited higher tensile stiffness), probably due to the particles that tend to remain glued to the geogrid (Table 5 and Figure 10). Allen and Bathurst [25] also pointed out that the initial modulus of the load-strain curves of some materials does not change and in some cases appears to be slightly greater after geosynthetics exhumation.

Figure 10 enhances the little influence of this damage processes on the tensile behaviour of this geogrid. It should also be emphasized that the geogrid tensile strength after 24 months of exposure to the soil or to C&D waste remains higher than its nominal value – 80 kN/m (Table 1).

SEM images of virgin and exhumed specimens were included in Figure 11. Figure 11(a), (c) and (e) show the longitudinal and transversal bars and the welded junction. It is clear that the welded junction remains stable after 24 months of exposure to the fill material. Figure 11(b), (d) and (f) compare the longitudinal bars (magnification x500) of intact and exhumed specimens. Some roughness is visible in the intact sample resulting from the manufacturing process. The exhumed samples do not seem to show additional damage. Only small particles of the fill materials remain gummed to the bars.

3.4. High strength geotextile

Table 6 summarises the results of tensile strength tests performed on virgin and exhumed samples of the high strength geotextile Even with the previous preparation of the geotextile specimens, mentioned in section 2.6, to avoid the sliding of the polyester yarns (Figure 6), the tensile strength obtained in laboratory tests was slightly lower than the nominal strength of this material (Table 1).

In contrast to what was observed in the geogrids and regardless the damage condition, the mean values of the tensile strength of exhumed specimens are outside the confidence interval of this parameter for virgin specimens. This evidence reveals the occurrence of geotextile degradation. Notwithstanding, the tensile stiffness for 2% of strain, $J_{2\%}$, remains inside the confidence interval for virgin specimens. This low variation in the geotextile tensile stiffness for low values of strain can also be observed in Figure 12. Figure 12 also shows that, regardless the tensile strength decrease, the geotextile strain for T_{max} is quite similar for all the conditions.

The geotextile specimens exhumed immediately after embankment construction exhibited a loss of tensile strength of around 17%. It should be noted that identical preparation of the geotextile specimens before the tensile test (nitrile based adhesive and use of steel rods) was also carried out for all exhumed specimens. The authors believe that this reduction of the tensile strength is most likely due to the less effective binding of the PET yarns to the nonwoven geotextile, caused by the handling during installation, rather than damage induced by the compaction.

The loss of tensile strength of the geotextile specimens exposed to C&D material for 24 months was roughly 26% (compared with virgin samples). This means a loss of strength 9% higher than that obtained for specimens exhumed immediately after embankment construction (Table 6). It can therefore be concluded that only 9% of the loss of tensile strength is due to the exposure to the C&D material during the 24 months, the remaining loss is due to the handling and construction procedures.

The geotextile tensile strength after 24 months of exposure to the soil or to the C&D waste is quite similar (slightly lower for soil exposure). Thus, one can conclude that the degradation of this geotextile cannot be attributed to the use of the recycled material.

The load-strain curve of geotextile specimens exposed to soil was slightly different from the other samples, in particular regarding the tensile stiffness for strain higher than 3% (Figure 12). This difference may be attributed to the fine particles that remained glued to the geotextile after exhumation, as evidenced in Figure 13(e) and (f).

SEM images of virgin and exhumed geotextile specimens are illustrated in Figure 13. Figure 13(a), (c) and (e) show one PET yarn and its connection to the nonwoven geotextile. Regardless the exposure condition, these connections are still visible but the wires tend to be more spread out. Figure 13(b), (d) and (f) compare the wires of one PET yarn (magnification x500) of intact and exhumed specimens. No damage is visible, but particularly in the sample exposed to the clayey sand, very fine particles remained gummed to the filaments.

3.5. Influence of fill material and geosynthetic type

Table 7 presents the values of the retained tensile strength, R_T, the retained peak strain, R_ε, and the retained secant modulus at 2% of strain, $R_{J2\%}$, evaluated according to equation (1), for the three geosyntetics and distinct exposure conditions.

Regardless of the geosynthetic type and exposure condition (immediately exhumed, exposed to C&D waste or exposed to soil), loss of tensile strength has occurred ($R_T < 1$). This loss of tensile strength was insignificant for Geogrid 1 ($R_T \approx 1$) and higher for the Geotextile. The decrease in the tensile stiffness for 2% of strain was small for both Geogrid 1 and Geotextile and there was a slight increase for Geogrid 2 ($R_{J2\%} > 1$).

The effect of exposing the geosynthetics to the C&D waste for 24 months had some relevance only for Geotextile. For both geogrids, the values of R_T for the specimens immediately exhumed and exposed through 24 months are equal (Geogrid 2) or similar (Geogrid 1).

The exposure to the recycled C&D material or to the soil for 24 months induced, in general, similar effects. Such effects can even be considered equivalents for the Geogrid 1 and the Geotextile.

The geosynthetic strain for T_{max} is not highly influenced by the exposure conditions ($R_\varepsilon > 0.93$ for all conditions), even for the Geotextile which has experienced the greatest degradation of tensile stiffness.

4. CONCLUSIONS

The main objective of this paper is to characterize the effects on the tensile behaviour of three geosynthetics (a HDPE geogrid, a PET geogrid and a high-strength composite geotextile) due to the potential degradation induced by a recycled C&D material. To achieve this goal, damage trial embankments were constructed and geosynthetics samples were exhumed immediately after their installation and after 24 months of exposure. It should be highlighted that the main purpose of the construction of these embankments was evaluating the chemical and environmental degradation induced by

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the exposure of the geosynthetics to recycled C&D material and not the damage during installation.

On the basis of the analysis and interpretation of the results, the following conclusions can be drawn.

- Laboratory leaching tests carried out on the recycled C&D material revealed that only the sulphates exceeds the maximum value established by the European legislation for inert landfill. All the other pollutants are significantly below the limits. The recycled C&D material collected from the embankments (after 24 months) exhibited, as expected due to the decrease in leachate concentration over time, a significant decrease of the value of sulphate and dissolved solids.
- Regardless of the exposure condition (specimens immediately exhumed, exposed to C&D waste and exposed to soil), the decrease in the HDPE geogrid tensile strength is very low (below 4% on average) and the tensile strength remains inside the confidence interval of this parameter for intact specimens.
- The effect of the exposure to soil for 24 months on the tensile strength of Geogrid 2 (PET geogrid) was negligible. The decrease on the tensile strength of specimens immediately exhumed and exposed to C&D material for 24 months is also very small (around 7%). As concluded for Geogrid 1, regardless the exposure condition, the mean value of the tensile strength of exhumed specimens is inside the confidence interval of this parameter for intact specimens. The geogrid tensile strength of exhumed specimens remained higher than its nominal value.
- Exposed specimens of Geogrid 2 exhibited higher tensile stiffness than intact specimens, probably due to small soil or C&D waste particles that remained glued to the geogrid.

- The geotextile specimens immediately exhumed after embankment construction exhibited a loss of tensile strength of around 17%. This decrease of the tensile strength is most likely due to the less effective binding of the PET yarns to the nonwoven geotextile, caused by handling during installation, rather than damage induced by the compaction.
- The effects of geotextile's exposure to the soil or to the C&D waste is quite similar (slightly lower for soil exposure), allowing to conclude that the degradation of the geotextile cannot be attributed to the use of the recycled material.
- For the geotextile, in contrast to what was concluded for the geogrids, and regardless the damage condition, the mean values of the tensile strength of exhumed specimens are outside the confidence interval of this parameter for intact specimens.

Although the soil used in this study (a clayey sand) has finer particles than the recycled C&D material, the exposure to the recycled material or to the soil for 24 months induced, in general, similar effects.

This research demonstrated that regarding the potential damage induced in the geosynthetics, recycled C&D materials can be seen as a feasible alternative to conventional backfilling materials. However, further studies, including confined-accelerated tests of geosynthetics and tensile creep tests carried out on exhumed geosynthetic samples, are required to support the overall conclusion of this study.

ACKNOWLEDGMENTS

This work was financially supported by: Project PTDC/ECI-EGC/30452/2017 - POCI-01-0145-FEDER-030452 - funded by FEDER funds through COMPETE2020 -

Programa Operacional Competitividade e Internacionalização (POCI) and by national funds (PIDDAC) through FCT/MCTES.

The authors also thank Tensar International, Naeu and TenCate Geosynthetics Iberia for providing the geosynthetics used in this study and RCD, SA for making facilities available to construct the trial embankments.

REFERENCES

[1] Arulrajah, A., Disfani, M.M., Horpibulsuk, S., Suksiripattanapong, C., and Prongmanee, N., *Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications.* Construction and Building Materials, 2014. **58**(0): p. 245-257.

[2] Pereira, P.M., Ferreira, F.B., Vieira, C.S., and Lopes, M.L. *Use of recycled c&d wastes in unpaved rural and forest roads – feasibility analysis*. in *Wastes: Solutions, Treatments and Opportunities III - Selected papers from the 5th International Conference Wastes: Solutions, Treatments and Opportunities* 2020.

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

[4] Poon, C.S. and Chan, D., *Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base.* Construction and Building Materials, 2006. **20**(8): p. 578-585.

[5] Agrela, F., Barbudo, A., Ramírez, A., Ayuso, J., Carvajal, M.D., and Jiménez, J.R., *Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain.* Resources, Conservation and Recycling, 2012. **58**(0): p. 98-106.

[6] Mohammadinia, A., Arulrajah, A., Sanjayan, J., Disfani, M., Bo, M., and Darmawan, S., *Laboratory evaluation of the use of cement-treated Construction and Demolition Materials in pavement base and subbase applications.* Journal of Materials in Civil Engineering, 2014. **DOI: 10.1061/(ASCE)MT.1943-5533.0001148.**

[7] Bassani, M., Tefa, L., Coppola, B., and Palmero, P., *Alkali-activation of aggregate fines from construction and demolition waste: Valorisation in view of road pavement subbase applications.* Journal of Cleaner Production, 2019. **234**: p. 71-84.

[8] Cristelo, N., Fernández-Jiménez, A., Vieira, C., Miranda, T., and Palomo, Á., *Stabilisation of construction and demolition waste with a high fines content using alkali activated fly ash.* Construction and Building Materials, 2018. **170**: p. 26-39.

[9] Santos, E.C.G., Palmeira, E.M., and Bathurst, R.J., *Behaviour of a geogrid reinforced wall built with recycled construction and demolition waste backfill on a collapsible foundation.* Geotextiles and Geomembranes, 2013. **39**: p. 9-19.

[10] Vieira, C.S., *Valorization of Fine-Grain Construction and Demolition (C&D) Waste in Geosynthetic Reinforced Structures.* Waste and Biomass Valorization, 2020. **11**: p. 1615–1626.

[11] Vieira, C.S. and Pereira, P.M., *Interface shear properties of geosynthetics and construction and demolition waste from large-scale direct shear tests.* Geosynthetics International, 2016. **23**(1): p. 62–70.

[12] Vieira, C.S., Pereira, P.M., and Lopes, M.L., *Recycled Construction and Demolition Wastes as filling material for geosynthetic reinforced structures. Interface properties.* Journal of Cleaner Production, 2016. **124**: p. 299-311.

[13] Santos, E.C.G., Palmeira, E.M., and Bathurst, R.J., *Performance of two geosynthetic reinforced walls with recycled construction waste backfill and constructed on collapsible ground.* Geosynthetics International, 2014. **21**(4): p. 256–269.

[14] Rahman, M.A., Imteaz, M.A., Arulrajah, A., and Disfani, M.M., *Suitability of recycled construction and demolition aggregates as alternative pipe backfilling materials.* Journal of Cleaner Production, 2014. **66**: p. 75-84.

[15] Vieira, C.S., Cristelo, N., and Lopes, M.L., *Geotechnical and geoenvironmental characterization of recycled Construction and Demolition Wastes for use as backfilling of trenches*, in *4th Edition of the International Conference Wastes: Solutions, Treatments and Opportunities*. 2017, CRC Press Taylor & Francis Group: Porto, Portugal. p. 175-181.

[16] Behera, M., Bhattacharyya, S.K., Minocha, A.K., Deoliya, R., and Maiti, S., *Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review.* Construction and Building Materials, 2014. **68**(0): p. 501-516.

[17] Rao, A., Jha, K.N., and Misra, S., *Use of aggregates from recycled construction and demolition waste in concrete.* Resources, Conservation and Recycling, 2007. **50**(1): p. 71-81.

[18] Silva, R.V., Brito, J., and Dhir, R.K., *Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete.* Journal of Cleaner Production, 2016. **112**: p. 2171–2186.

[19] Richardson, G., *Field evaluation of geosynthetic survivability in aggregate road base.* Geotechnical Fabrics Report, 1998. **16**(7): p. 34–38.

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

[21] Pinho-Lopes, M. and Lopes, M.L., *Tensile properties of geosynthetics after installation damage.* Environmental Geotechnics, 2014. **1**(3): p. 161-178.

[22] Troost, G.H. and Ploeg, N.A., *Influence of weaving structure and coating on the degree of mechanical damage of reinforcing mats and woven goegrids caused by different fills during installation*, in *Fourth International Conference on Geotextiles, Geomembranes and Related Products*. 1990: Den Haag. p. 609-614.

[23] Rosete, A., Lopes, P.M., Pinho-Lopes, M., and Lopes, M.L., *Tensile and hydraulic properties of geosynthetics after mechanical damage and abrasion laboratory tests.* Geosynthetics International, 2013. **20**(5): p. 358–374.

[24] Lim, S.Y. and McCartney, J.S., *Evaluation of effect of backfill particle size on installation damage reduction factors for geogrids.* Geosynthetics International, 2013. **20**(2): p. 62–72.

[25] Allen, A.M. and Bathurst, R.J., *Characterization of geosynthetic load-strain behaviour after installation damage.* Geosynthetics International, 1994. **1**(2): p. 181-199.

[26] Carlos, D.M., Carneiro, J.R., and Lopes, M.L., *Mechanical damage of geotextiles caused by recycled C&DW and other aggregates.* Wastes – Solutions, Treatments and Opportunities III, CRC Press/Balkema, 2020: p. 287-292.

[27] Vieira, C.S. and Lopes, M.L., *Damage induced by recycled aggregates on the short-term tensile behaviour of a high-strength geotextile.* Procedia Engineering, 2016. **143**: p. 212-219.

[28] Fleury, M.P., Santos, E.C.G., Lins da Silva, J., and Palmeira, E.M., *Geogrid installation damage caused by recycled construction and demolition waste.* Geosynthetics International, 2019. **26**(6): p. 641-656.

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

[30] FHWA, *Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes*, in *FHWA-NHI-10-024* R.R. Berg, B.R. Christopher, and N.C. Samtani, Editors. 2010: Washington D.C.

[31] Koerner, G.R., Hsuan, Y.G., and Koerner, R.M., *The durability of geosynthetics*, in *Geosynthetics in Civil Engineering*, R.W. Sarsby, Editor. 2007, Woodhead publishing Limited and CRC Press.

[32] Koerner, R.M., Hsuan, Y.G., and Koerner, G.R., *Lifetime predictions of exposed geotextiles and geomembranes.* Geosynthetics International, 2017. **24**(2): p. 198–212.

[33] Vieira, C.S. and Pereira, P.M., *Damage induced by recycled Construction and Demolition Wastes on the short-term tensile behaviour of two geosynthetics.* Transportation Geotechnics, 2015. **4**: p. 64–75.

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

[35] LNEC E474, *Guide for use of recycled materials coming from construction and demolition waste in embankment and capping layers of transport infrastructures*, in *LNEC* 2009. p. 5.

[36] EN 12457-4, *Characterisation of waste - Leaching - Compliance test for leaching of granular waste materials and sludges - Part 4: One stage batch test at liquid to solid ratio of 10l/kg for materials with particle size below 10 mm (without or with size reduction)*, in *CEN*. 2002.

[37] EN ISO 10319, *Geosynthetics - Wide width tensile test*, in *International Organization for Standardization, TC 221*. 2008.

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

[39] Council Decision 2003/33/EC, *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, 2003.

[40] Jang, Y.-C. and Townsend, T., *Sulfate leaching from recovered construction and demolition debris fines.* Advances in Environmental Research, 2001. **5**: p. 203-217.

[41] Barbudo, A., Galvín, A.P., Agrela, F., Ayuso, J., and Jiménez, J.R., *Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes.* Waste Management, 2012. **32**: p. 1229-1235.

[42] Galvín, A.P., Ayuso, J., García, I., Jiménez, J.R., and Gutiérrez, F., *The effect of compaction on the leaching and pollutant emission time of recycled aggregates from construction and demolition waste.* Journal of Cleaner Production, 2014. **83**: p. 294-304.

[43] Dhir, R.K., Brito, J., Silva, R.V., and Lye, C.Q., *Sustainable Construction Materials*. 2019, Cambridge, UK: Woodhead Publishing.

[44] Chen, J., Tinjum, J., and Edil, T., *Leaching of alkaline substances and heavy metals from recycled concrete aggregate used as unbound base course.* Transportation Research Record: Journal of the Transportation Research Board, 2013. **2349**: p. 81-90.

[45] Engelsen, C.J., van der Sloot, H.A., and Petkovic, G., *Long-term leaching from recycled concrete aggregates applied as sub-base material in road construction.* Science of the Total Environment 2017. **587–588**: p. 94–101.

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DOI: 10.1016/j.conbuildmat.2020.122031

TABLES

Table 1. Properties of the geosynthetics provided by manufacturers.

	Geogrid 1	Geogrid 2	Geotextile
Raw material	HDPE	PET	PP & PET
Unit weight (g/m^2)	450	380	340
Aperture dimensions (mm)	16×219	30×73	-
Mean value of the tensile strength (kN/m)	68	80/20#	75/14#
Elongation at maximum load (%)	11±3	≤ 8	10

Machine direction / Cross direction.

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671 Table 2. Classification of recycled C&D material constituents [33].

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

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Table 3. Laboratory leaching test results and limits to inert landfills.

Parameter	Initial C&D material (mg/kg dry matter)	C&D material after 24 months (mg/kg dry matter)	Acceptance criteria – Inert landfill (Council Decision 2003/33/EC)
Arsenic, As	0.013	0.020	0.5
Lead, Pb	< 0.01*	< 0.01*	0.5
Cadmium, Cd	< 0.003*	< 0.003*	0.04
Chromium, Cr	< 0.01*	< 0.01*	0.5
Copper, Cu	0.029	0.041	2
Nickel, Ni	0.01	< 0.01*	0.4
Mercury, Hg	< 0.002*	< 0.002*	0.01
Zinc, Zn	< 0.1*	< 0.1*	4
Barium, Ba	0.069	0.085	20
Molybdenum, Mo	0.036	0.011	0.5
Antimony, Sb	0.011	< 0.01*	0.06
Selenium, Se	< 0.02*	< 0.02*	0.1
Chloride, Cl	19	< 6*	800
Fluoride, F	< 1.5*	1.6	10
Sulphate, SO_4	**2100**	630	1000
Dissolved Organic Carbon, DOC	25	29	500
Dissolved Solids, DS	3030	1510	4000
pH	8.3	6.8	-

(*) limit of quantitation (LoQ)

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Table 4. Summary of results of tensile tests carried out on Geogrid 1.

	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{2\%}$ (kN/m)	J_{Tmax} (kN/m)
Virgin samples				
Mean value	60.3	10.1	1085	597
Confidence interval of 95%	60.3 ± 3.1	10.1 ± 0.4	1085 ± 79	597± 36
Samples immediately exhumed				
Mean value	59.0	10.5	1023	561
Confidence interval of 95%	59.0 ± 2.7	10.5 ± 0.3	1023 ± 69	561 ± 26
Samples exposed to recycled C&D material				
Mean value	57.9	10.4	1068	558
Confidence interval of 95%	57.9 ± 3.2	10.4 ± 1.2	1068 ± 51	558 ± 27
Samples exposed to clayey sand				
Mean value	59.1	10.9	1087	543
Confidence interval of 95%	59.1 ± 4.8	10.9 ± 0.6	1087 ± 26	543 ± 17

679 Table 5. Summary of results of tensile tests carried out on Geogrid 2.

	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{2\%}$ (kN/m)	J_{Tmax} (kN/m)
Virgin samples				
Mean value	92.2	5.6	1921	1638
Confidence interval of 95%	92.2 ± 9.3	5.6 ± 0.4	1921 ± 98	1638 ± 36
Samples immediately exhumed				
Mean value	86.1	5.4	1945	1592
Confidence interval of 95%	86.1 ± 4.0	5.4 ± 0.4	1945 ± 51	1592 ± 39
Samples exposed to recycled C&D material				
Mean value	85.8	5.2	2039	1655
Confidence interval of 95%	85.8 ± 4.9	5.2 ± 0.5	2039 ± 109	1655 ± 127
Samples exposed to clayey sand				
Mean value	86.7	5.2	1999	1681
Confidence interval of 95%	86.7 ± 4.6	5.2 ± 0.1	1999 ± 66	1681 ± 66

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681 Table 6. Summary of results of tensile tests carried out on Geotextile.

	T_{max} (kN/m)	ε_{Tmax} (%)	$J_{2\%}$ (kN/m)	J_{Tmax} (kN/m)
Virgin samples				
Mean value	70.6	9.7	647	728
Confidence interval of 95%	70.6 ± 3.2	9.7 ± 0.8	647 ± 93	728 ± 62
Samples immediately exhumed				
Mean value	58.8	9.4	627	631
Confidence interval of 95%	58.8 ± 4.1	9.4 ± 1.3	627 ± 101	631 ± 40
Samples exposed to recycled C&D material				
Mean value	52.4	9.3	598	566
Confidence interval of 95%	52.4 ± 1.9	9.3 ± 1.0	598 ± 51	566 ± 45
Samples exposed to clayey sand				
Mean value	51.7	9.5	624	549
Confidence interval of 95%	51.7 ± 3.4	9.5 ± 1.3	624 ± 88	549 ± 77

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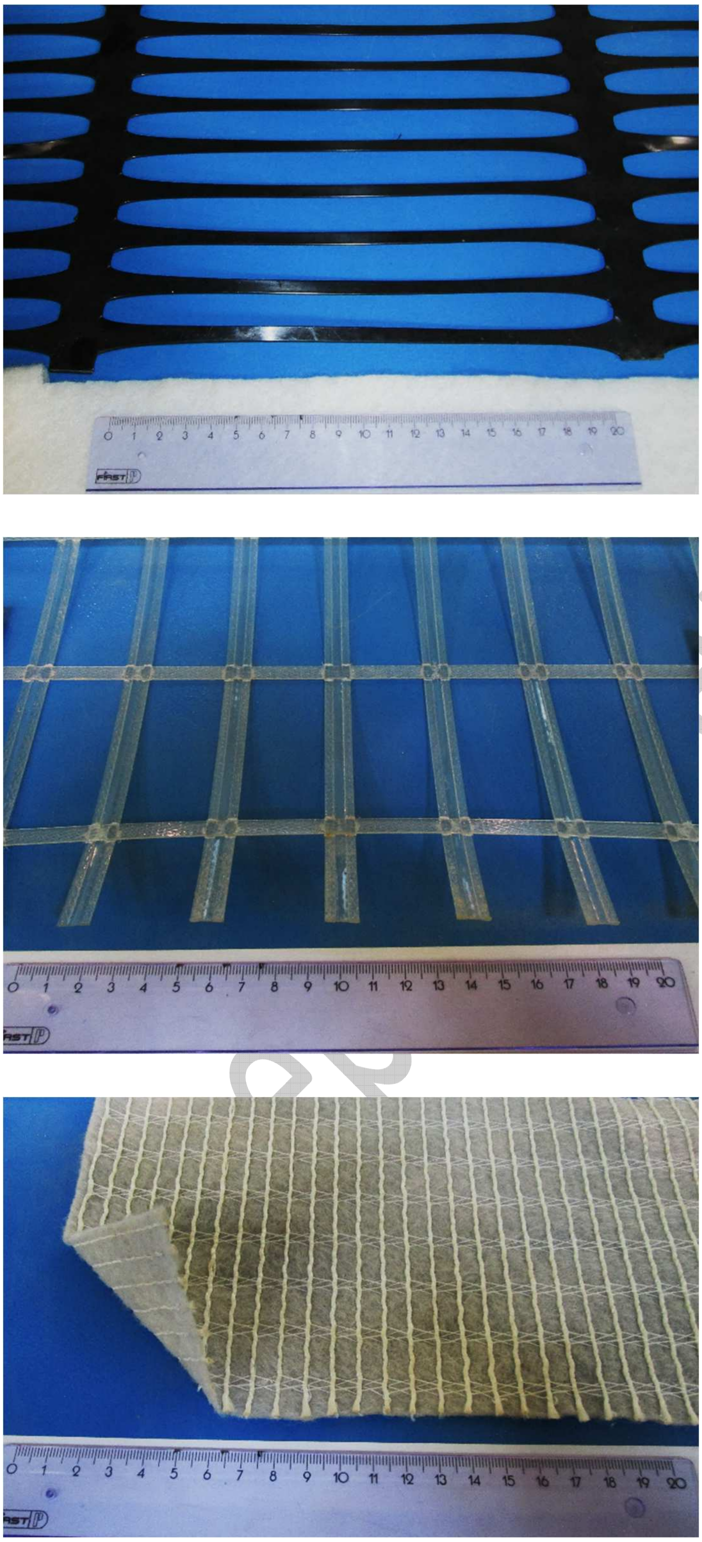
Table 7. Mean values of retained tensile strength, R_T, retained peak strain, R_ε, and retained secant modulus, $R_{J2\%}$.

	Geogrid 1			Geogrid 2			Geotextile		
	R_T	R_ε	$R_{J2\%}$	R_T	R_ε	$R_{J2\%}$	R_T	R_ε	$R_{J2\%}$
Immediately exhumed	0.98	1.04	0.94	0.93	0.96	1.01	0.83	0.96	0.97
Exposed to C&D material	0.96	1.03	0.98	0.93	0.93	1.06	0.74	0.96	0.92
Exposed to clayey sand	0.98	1.08	1.00	0.98	0.94	1.04	0.73	0.98	0.97

FIGURES



(a)

(b)

(c)

Figure 1 – Visual aspect of intact geosynthetics (ruler in centimetres): (a) uniaxial high-density polyethylene geogrid (Geogrid 1); (b) polyester geogrid (Geogrid 2); (c) high-strength composite geotextile (Geotextile).

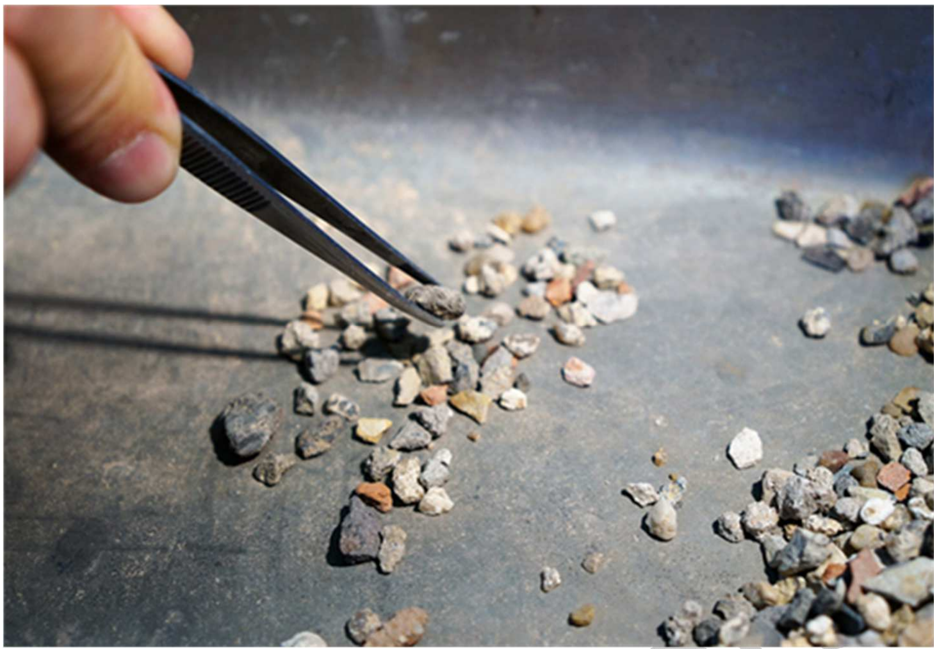


Figure 2 - Manual sorting of recycled C&D material to determine its constituents.

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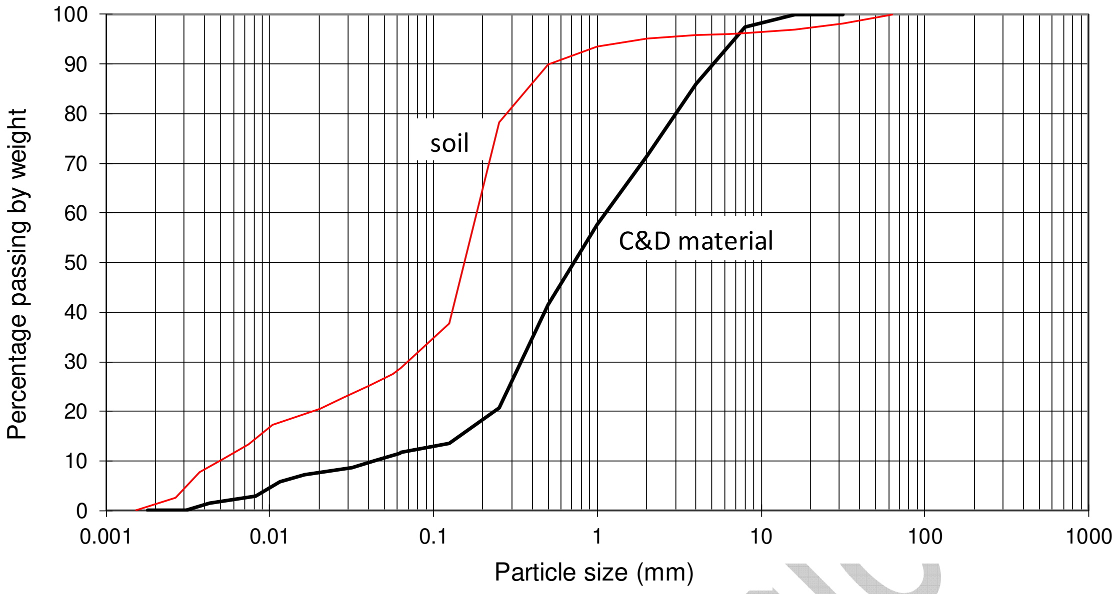

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699 Figure 3 - Particle size distribution of the materials used in construction of the trial

700 embankments.

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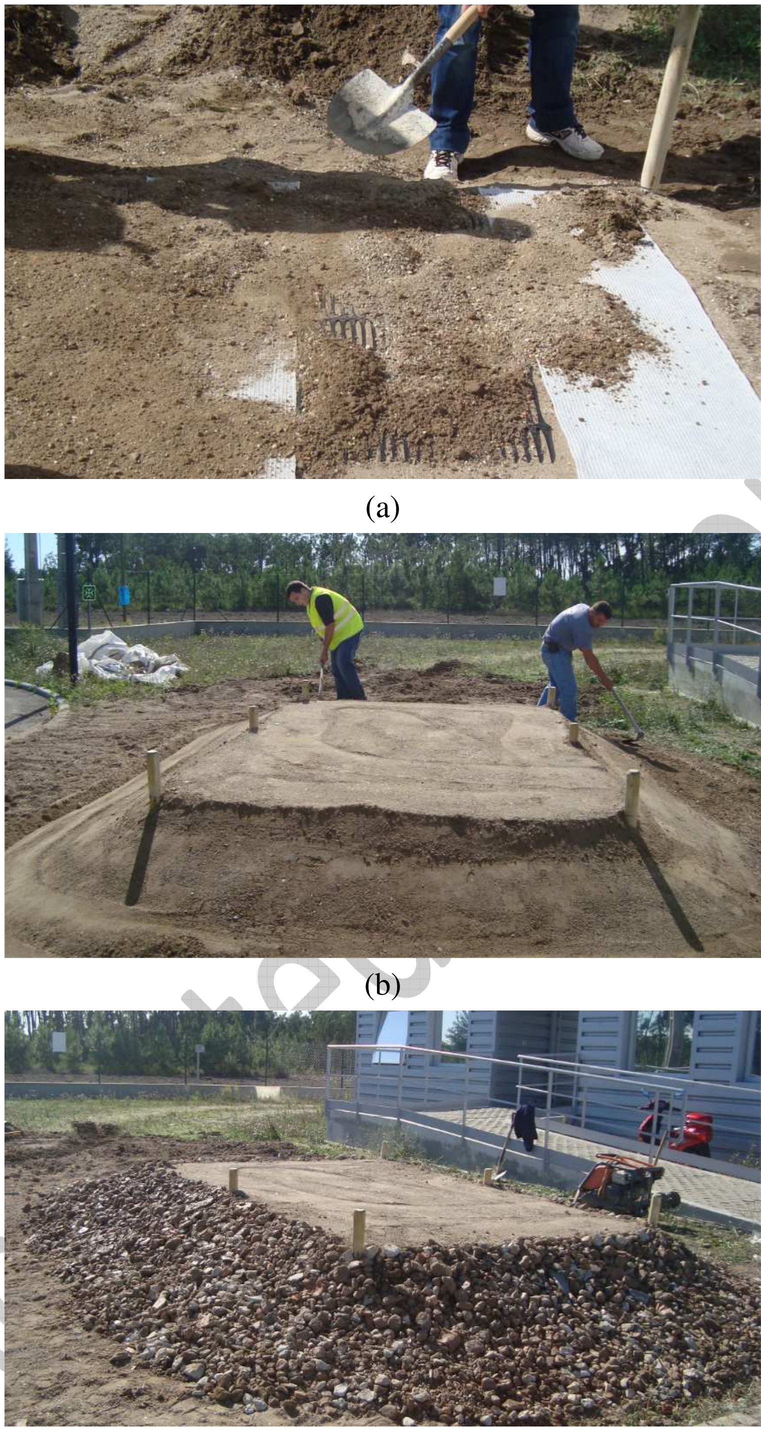

(a)

(b)

(c)

Figure 4 - Trial embankments construction: a) manual placement of the recycled C&D material over the geosynthetics; b) end-of-construction before lateral protection; c) lateral protection of the slopes with coarse aggregates.

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(a)

(b)

(c)

Figure 5 – Geosynthetic specimens' exhumation: a) and b) careful exhumation of the specimens; d) plant roots crossing the geotextile.

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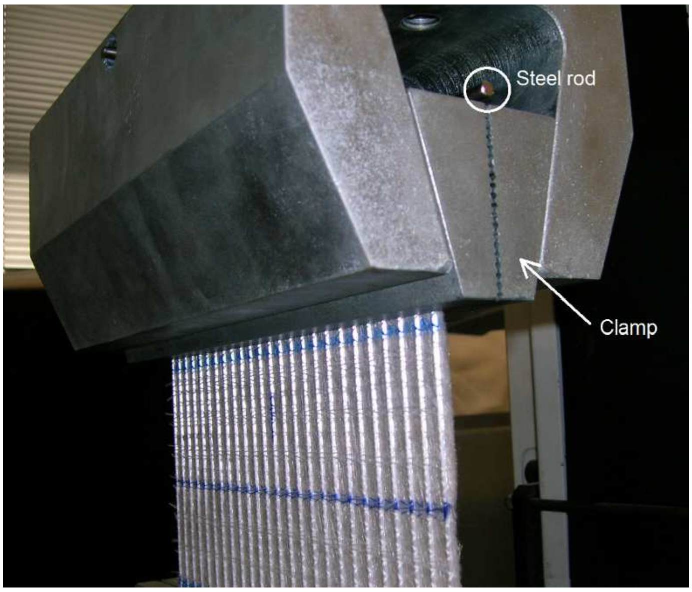
723 

724 Figure 6 – Detail of the clamping system for tensile strength tests of the high strength

725 geotextile.

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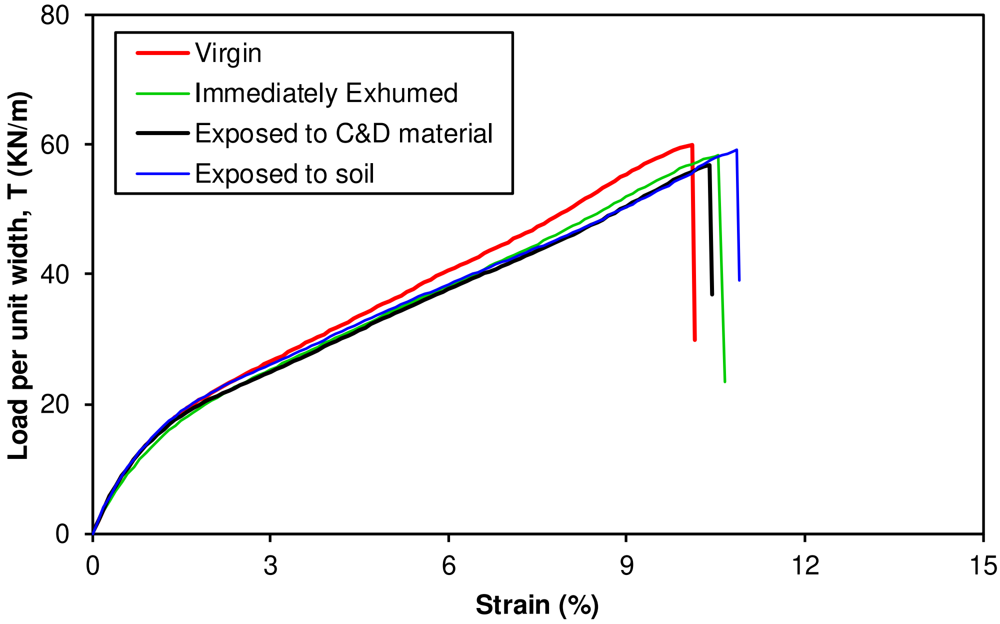
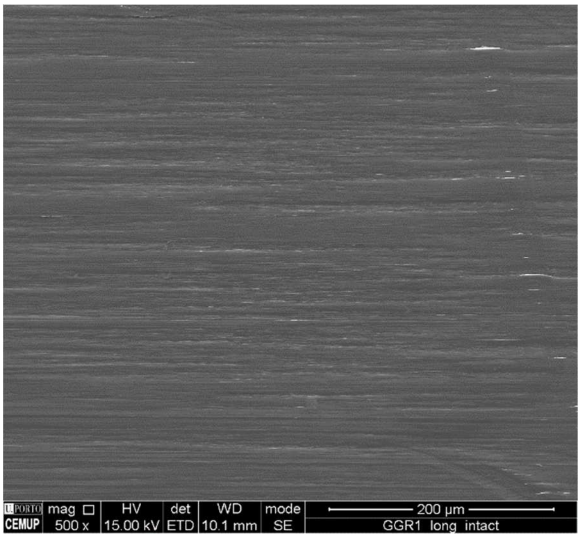
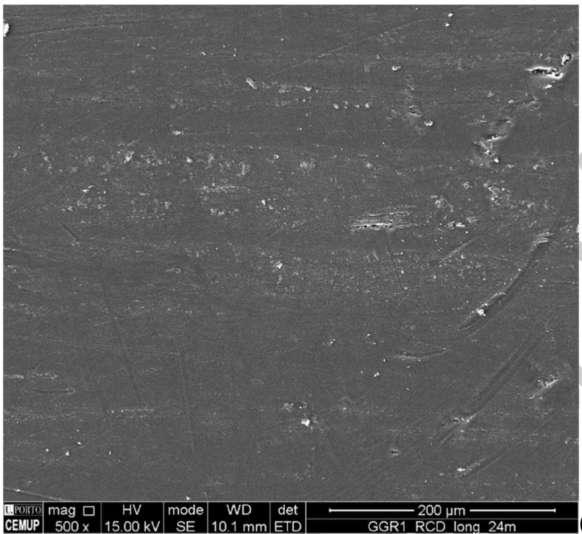


Figure 7 - Comparison of load-strain curves of virgin and exhumed specimens for Geogrid 1.

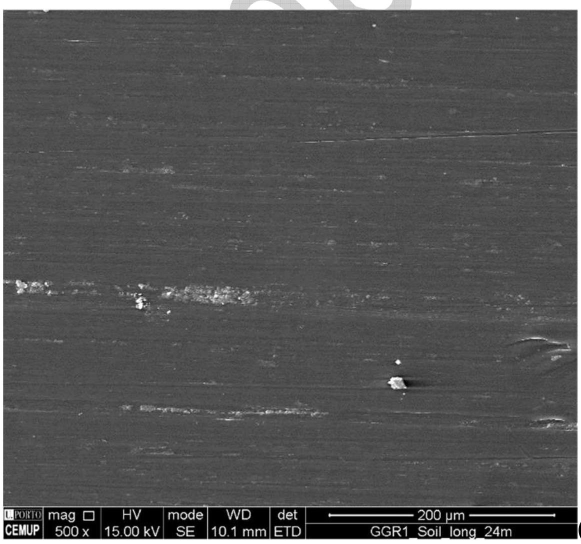
[DOI: 10.1016/j.conbuildmat.2020.122031](https://doi.org/10.1016/j.conbuildmat.2020.122031)



(a)

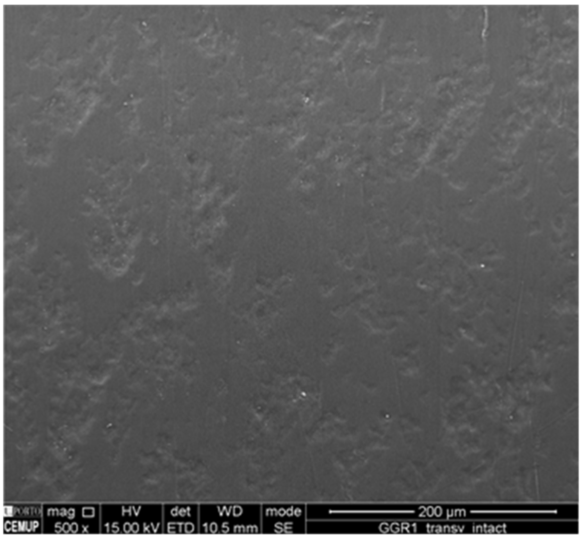


(b)



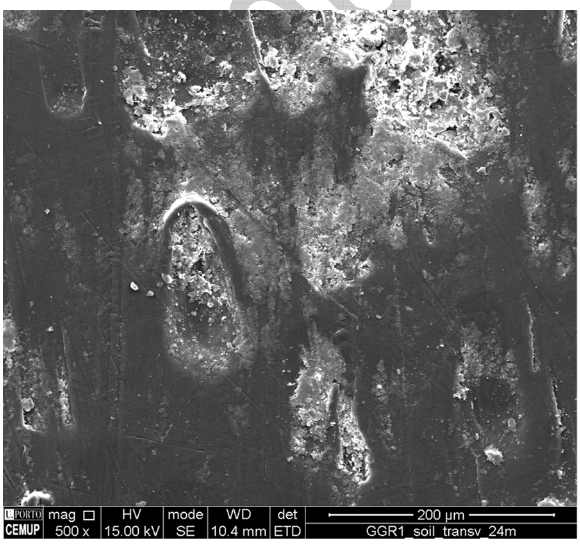
(c)

Figure 8 – SEM images of the longitudinal bars of the Geogrid 1 (×500): a) intact specimen; b) exposed to recycled C&D material; c) exposed to soil.



(a)

(b)



(c)

Figure 9 – SEM images of the transversal bars of the Geogrid 1 (×500): a) intact specimen; b) exposed to recycled C&D material; c) exposed to soil.

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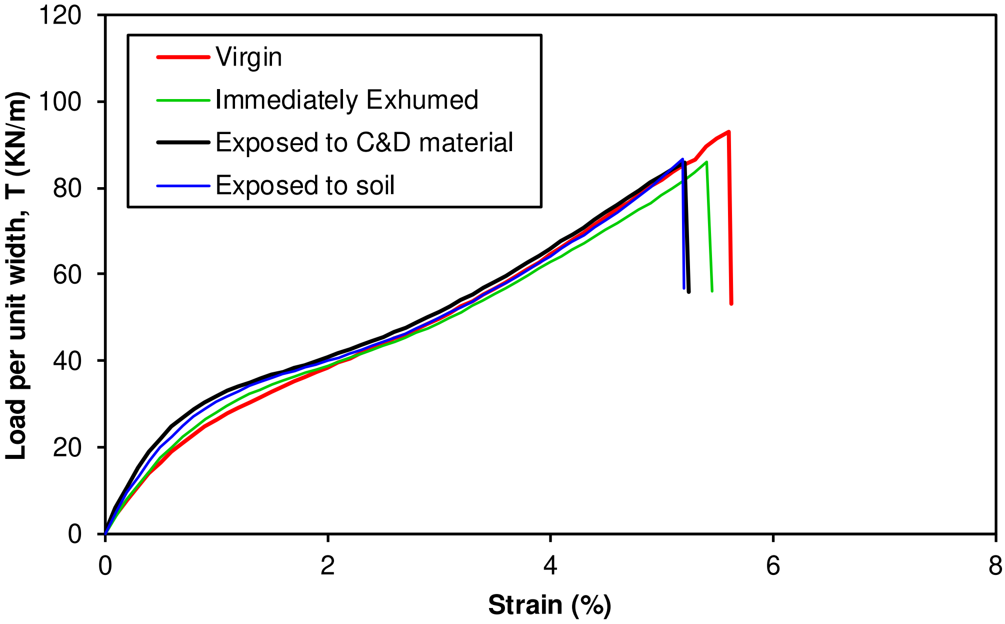
741 

742 Figure 10 - Comparison of load-strain curves of virgin and exhumed specimens for

743 Geogrid 2.

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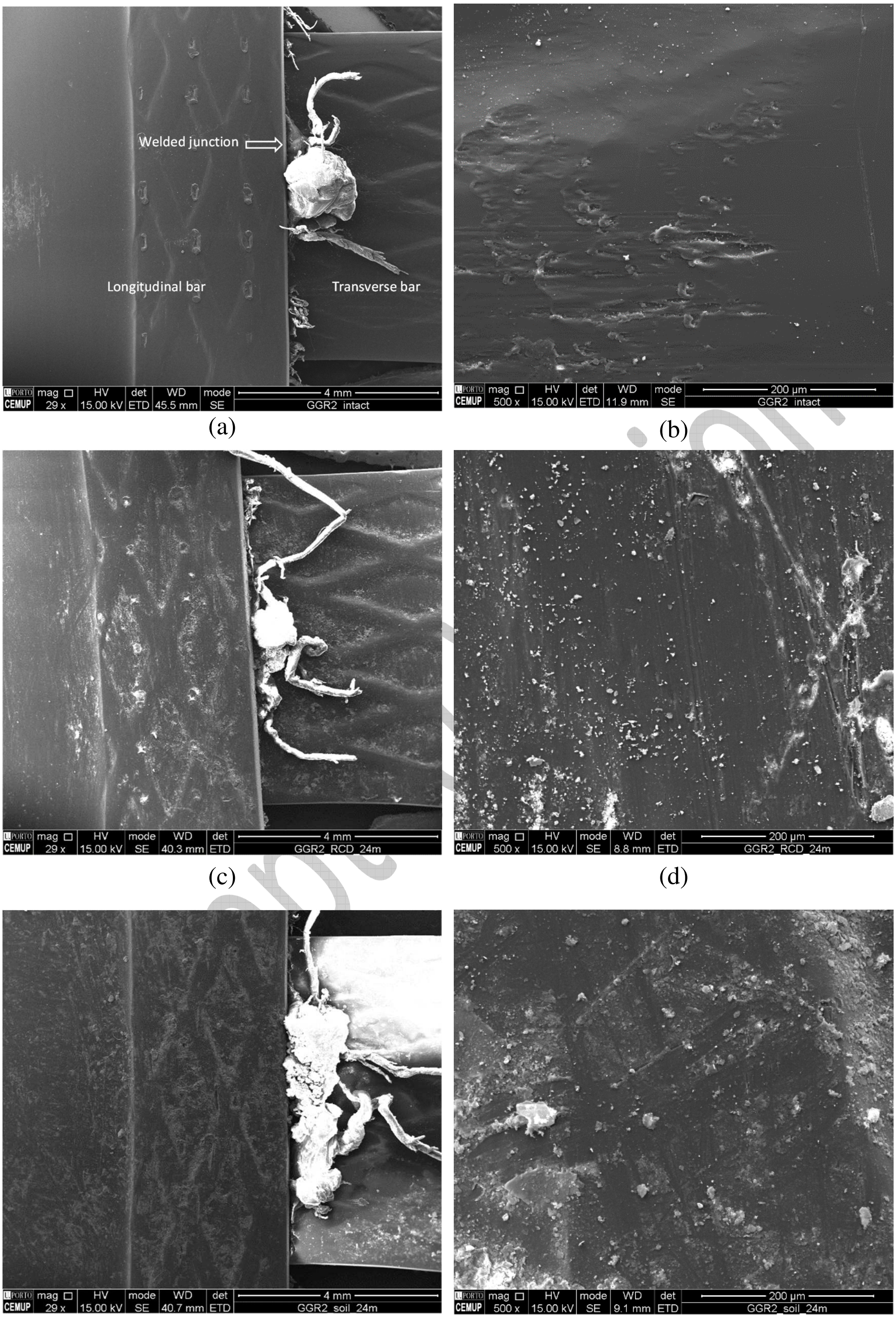

Figure 11 – SEM images of Geogrid 2 specimens: a) intact (×29); b) intact – longitudinal bar (×500); c) exposed to C&D material (×29); d) exposed to C&D

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material – longitudinal bar (×500); e) exposed to soil (×29); f) exposed to soil – longitudinal bar (×500).

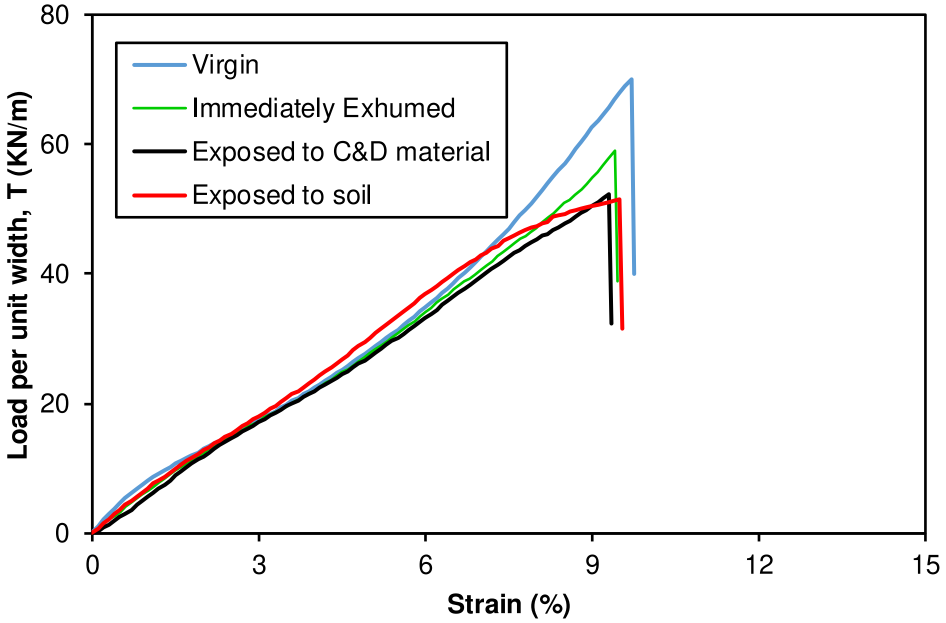

Figure 12 - Comparison of load-strain curves of virgin and exhumed specimens for Geotextile.

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[DOI: 10.1016/j.conbuildmat.2020.122031](https://doi.org/10.1016/j.conbuildmat.2020.122031)

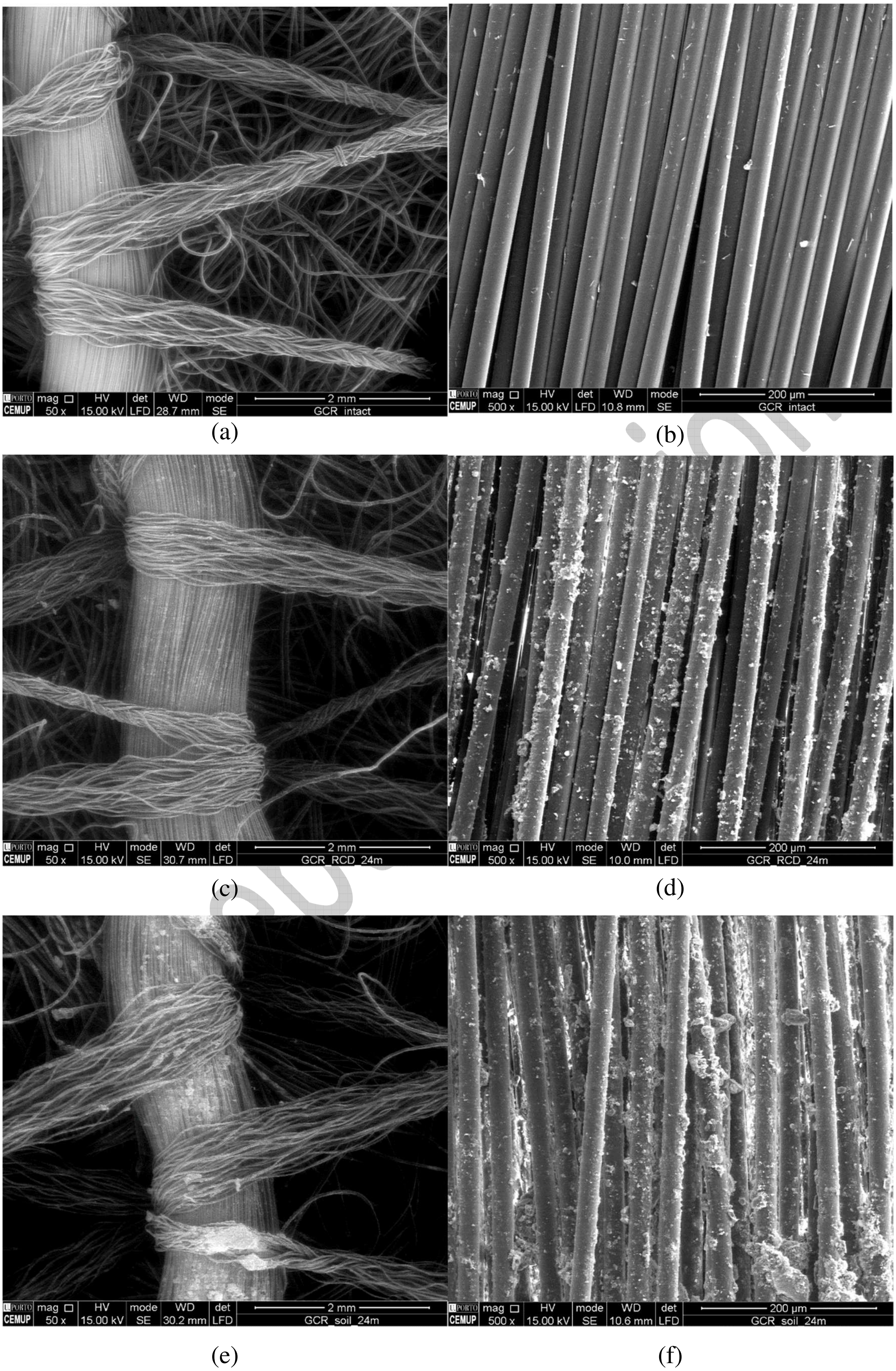

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Figure 13 – SEM images of geotextile specimens: a) intact (×50); b) intact – PET filament (×500); c) exposed to C&D material (×50); d) exposed to C&D material – PET filament (×500); e) exposed to soil (×50); f) exposed to soil – PET filament (×500).