Geogrid Mechanical Damage Caused by Recycled Construction and Demolition Waste (RCDW): Influence of Grain Size Distribution

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Abstract. Recent studies have shown that recycled construction and demolition waste (RCDW) can be used as backfill material in geosynthetics reinforced soil (GRS) structures. However, besides the environmental and economic benefits of this practice, it is necessary to evaluate the mechanical damages that RCDW could cause to the reinforcement elements. This study aims to investigate the influence of RCDW grain size distribution on short-term geosynthetic mechanical damages. The RCDW used in this investigation was collected at a recycling plant and the geosynthetics consisted of geogrids usually employed in GRS structures. In order to simulate the mechanical damages, a steel box was used and the applied loads within the magnitudes of values normally observed in this type of engineering work. The results showed no significant reduction for tensile strength of geogrids. On the other hand, it was possible to notice the effects of loading process on strain at rupture and stiffness. However, the reduction factors obtained from the damaged geogrids could be applied during GRS design stage. This study concludes that the damages caused by RCDW to geogrids would not prevent the use of this new composite in several engineering works.

Keywords: debris, durability, geosynthetics, granulometry, loading process, sustainability.

1. Introduction

Due to its need of using a tremendous variety of materials and processes, the construction industry plays a significant role in environmental issues, not just as a domestic industry, but on a global scale. The construction industry stands pointed out as one of the largest producers of solid waste on the planet, being responsible for over 10 billion tons generated worldwide every year (Wu *et al.*, 2019). Therefore, preventing environmental, economic, and social impacts caused by the construction and demolition wastes (CDW) demands attitude changes in order to turn the efficient management and reuse of these wastes into worldwide goals.

In this context, geosynthetics appear as modern and environmentally friendly products derived from researches and development of the polymer industry and geotechnical engineering. These materials have been increasingly used in geotechnical engineering due to their economic and environmental benefits. Over the last decades, geosynthetic reinforced soil (GRS) walls have presented a series of positive ecological parameters when compared to traditional concrete cantilever walls (Jones, 1994), which include 40 % less SO₂ released into the atmosphere during the fabrication of their component parts.

Reinforcement material durability is an important issue related to the design and performance of GRS walls. Therefore, besides promoting good interaction with the geosynthetic, the filling material is expected to be biochemically and mechanically low-aggressive. Bearing in mind these aspects, even though the proposal of using recycled construction and demolition waste (RCDW) as backfill material in GRS structures seems to be an interesting strategy to promote the concept of sustainable development in Civil Engineering, it is crucial to investigate the eventual damages caused by this non-conventional filling material in a field condition.

1.1. Characteristics of RCDW grain

The definition of CDW is not a consensus, varying from one country to another. But, apart from some peculiar local construction characteristics, the CDW consist of a mixture of different materials: i) ceramics, ii) concrete blocks, iii) mortar, iv) steel, v) plastic, vi) wood and others. The diversity of materials composing the CDW and the different procedures adopted at recycling plants lead up to products with different properties and grain size distribution (Kartam *et al.*, 2004; Esin & Cosgun, 2007; Angulo *et al.*, 2011; Leite *et al.*, 2011; Ossa *et al.*, 2016).

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The granulometric variability of RCDW sampled at recycling plants has been reported in some geotechnical investigations (Santos, 2007; Barbosa, 2017; Santos *et al.*, 2013; Fleury, 2018; Silvestre, 2019) and maximum values (highest coefficient of variation of material percentage passing through a specific mesh aperture) were noted, ranging from 15 % (Barbosa, 2017) to 109 % (Silvestre, 2019). Given that the grain size distribution of RCDW is one of the features that affect the degree of interlocking between its particles, hence affecting the contact area, the evaluation of the granulometric variability can help indicate how standardized it will be.

Another important factor that affects the interlocking characteristic of particulate media is the particle shape. The results reported by Leite *et al.* (2011) revealed that RCDW composition influenced the shapes of the grains - cementitious materials and crushed rocks have a wide predominance of cubic grains - and the particles presented a higher percentage of cubic grains after compaction test. The study concluded that cubic particles could contribute to better densification and higher shear strength. On the other hand, flat and elongated particles would be more susceptible to breaking when compacted. When testing individual RCDW grains, it was possible to verify that particle shapes play a more prominent role in particle breakage phenomena than mineralogy and microstructure (Afshar *et al.*, 2017).

1.2. Geosynthetic mechanical damages caused by RCDW

The reduction of geogrid ultimate tensile strength (T_{ult}) due to installation damage becomes a problem for determining its allowable tensile strength (T_{al}). To deal with the damage caused by installation activities, and others which geosynthetics are exposed to, GRS structure designers consider the application of reduction factors to determine T_{al} , according to (Allen & Bathurst, 1996):

$$T_{al} = \frac{T_{ult}}{RF} = \frac{T_{ult}}{RF_{ID} \cdot RF_{CR} \cdot RF_D} \quad (1)$$

where T_{ult} is the ultimate tensile strength; RF , the global reduction factor; RF_{ID} is the installation damage reduction factor; RF_{CR} , the creep reduction factor; and RF_D is the durability reduction factor. The RF_{ID} is calculated according to

$$RF_{ID} = \frac{T_{ult_v}}{T_{ult_d}} \quad (2)$$

where T_{ult_v} and T_{ult_d} represent the ultimate tensile strength mean value of virgin (undamaged) and damaged specimens, respectively.

This damage can be more severe when geogrids are used together with larger size aggregate particles and compacted with high energy (Huang & Wang, 2007; Pinho-Lopes; Lopes, 2014; Fleury *et al.*, 2019). Mechanical dam-

age to geosynthetics can be evaluated by i) tensile strength, ii) strain at rupture and ii) secant stiffness, from the curves tensile strength against strain obtained in laboratory tensile tests (Allen & Bathurst, 1994).

Some researchers (Paula *et al.*, 2004; Huang, 2006; Huang & Chiou, 2006; Huang & Wang, 2007; Yoo *et al.*, 2009; Rosete *et al.*, 2013; Gonzalez-Torre *et al.*, 2014) carried out the standard laboratory test, according to EN ISO 10722:2007 (BSI, 2007), focused on assessing the mechanical damage to geogrids under repeated loading with granular materials. The values of reduction factors for mechanical damages (RF_{MD}), for different repeated loads and granular materials, ranged between 0.93 and 1.54.

Mechanical damages caused by RCDW to geosynthetic reinforcement elements used in an in-field experimental large-scale wall were investigated by Santos *et al.* (2012). The RCDW collected in a construction site located in Brasília, Brazil, consisted of demolition waste submitted to primary crushing in order to reduce its particle size. The geotechnical characterization showed that the RCDW was classified as a sandy gravel. Based on a statistical analysis proposed by Santos (2011), the results revealed that different compaction procedures (lightweight roller or vibratory hammer) caused distinct damages to polyester (PET) geogrid (GG) ($T_{ult} = 20$ kN/m).

An investigation of the effects of dropping height (0.0 m, 1.0 m and 2.0 m) and compaction procedure (vibratory plate) on the mechanical damages of a polyester (PET) geogrid ($T_{ult} = 35$ kN/m) revealed that the RCDW, classified as gravely sand, caused damages with low or very low magnitudes, considering all the scenarios investigated (Barbosa & Santos, 2013).

In a recent study, Fleury *et al.* (2019) investigated the occurrence of mechanical damage during the installation of geogrids in an in-field test facility with RCDW backfill material. The results showed that the variation of dropping height (0.0 m, 1.0 m, and 2.0 m) caused a slight reduction in the ultimate tensile strength (T_{ult}) ($RF_{ID} = 0.94$ to 1.21). However, the authors also observed that compaction methods were a relevant factor for geogrid installation damage in most of the investigated scenarios, with RF_{ID} ranging from 0.98 to 1.22, with the vibratory hammer compaction promoting the highest reduction effect.

Despite the contribution made by laboratory and in-field tests, the investigation of mechanical damage to geosynthetic products caused by non-conventional material brings together the need to evaluate some issues so far not assessed. Bearing in mind the proposal of using RCDW as backfill material, the evaluation of grain size distribution may raise another aspect that could affect the level and way mechanical damages occur to geosynthetic products: particle breakage during the loading process. Therefore, this paper aims to evaluate and quantify the effect of grain size distribution curves on RCDW breakage and its consequence for the mechanical damage caused to geogrids.

2. Materials and Methods

2.1. Materials

2.1.1. RCDW

The RCDW used in this investigation were produced by a recycling plant in Aparecida de Goiânia-GO, Brazil. The recycling plant uses a jaw crusher, in a single operation, to reduce the particle size of CDW and to produce different materials, such as: i) Aggregate A ($9.5 \text{ mm} > d > 4.75 \text{ mm}$), ii) Aggregate B ($19 \text{ mm} > d > 9.5 \text{ mm}$), iii) Aggregate C ($d < 19 \text{ mm}$), iv) Aggregate D ($d > 19 \text{ mm}$), v) Sand A ($d < 4.75 \text{ mm}$, sand composed of crushed CDW), vi) Sand B ($d < 4.75 \text{ mm}$, sand composed of crushed concrete) and vii) By-product. Bearing in mind the aims of this study and size limitations of the test box, the RCDW were selected based on their potential to be used as backfill material in GRS structures.

Three types of recycled products were investigated: i) Aggregate A, ii) Aggregate B and iii) Aggregate C (Fig. 1). According to the manufacturer, Aggregate C is composed of equal volumes of Aggregate A, Aggregate B and Sand B. It is important to point out that Aggregate C represents around 44 % of the products sold by the recycling plant nowadays.

2.1.2. Geosynthetics

To investigate the influence of geogrid structure on the strength against mechanical damages, tests were carried out with three types of geogrids, being one composed of polyvinyl alcohol yarns (GGPVA, $T_{ult} = 35 \text{ kN/m}$; mass per unit area, $M_A = 160 \text{ g/m}^2$) and two others of polyester yarns

(GGPET 01, $T_{ult} = 55 \text{ kN/m}$, $M_A = 280 \text{ g/m}^2$; GGPET 02, $T_{ult} = 35 \text{ kN/m}$, $M_A = 185 \text{ g/m}^2$). These geogrids are usually used as reinforcement elements in GRS structures. Figure 2 presents the images of the geogrids.

The dimensions of the geogrid specimen submitted to tensile strength testing consisted of 200 mm (transversal direction) by 1,200 mm (longitudinal direction). The processes of storage, transportation and cutting of the geogrid specimens were carried out carefully to avoid any damages to the virgin samples, as well as any additional damages to the tested specimens.

2.2. Experimental program

2.2.1. RCDW characterization

For each kind of RCDW, five samples were collected at one-monthly intervals trying to verify eventual variability of the recycled products, and the sampling procedure was carried out in different parts of the waste pile (bottom, middle and top). The laboratory tests followed the Brazilian standards and consisted in those usually performed for soil characterization: i) specific gravity (NBR 6458, ABNT, 2016a), ii) grain size distribution (NBR 7181, ABNT, 2016b), iii) Atterberg limits (NBR 6459, ABNT, 2016c; NBR 7180, ABNT, 2016d), iv) compaction test (Standard Proctor) (NBR 7182, ABNT, 2016e), and v) gravimetric composition.

Once the RCDW samples were sieved before and after each test of damage reproduction, it was possible to compare grain size distribution curves and particle shapes before and after the loading process. The use of a microscope also aimed to identify the roughness of RCDW particles.

Figure 1 - RCDW: a) Aggregate A, b) Aggregate B and c) Aggregate C.

Figure 2 - Geogrids: a) GGPVA, b) GGPET 01 and c) GGPET 02.

The gravimetric composition was carried out according to the procedure presented by Santos (2007). Initially, 10.0 kg of Aggregate C were sieved on a mesh of 4.75 mm under running water; the retained material was left to dry in an oven for at least 12 h; finally, the retained material was sorted by visual analysis (naked eye) according to the different gravimetric compositions. Particles of RCDW smaller than 4.75 mm (including those removed during the washing process) were classified as 'soil'.

The procedure of evaluating the shape and roughness of RCDW particles, consisting of visual analysis by means of a digital microscope, was used to verify the shape and surface roughness of the RCDW particles. The equipment used has magnification ranging from 5× to 100×. The images of coarse grains (dimensions varying from 2.0 mm to 10.0 mm) were taken using a magnifying glass.

2.2.2. Laboratory damage reproduction

The mechanical damage was carried out reproducing the loading process using a steel-made box (440 long × 300 wide × 300 mm high) which is divided into two parts (upper and bottom). At the middle height, the test box has an aperture for geosynthetic installation. Figure 3 shows the equipment dimensions in a perspective view. The mechanical damage tests were performed with the last collected samples of each kind of aggregate (nominated 'samples #5').

The test procedure consisted of placing the RCDW (dry condition) in the test box up to its medium height (bottom part completely filled). Then, the RCDW was statically compacted (one-dimensional compression) using a universal testing equipment until the material achieved a compaction degree approximately equal to 85 % (Standard Proctor) - Fleury *et al.* (2019) reported a value of 89 % when compacting recycled materials from the same recycling plant with a vibratory roller. Then, the central part of the geogrid specimen (300 mm long and 200 mm wide) was laid in contact with the RCDW - the extreme portions of the geogrid remained outside the box and not damaged. Finally, the upper part of the test box was positioned, filled up with

Figure 3 - Test box perspective view and dimensions.

RCDW and also statically compacted to the same degree of compaction.

Once the test box had been totally assembled, the normal stress was applied (increment of 10.2 kN/min) on a steel plate of 20 × 200 × 340 mm using the universal testing equipment. Considering a GRS higher than 10.0 m and eventual external loads, tests were carried out with 150 kPa, 300 kPa, and 600 kPa. Once achieved the intended load, it was kept for 5 min - enough time to stabilize plate displacement detected by monitoring instruments. Bearing in mind the variability of RCDW, five tests (non-reuse) were performed for each load, which resulted in a total amount of 135 specimens.

Following that, the specimens were carefully exhumed to prevent the occurrence of additional mechanical damages, properly identified and submitted to tensile tests - this last one, at São Carlos School of Engineering (EESC), University of São Paulo (USP). The tensile tests were carried out according to ASTM D-6637-15 - Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method (ASTM, 2015). Figure 4 shows the executive sequence of the damage simulation test.

2.2.3. Validation and quantification of damage

To determine valid the occurrence of damage, the method proposed by Santos (2011) was used with the reduction factors (RF) being calculated considering the variability of virgin specimens. According to the method, the confidence interval (nominated F_0) of the properties of in-

Figure 4 - Executive sequence: a) static compaction of RCDW in the box bottom part, b) geosynthetic laid in contact with the RCDW, c) application of load during the test, d) exhumation of geogrid specimen.

terest (T_{ult} , ϵ_{rup} , and J_{sec}) was obtained from the tests of virgin specimens using Student's t -distribution with the sample mean value confidence given by

$$t = \frac{\bar{X} - \mu}{\frac{S}{\sqrt{n}}} \quad (3)$$

where t is the value of the Student's t -distribution variable, $\bar{X}$ is the mean value of the virgin sample; μ , the population mean; S , sample standard deviation; and n is the sample size.

To calculate the value of RF , two scenarios were evaluated: i) the damaged sample mean value ($\bar{X}_d$) into the virgin sample confidence level interval raises doubt about the occurrence of damage, hence the reduction factor was assumed as equal to 1.0; ii) in the case of the damaged sample mean value ($\bar{X}_d$) out of the virgin sample confidence level interval, the reduction factor was calculated according to

$$RF_x = \frac{\bar{X}}{\bar{X}_d} \quad (4)$$

where RF_x is the reduction factor related to the X parameter, $\bar{X}$ is the virgin sample mean value of the analyzed parameter and $\bar{X}_d$ is the damaged sample mean value of analyzed parameter.

3. Results and Discussion

3.1. Recycled construction and demolition waste

3.1.1. Granulometric analysis

The grain size distribution curves of RCDW showed a significant variability, which made the samples be better evaluated using a 'grain size distribution range'. These results revealed that the procedures adopted at the recycling plant presented different levels of efficiency, being less efficient (higher variability) when involving processes of mixture of some products for producing a new one. Another factor that must be pointed out is related to the weather conditions during the recycling process, given that samples of Aggregate A (A-A #3 and #4), collected on rainy days, showed higher amount of fine materials. Figures 5 to 7 present the grain size distribution curves of investigated recycled aggregates and show the grain size distribution ranges for each sample of RCDW. Table 1 presents RCDW classification according to the Unified Soil Classification System (USCS) - (ASTM, 2017).

3.1.2. Gravimetric composition

The gravimetric composition analysis revealed that approximately 98 % of the composite materials of Aggregate C #1 can be classified as inert materials (soil, concrete, ceramic materials, and natural gravel), with no more than 2 % composed of metal, wood, paper, plastic and other materials - similar results have been found by Herrador *et al.*

(2012) and Santos *et al.* (2013, 2014). Percentages of soil, Portland cement concrete and ceramics showed significant values of coefficient of variation (COV) equal to 45.19 %, 27.90 % and 70.92 %, respectively. Figure 8 shows the results of the gravimetric composition analysis of the Aggregate C samples.

The variation of soil amount in the RCDW composition can be justified by the fact that buildings in the

Figure 5 - Aggregate A grain size distribution curves.

Figure 6 - Aggregate B grain size distribution curves.

Figure 7 - Aggregate C grain size distribution curves.

Table 1 - Classification of the RCDW according to the USCS system.

Sample	Aggregate A	Aggregate B	Aggregate C
#1	GP-GM with sand	GP	GW-GM with sand
#2	GP with sand	GP	SW-SM with gravel
#3	SP-SM with gravel	GP	SW-SM with gravel
#4	SW-SM with gravel	GP	GP-GM with sand
#5	GP with sand	GP	GP-GM with sand

Note: GW = well graded gravel; GP = poorly graded gravel; GM = silty gravel; SW = well-graded sand, fine to coarse sand; SP = poorly graded sand; SM = silty sand.

metropolitan area where the recycling plant is located possess underground structures (underground garage, for example), once the deep water table verified at the region allows this type of construction. Therefore, this kind of underground construction is responsible for a significant amount of excavated soil sent to the recycling plant.

The variation of Portland cement concrete and ceramic materials amount reveals, besides the main construction characteristics of the local buildings, the lack of waste management in the construction site. Given that the constructions have several types of materials, such as reinforced concrete, metallic structures, wood, soil, tile, bricks, etc., these materials should be submitted to a process of segregation/separation in the construction site. However, at present, the segregation process is not carried out in most construction sites in Goiânia-GO, Brazil.

3.1.3. Specific gravity

Due to the diverse materials found in RCDW, the specific gravity (G_s) of i) particles passing in the 4.75-mm sieve and ii) particles passing in the 19-mm sieve and retained by the 4.75-mm sieve were investigated. Results showed that the mean value of G_s for the particles passing in the 4.75-mm sieve was practically the same for Aggregate B (2.602 g/cm³, $COV = 0.54\%$) and Aggregate C (2.603 g/cm³, $COV = 3.28\%$); and Aggregate A presented a mean value approximately 20 % smaller than the other materials (G_s equal to 2.166 g/cm³).

The G_s of the grains retained in the 4.75-mm sieve, considering the three materials (A-A, A-B, and A-C) showed mean values ranging from 2.658 g/cm³ to 2.684 g/cm³, similar to the ones reported by Santos & Leite (2018) and approximately 21 % higher than those presented by Angulo *et al.* (2011). This fact can be justified by the different focus given to the RCDW studied, since the latter au-

Figure 8 - Percentage of composite materials.

thors investigated the use of recycled aggregates in non-structural concrete.

The results revealed low variability of G_s of the RCDW. The variability of the material passing in the 4.75-mm sieve ranged from 0.54 % to 4.21 %, and the variability of the material retained in the 4.75-mm sieve (and passing the 19-mm sieve) ranged from 0.27 % to 1.63 %.

It was observed that Aggregate C presented considerable amount of soil in its composition. Previous studies on the local soil (tropical soil) revealed values of G_s varying from 2.664 g/cm³ (Silva *et al.*, 2019) to 2.740 g/cm³ (Mascarenha *et al.*, 2018). Aggregate A visibly exhibited a greater amount of ceramic material, which is probably responsible for the reduction of its G_s .

3.1.4. Atterberg limits

All the samples presented non-plastic behavior, which can be explained by the fact of having low presence of clay particles (diameter < 0.002 mm). These results also follow those found by Santos *et al.* (2013, 2014) and Ossa *et al.* (2016). It is worth mentioning that these results validate the application of RCDW as backfill material in GRS, according to the recommendation of BSI 8006 (2010).

3.1.5. Compaction

Standard Proctor compaction tests were carried out only on four samples of Aggregate C, once the very low amount of fine material did not allow making the test with sample A-C #4. Aggregate A and Aggregate B also were not tested for the same reason. Figure 9 and Table 2 present the results of the compaction test carried out without reuse of material.

Figure 9 - Compaction test curves - Aggregate C (except sample A-C #4).

Table 2 - Maximum dry unit weight and optimum water content - Aggregate C (except sample A-C #4).

Property	A-C #1	A-C #2	A-C #3	A-C #5	Mean	COV (%)
γ_{d-max} (kN/m ³) ^a	17.150	16.925	16.660	16.758	16.859	1.13
w_{op} (%) ^b	17.10	18.00	18.70	19.00	17.60	4.70

Note: ^aMaximum dry unit weight; ^bOptimum water content.

The results of the compaction test revealed the direct influence of ceramic material content. Higher amount of ceramic material causing higher values of optimum water content was observed. These results follow those presented by Silva *et al.* (2016) and Cardoso *et al.* (2016). However, sample A-C #1, despite having the highest content of ceramic aggregates, showed the lower optimum water content. This discrepancy encourages further investigation into the properties of the ceramic materials present in RCDW.

3.2. Influence of loading process on RCDW properties

Considering that the process of applying loads of 150 kPa, 300 kPa and 600 kPa could break the low-resistance particles of RCDW, specific gravity tests carried out and grain size distribution curves were drawn using samples from different loading conditions.

3.2.1 Characterization of materials

The results showed that there was no great variation of the values of G_s of the recycled materials submitted to different loads in comparison to the one presented by the intact material (without loading), even considering both analyzed particle sizes (passing in the 4.75-mm sieve or retained in the 4.75-mm sieve). Table 3 presents the G_s values of tested materials.

The effects of loading on RCDW characteristics were also investigated with grain size distribution analysis of the tested samples. For this purpose, tests were performed on the materials applying different loads and, to show the percentage difference for different samples and scenarios, curves were drawn in comparison to those not submitted to loading (Fig. 10).

It was noticed that the higher the load applied, the greater the quantity of fine grains in all the tested materials. However, it is possible to point out that specific changes were observed. The highest particle size variations for all samples (A-C, A-B, and A-A) occurred around the grain dimensions of 4.75 mm. In general, the grain breakage showed increase up to the diameter of 4.75 mm and decreased after this diameter.

The Aggregate A appeared as the most sensitive in relation to breakage by increased loading, probably due to its uniform grain size distribution and the presence of some particles of ceramic materials. This statement is strengthened by the results of Aggregate B, which presented smaller breakage value for the different loads. Even though

presenting a uniform grain size distribution, this aggregate was predominantly composed of concrete.

Table 3 - Effect of loading process on specific gravity of the RCDW aggregates.

Sample	Specific gravity - G_s (g/cm ³)	
	Passing (4.75-mm)	Retained (4.75-mm)
A-A - No Loading ^a	2.166	2.684
A-A - 150 kPa	2.156	2.650
A-A - 300 kPa	2.117	2.664
A-A - 600 kPa	2.224	2.776
A-B - No Loading ^a	2.602	2.658
A-B - 150 kPa	2.660	2.645
A-B - 300 kPa	2.643	2.635
A-B - 600 kPa	2.614	2.686
A-C - No Loading ^a	2.603	2.674
A-C - 150 kPa	2.600	2.658
A-C - 300 kPa	2.586	2.678
A-C - 600 kPa	2.609	2.678

Note: ^aMean value of five samples.

3.2.2. RCDW particle shape and roughness

Images of the studied materials (A-A, A-B, and A-C) - intact and subjected to the loading process - were taken using a microscope to analyze the effect of loading on particle shape and roughness. The materials retained in sieves 9.5-mm, 4.75-mm, and 2.0-mm were analyzed separately, so their characteristics could be verified in relation to the specific applied load.

The images did not allow to verify any difference related to particle shapes. No relationship between loading process and grain roughness changes was observed in grains retained in sieves 2.00-mm and 4.75-mm. This can be justified by the fact that coarser particles are the ones presenting most modification in relation to the shape when subject to loading, as stated by Leite *et al.* (2011). The image of Aggregate C particles retained in the sieve 9.5-mm (Fig. 11) revealed a smooth surface for loading of 600 kPa. Results revealed that the maximum load of 600 kPa, although not enough to break the particle when it consisted of natural aggregate (rock), could remove the mortar around the natural aggregate. This can explain the changes showed when comparing the grain size distribution of materials subject to the loading process.

Figure 10 - Granulometric analysis of aggregates for different loads: a) Grain size distribution curves, b) Percentage difference of particle passing.

Figure 11 - Grains of A-C retained sieve 9.5-mm: a) No loading, b) 150 kPa, c) 300 kPa, d) 600 kPa.

3.3. Geogrids

3.3.1. Tensile test in virgin samples and determination of confidence interval

The results of tensile tests carried out on five virgin samples of each geogrid type revealed smaller ultimate tensile strength (T_{ult}) compared to the manufacturer's information (see section 2.1.2). GGPVA presented a mean value of T_{ult} equal to 26.3 kN/m and the lowest variability ($COV = 7.8\%$), meanwhile GGPET01 showed a mean value of T_{ult} equal to 38.7 kN/m and the highest variability ($COV = 13.2\%$). GGPET02 presented a mean value of T_{ult} equal to 27.4 ($COV = 12.2\%$).

In relation to the tensile stiffness, the GGPVA showed the lowest variability for stiffness at 2% ($J_{2\%}$). This geogrid revealed an average $J_{2\%}$ equal to 550.00 N/m and value of COV equal to 6%. Due to the fact that the tensile rupture occurred below the strain of 5%, the stiffness for this scenario ($J_{5\%}$) was not calculated. The results showed that the GGPET 01 presented mean values of $J_{2\%}$ and $J_{5\%}$ equal to 694.00 N/m ($COV = 25\%$) and 555.20 N/m

($COV = 16.2\%$), respectively. The GGPET 02 revealed $J_{2\%}$ equal to 680.00 N/m with the highest variability ($COV = 33.4\%$) and $J_{5\%}$ equal to 408.80 N/m ($COV = 16.6\%$).

The virgin samples presented values of strains at rupture (ϵ_{rup}) below 5% for the GGPVA, and below 10% for the polyester geogrids (GGPET 01 and GGPET 02). The virgin samples of GGPVA presented the lowest variability of ϵ_{rup} , showing value of COV equal to 5.4% (mean value of $\epsilon_{rup} = 4.7\%$), meanwhile GGPET 01 showed the highest variability, with value of COV equal to 21.7% (mean value of $\epsilon_{rup} = 6.6\%$). GGPET 02 revealed value of COV equal to 21.5% (mean value of $\epsilon_{rup} = 5.8\%$) for virgin samples.

Based on the data obtained from the virgin samples, the confidence intervals for each kind of geogrid were determined by means of the Student's t -distribution. Table 4 presents the confidence limits for each of the parameters of interest and their respective confidence levels. It can be observed that the confidence level values were between 96% and 98%, very similar to the ones found by Barbosa & Santos (2013) and Santos *et al.* (2014).

Table 4 - Results from tests on virgin samples (5 specimens) associated with the Student's t -distribution analysis.

Geogrid	Tensile strength (kN/m)	Strain at rupture (%)	$J_{2\%}$ (N/m)	$J_{5\%}$ (N/m)
GGPVA	$\bar{T}_{ult} = 26.3$	$\bar{\epsilon}_{rup} = 4.7$	$\bar{J}_{2\%} = 550.0$	n.a.
	$COV = 7.8\%$	$COV = 5.4\%$	$COV = 6\%$	
	$22.55 < F_0 < 30.05$	$4.15 < \epsilon_{rup} < 5.26$	$488.43 < J_{2\%} < 611.57$	
	$CL = 98\%$	$CL = 98\%$	$CL = 98\%$	
GGPET 01	$\bar{T}_{ult} = 38.7$	$\bar{\epsilon}_{rup} = 6.6$	$\bar{J}_{2\%} = 694.0$	$\bar{J}_{5\%} = 555.2$
	$COV = 13.2\%$	$COV = 21.7\%$	$COV = 25\%$	$COV = 16.2\%$
	$31.05 < F_0 < 46.35$	$3.98 < \epsilon_{rup} < 9.22$	$434.13 < J_{2\%} < 953.87$	$420.26 < J_{5\%} < 690.14$
	$CL = 96\%$	$CL = 98\%$	$CL = 96\%$	$CL = 96\%$
GGPET 02	$\bar{T}_{ult} = 27.4$	$\bar{\epsilon}_{rup} = 5.8$	$\bar{J}_{2\%} = 680.0$	$\bar{J}_{5\%} = 408.8$
	$COV = 12.2\%$	$COV = 21.5\%$	$COV = 33.4\%$	$COV = 16.6\%$
	$22.45 < F_0 < 32.35$	$3.55 < \epsilon_{rup} < 8.05$	$254.42 < J_{2\%} < 1105.58$	$307.07 < J_{5\%} < 510.53$
	$CL = 96\%$	$CL = 98\%$	$CL = 98\%$	$CL = 96\%$

Note: T_{ult} = ultimate tensile strength; ϵ_{rup} = strain at rupture; $J_{2\%}$ = stiffness at 2% strain; $J_{5\%}$ = stiffness at 5% strain; CL = confidence level; n.a. = not available.

3.3.2. Geogrids' tensile strength, strain at rupture and secant tensile stiffness after loading

3.3.2.1. GGPVA

Considering all the scenarios, it was observed that GGPVA did not present the mean value of ultimate tensile strength $\bar{T}_{ult}$ outside the limits calculated for this parameter. However, the strain at rupture (ε_{rup}) appeared as a sensitive parameter to the loading process, which can be verified evaluating the reduction of T_{ult} values and the increase of COV . Figure 12a shows the strength values obtained while testing the GGPVA with each kind of RCDW.

Aggregate C - classified as a poorly graded gravel with silt - caused the higher reduction factor of average ε_{rup} when the GGPVA was submitted to the load of 150 kPa, which confirms that the responses of this parameter were not affected in a direct relation to loading (Fig. 12b). However, it was possible to see that other load magnitudes caused reductions of this parameter close to the lower limit established by statistical analysis. It is also possible to visualize the increase of COV when strain at rupture of virgin and exhumed specimens are compared.

Results revealed that Aggregate B - classified as poorly graded gravel - caused the greatest reduction of ε_{rup} and the highest variability when tested with a load of 300 kPa if compared to the other loads applied for that same material (Fig. 12b). Evaluating the results from tests with Aggregate A - classified as poorly graded gravel -, it is possible to observe that a load of 600 kPa caused the highest reduction of ε_{rup} , but this reduction was not directly related to load (Fig. 12b). These results show the need for a better separa-

tion of the materials that compose the RCDW, once the existence of components that could be broken easily (*e.g.* ceramic materials) can cause different damages in the geogrid tested.

In general, the analyses of stiffness at 2 % ($J_{2\%}$) showed that different scenarios (recycled aggregate *vs.* load) have not changed the mean values of this parameter, with most of the values ranging within the limits of virgin specimens - except for scenario Aggregate B submitted to 300 kPa (Fig. 12c). As pointed out during the discussion of the values of T_{ult} , the results revealed an increase of the COV of exhumed samples.

3.3.2.2. GGPET 01

The evaluation of all scenarios revealed that GGPET 01 did not present average ultimate tensile strength ($\bar{T}_{ult}$) outside the limits calculated for this parameter using the virgin specimen data and the Student's *t*-distribution. The mean values of ε_{rup} , $J_{2\%}$, and $J_{5\%}$ were also within the limits calculated, however, for these parameters, some specimens presented values beyond the limits. Figures 13a to 13d show the results of each investigated parameter.

GGPET 01 presented the value of strain at rupture, for the sample Aggregate B and load of 300 kPa, with a COV value of 13 % (Fig. 13b). The high variation of GGPET 01 samples was beyond the upper limit of the confidence interval, and this performance could be a limitation for its use in some geotechnical works.

3.3.2.3. GGPET 02

Considering the different scenarios analyzed, it was noticed that GGPET 02 did not present average ultimate

Figure 12 - GGPVA: a) Tensile strength; b) Rupture Strain; c) Stiffness - 2 % Strain.

Figure 13 - GGPET 01: a) Tensile strength; b) Rupture Strain; c) Stiffness - 2 % Strain; and d) Stiffness - 5 % Strain.

tensile strength ($\bar{T}_{ult}$) values outside the calculated limits (Fig. 14a). However, the Aggregate B sample (300 kPa) stands out due to the greater variation of the deformation at rupture (ϵ_{rup}) (Fig. 14b).

Aggregate C caused the higher reduction factor of average deformation at rupture ($\bar{\epsilon}_{rup}$) when GGPET 02 was submitted to the load of 150 kPa (Fig. 14b), which proves that the responses of this parameter were not affected in a direct relation to load - as well as GGPVA. Results revealed that Aggregate B caused an increase of ϵ_{rup} for all applied loads (Fig. 14b), with the load of 600 kPa being the most expressive one. For Aggregate A, it is possible to observe that a load of 600 kPa caused a higher increase of ϵ_{rup} , and this reduction was not directly related to load (Fig. 14b).

In general, the analyses of stiffness at 2 % ($J_{2\%}$) showed that the virgin sample presented a high value of COV (33.4 %). Besides that, all tested geogrids presented values smaller than the virgin sample (Fig. 14c). The Aggregate C and Aggregate A showed values within the confidence level. Only Aggregate B presented a reduction of $J_{2\%}$ for loads of 300 kPa and 600 kPa (Fig. 14c). For this aggregate, the results revealed an increase of the COV of damaged samples in comparison to the one of virgin ones (e.g. scenario of 300 kPa presented a $COV = 98.4\%$).

Considering the mean values of stiffness at 5 % ($J_{5\%}$) (Fig. 14d), for all loads, Aggregate A and Aggregate C did not cause any reduction beyond the limits. Aggregate B caused some reduction in the $J_{5\%}$ proportional to the applied

load, with the largest reduction of this parameter being observed for the load of 600 kPa. Although Aggregate A and Aggregate C did not cause any reduction factor ($J_{5\%}$) in tested samples, these aggregates did present average values lower than virgin samples. Thus, the results revealed that the fact of Aggregate B being the coarser material can be pointed out as the reason why the greatest damages were observed in geogrids when using this material.

3.3.3. Reduction factors due to loading process

The results showed that the reduction factor (RF) presented diverse magnitudes for each parameter and scenario. Considering the different scenarios evaluated (aggregates vs. loads), it was noticed that all tested geogrids (PVA or PET), irrespective of their catalogue tensile strength (35 kN/m or 55 kN/m), did not present average ultimate tensile strength values ($\bar{T}_{ult}$) outside the calculated limits (confidence intervals). For other parameters, only the cases with 35 kN/m geogrids (GGPVA and GGPET 02) presented values of RF other than 1.0. In terms of reduction factors related to deformation at failure ($RF\epsilon_{rup}$), the PVA geogrid showed values ranging from 1.15 to 1.21 (Table 5), hence becoming the most sensitive geogrid to the loading process. Aggregate A - classified as a poorly graded gravel with sand - presented moderate damages; while Aggregate B - classified as poorly graded gravel - contributed to a higher occurrence of damages. Aggregate C - classified as

Figure 14 - GGPET 02: a) Tensile strength; b) Rupture Strain; c) Stiffness - 2 % Strain; and d) Stiffness - 5 % Strain.

poorly graded silty gravel with sand - was the least aggressive material.

Concerning the reduction factors related to stiffness at 2 % ($RF_{J_{2\%}}$), the PET geogrid (35 kN/m) presented values from 3.29 to 4.12 (Table 5), when tested with Aggregate B, for loads of 300 kPa and 400 kPa, respectively. However, as reported by Fleury *et al.* (2019), it is worth mentioning that the method of monitoring the strain during the tensile strength test (in only one longitudinal rib) may have been the reason for the wide range of secant tensile stiffness values obtained. Therefore, once virgin samples presented excessively broad confidence intervals, it is reasonable to have a high occurrence of reduction factors equal to 1.00. Moreover, whenever different values are observed, overstated magnitudes become evident. The results have also shown that the difficulty of obtaining reduction factors increases when concerning $RF_{J_{2\%}}$.

The values of reduction factor related to tensile stiffness at 5 % ($RF_{J_{5\%}}$) varied from 1.41 to 1.66 for PET geogrid (35 kN/m) (Table 5), when tested with Aggregate B. Although the values of $RF_{J_{5\%}}$ had shown a direct relation to load, one must bear in mind that this case was not observed in most of the scenarios investigated. Unlike what was perceived in the values of stiffness at 2 % ($J_{2\%}$), those of stiffness at 5 % ($J_{5\%}$) did not present a high variability (COV up to 16.6 %). Therefore, $RF_{J_{5\%}}$ seems very reasonable.

Given that the majority of scenarios presenting values of RF greater than 1.00 were related to tests carried out with Aggregate B, it is possible to state that the characteristics of this material, correlated to i) the predominance of coarse particles (gravel, $D_{85} = 18$ mm, $D_{50} = 11$ mm, $D_{10} = 6.5$ mm), ii) poorly graded grain size distribution ($C_u = 1.85$), and iii) lower particle breakage occurrence, contributed to damage generation and its degree of severity. These characteristics create a condition with few points of contact between the aggregate (particles) and geogrid elements, causing a concentration of load and, as a consequence, more severe damages.

On the other hand, despite also presenting coarse particles (gravel with silt, $D_{85} = 12$ mm, $D_{50} = 7.5$ mm, $D_{10} = 0.22$ mm), Aggregate C, due to the content of coarse, medium and fine sands (total amount around 26 %), the considerable value of coefficient of uniformity ($C_u = 38.64$) and high particle breakage, was able to provide a condition of large particles surrounded by small ones, setting up better load transfer (large contact area) between its particles and the geogrids. This condition made Aggregate C (material produced from a mixture of three recycled materials) the least aggressive material, presenting only one scenario with RF greater than 1.0 (GGPAV, 150 kPa, $RF_{\epsilon_{rup}} = 1.18$). Moreover, this aggregate is the cheapest material produced by the recycling plant. Table 5 summarizes all the reduction factors obtained by the tensile test.

Table 5 - Reduction factors related to the investigated parameters.

Aggregate	$RF\varepsilon_{rup}^a$		$RF_{J2\%}^b$		$RF_{J5\%}^c$	
	GGPVA	GGPET 02	GGPVA	GGPET 02	GGPVA	GGPET 02
A-C	1.18 (150)	1.00 (150)	1.00 (150)	1.00 (150)	-	1.00 (150)
	1.00 (300)	1.00 (300)	1.00 (300)	1.00 (300)	-	1.00 (300)
	1.00 (600)	1.00 (600)	1.00 (600)	1.00 (600)	-	1.00 (600)
A-B	1.15 (150)	0.67 ^d (150)	1.00 (150)	1.00 (150)	-	1.41 (150)
	1.21 (300)	0.66 ^d (300)	0.87 ^d (300)	3.29 (300)	-	1.53 (300)
	1.00 (600)	0.61 ^d (600)	1.00 (600)	4.12 (600)	-	1.66 (600)
A-A	1.15 (150)	0.70 ^d (150)	1.00 (150)	1.00 (150)	-	1.00 (150)
	1.00 (300)	1.00 (300)	1.00 (300)	1.00 (300)	-	1.00 (300)
	1.21 (600)	0.66 ^d (600)	1.00 (600)	1.00 (600)	-	1.00 (600)

Note: ^aReduction factor related to the strain at failure; ^bReduction factor related to the secant tensile stiffness at 2 %; ^cReduction factor related to the secant tensile stiffness at 5 %; ^dThe adoption of reduction factor equal to 1.0 is recommended. Loads are presented between parentheses in kPa.

4. Conclusions

This paper reported on mechanical damage caused to geogrids by recycled construction and demolition wastes (RCDW) with different grain size distributions. Laboratory tests were carried out to apply loads simulating the field condition to the composite (geogrid + RCDW). Tensile tests were performed on damaged geogrid specimens, and the RCDW grain size distribution was evaluated before and after the loading application. The main conclusions obtained are presented below.

- (1) The geotechnical characterization revealed that the RCDW presented non-plastic and non-liquid behavior. Besides, according to USCS, these materials presented grain size distributions from clean gravel to gravel with few fines. The mean value of dry unit weight was equal to 16.859 kN/m³ and mean optimum water content was equal to 17.6 %, which showed that the content of ceramic materials is directly proportional to the optimum water content.
- (2) The grain size distribution curves of RCDW presented significant changes when subjected to different loading. No abrupt breakage of recycled aggregates subjected to loading was noticed, except for the removal of fines around the particles with loading. Thus, after application of the load, the material presented a smooth surface (less rough).
- (3) The analysis of grain roughness revealed that the particles larger than 9.5 mm were the ones most affected with the application of the load. The grain breakage can influence the mechanical and hydraulic properties of the materials.
- (4) The test simulating mechanical damage in geogrids revealed that: i) although the results presented some values of tensile strength outside the limits calculated based on virgin specimens, the mean values for all in-

vestigated scenarios were within the minimum and maximum limits; ii) the reduction factors related to the strain at rupture wound up being greater than those obtained for other analyzed parameters; iv) the GGPVA and GGPET 02 geogrids presented higher reduction factors related to strain at rupture and stiffness.

- (5) The damage caused by Aggregate B turned out to be more severe, given that this aggregate was the coarser one, presenting a poorly graded grain size distribution and revealing the lowest particle size variation (breakage) due to loading process. The aggregate mostly produced and sold by the recycling plant (Aggregate C), with the lowest selling price, was also the least aggressive material.
- (6) The values of RF calculated revealed the need for proper investigation when using RCDW as backfill material, which could enable them in the design phase. The authors believe the results presented may contribute to a better understanding of the processes involved in mechanical damage of polymeric reinforced elements, and to the goal of achieving positive economic, social and environmental benefits related to the use of recycled materials in geotechnical works.

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List of Symbols and Abbreviations

- ABNT: Brazilian Association of Technical Standards
 ASTM: American Society for Testing and Materials
 A-A: aggregate A ($9.5 \text{ mm} > d > 4.8 \text{ mm}$)
 A-B: aggregate B ($19 \text{ mm} > d > 9.5 \text{ mm}$)
 A-C: aggregate C ($d < 9.5 \text{ mm}$)
 CDW: Construction and Demolition Waste
 CL: confidence level (dimensionless)
 C_u : soil coefficient of uniformity ($C_u = D_{60}/D_{10}$)
 d: diameter of the particle (m)
 D_{10} : diameter of the particle for which 10 % of soil in mass is smaller (than that diameter)

D_{50} : diameter of the particle for which 50 % of soil in mass is smaller (than that diameter)

D_{85} : diameter of the particle for which 85 % of soil in mass is smaller (than that diameter)

EECA-UFG: School of Civil and Environmental Engineering of the Federal University of Goiás

EESC-USP: School of Engineering of São Carlos, University of São Paulo

F_0 : tensile strength of virgin samples

GRS: Geosynthetic Reinforced Soil

G_s : specific gravity (g/cm^3)

GGPVA: polyvinyl alcohol geogrid

GGPET 01: polyester geogrid with resistance of 55 kN/m

GGPET 02: polyester geogrid with resistance of 35 kN/m

J_{sec} : secant tensile stiffness

$J_{2\%}$: secant tensile stiffness at 2 % strain (N/m)

$\bar{J}_{2\%}$: secant tensile stiffness at 2 % strain mean value (N/m)

$J_{5\%}$: secant tensile stiffness at 5 % strain (N/m)

$\bar{J}_{5\%}$: secant tensile stiffness at 5 % strain mean value (N/m)

M_A : mass per unit area (g/m^2)

RCDW: Recycled Construction and Demolition Waste

RF : global reduction factor

RF_{CR} : creep reduction factor

RF_D : durability reduction factor

RF_{ID} : installation damage reduction factor

RF_{MD} : mechanical damage reduction factor

T_{al} : allowable tensile strength

T_{ult} : ultimate tensile strength

$\bar{T}_{ult}$: ultimate tensile strength mean value

$T_{ult,v}$: ultimate tensile strength mean value of virgin (undamaged) samples

$T_{ult,d}$: ultimate tensile strength mean value of damaged samples

w_{op} : optimum water content (%)

USCS: Unified Soil Classification System

ε_{rup} : strain or elongation at rupture mean value (dimensionless)

$\bar{\varepsilon}_{rup}$: strain or elongation at rupture mean value (dimensionless)