VALORIZATION OF FINE-GRAIN CONSTRUCTION AND DEMOLITION (C&D) WASTE IN GEOSYNTHETIC REINFORCED STRUCTURES

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This is a post-peer-review, pre-copyedit version of an article published in Waste and Biomass Valorization. The final authenticated version is available online at: https://doi.org/10.1007/s12649-018-0480-x

ABSTRACT

Current environmental awareness compels all citizens to reduce the production of waste and use recycled materials. Recycled materials coming from Construction and Demolition (C&D) waste are progressively being used in civil engineering applications, such as base and sub-base layers of transport infrastructures and concrete production. However the fine grain fraction of C&D recycled materials is not considered appropriate for those applications, being frequently landfilled instead of reused. This paper assesses the possibility of using fine grain C&D recycled materials as backfilling of geosynthetic reinforced structures (embankments and retaining walls), replacing the soils typically used in the construction of these structures. The study has involved physical, mechanical and environmental characterization of C&D recycled materials, characterization of the interfaces between the fill material and three geosynthetics, through direct shear and pullout tests, and the evaluation of the potential damages induced by the C&D recycled materials on the short-term tensile behaviour of the geosynthetics. The results presented in this paper support the suitability of using C&D recycled materials in the construction of geosynthetic reinforced structures and thus diminishing our carbon footprint, through the reduction of the environmental impacts induced by C&D waste landfilling and by the extraction of natural aggregates.

KEYWORDS: Waste Valorization; Sustainable construction; Construction and Demolition Waste; Recycled fill material; Geosynthetic reinforced structures

1. INTRODUCTION

The decrease of non-renewable natural resources is a major concern of the current society which should encourage the use of alternative materials. In recent decades the environmental sustainability has been compelling the enhancement of waste recycling, having taking place, in all developed countries, numerous awareness-raising campaigns on the importance of recycling, particularly, associated to urban solid waste. Since the construction industry is one of the sectors with the greatest consumption of natural resources, recycling or reuse of waste is currently an imperative in this industry.

In recent decades, several research studies and applications of Construction and Demolition (C&D) recycled materials have been carried out, mostly related to the production of aggregates for concrete [1-5], and to be used in base layers of transportation infrastructures [6-9]. More recently the stabilization of C&D recycled materials with fly ash and slag geopolymers for application in base and sub-base layers of transportation infrastructures have also been studied [10,11]. However, the fine grain fractions of C&D recycled materials, due to their high fines content and heterogeneous composition (concrete, mortars, soil, glass, clay masonry units, etc.) are generally not considered suitable for the above-mentioned applications. To overcome this barrier some studies on the use of fine-grain recycled C&D materials have recently been carried out.

To assess their suitability as backfilling materials for stormwater and sewer pipes, three different C&D recycled materials (crushed brick, recycled concrete aggregate and reclaimed asphalt pavement) were investigated by [12]. These authors have concluded that recycled concrete aggregates and crushed bricks satisfied the criteria established by the various regulatory authorities, while the reclaimed asphalt pavement did not meet the criteria for its use as pipe backfilling material. The geotechnical and geoenvironmental characterization of a fine grain non-selected C&D material was carried out by [13] to evaluate its feasibility as backfilling material of trenches. The high value of floating particles of this C&D recycled material, resulting from impurities such as wood, plastics and foams, has proved to be an obstacle to its use as pipe backfilling material.

Some studies on the use of fine C&D waste in the construction of geosynthetic reinforced structures have also been reported in recent years [14-17], showing the feasibility for their valorization but suggesting the pursuit of further studies.

The usage of crushed concrete fines (i.e., previously selected C&D waste) in decorative concrete has been presented by [18]. The authors have found that the admixture of the crushed concrete fines has little effect on the colour characteristics of the decorative concrete products, however this evidence might not be valid for non-selected C&D recycled materials.

The construction industry in southern European countries does not yet have a relevant tradition in recycling C&D wastes. While other industries, such as plastic and paper industries, have already well established procedures to collect and recycle their products, mainly due to stricter environmental legislation referring to Municipal Solid Waste, construction and demolition companies are currently starting to adopt environmentally friendly practices. Even so, it is not uncommon the illegal disposal of C&D wastes at the road-side and the resulting environmental impacts.

Trying to contribute to the increase of Portuguese recycling rate of C&D waste, a research project involving the fine grain fraction of C&D recycled materials, without acceptance for use in concrete production, has been developed. The research project deals with the use of these recycled materials as backfilling of geosynthetic reinforced structures (steep slopes and retaining walls), studying the feasibility of replacing the natural soils used traditionally in the construction of these structures. This paper presents some results of this research project, including the physical, mechanical and environmental characterization of C&D recycled materials produced at different periods of time (two batches), the characterization of the interfaces between the fill material and three geosynthetics, through direct shear and pullout tests, and the evaluation of the potential damages induced by the C&D recycled materials on the tensile behaviour of the geosynthetics. It represents a significant advance over past works since it points out a comprehensive study on several issues related to this particular application (physical, mechanical and environmental characterization, interfaces behaviour and effects on geosynthetics) involving two materials.

2. MATERIALS AND METHODS

To achieve good quality recycled aggregates and, simultaneously, to reduce C&D waste discharged on landfills, the selective demolition must be encouraged and really implemented. However, particularly in Southern European Countries, this practice is not well established due to its higher time consuming and higher expenses when compared to the conventional demolition. Thus, C&D waste discharged at the recycling plants to be recycled are mainly mixed waste.

The recycled materials derived from mixed C&D waste have limited market acceptance, particularly to concrete production, being most of the times applied as aggregates in sub-base layers of transportation infrastructures. The fine grain fraction resulting from the C&D waste recycling process is sometimes sent to landfills, due to the difficulties in their market implementation, and more recently, used in the construction of structural embankments. This study deals with this particular granulometric fraction of C&D recycled material.

The C&D recycled materials were collected at a Portuguese recycling plant, produced at two different periods of time with an interval of about 9 months (two batches). Based on their technical sheets, both materials come mainly from the demolition of residential buildings, masonry fences and cleaning of lands with illegal disposal of C&D waste. These C&D materials result from a recycling process in which unwanted materials (steel, wood, plastics and rubbers, paper and cardboard, foams, cork, textiles and others) are removed, the materials are fragmented and subjected to grain-size separation. The constituents and properties of C&D recycled materials will be presented and discussed afterwards.

Three commercial geosynthetics, used commonly as reinforcement, were studied (Figure 1): a uniaxial high density polyethylene (HDPE) geogrid, GGR1 (Figure 1a), a uniaxial geogrid manufactured of extruded polyester (PET) bars with welded rigid junctions, GGR2 (Figure 1b) and a high-strength composite geotextile consisting of polypropylene (PP) continuous-filament needle-punched nonwoven and high-strength PET yarns, GCR (Figure 1c). The main properties of the geosynthetics are summarized in Table 1.

The geotechnical characterization of C&D recycled materials was carried out following the current standards used for soils. As these materials have large amount of fines, the particle size distribution was evaluated following the standard ISO/TS 17892-4 [19] .

Modified Compaction Proctor tests were carried in accordance with the European Standard EN 13286-2 [20] to determine the dry density-moisture content relationship. The constituents of the recycled materials were evaluated following the test procedure depicted in the European Standard EN 933-11 [21]. Given that the classification of particles with dimensions below 4 mm is humanly impossible and also the stipulated in EN 933-11, only the masses comprised between the sieves 63 mm and 4 mm were identified.

Recycled materials used in any construction project must have a suitable leaching behaviour to avoid potential risks to the environment. Laboratory leaching tests were carried out following the procedures specified in the standard EN 12457-4 [22] to assess the environmental behaviour of C&D recycled materials.

In the design and performance of geosynthetic reinforced structures, the interaction mechanisms between the fill (soil or alternative material) and the reinforcement elements play a crucial role. The assessment of the interaction mechanisms, as well as, the selection of the most appropriate tests to their correct characterization are important issues to deal with.

Figure 2 illustrates a potential failure mechanism of a geosynthetic reinforced steep slope. In the higher zone of the retained fill mass, due to high tensile forces the reinforcement can be pulled out from the fill, thus the interaction mechanism should be evaluated through pullout tests. Closer to the slope base, sliding through the interface between the two materials may occur and the interaction mechanism is better characterised through direct shear tests [23].

The strength of the interfaces is commonly defined by a coefficient of interaction, obtained from direct shear or pullout tests. For direct shear tests the coefficient of interaction, f_g, is defined as the ratio of the maximum shear stress achieved in a C&D material/geosynthetic interface, to the maximum shear stress achieved for C&D material, under the same normal stress, σ:

$$f_g = \frac{\tau_{C\&D/geo}^{max}(\sigma)}{\tau_{C\&D}^{max}(\sigma)} \quad (1)$$

The pullout interaction coefficient, f_b, could be estimated by the following equation:

$$f_b = \frac{\tau_{pullout}^{max}(\sigma)}{\tau_{direct\ shear}^{max}(\sigma)} \quad (2)$$

where $\tau_{pullout}^{\max}$ is the maximum shear stress mobilised at the interface during a pullout test and $\tau_{direct\,shear}^{\max}$ is the direct shear strength of the C&D recycled material for the same value of the confining pressure, σ.

The value of $\tau_{pullout}^{\max}$ could be estimated by:

$$\tau_{pullout}^{max}(\sigma) = \frac{P_R(\sigma)}{2 \times L_R} \quad (3)$$

where P_R is the maximum pullout force, per unit width, under the confining pressure of σ and L_R is the confined length of the geosynthetic at the maximum pullout force.

Direct shear strength of C&D recycled materials and interface direct shear strength were studied on a large scale direct shear test prototype. The apparatus was designed and built at the University of Porto [23]. The shear box (split into two halves) has dimensions of 300 mm × 600 mm in plant and 100 mm in height. The upper shear box is fixed on the horizontal direction and its vertical positioning is controlled by two hydraulic actuators. The lower shear box moves in the horizontal direction, under a pre-defined displacement rate. A constant displacement rate of 1 mm/min was used and the direct shear tests were performed under normal stresses in the range 25-150 kPa.

Pullout tests were carried out on a large-scale apparatus also designed and constructed at the University of Porto [24]. The test apparatus comprises a pullout box with internal dimensions of 1000 mm (width) × 1530 mm (length) × 800 mm (height), a vertical load system, a horizontal hydraulic actuator and all the required instrumentation devices. At the mid-height of the box there is an aperture in the front wall to allow the pullout of the geosynthetics and another aperture in the back wall to permit the passage of the inextensible wires to measure the displacements along the geosynthetics length. The pullout force is transmitted to the specimen by a clamp through a hydraulic system allowing the application of a constant displacement rate. The confinement stress is applied by 10 cylindrical masses on the top of the box. To reduce the influence of the top boundary and to make the vertical load distribution more uniform a smooth 25 mm thick neoprene slab is placed over the fill material [24].

Pullout tests were carried out only with C&D recycled material collected from batch 2 compacted at 90% of its maximum Modified Proctor dry density and at the optimum moisture content. The test were carried out with a constant displacement rate of 2 mm/min (pullout direction) and under normal stress of approximately 16 kPa at interface level (half height of the box).

Aiming the study of the potential chemical and environmental degradation induced by the C&D recycled materials on geosynthetics tensile behaviour, two damage trial embankments (2m x 3m in plan) were constructed (Figure 3). Inside each embankment, geosynthetic samples were positioned in 2 levels with vertical space of 0.20 m. The geosynthetic samples were carefully placed without overlapping and were manually covered with a first layer of C&D recycled material to prevent mechanical damage (Figure 3a). Then additional quantities of C&D material were distributed and compacted to reach a lift with final thickness of about 0.20 m.

To reduce as much as possible the installation damage induced on the geosynthetics during construction, a lightweight compaction equipment was adopted (Figure 3b). More details on the embankments construction can be found in [9].

After 6, 12 and 24 months of exposure to the C&D material, the geosynthetic samples were carefully exhumed from the embankment, being the fill directly above the geosynthetics removed with the hands to prevent additional damages (Figure 4). The exhumed samples were inserted into plastic bags and carried to the laboratory where they remained at approximately 20ºC until be tested.

This paper describes the effects provoked by the C&D recycled material on geosynthetic samples exhumed after 12 months of the embankment construction. The tensile behaviour of the geosynthetics were characterised through wide width tensile tests carried out in accordance with EN ISO 10319 [25] on exhumed and intact (as-received) geosynthetic samples. The short-term tensile behaviour of exhumed samples is compared to the behaviour of intact samples. Scanning Electron Microscope (SEM) analyses have also been performed to evaluate the damage in more detail.

The SEM analyses were carried out on a high resolution Environmental Scanning Electron Microscope (Quanta 400 FEG ESEM / EDAX Genesis X4M) from the Materials Centre of University of Porto.

3. RESULTS AND DISCUSSION

3.1 Geotechnical and environmental properties of C&D recycled materials

Figure 5 presents the particle size distribution of C&D materials collected from two distinct batches with an interval of 9 months. Table 2 provides additional physical and mechanical properties of these recycled materials.

The results presented in Figure 5 and Table 2 point out that both materials can be classified as silty sand (SM), according to the Unified Soil Classification System (USCS), being their maximum dimension lower than 20 mm, as specified by the technical sheet.

The fines content of these materials (15.5% and 14% for batch 1 and batch 2, respectively) is one of the main issues to the valorisation of these recycled materials, since some legal normatives (Portuguese Specifications, for instance) do not allow their application in specific uses, like embankment and capping layers of transport infrastructures or backfilling of trenches, where the limit is 10 or 12%.

Table 3 presents the constituents of the C&D recycled materials. The constituents of both materials are similar comprising, mainly, concrete, masonries, mortars, unbounded aggregates and soils. However, batch 2 has a lower proportion of soil and higher quantities of concrete products. It is important to point out that if the total mass of the samples (including particles with diameter lower than 4 mm) was considered, the proportion of soil would be surely higher. It should be highlighted the high values of the floating particles, particularly in batch 2, which means that the removal of impurities from the original C&D waste was not very efficient.

Table 4 shows results of laboratory leaching tests performed on samples of C&D materials collected from both batches. The last column of Table 4 presents the limit values stipulated by the European Council Decision 2003/33/EC [26] for the acceptance of waste at inert landfills, meaning that if the C&D material fulfils this limits can be classified as inert. The values highlighted in bold are those not complying with these limits.

The sulphate value obtained for the two C&D materials exceeds the limit established by the European legislation (batch 2 largely). Total Dissolved Solids (TDS) found out in the samples from batch 2 are also widely higher than the limit. Nevertheless these shortcomings, according to the Directive [26], the evaluation of TDS is not compulsory to the classification as inert material and if the material does not meet the limit for sulphate, the acceptance criteria may still be considered as respected provided that the leaching does not exceed 6000 mg/kg.

High concentrations of TDS and sulphate have also been reported by other researchers on mixed C&D wastes [27,28].

The pH values of the leachates obtained from C&D recycled materials are also presented in Table 4. It is important to mention that design and construction guidelines provided by the Federal Highway Administration (USA) [29] recommend for the construction of mechanically stabilized earth walls and reinforced soil slopes, backfill materials with a pH value between 5 and 10. Both recycled materials have shown alkaline pH value within the mentioned range.

Table 5 summarizes direct shear strength parameters achieved by large-scale direct shear tests carried out on fine grain C&D recycled materials (batch 1 and batch 2) under normal stress in the range 25 - 150 kPa. These tests were performed on recycled materials at their air-dried moisture content, with relative density (I_D) of 70% or 80% and at their optimum moisture contents (OMC) and degree of compaction (DC) in the range 87% to 97%. Note that the degree of compaction is defined as the ratio of the adopted C&D dry density to the maximum Modified Proctor dry density (γ_{dmax}).

As expected, the increase of the moisture content of C&D materials (from air dry condition to optimum moisture content) has induced the decrease of their shear strength. When the proportion of soil is higher (batch 1) this reduction is evident in both parameters (cohesion and friction angle), while in batch 2 the decrease occurs only in the friction angle. Obviously, improving the degree of compaction of the C&D recycled material, its shear strength also grows.

3.2 Direct shear and pullout strength of the interfaces

As previously mentioned, the strength of the interfaces is usually estimated through coefficients of interaction obtained from direct shear or pullout tests. The coefficients of interaction, f_g, for different compaction conditions, as a function of the normal stress, are summarised in Table 6. For the recycled material coming from the batch 1 (higher portion of soil), regardless the interface the highest coefficients of interaction were obtained for C&D material compacted to DC = 87% at its optimum moisture content. Excepting for this filling condition (DC = 87% at OMC), the coefficients of interaction achieved for the interface with the high-strength composite geotextile (GCR) were lower than those for geogrid interface.

The lowest coefficients of interaction achieved for DC = 97% are, possibly, justified by the difficulty in reaching at the interface level so high DC value (due to the compressibility of the geotextile and apertures of geogrid).

The results presented in Table 6 for the material collected from batch 2 suggest that, for this particular case, moisture content of the C&D material has little effect on the coefficient of interaction, f_g, for the interfaces with the geogrid GGR1 and the geotextile GCR. For the interface C&D/geogrid GGR2, the increase of the moisture content has induced a significant decrease on f_g. Such decrease is partly justified by the high cohesion recorded for the C&D material under the same compaction condition (Table 5).

In general, the highest coefficients of interaction were achieved for the interface with the geogrid GGR2, due to the larger contact area backfill-to-backfill (Figure 1b).

Regardless the batch of the C&D recycled material, the values of f_g are in the range 0.66 - 0.92 and 0.61 - 0.94 for the geogrid interfaces and geotextile interface, respectively. These values compare well with those published in the literature for soil/geogrid and soil/geotextile interfaces [30,31,23].

The development of the pullout force, per unit width, with the displacement of the horizontal actuator for the three interfaces under analysis is represented in Figure 6. While all the samples of the geogrid GGR1 failed by lack of tensile strength under pullout test conditions (sudden failure), the geogrid GGR2 and the geotextile GCR occurred failed due to loss of adherence with the surrounding material, i.e pullout failure occurred. The sudden small drops recorded for the high strength geotextile result from the slipping of the PET yarns (Figure 1c).

The pullout strength for the C&D/geosynthetic interfaces, $\tau_{pullout}$, the direct shear strength of the recycled C&D material, $\tau_{direct\ shear}$, and the pullout interaction coefficient, f_b, estimated in accordance with equation (2) are summarised in Table 7.

Although the differences shown in Figure 6 regarding the maximum pullout force, per unit width, P_R, for the three interfaces, the mean values of the maximum shear stress mobilised at the interfaces, $\tau_{pullout}$, are quite similar and thus, close values of the pullout interaction coefficient, f_b, were achieved (Table 7).

3.3 Damage caused by C&D recycled material on the geosynthetics tensile behaviour

Apart from local damages due to the growth of plant roots crossing the nonwoven geotextile (GCR), some of them with 4-5 millimetres in diameter, the visual inspections of exhumed geosynthetic samples have not revealed significant damages induced by the construction and exposure to the C&D recycled material. As previously mentioned, to appraise the damage in more detail, SEM analyses have been performed.

SEM images of intact and exhumed specimens of the three geosynthetics are compared in Figure 7. The exhumed samples of the geogrids (Figure 7b and d) show small holes and grooves appearing to be caused by hard particles of the recycled C&D material. However, the intact samples also show some irregularities (Figure 7a and c).

Given that the holes created in the geotextile by the plant roots are local damages, a more representative area was used to cut the specimens for SEM analyses. Comparing Figure 7e and Figure 7f, no damages are identified, only very small particles seems to be held to the threads of the geotextile.

Figure 8 compares load-strain curves of intact geogrid and exhumed geosynthetic specimens. From the analysis of these average curves (5 samples for each condition), one can conclude that both geogrids have suffered a slight decrease of their tensile strength and tensile stiffness for larger deformations, while the high strength geotextile has maintained its tensile stiffness but has suffered a significant loss of strength.

The reduction of the tensile strength of the geotextile GCR is probably explained by a less effective binding of the PET yarns to the nonwoven geotextile (Figure 1c), which probably triggered their premature failure.

The damage on geosynthetics is commonly evaluated through the retained value of meaningful parameters (tensile strength, strain at maximum load, stiffness modulus). The retained value is defined as the ratio between the mean value of the parameter under analysis obtained in exhumed specimens (or damaged) specimens and the corresponding mean value for intact specimens.

The retained values of the tensile strength, R_T, the retained peak strain, R_ε, and the retained secant modulus at 2% of strain, $R_{J2\%}$, estimated as mentioned above, are summarised in Table 8. As mentioned, the damages induced by the recycled material have some meaning only on the tensile behaviour of the geotextile, for which the loss of strength was about 30%.

4. CONCLUSIONS

The fine-grain materials resulting from the recycling process of C&D waste, i.e. materials having a maximum dimension of about 10 mm, are commonly not considered for concrete production or to be used in base layers of transportation infrastructures. This paper evaluates and discusses the feasibility of the use of finegrain C&D recycled materials as backfilling of geosynthetic reinforced structures (embankments with steep slopes and retaining walls), replacing the natural soils used traditionally in the construction of these structures.

The study has involved the physical, mechanical and environmental characterization of C&D recycled materials, the characterization of the interfaces between this fill material and three geosynthetics, through direct shear and pullout tests, and the evaluation of the potential damages induced by the C&D recycled materials on the short-term tensile behaviour of the geosynthetics.

The analysis and interpretation of the results lead to the following conclusions.

- Laboratory leaching tests have detected high concentrations of sulphate and total dissolved solids (the latter only in one of the materials). Nevertheless, no environmental concerns were identified and both C&D recycled materials can be classified as inert;
- If properly compacted C&D recycled materials exhibit suitable shear strength to be used in the construction of geosynthetic reinforced structures;
- The coefficient of interactions reached in this study for C&D material/geosynthetic interfaces are within the usual range for soil/geosynthetic interfaces under similar conditions;
- The exposure of two geogrids made from distinct polymers (HDPE and PET) to the C&D recycled material, under real atmospheric conditions for 12 months, did not induce the geogrids degradation. The high strength composite geotextile has revealed a significant loss of strength explained, possibly, by a less effective binding of the PET yarns to the nonwoven geotextile due to its management during and after installation.

Currently recycling or reuse of waste is an imperative to the construction industry. This work has proved that the use of C&D recycled materials as filling material in the construction of geosynthetic reinforced structures is a feasible solution and thus, it contributes to broadening the application of these recycled materials, particularly their fine portion (below 10 mm) with lower value to other applications such as the concrete production or base layers of transportation infrastructures.

ACKNOWLEDGMENTS

This work was financially supported by the Research Project CDW_LongTerm, 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 author would like to thank *Tensar International*, *Naue* and *TenCate Geosynthetics Iberia* for providing the geosynthetics used in the study and the company RCD, S.A. for the supply of the construction and demolition recycled materials.

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FIGURES

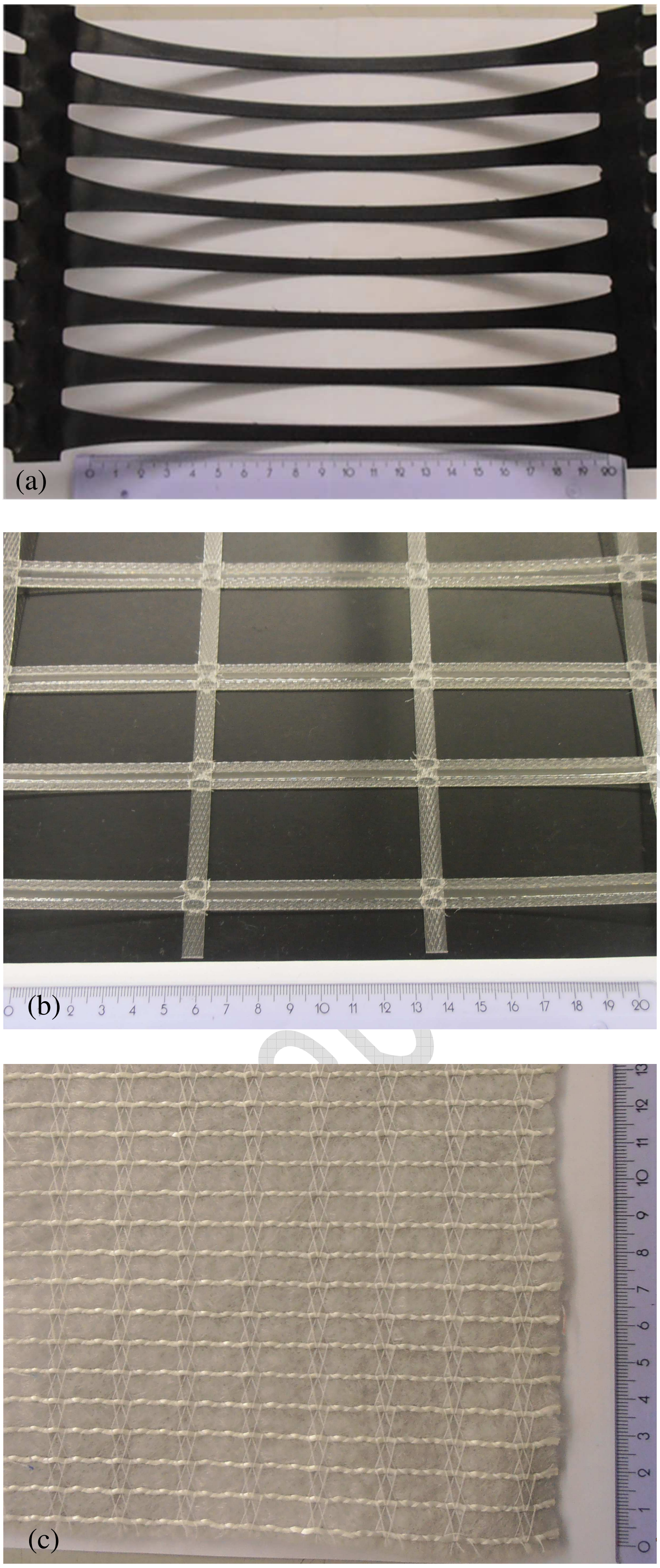

Figure 1: Geosynthetics used in the experimental study: (a) High-density polyethylene geogrid (GGR1); (b) Polyester geogrid (GGR2); (c) high-strength composite geotextile (GCR).

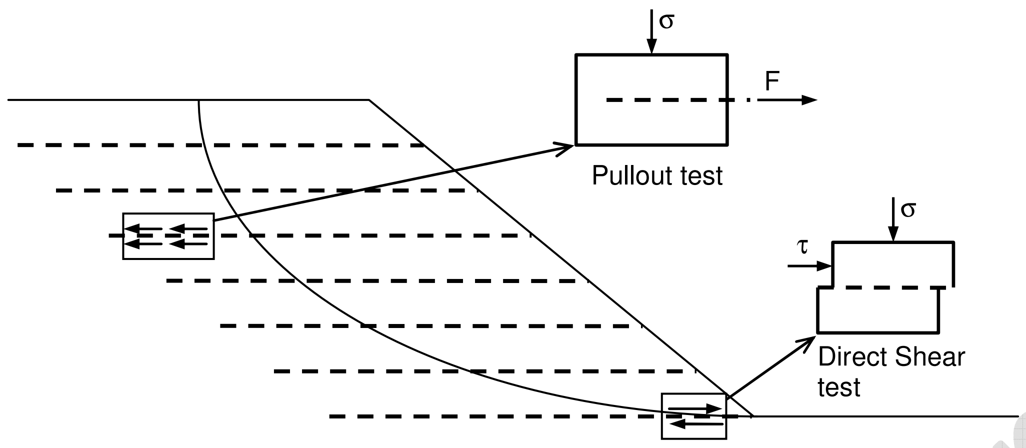

Figure 2: Potential failure mechanism of a reinforced steep slope and the most suitable laboratory tests to fill-reinforcement characterization [23].

(a) (b)

Figure 3: Trial embankments construction: a) manual placement of the C&D recycled material over the geosynthetics; c) lightweight compaction of the layer.

Figure 4: Careful exhumation of the geosynthetic specimens from the embankment.

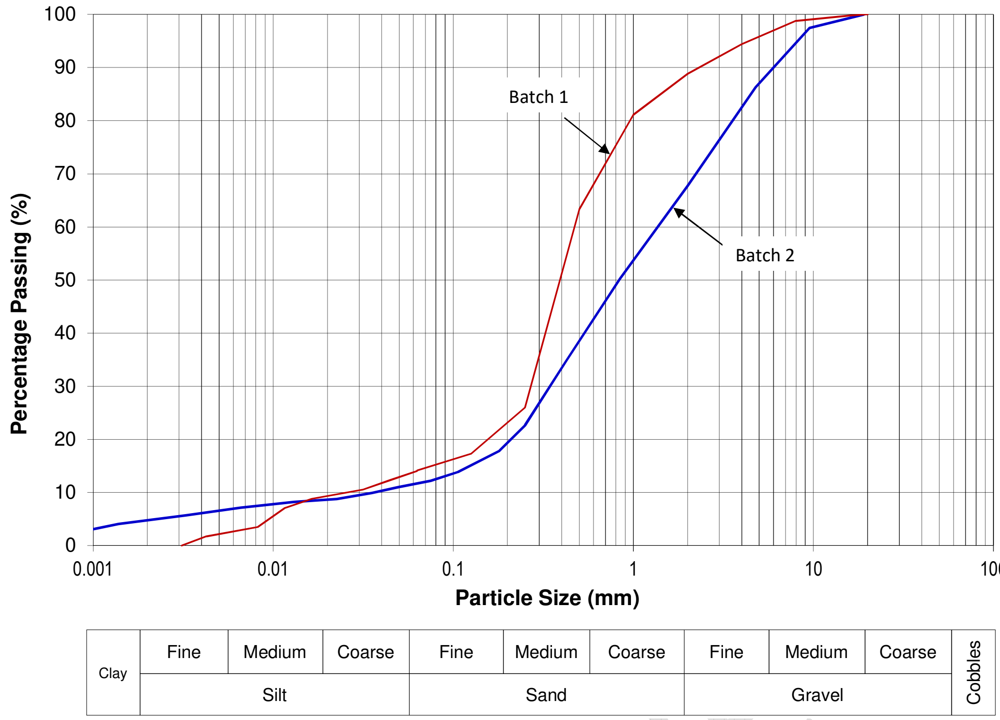

Figure 5: Particle size distribution of C&D recycled materials.

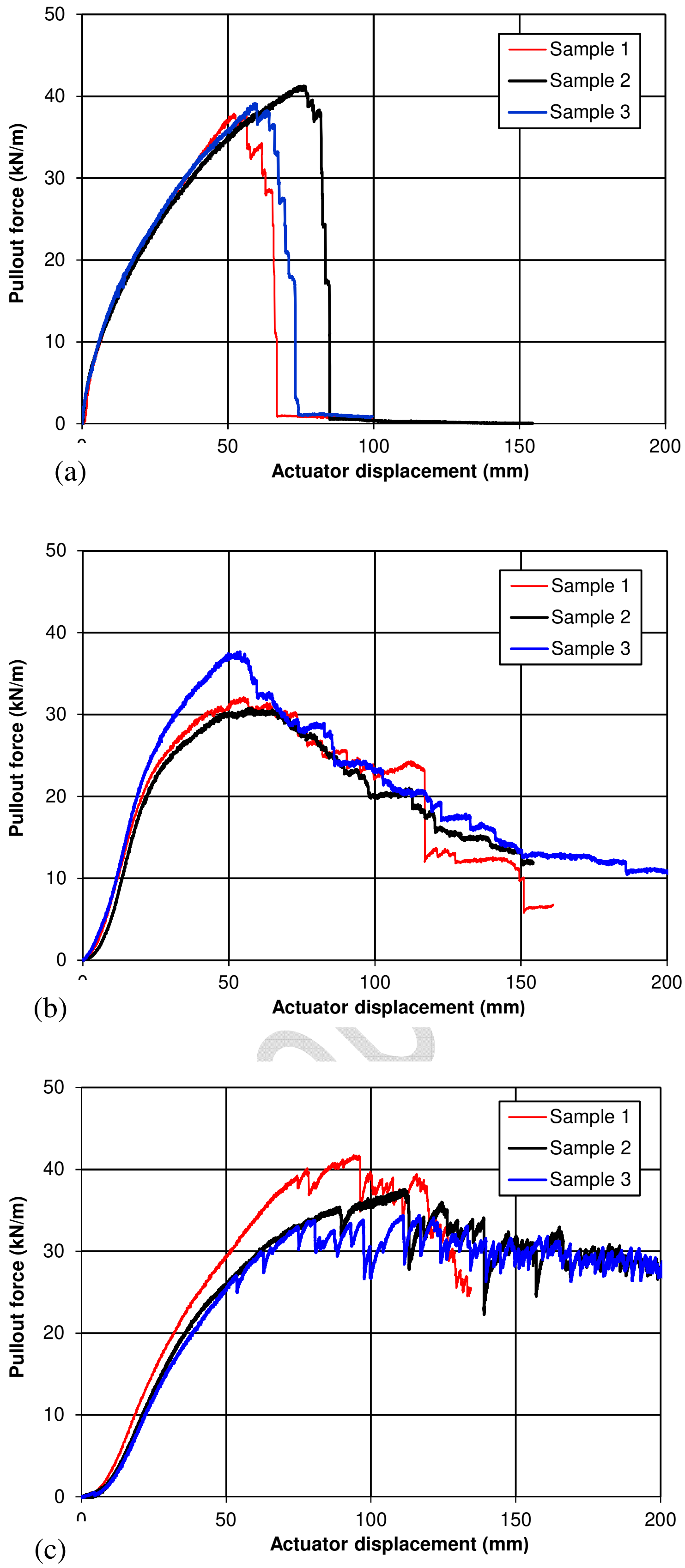

Figure 6: Results of pullout test for: (a) geogrid GGR1; (b) geogrid GGR2; (c) geotextile GCR.

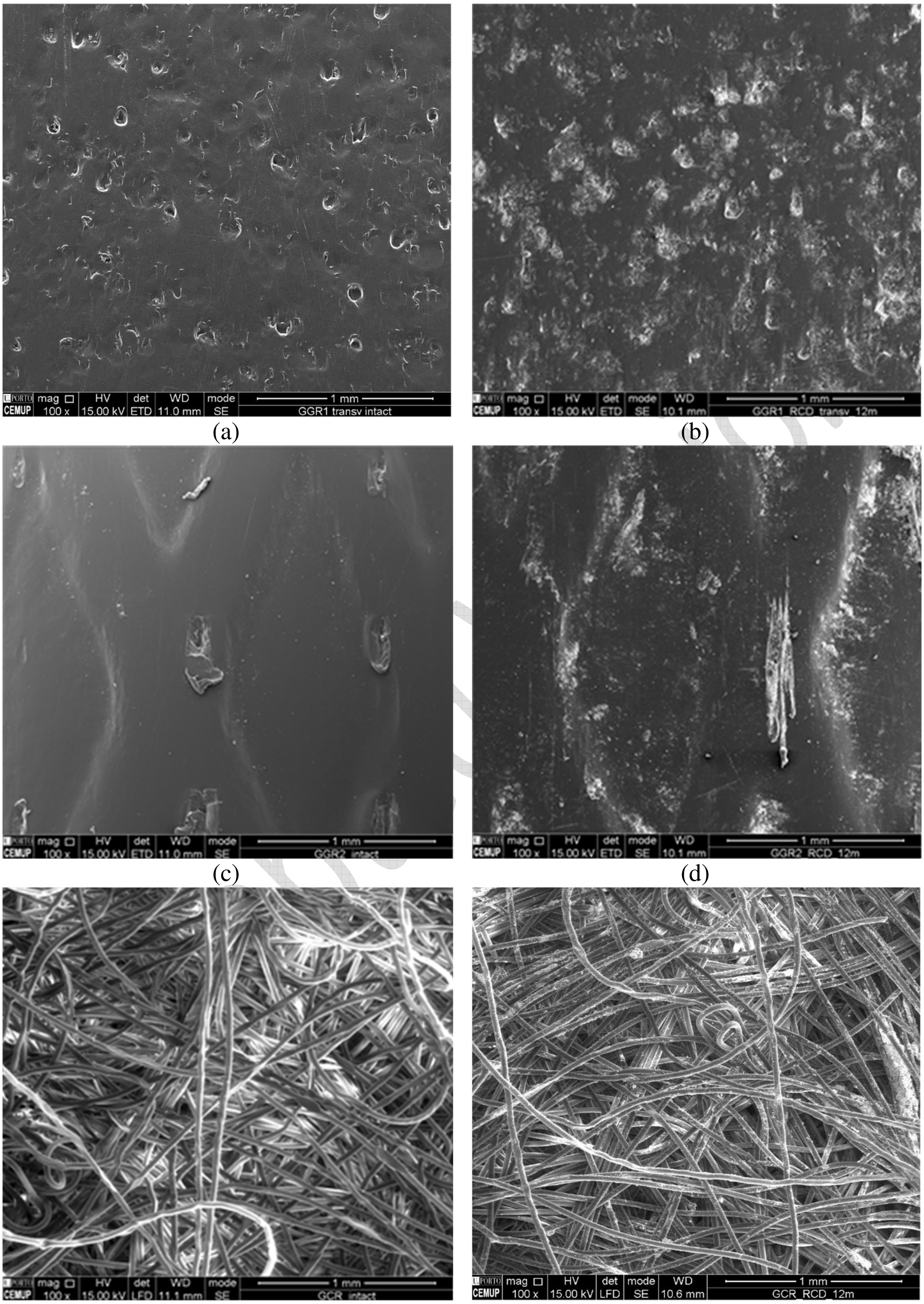

Figure 7: SEM images of geosynthetic specimens (×100): (a) GGR1 intact; (b) GGR1 exhumed; (c) GGR2 intact; (d) GGR2 exhumed; (e) GCR intact; (f) GCR exhumed.

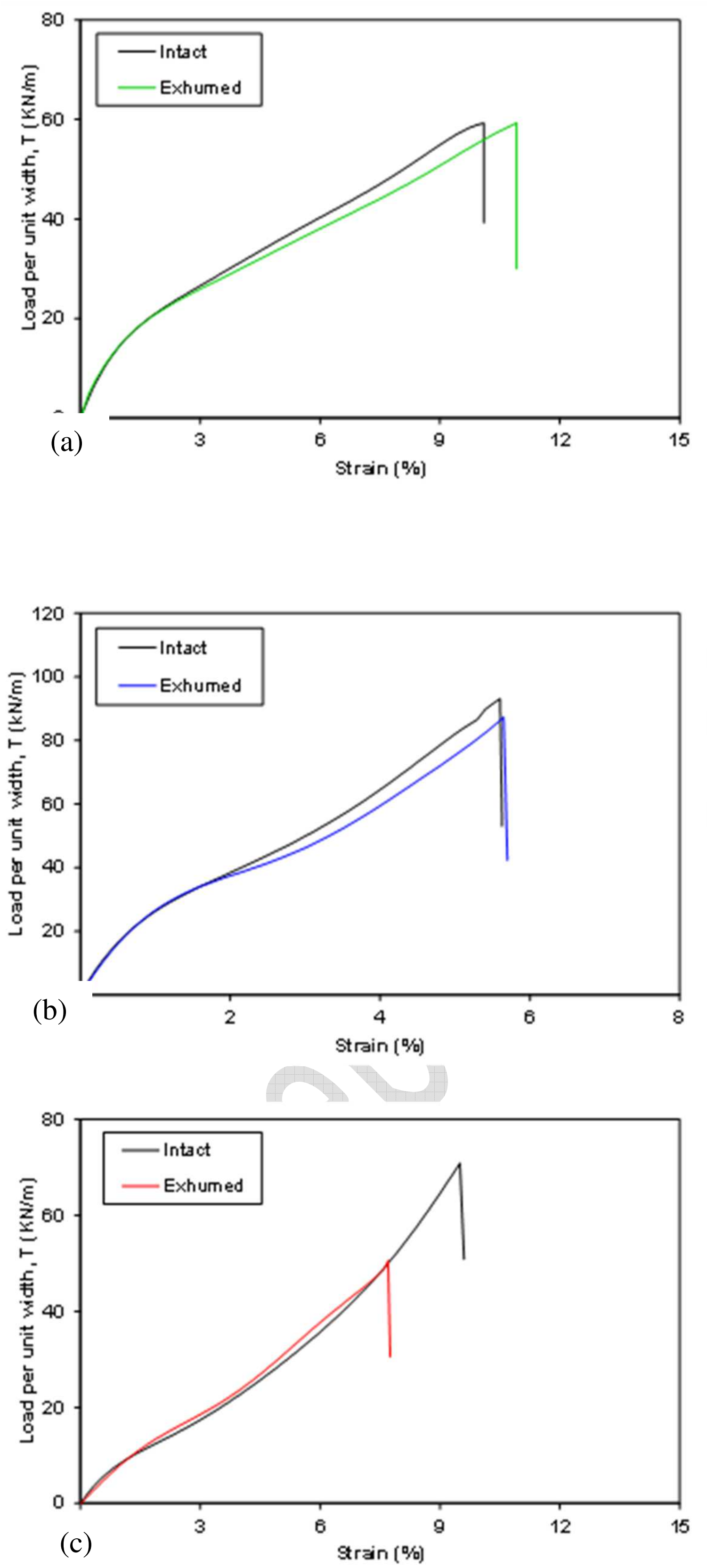

Figure 8: Comparison of mean load-strain curves of intact and exhumed specimens: (a) geogrid GGR1; (b) geogrid GGR2; (c) geotextile GCR.

TABLES

Table 1: Properties of the geosynthetics used in the experimental study.

	GGR1	GGR2	GCR
Raw material	HDPE	PET	PP & PET
Mass per unit area (g/m^2)	450	380	340
Aperture dimensions (mm)	16×219	30×73	-
Mean value of the tensile strength (kN/m)	60	88	71
Elongation at maximum load, ε_{Tmax} (%)	10	9	10
Secant tensile stiffness at 2% strain (kN/m)	1085	1182	647
Secant tensile stiffness at 5% strain (kN/m)	718	928	577
Secant tensile stiffness at ε_{Tmax} (kN/m)	597	907	728

Table 2: Some physical and mechanical properties of the C&D recycled materials.

Properties	Batch 1	Batch 2
D_{10} (mm)	0.03	0.04
D_{30} (mm)	0.27	0.35
D_{50} (mm)	0.39	0.84
D_{60} (mm)	0.47	1.35
Particles density, G_s	2.72	2.70
Minimum void ratio, e_{min}	0.508	0.549
Maximum void ratio, e_{max}	0.853	0.908
Maximum dry density, γ_{dmax} (kN/m^3)	19.5	19.2
Optimum moisture content, OMC (%)	10.0	12.5

D_{10}, D_{30}, D_{50} and D_{60} characteristic grain diameters

Table 3: Composition of C&D recycled materials.

Constituents	Batch 1	Batch 2
Concrete, concrete products, mortar, concrete masonry units, R_c (%)	31.9	40.0
Unbound aggregate, natural stone, hydraulic bound aggregate, R_u (%)	31.1	36.5
Clay masonry units, calcium silicate masonry units, R_b (%)	8.9	10.8
Bituminous materials, R_a (%)	2.5	0.5
Glass, R_g (%)	0.2	1.2
Soils, R_s (%)	25.2	10.8
Other materials, X (%)	0.2	0.1
Floating particles, FL (cm^3/kg)	6.7	10.0

Table 4: Results of laboratory leaching tests and acceptance criteria for inert landfill.

Parameter (mg/kg)	Batch 1	Batch 2	Acceptance criteria for leached concentrations – Inert landfill [26]
Arsenic, As	0.020	0.021	0.5
Lead, Pb	< 0.01	< 0.01	0.5
Cadmium, Cd	< 0.003	< 0.003	0.04
Chromium, Cr	0.015	0.012	0.5
Copper, Cu	0.12	0.10	2
Nickel, Ni	< 0.01	0.011	0.4
Mercury, Hg	< 0.002	< 0.002	0.01
Zinc, Zn	< 0.1	<0 .1	4
Barium, Ba	0.12	0.11	20
Molybdenum, Mo	0.027	0.018	0.5
Antimony, Sb	< 0.01	< 0.01	0.06
Selenium, Se	< 0.01	< 0.02	0.1
Chloride, Cl	130	300	800
Fluoride, F	2,7	6.1	10
Sulphate, SO_4	1900	3200	1000
Phenol index	< 0.05	< 0.05	1
Dissolved Organic Carbon, DOC	47	220	500
Total Dissolved Solids, TDS	2630	6580	4000
pH	7.8	8.2	-

Table 5: Direct shear strength parameters of C&D recycled materials.

	Batch 1		Batch 2		
	Air-dried I_D = 80%	OMC DC = 87%	OMC DC = 97%	Air-dried I_D = 70%	OMC DC = 90%
Cohesion (kPa)	29.7	9.3	23.3	13.0	13.8
Friction angle (°)	38.9	34.4	40.2	45.9	40.4

Table 6: Coefficients of interaction, f_g, for different compaction conditions and as a function of the normal stress.

Batch 1

Compaction conditions	Air-dried I_D = 80%			OMC DC = 87%			OMC DC = 97%		
Normal stress (kPa)	50	100	150	50	100	150	50	100	150
Interface C&D/GGR2	0.80	0.82	0.88	0.92	0.82	0.89	0.80	0.76	0.72
Interface C&D/GCR	0.72	0.74	0.78	0.94	0.90	0.93	0.61	0.71	0.72

Batch 2

Compaction conditions	Air-dried I_D = 70%				OMC DC = 90%			
Normal stress (kPa)	25	50	100	150	25	50	100	150
Interface C&D/GGR1	0.70	0.74	0.70	0.73	0.71	0.73	0.70	0.73
Interface C&D/GGR2	0.87	0.83	0.82	0.86	0.70	0.66	0.72	0.74
Interface C&D/GCR	0.76	0.75	0.70	0.77	0.73	0.76	0.70	0.70

Table 7: Values of the parameters $\tau_{pullout}$, $\tau_{direct\ shear}$ and f_b.

Interface	$\tau_{pullout}$ (kPa)	$\tau_{direct\ shear}$ (kPa)	f_b
C&D material/GGR1	23.56		0.86
C&D material/GGR2	24.15	27.42	0.88
C&D material/GCR	23.89		0.87

Table 8: Values of the retained tensile strength, R_T, retained peak strain, R_ε, and retained modulus, $R_{J2\%}$.

	R_T (%)	R_ε (%)	$R_{J2\%}$ (%)
Geogrid GGR1	98.4	108.1	99.2
Geogrid GGR2	94.6	100.0	97.4
Geotextile GCR	71.3	78.9	107.9