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Geogrid mechanical damage caused by recycled construction and demolition waste (RCDW) under in-field cyclic loading

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Article

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Abstract

Despite the advances observed over the last decade, Brazil still suffers from the scarce use of recycled construction and demolition waste (RCDW). On the other hand, most of the roads in the country are unpaved and present low loading support. In this context, the construction of geosynthetic reinforced unpaved roads with RCDW could stimulate the market of recycled materials and increase the performance of these roads. This study aims to evaluate the mechanical damage of two types of geogrids due to in-field cyclic loading of RCDW. The simulation of three scenarios of damage revealed specific reduction factors for each geogrid, which could be easily used in project design. This study reinforces the importance of carrying out investigation of geogrid damage using the specific conditions (material, construction method and loading) of each work. Based on these findings, sustainable development can be implemented using RCDW and provide roads to the society with better operational performance.

1. Introduction

The construction industry is vast and one of the most important industries worldwide due to its role in the growth of the national gross domestic product (GDP) of countries. However, despite being an important economic sector in Brazil, its activities are responsible for over 50% of waste generated in large Brazilian cities (Gusmão, 2008; John, 2000; Pinto, 1999). Nowadays construction and demolition waste (CDW) became a serious problem for the entire society.

A survey, which evaluated 310 recycling plants in Brazil, has shown they were operating at 47% of the maximum capacity, representing a potential to recycle only 16% of the total amount of CDW generated that year (Miranda, 2013). In addition to the low recycling capacity, the country suffers from the irregular dumping of these wastes. About 44.5 million tons of CDW were collected from public places in 2018, representing more than 61% of the total amount of waste collected by the municipal public services (ABRELPE, 2019).

CDW recycling appears as a very promising alternative, given that this waste mainly consists of materials (90% in mass) with the potential to be recycled for the production of new aggregates (Gusmão, 2008). Moreover, choosing materials that allow a simple treatment, such as recycled construction and demolition waste (RCDW), ensures low energy consumption and, as a consequence, low embodied energy. The recycling of CDW could recover from 37% to 42% of the embodied energy of a building (Thormark, 2002).

Bearing in mind that approximately 79% of the Brazilian roads are not paved (CNT, 2019), the proposal to use RCDW in geosynthetic reinforced unpaved roads would be an excellent option to demand great volumes of these materials, and therefore to increase the operational levels of the recycling plants and encourage the establishment of new ones. This could be a strategy to promote a vast market for recycled materials across the country and to preserve its natural resources.

Through laboratory tests, which simulated field conditions of reinforced unpaved roads, a combination of geogrid reinforcement and RCDW significantly increased the number of load repetitions sustained by the road, which could extend the life of the structure and reduce maintenance costs (Góngora & Palmeira, 2012). Large scale studies of unpaved roads (Fannin, 1986; Fannin & Sigurdsson, 1996; Watts et al., 2004; Hufenus et al., 2006; Palmeira & Antunes, 2010; Mekkawy et al., 2011) have shown the effectiveness of geogrid reinforcement related to the reduction of rutting

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formation, and consequently a better condition of supporting compared to non-reinforced roads.

However, geogrids may experience a reduction of their initial strength in both short- and long-term. The short-term effects are caused during the service strains due to the efforts from handling, installation and compaction (Hufenus et al., 2005). Long-term effects are not directly related to short-term effects, but geosynthetics that have suffered installation damage are more susceptible to long-term damage since they are unprotected, presenting higher reduction factors (Greenwood, 2002).

Reduction factor values for geogrid installation damage related to polymer type, protective coating and backfill material were published by Elias et al. (2001). Although important, these values have a relatively wide range. Laboratory and in-field studies have been performed aiming to define more specific reduction factors (Huang & Chiou, 2006; Huang & Wang, 2007; Pinho-Lopes & Lopes, 2014, 2015; Lim & McCartney, 2013). It was observed that they are directly related to the type of geosynthetics used, the nature of the polymer, compaction energy, and filling material.

Fleury et al. (2019) investigated the geogrid mechanical damage caused by RCDW due to installation procedures. The study revealed that, although the dropping heights reduced the tensile strengths, the compaction methods caused more severe damage. Similar results have been reported by Barbosa & Santos (2013) and Barbosa et al. (2016). However, the reduction factors presented by these studies encourage the use of RCDW in geosynthetic reinforced structures.

In a recent study, Domiciano et al. (2020) reported on short-term mechanical damage caused to geogrids by RCDW with different grain size distributions. Laboratory tests were carried out with a steel box and static loading within the magnitudes of values normally observed in the field conditions. The reduction factors calculated revealed the need for proper investigation when using RCDW as backfill material, which could enable them in the design phase.

In this context, given the variability of RCDW characteristics, the use of these materials could cause damage to the geogrids due to presence of coarse and/or angular grains, as well as perforating materials. The damage could also be influenced by the nature of loading processes. Thus, this study aims to investigate the mechanical damage of reinforcement elements when RCDW are used as backfill material and submitted to in-field cyclic loading.

2. Materials and methods

2.1 RCDW production

The RCDW used in this study was collected at a recycling plant located in Camaragibe, PE, Brazil. According to the operational manager, the RCDW is classified as ‘mixed material’, consisting predominantly of soil and, with a lower amount, concrete, ceramic and rock fragments. The recycling process consists of: i) visual inspection to verify if the CDW has up to 30% of contaminants (such as wood, plastic, paper, and metals); ii) if the contaminant limit is acceptable (< 30%), the CDW is crushed (jaw crusher) and sieved – the last of the contaminants are removed during sieving and the metallic elements are removed by a magnetic conveyor belt. The simplicity of this process ensures that production has low energy consumption, and therefore the recycled aggregate presents a low embodied energy.

2.2 Material characterization

To characterize the RCDW, samples were collected in two different periods. Firstly, five samples – codes RCDW 01 to 05 – were collected from March 29th to April 27th, 2016, in 7-day intervals in order to evaluate the mixed RCDW production process and property variability. Finally, two samples – codes RCDW 06 and RCDW 07 – were collected during the experimental section tests (September 6th, 2016). It is worth mentioning that RCDW was always collected from piles which contained the most recently produced materials. The samples were homogenized in the laboratory – according to ABNT (1986a) – and characterized following the procedures prescribed by Brazilian standards.

2.3 Geogrid

Two geogrids commercially used as reinforcement for paving were used in this study: i) uniaxial polyester (PET) geogrid coated with PVC (Figure 1a); and ii) flexible biaxial polypropylene (PP) geogrid (Figure 1b). Table 1 summarizes the main geogrid properties provided by the manufacturer. Specimens were cut according to the following dimensions: 200 mm width and 1,200 mm length, adopting the transversal machine direction for testing, once it would allow similar tensile strengths for both geogrids.

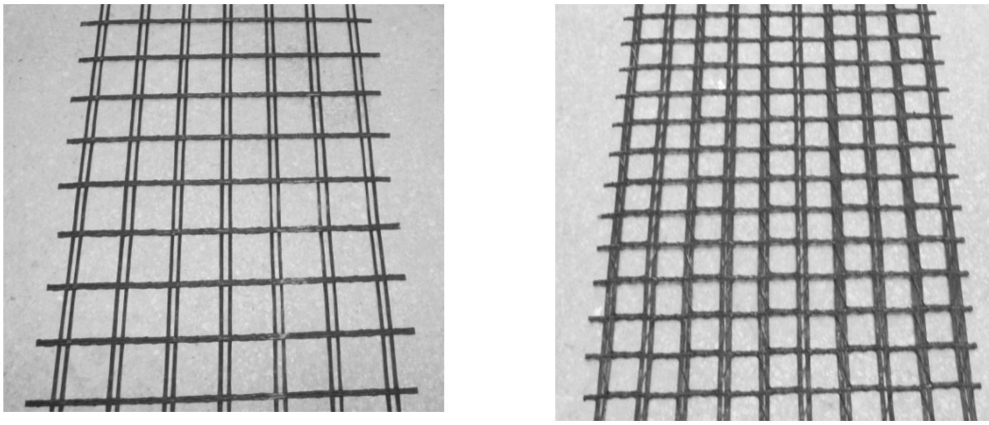
2.4 Description of the experimental section

To evaluate the mechanical damage caused by RCDW in the field, an experimental section of unpaved road (12.0 m long, 5.0 m wide and 0.30 m deep) was constructed in Camaragibe,

Table 1. Geogrid properties (provided by manufacturer).

Properties	PET Geogrid	PP Geogrid
MD ultimate tensile strength (kN/m)	≥ 35	≥ 15
CMD ultimate tensile strength (kN/m)	≥ 20	≥ 24
Stiffness at 5% strain along MD (kN/m)	350	400
Maximum tensile strain (%)	≤ 10	≤ 10
Aperture dimensions (mm)	25 x 25	15 x 15

Note: MD = machine direction; CMD = cross-machine direction.



(a) (b)

Figure 1. Visual aspect of virgin geogrid: (a) PET geogrid; (b) PP geogrid.

PE, Brazil. The section consisted of a natural soil subgrade under two structural layers consisting of RCDW: i) base course (100 mm) and ii) surface course (200 mm), exposed to wear. The thickness of the base course was chosen to simulate shallow repair of unpaved road. Between the RCDW layers, specimens of geogrid were installed.

The standard procedure for performing the in-field loading was as follows:

i) excavation of the experimental section (Figure 2a);
ii) subgrade compaction using a vibratory roller (1.2 ton) with previous soil wetting;
iii) launching and spreading the RCDW for base layer construction;
iv) compaction of the base course (100 mm thick) – vibratory roller (1.2 ton);
v) installation of geogrid specimens (Figure 2b);
vi) launching and spreading of RCDW to construct the surface course (Figure 2c);
vii) compaction of the surface course (200 mm thick) – with interest equipment (Figure 2d);
viii) checking in-field density (ABNT, 1986b); and
ix) exhumation of geogrid specimens.

2.5 Damage induced

Geogrid samples were submitted to three damage scenarios: i) installation damage due to compaction with vibratory hammer; ii) installation damage due to compaction using a vibratory roller; and iii) installation damage (vibratory roller) and cyclic loading caused by truck traffic. The compaction degree in the field was intended to be no less than 95% (standard Proctor). More details on the compaction equipment are presented in Table 2.

Five specimens were exhumed for each scenario. Tensile tests were performed according to ISO 10319 (ISO, 2008). The geogrid specimens (virgin and damaged) were tested at the Geosynthetics Laboratory at the São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil.

Table 2. Compaction equipment (provided by manufacturer).

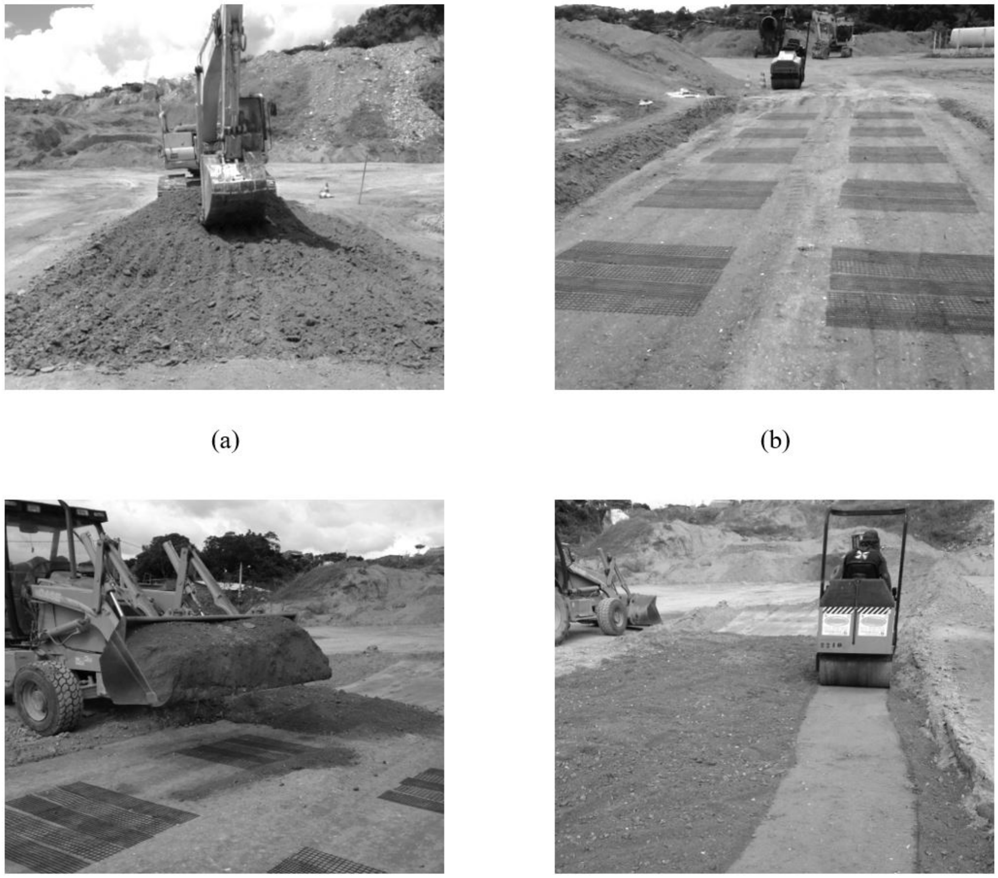
Equipment	Weight	Centrifugal force	Frequency	Compaction depth
	(tf)	(kN)	(Hz)	(mm)
Vibratory plate	0.12	20	98	Up to 300
Vibratory roller	1.2	15	68	150 to 300

To determine the occurrence of damage, the methodology proposed by Santos (2011), which determines a confidence interval by means of Student's *t*-distribution, was used for statistical inferences. The methodology consists of:

i) the determination of mean value of tensile strength of virgin (no damaged) specimens (F_0);
ii) the definition of confidence interval for F_0, which covers all the tensile strength values obtained from virgin specimens (Equation 1);
iii) the determination of mean values of tensile strength for each damage scenario (F_i);
iv) verification if F_i is contained in the confidence interval of F_0. Values of F_i within the confidence interval of F_0 would represent uncertainties about the repercussion of the damage for the adopted reliability and, in this case, value of reduction factor (*RF*) equal to 1.0 was assumed. If values of F_i are presented out of confidence interval of F_0, the *RF* is calculated according to Equation 2.

$$t = \frac{\bar{X} - \mu}{s/\sqrt{n}} \tag{1}$$

where t = Student's *t*-distribution random variable; $\bar{X}$ = sample mean; μ = population mean; s = standard value deviation; n = number of samples.



(a) (b) (c) (d)

Figure 2. Construction of experimental section: (a) base course excavation; (b) geogrid specimen disposition; (c) RCDW launching; (d) compaction of the surface course with vibratory roller.

$$RF = \frac{F_0}{F_i} \tag{2}$$

where RF = reduction factor; F_0 = tensile strength mean value of virgin specimens; F_i = tensile strength mean value of scenario i.

2.6 Cyclic loading effect

The destructive effects of load per axle or set of axles on pavements can be related to a certain number of passages (N) of a standard axle through the Load Equivalency Factor (LEF). Thus, studies conducted by the American Association of State Highway and Transportation Officials (AASHTO) Road Test, in the late 1950s, defined the standard axle as a single double-axle (SDA) with a load of 18,000 lb or 82 kN (8.2 tf) and 80 psi (552 kPa) tire inflation pressure (Albano, 2005). The equivalence factors adopted in Brazil by the National Department of Transport Infrastructure (DNIT, in Portuguese) through DNER PRO 159/85 (DNER, 1985) based on the general equation of behavior of AASHTO (1972) are presented in Table 3.

Table 3. LEF equations (DNER, 1985).

Axle	Equation (P in tf)	Source
SAAW	$LEF = \left(P/7.77\right)^{4.32}$	(GEIPOT, 1977)
SADW	$LEF = \left(P/8.17\right)^{4.32}$	(AASHTO, 1972)
DTA	$LEF = \left(P/15.08\right)^{4.14}$	(AASHTO, 1972)

In this study, the number of truck passages was obtained from the balance reports of the recycling plant. Each truck passed 2 (two) times through the experimental section; one empty (without CDW) and another loaded (with CDW). Two types of trucks have passed through the experimental section of unpaved road: (i) solo axle truck with simple wheel and solo axle truck with double wheels (SAAW + SADW); and (ii) solo axle truck with simple wheel and dual tandem axle (SAAW + DTA). The Vehicle Factors (VF) adopted in this study were: i) those defined by DNIT (2010), for empty trucks; and ii) the sum of the LEF values with maximum axle load established by Brazilian legislation (see Table 3), for loaded trucks. Table 4 presents a summary of the *VF*.

During the period of exposure to cyclic loading, 39 (SAAW + SADW) and 23 (SAAW + DTA) were recorded, which corresponds to 124 in total, given that each truck passed twice over the experimental section. The total sum of *VF* was 158.452. This means that the total amount of axle loads to which the experimental section was submitted has the same effect (damage) of approximately 158 passes of a standard axle (SADW) loaded with 18,000 lb or 82 kN (8.2 tf). Given that the geogrids were arranged in a way that the wheels of the trucks (left- or right-hand side) passed over the central part of the specimens, it can be considered that each specimen has received an estimated load equivalent to half of the total passes of the SADW, which represents a total number of approximately 79 cycles.

Figure 3a illustrates the traffic of trucks over the experimental section on the second day of cyclic loading (September 9th, 2016). The third day of cyclic loading (September 12th, 2016) was adversely affected by an intense rain precipitation that occurred during the weekend. According to Pernambuco State Agency for Water and Climate (APAC, in Portuguese), an average rain precipitation of 18 mm was recorded on the day before the cyclic loading. Due to the lack of drainage system at the recycling plant area, this precipitation was enough to keep the experimental area flooded during the whole precipitation period. Therefore, in order to prevent additional damage, 5 (five) specimens of each geogrid were exhumed before the recycling plant started its operation. After this, the traffic caused the section failure, which was characterized by the formation of grooves of 45 to 110 mm deep, as illustrated in Figure 3b. However, it should be mentioned that, in general, this level of rut depth would still be acceptable for unpaved roads.

Table 4. Vehicle factors according to DNIT (2010).

Composition	Vehicle factors (VF)	
	Empty	Loaded [1]
SAAW + SADW	0.103	2.722
SAAW + DTA	0.129	1.970

Note: [1] Sum of the LEF values with maximum axle load.

3. Results and discussion

3.1 Recycled CDW

The grain-size distribution curves of RCDW revealed a low variability for samples tested (Figure 4), with predominance of sand and gravel fractions (Table 5). The RCDW presented an average coefficient of uniformity (C_U) equal to 38.86, with coefficient of variation (*COV*) of 40.44%, and coefficient of curvature (C_C) equal to 1.73, with *COV* of 35.76%. The percentage of grains smaller than 0.42 mm was 40.49% (*COV* = 9.80%).

The RCDW also showed low variability for other geotechnical parameters investigated (Table 6), presenting non-expansive and non-plastic behavior (ABNT, 1984b). It is worth mentioning that the recycling plant carries out a standard process to produce recycled materials, with low energy incorporated, by means of a simple treatment (sorting and crushing). This guarantees a RCDW with low embodied energy.

3.2 Tensile tests

The confidence intervals obtained for the average strengths of virgin specimens presented confidence levels of 95%, for both geogrids, and values equal to:

Table 5. Granulometric composition of RCDW.

Classification	Mean (%)
Gravel	31.20
Coarse sand	17.32
Medium sand	23.65
Fine sand	15.39
Silt	3.24
Clay	9.21

(a)

(b)

Figure 3. Experimental section #2: (a) truck traffic; (b) formation of grooves after intense rain precipitation.

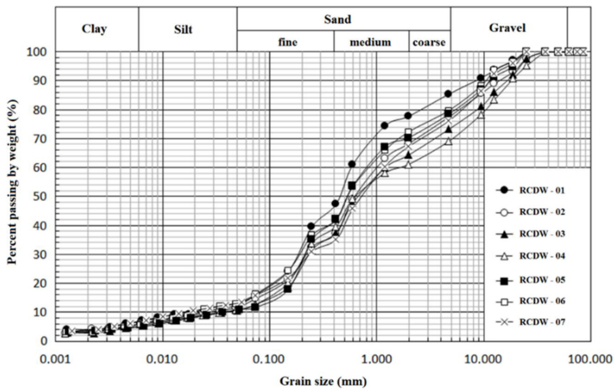


Figure 4. Grain-size distribution curves of RCDW – tested according to NBR 7181 (ABNT, 1984a).

PET geogrid: 16.85 kN/m < F_0 < 19.44 kN/m; and
PP geogrid: 22.82 kN/m < F_0 < 23.86 kN/m.

The *COV* of virgin samples were 5.7% and 1.8%, for PET and PP geogrids, respectively. These values were smaller in comparison to field-damaged geogrid samples – considering all the damage scenarios. The curves of load versus strain of tensile strength tests are shown in Figure 5. The comparative results of the geogrid properties after test with its respective *COV* (presented between parentheses) are shown in Table 7 and 8.

It was observed that the average values of maximum tensile strength (T_{max}) for damaged PET geogrid samples presented values outside the confidence interval of virgin samples, with a reduction factor (*RF*) higher than 1.0 for

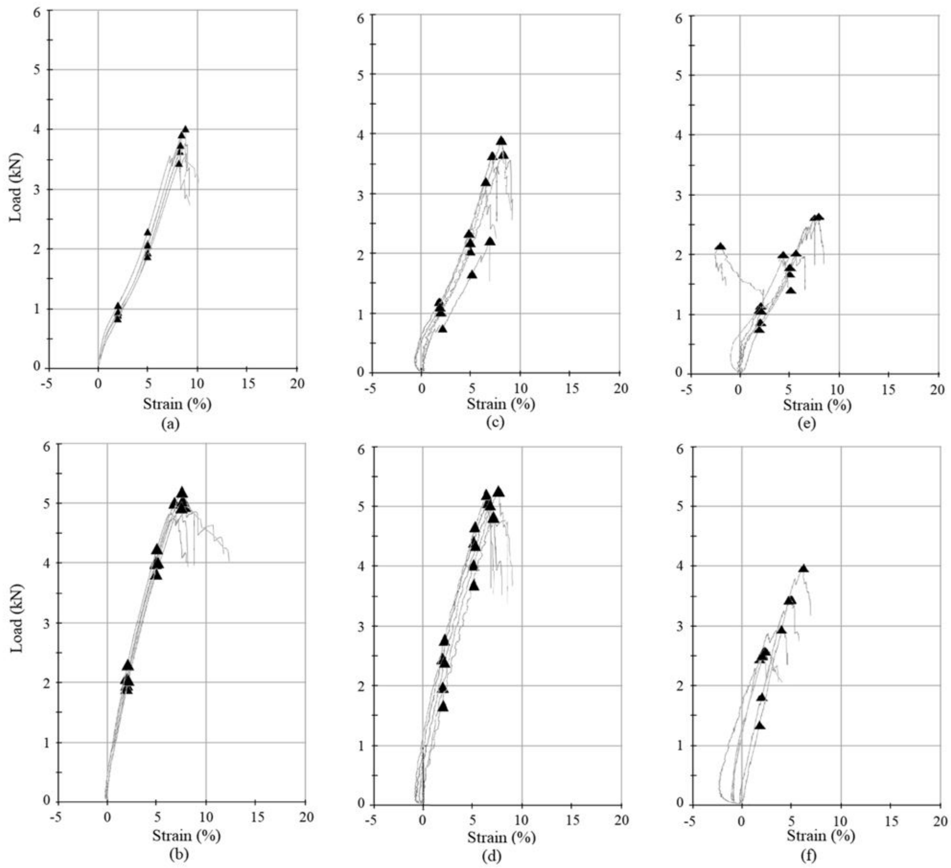


Figure 5. Load versus strain curve (width - 200mm): (a) PET geogrid - virgin; (b) PET geogrid - installation damage; (c) PET geogrid - Installation and loading damage; (d) PP virgin geogrid; (e) PP geogrid - Installation damage; (f) PP geogrid - Installation and loading damage.

Table 6. Summary of the laboratory and the in-field testing program of the RCDW.

	Percent of soil [1]	G_S [2]	$\gamma_{d\,max}$ [3]	w_{ot} [4]	*CBR* [5]	*w* [6]	γ [7]
	(%)		(kN/m³)	(%)	(%)	(%)	(kN/m³)
Mean	78	2.641	18.55	12.62	25	10.33*	18.20*
COV [8] (%)	6.20	3.35	1.39	6.09	24.99	2.28*	0.62*

Note: 1. RCDW smaller than 4.75 mm was classified as 'soil'; 2. Specific gravity (ABNT, 1984c); 3. Maximum dry unit weight (ABNT, 1986c); 4. Optimum water content (ABNT, 1986c); 5. California Bearing Ratio (ABNT, 1987); 6. Moisture content in the field by Speedy Moisture Test; 7. Density in the field after compaction (ABNT, 1986b); 8. Coefficient of variation; (*) Value obtained from 3 (three) tests.

Table 7. Results of PET geogrid.

Scenario	T_{max} (kN/m)	ε_{rup} (%)	$J_{2\%}$ (kN/m)	$J_{5\%}$ (kN/m)
Virgin specimen	18.15 (5.7)	8.38 (2.8)	227.5 (7.6)	199 (7.1)
Installation damage (VP)	14.73 (15.3)	6.96 (22.6)	224.0 (18.9)	185.6 (9.7)
Installation damage (VR)	16.2 (18.2)	7.5 (9.3)	249 (14.5)	205.4 (11.9)
Installation and loading damage (VR + TT)	11.38* (16.01)	6.23* (26.4)	234.0* (18.8)	163* (10.3)

Note: VP = vibratory plate; VR = vibratory roller; TT = truck traffic; (*) Except sample PET #01 (see Figure 5c).

Table 8. Results of PP geogrid.

Scenario	T_{max} (kN/m)	ε_{rup} (%)	$J_{2\%}$ (kN/m)	$J_{5\%}$ (kN/m)
Virgin specimen	23.34 (1.8)	7.56 (5.3)	479 (6.4)	316 (9.6)
Installation damage (VP)	15.16 (8.2)	6.6 (27.6)	292 (40.5)	226.6 (29.8)
Installation damage (VR)	23.08 (3.0)	6.7 (7.1)	515 (16.8)	384.4 (7.9)
Installation and loading damages (VR + TT)	14.16 (17.2)	4.06 (40.5)	486 (21.9)	313* (0.30)

Note: VP = vibratory plate; VR = vibratory roller; TT = truck traffic; (*) Except sample PET #01, #2 and #4 (see Figure 5f).

Table 9. Reduction factor (*RF*) for geogrids.

Scenario	PET	PP
Installation damage (VP)	1.23	1.54
Installation damage (VR)	1.12	1
Installation and loading damages (VR + TT)	1.44	1.65

both compaction methods (Table 9). It was observed that the compaction with vibratory plate causes more severe damage (*RF* = 1.23) compared to the vibratory roller (*RF* = 1.12). This finding becomes more evident analyzing the results of the PP geogrid, once only the compaction with vibratory plate caused damage to the geogrid (*RF* = 1.54) - the compaction using vibratory roller did not cause damage (*RF* = 1.0). This finding is in accordance with those presented by Fleury et al. (2019).

Geogrid samples that have been subjected to cyclic loading (79 cycles of standard axle) presented a great increment of damage in a short period of time (2 days). An increase of 28.5% has been observed for PET geogrid, which had the *RF* changed from 1.12 to 1.44 (see Table 9). More evidence of the cyclic effect on geogrid mechanical damage was verified for PP geogrid, which has exhibited an increase of 65%, with *RF* presenting a change from 1.0 (no damage) to 1.65. Regarding the conditions investigated in this study, PET geogrid samples were more resistant to damage induced by cyclic loading, with a strength loss of 29.7% in relation to samples damaged by the installation procedure, while the PP geogrid samples showed a loss of 38.6%.

4 Conclusions

This paper showed the effect of RCDW on the short-term mechanical behavior of two types of geogrids. In-field tests were carried out to evaluate the induced installation and cyclic loading damage on tensile strength of the geogrids. The conclusions of this study are presented as follows:

- The RCDW presented excellent values of geotechnical properties, with low variability and non-expansive and non-plastic behaviors, following the recommendations prescribed by the Brazilian standards for unpaved roads;
- The standard procedures adopted by the recycling plant revealed that it is possible to produce a recycled material with high quality and low embodied energy using simple treatments (sorting and crushing);
- The PP geogrid presented resistance to the induced installation procedure (no damage), while the PET geogrid presented loss of tensile strength of 20%;
- The cyclic loading damage was more severe to PP geogrid than PET geogrid, with reductions of tensile strength equal to 38.6% and 29.7%, respectively, compared to samples submitted only to installation damage; and
- This study reinforces the importance of carry out investigation of geogrid damage using the specific conditions (material, construction method and loading) of each work and the need of evaluating the occurrence of damage in short- and long-term.

In addition, the results presented are considered preliminary and further research is needed to better understand the factors affecting the performance of geogrids in unpaved roads constructed with alternative low-cost materials.

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Declaration of interest

The authors have no affiliation with or involvement in any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript that could bias its results. All co-authors have seen and agree with the contents of the manuscript and certify that it has not been submitted to, nor is under review at, another journal or other publishing venue.

Authors' contributions

Kátia R. M. Barbosa: methodology, investigation, validation, writing - original draft preparation. Eder C. G. Santos: conceptualization, methodology, supervision, validation, funding acquisition, writing - reviewing and editing. Alexandre D. Gusmão: funding acquisition, supervision, writing - reviewing and editing.

List of symbols

AASHTO	American Association of State Highway and Transportation Officials
ABNT	Brazilian Association of Technical Standards
ABRELPE	Brazilian Association of Urban Cleaning and Special Solid Waste Companies
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio (%)
CDW	Construction and demolition waste
C_C	Coefficient of curvature (dimensionless)
CNT	National Confederation of Transport
COV	Coefficient of variation (%)
C_U	Coefficient of uniformity (dimensionless)
DNER	National Department of Roads
DNIT	National Department of Transport Infrastructure
DTA	Dual tandem axle
FEC	Load equivalency factor (tf)
F_i	Tensile strength mean value of scenario i (kN/m)
F_0	Tensile strength mean value of virgin specimens (kN/m)
G_S	Specific gravity (dimensionless)
$J_{2\%}$	Secant tensile stiffness at 2% strain (kN/m)
$J_{5\%}$	Secant tensile stiffness at 5% strain (kN/m)
n	Number of samples (dimensionless)
N	Number of passages of a standard axle (dimensionless)
NBR	Brazilian Standard
P	Weight (tf)
PET	Polyester
PP	Polypropylene
PVC	Polyvinyl chloride
RCDW	Recycled construction and demolition waste
RF	Reduction factor (dimensionless)
s	Standard value deviation (parameter dependent)
SAAW	Solo axle truck with simple wheel
SADW	Solo axle truck with double wheels
SDA	Single double-axle
t	Student's t-distribution random variable (dimensionless)
T_{max}	Tensile strength at rupture (kN/m)
TT	Truck traffic
$\overline{X}$	Sample mean (parameter dependent)
VF	Vehicle Factor (dimensionless)
VP	Vibratory plate
VR	Vibratory roller
w_{ot}	Optimum water content (%)
ε_{rup}	Strain or elongation at rupture mean value (%)
$\gamma_{d\,max}$	Maximum dry unit weight (kN/m^3)
μ	Population mean (parameter dependent)

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