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Pull-out response of a geogrid buried in recycled sands

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Article

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Abstract

Recycled construction and demolition waste (RCDW) has demonstrated geotechnical properties that encourage it to be used in reinforced soil structures (RSS) with geosynthetics. However, the interaction between RCDW and reinforcements needs to be better understood, given its importance for design. This paper presents a qualitative study on the interaction between geogrid and recycled sands by means of pull-out tests performed on small equipment. Tests with the same degree of compaction and a geogrid buried in different types of recycled and natural sands (for comparison purposes) were performed. The characterisation of the materials was carried out in the laboratory and the variability of their geotechnical properties was evaluated. In addition, fill material moisture content was investigated as another potential factor influencing soil-geogrid interface shear. The results of the pull-out tests demonstrated the specific influences of the factors investigated. The comparative study showed that recycled sands can be suitable materials to be used as backfill in geosynthetic reinforced soil structures, meeting physical, mechanical and environmental requirements for this kind of work.

1. Introduction

Global development and the consequent demand for services and goods from the construction industry have caused an increase in the volume of so-called ‘construction and demolition waste (CDW)’. It is estimated that 10 billion tons of CDW are generated annually in the world and most of this waste has recycling potential (Wu et al., 2019). According to Peng et al. (1997), recycling these materials leads to a new possibility for the input market, and is an environmentally friendly alternative for the inadequate disposal of CDW. Therefore, CDW can be reintroduced into the geotechnical construction works.

Geosynthetics are products whose applications have not only entered the market in various sectors of the construction industry, because of their well-defined properties, but have also exceeded conventional products. The economic and environmental benefits have led to an increasing use of geosynthetics in geotechnical works (Koerner, 1990). Reduced energy consumption, low transportation costs and lower environmental impacts are some ecologically positive factors when comparing the use of these materials with the traditional ones found in retaining structures (Jones, 1994; Stucki et al., 2011; Heerten, 2012; Damians et al., 2016).

In most cases, soil-inclusion interaction can be pointed out as the main factor for the adequate performance of reinforced soil structures (RSS) because these materials show complementary behaviour. Bearing in mind that the use of recycled construction and demolition waste (RCDW) in RSS seems to be an interesting strategy to promote the concept of sustainability in the construction industry, it is essential to examine the characteristics of this non-conventional material and its interaction, under field and laboratory conditions, with geosynthetics.

1.1 Characteristics of RCDW used in geotechnical works

CDW is made up of different types of materials that are part of the building or infrastructure during construction, reconstruction, extension, alteration, maintenance, and demolition, which is the result of different activities and techniques in the construction industry (Kartam et al., 2004; Esin & Cosgun, 2007; Wang et al., 2010; Vieira & Pereira, 2015; Di Maria et al., 2018; Rosado et al., 2019). It is worth mentioning that currently CDW does not have a consensus about its definition, varying from country to country (Domiciano et al., 2020). However, despite the heterogeneity of CDW, it can be observed that they mainly consist of crushed concrete, bricks, tiles, pieces of wood, glass, plastic, metal, and cardboard (Huang et al., 2002; Lai et al., 2016; Asgari et al., 2017; Di Maria et al., 2018).

The physical properties of RCDW depend mainly on their composition (Ossa et al., 2016), thus the composition of

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CDW is decisive for the properties of the former. Materials derived from the incorporation of ceramic or asphalt materials usually present lower density, resistance to fragmentation and load capacity, given that they have a larger number of pores compared to those derived solely from Portland cement (Nagataki et al., 2004; Brito et al., 2005; Silva et al., 2014). The issues surrounding RCDW are not only related to environmental aspects, but also to the mechanical properties that control their stiffness and resistance to permanent deformation (Niekerk et al., 2002).

Concerning the particle size distribution of the RCDW investigated for geotechnical purposes, it can be observed that there is a wide range of grain sizes. The variability of particle size distribution is usually affected by the techniques adopted at the recycling plant, such as crusher equipment, a set of sieves, and process quantity control (Nagataki et al., 2004; Brito et al., 2005). Some studies revealed that RCDW collected at a recycling plant presented acceptable variabilities for geotechnical purposes, enabling their application in reinforced soil structures (RSS) (Santos & Vilar, 2008; Santos et al., 2010, 2013, 2014; Fleury et al., 2019). In addition, some characteristics encourage the use of RCDW in RSS: the specific gravity seemed similar to those found for soil, and non-plastic behaviour is highly recommended by some international standards (Santos and Vilar, 2008; Fleury et al., 2019; Domiciano et al., 2020).

1.2 RCDW pull-out tests

According to Koerner (1990), reinforcing the soil with geosynthetics has become increasingly attractive and allows safer, more economical and audacious construction works. The strain responses of the structures, as well as the redistribution of stresses, depend on the shear strength properties of the soil, tensile properties of the inclusions, and the mechanism of stress transfer between soil and inclusions (Jewell et al., 1984; Palmeira, 1987; Gilbert et al., 1992; Teixeira et al., 2007).

Great efforts have been made in recent decades to understand the behaviour of RSS, and research has been conducted to investigate several aspects: i) performance against earthquake (Liu et al., 2014); ii) the influence of soil wetting (Chen and Wu, 2012; Balakrishnan & Viswanadham, 2016) and iii) different faces (Rowshanzamir & Aghayarzadeh, 2015). Studies involving the geosynthetic-RCDW interaction mechanism are quite scarce. The study carried out by Santos et al. (2010, 2013, 2014) investigated the use of RCDW as backfill material in two 3.6 m-high RSS. The authors pointed out that the performance and deformations of the wall, the durability of the reinforcement and the forces in the reinforcement were satisfactory and similar to the performance of comparable structures built with conventional granular embankments.

Designs or analysis parameters of RSS can be obtained by pull-out tests, thus determining the geogrid-soil interaction, which is the combination of frictional interaction and passive strength of the cross members happening simultaneously (Palmeira, 1987, 2004, 2009). Research has been conducted in different conditions to obtain these parameters: laboratory tests and in-field. Investigations in the laboratory are normally carried out with soils and geosynthetics in rigid metal boxes built with rectangular cross-sections and classified according to their size: i) large scale (Palmeira, 1987; Christopher and Berg, 1990; Farrag et al., 1993; Lopes & Ladeira, 1996; Palmeira, 2004, Teixeira et al., 2007; Chen & Wu, 2012; Sadat Taghavi & Mosallanezhad, 2017, for instance); and ii) small scale (Nakamura et al., 2003; Hataf & Sadr, 2014; Portelinha et al., 2018, for instance).

In a small-scale box, the short length of the testing sample and the difficulty of installing accessories, such as sleeves to reduce the effects of stress developed on the wall internal frontal face, can significantly increase the measured pulling force due to the increase in the normal stress on the geogrid surface (Farrag et al., 1993). In addition, experimental results have shown that boundaries above and below the reinforcement can lead to increases in the normal stress in the vicinity of the geogrid surface, especially when the soil thickness is small and the soil dilatancy restrained (Farrag et al., 1993; Palmeira, 2004). Although a large-scale box is preferable due to the fact of low boundary condition effects, a small-scale box may be used to perform initial studies, mainly on a qualitative basis, on the interaction that occurs between the fill material and the geogrid when subjected to pull-out.

Laboratory pull-out tests have already been carried out aiming to analyse several influence factors on the strength parameters: i) system of confinement stress application (Palmeira & Milligan, 1989); ii) condition of the frontal face (Palmeira, 1987, 2004, 2009; Raju, 1995; Sugimoto et al., 2001); iii) soil moisture content (Portelinha et al., 2018); iv) stiffness of the testing box walls (Farrag et al., 1993); v) grain size, geogrid aperture size and element thickness (Jewell et al., 1984; Palmeira 2004, 2009); and others. However, there are few studies on pull-out tests using RCDW as fill material (Santos, 2007; Santos & Vilar, 2008; Vieira et al., 2016; Araújo Neto, 2017, for instance). Therefore, this fact highlights the importance of determining interaction parameters when using such unconventional backfill material in RSS.

2. Materials and methods

2.1 Materials

2.1.1 Granular materials

The RCDW used in the tests was provided by a recycling plant located at Aparecida de Goiânia-GO, Brazil. The RCDW is named by the company as “grey recycled sand” (GRS). This material (GRS) is obtained from the crushing (jaw crusher) and sieving processes of CDW predominantly comprised of concrete blocks.

For the sake of comparison, another fill material was used in the pull-out tests, namely natural sand (NS) – material in accordance with the international standard recommendations for RSS works – which was purchased from a local supplier. In addition, a material produced in the laboratory, from sieving the GRS sample, was investigated. This material was called 'produced grey recycled sand' (PGRS). It should be noted that PGRS was produced to present its particle size distribution to be as similar as possible to that of NS.

2.1.2 Geogrid

A polyester geogrid with high tenacity and low creep susceptibility, with a protective polymeric coating, was tested. Geogrid samples of the same length (1,200 mm) and width (200 mm). Figure 1 shows an image of the geogrid. Table 1 shows some properties of the geogrid tested.

2.2 Experimental program

2.2.1 Materials characterisation

To verify possible variability of RCDW, five samples were collected, and the sampling procedure was carried out in different parts of the waste pile (bottom, middle and top) following the Brazilian Standard ABNT NBR 10007 (ABNT, 2004). An additional collection was made to investigate geotechnical properties and carry out the pull-out tests. The laboratory tests consisted of i) specific gravity, ii) grain-size distribution iii) Atterberg limits, iv) compaction test (standard Proctor), and v) maximum and minimum void ratios.

Direct shear tests were performed for different values of normal stresses: 50 kPa, 100 kPa, 150 kPa, and 200 kPa. The tests were performed using equipment with box dimensions equal to 60.00 mm (length) × 60.10 mm (width) × 19.68 mm (height). Samples were tested at optimum (w_{op}) and hygroscopic (w) moisture contents, and both conditions had a degree of compaction (*DC*) of 90%.

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) tests were conducted with JSM-7100 F equipment (JEOL Ltd.) on the NS and GRS samples.

Table 1. Geogrid properties (provided by the manufacturer).

Property	Value
Polymer	Polyester
Aperture size (mm × mm)	20 × 25
Ultimate tensile strength (kN/m)	35
Strain at rupture (%)	< 10
Secant stiffness at 5% strain (kN/m)	≥ 350

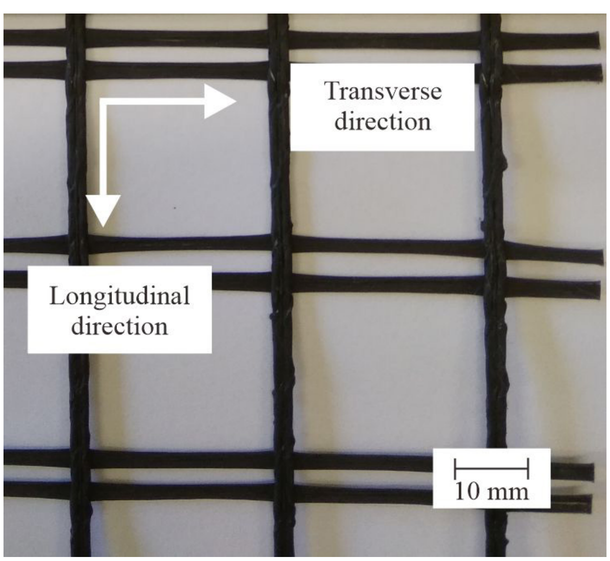


Figure 1. Geogrid.

2.2.2 Laboratory pull-out test

The equipment (small scale) consists of a test box built with 3 mm-thick steel plates. It is 250 mm long, 300 mm wide and 150 mm high, resulting in a volume of approximately 0.01 m^3. The box has a 10 mm-high opening along its entire width on the frontal wall, through which the geosynthetic material is pulled out. The normal confinement pressure is applied by a pressurised rubber bag attached to the lid of the box. Figure 2 shows the equipment dimensions.

The granular materials were air-dried and sieved (aperture mesh of 4.8 mm) before being used. The NS was tested after being air-dried. The GRS and PGRS were tested in two moisture content conditions: i) at hygroscopic moisture; ii) at optimum water content. The compaction was performed in four layers by depositing the materials to obtain the compaction degree of 90% as this was the value obtained by Fleury et al. (2019) when investigating the use of RCDW as backfill material. A total pressure cell (TPC) was installed at the top of the second layer – in the centre of the box and 10 mm below the reinforcement – to monitor the internal stress development during the tests. The pull-out force was applied using a universal test machine with 300 kN capacity. All tests were carried out at the same speed of 4.6 mm/min, consistent with the displacement rate adopted by Teixeira et al. (2007). Figure 3 shows the testing setup.

The variable used for the pull-out test analyses consisted of the: i) filler material (recycled sands or natural sand); and ii) moisture content (hygroscopic moisture and optimum water content). All test scenarios were subjected to the following normal confinement pressure: 12.5 kPa, 25 kPa, 37.5 kPa, 50 kPa, 75 kPa, and 100 kPa.

The authors acknowledge that the size of the equipment (0.01125 m^3) is rather small compared to others in the literature (e.g. 0.03675 m^3, Hataf & Sadr, 2014; 1.224 m^3,

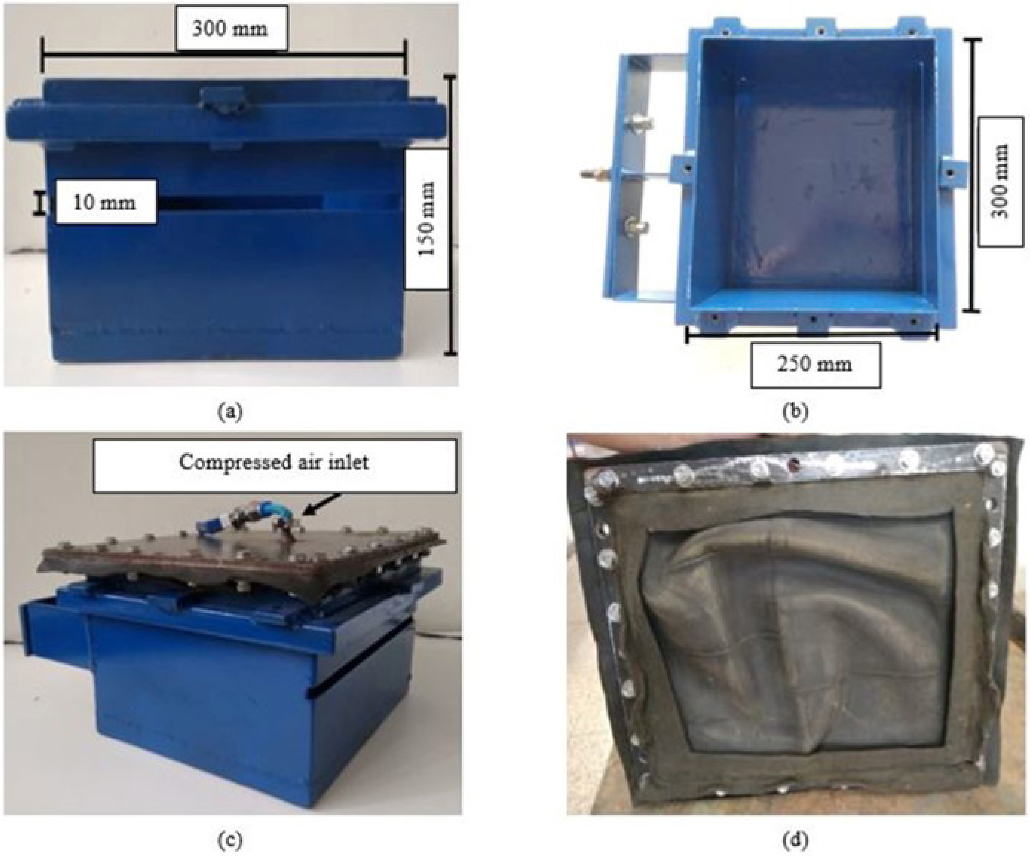
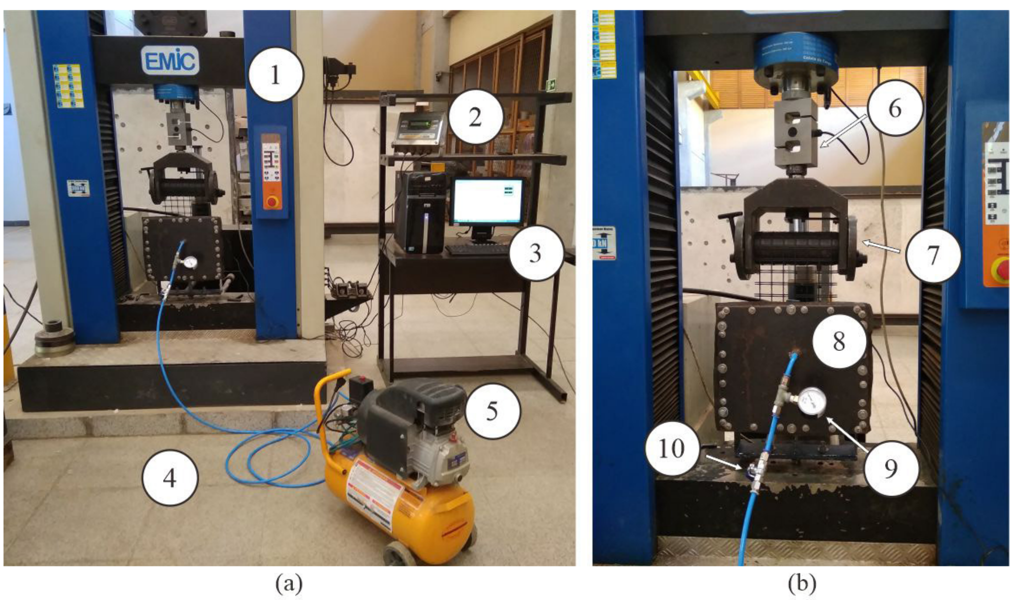


Figure 2. Pull-out box: (a) Front view; (b) Top view; (c) Perspective view of the closed box; and (d) Rubber bag attached to the box cover.



Legend:	1 - Universal test machine	2 - Total pressure cell monitor
3 - Computer	4 - Compressed air hose	5 - Air compressor
6 - Load pressure cell	7 - Roller clamp	8 - Pull-out test box
9 - Manometer	10 - Compressed air valve	

Figure 3. Pull-out test setup: (a) general view and (b) detailed view.

Lopes & Ladeira, 1996). Thus, some effects of boundaries would be expected. The internal frontal face of the box was covered by plastic layers and grease to minimise friction along that boundary. However, the main aim of the research was to validate the use of RCDW as fill material under similar conditions to other materials recommended and commonly used in practice. Therefore, the results must be seen as index and qualitative values, aiming to investigate the potential for using alternative fill materials as substitutes for conventional ones. In this type of investigation, using small equipment brings versatility and allows the execution of a large number of tests in less time, which is interesting for comparing different fill materials.

3. Analysis and results

3.1 Geotechnical analyses of granular materials

The GRS samples presented an average specific gravity (G_s) of 2.706, with a coefficient of variation (CV) of 0.28%. The NS and PGRS samples showed similar values of G_s equal to 2.713 and 2.710, respectively. Low variability value for G_s of RCDW collected at the same recycling plant was found by Fleury et al. (2019). The original features of CDW, such as material quality and particle sizes, and recycling procedures are factors that affect the G_s of RCDW aggregates (Silva et al., 2014). It is worth mentioning that the GRS presented the average G_s inside the range found for the local soil (tropical soil): from 2.664 (Silva et al., 2019) to 2.740 (Mascarenha et al., 2018).

An analysis of the grain size distribution of the GRS samples showed a low variability. However, sample GRS-06 presented a grain size distribution distinct from the other ones. This fact can be explained due to changes adopted by the company in the recycling process. In addition, changes in the shape of the curves have been reported due to the variability of materials found in the samples of other recycled aggregates from the same recycling plant (Fleury et al., 2019). The PGRS grain size distribution curve revealed that the attempt to construct it was successful, presenting a curve similar to the one of NS.

An analysis of the grain size distribution of GRS revealed that the GRS-06 sample was the one that best matched the specifications of standard BS 8006 (BSI, 2010), and manuals FHWA (2010) and NCMA (2010) for the selection of backfill material in RSS. Considering FHWA (2010) recommendations, it was observed that some granulometric corrections would be needed for the complete adjustment of the GRS material (Figure 4). The upper part of the GRS grain size distribution curves (defined by the grains greater than 0.3 mm) should be corrected to be within the limits recommended by all the mentioned standards.

It was also observed that the NS and PGRS samples presented curves that were within the range recommended by BS 8006 (BSI, 2010), but some granulometric corrections related to particles greater than 0.4 mm would be needed to attend the limits stated in FHWA (2010) and NCMA (2010) manuals, as can be seen in Figure 4. Table 2 presents the main properties of the fill materials.

In general, the SEM images revealed that both materials (GRS and NS) have grains with angular shapes and rough surfaces (Figure 5). Although the presence of cementitious material is verified on the surface of GRS grains, the effects of such an occurrence are not the focus of this study. Energy-dispersive X-ray spectroscopy (EDS) tests for the same granulometric ranges identified the material composition of the GRS and NS samples (Figure 6). The EDS tests

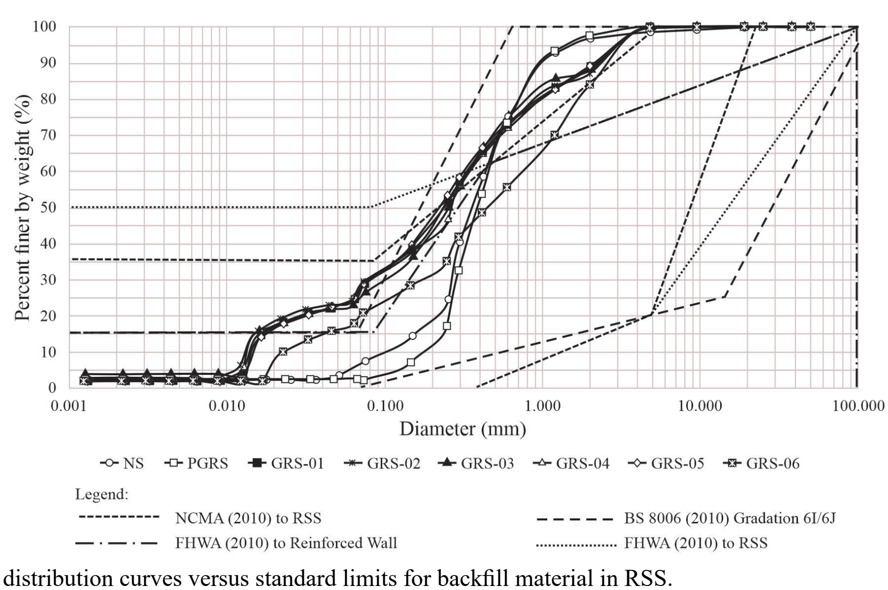


Figure 4. Grain size distribution curves versus standard limits for backfill material in RSS.

Table 2. Geotechnical properties of fill materials.

Parameter	Average Value		
	NS	GRS	PGRS
Specific gravity of the particles, *Gs*	2.71	2.71	2.71
D_{50} (mm)	0.34	0.28	0.28
D_{85} (mm)	0.84	1.36	0.84
C_C	1.61	1.42	3.81
C_U	4.20	24.07	13.60
e_{max}	0.87	1.06	0.98
e_{min}	0.58	0.69	0.64
Maximum dry unit weight, γ_{dMax} (kN/m^3)	n.a.	16.31	16.15
Optimum water content, w_{op}, (%)	n.a.	19.48	20.00
c (kPa) - w_{op}	n.a.	7.30	24.80
ϕ (degrees) - w_{op}	n.a.	37.90	41.00
c (kPa) - hygroscopic moisture	2.6	2.40	0.00
ϕ (degrees) - hygroscopic moisture	39.4	44.10	46.40

Note: NS = natural sand; GRS = grey recycled sand; PGRS = produced grey recycled sand; n.a. = not available.

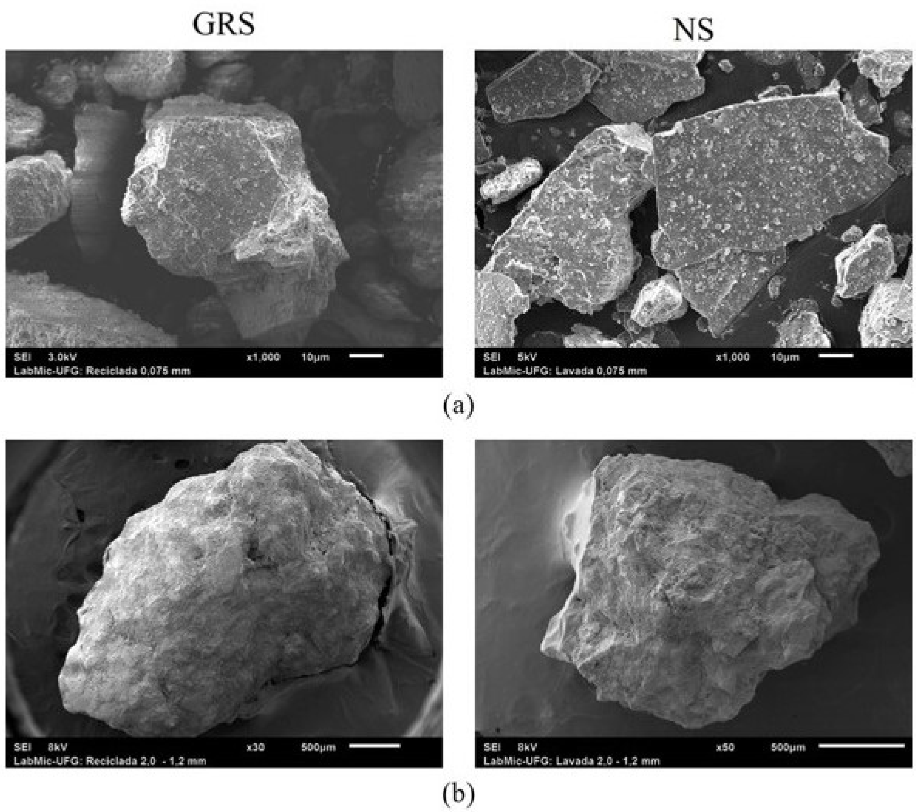


Figure 5. SEM images of GRS and NS samples of different granulometric size ranges (a) $D < 0.075$ mm; (b) 1.2 mm $< D <$ 2.0 mm.

performed at the GRS samples identified the predominant presence of silica (SiO_2, quartz), calcium oxide (CaO), alumina (Al_2O_3), ferrous oxide (Fe_2O_3), potassium oxide (K_2O) and magnesium oxide (MgO). The fact that GRS consists of Portland concrete and mortar justifies the presence of calcium. Studies on concrete-made aggregates revealed higher content of SiO_2, Al_2O_3, and CaO (Angulo et al., 2009; Medina et al., 2014; Oliveira et al., 2020). The EDS tests on the NS particles revealed a predominance of silicon (Si) and aluminium (Al) components of silica (SiO_2, quartz), which is consistent with the typical mineralogical composition of local natural sands (Figure 6).

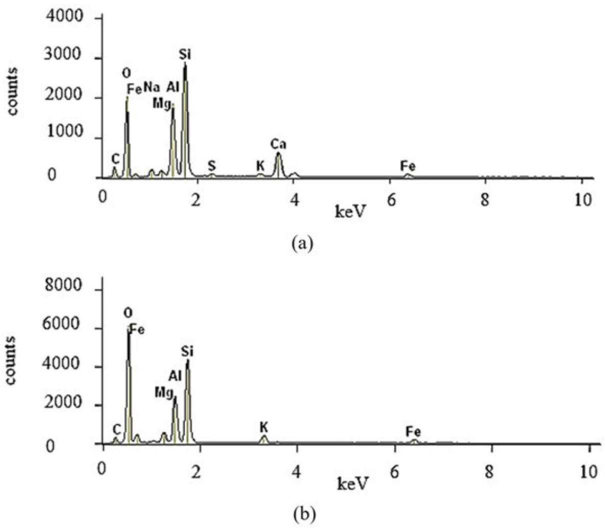


Figure 6. EDS results for fill material particles (2.00 mm < D < 4.80 mm): (a) GRS and (b) NS.

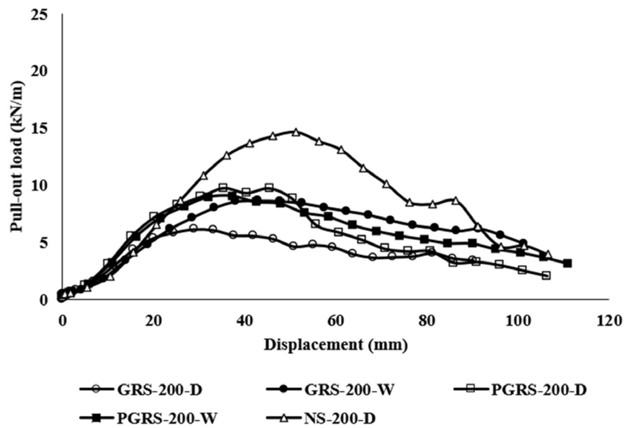


Figure 7. Pull-out test with normal stress of 12.5 kPa. Note: GRS = grey recycled sand; PGRS = produced grey recycled sand; NS = natural sand; 200 = two-hundred-millimetre width of the geogrid sample; W = optimum moisture; D = hygroscopic moisture.

3.1.1 Analysis of pull-out force versus pull-out displacement

Materials tested with different moisture contents (dry or wet) and the same compaction degree (90%) allowed the geogrid pull-out at low values of normal confinement pressure (from 12.5 kPa to 37.5 kPa). There was a rupture of the fill material and greater mobilisation of the transverse elements nearest to the point of load application (box frontal opening), a characteristic behaviour of reinforcements with low tensile stiffness. At these low confinement stresses (from 12.5 kPa to 37.5 kPa), all materials presented curves with typical behaviour, in which the applied force values increased until reaching a peak followed by a decrease in the value of the pull-out force (Figure 7).

Geogrids buried in NS experienced more damage during the pull-out tests than those buried in recycled sands. The exhumation of the geogrid tested with NS (Figure 8a) revealed great mobilisation of longitudinal elements located at the lateral edges of the specimen and some damage to the transverse elements (at some junctions, these elements were completely separated from the longitudinal members).

Results of the tests performed with normal confinement pressure equal to 50 kPa showed steeper curves compared to the curves of the tests with lower normal stress (Figure 9). A small portion of the specimen was mobilised, where the geogrid elements presented deformation – only at the external portion of the box. Thus, rupture occurred by an isolated tensile mechanism, in which the testing box worked as a clamp. Mobilisation of a few points of the buried portion of the specimen was observed in tests with NS, in which most elements remained intact (Figure 10a), which was the opposite behaviour compared to the test with normal confinement pressure equal to 12.5 kPa). Further studies on the geogrid damage during the pull-out tests are required.

Tests with normal confinement pressure equal to 75 kPa and 100 kPa showed no mobilisation of the specimens in their buried portions. Thus, the geogrid pull-out mechanism was not observed for all fill material types and test configurations. The rupture of the geogrid occurred in which the testing box worked as a clamp.

It was found that increasing the normal stress value and the value of the pull-out force caused an increase in the stiffness of the soil-geogrid system. This fact was previously verified in other studies (Alfaro et al., 1995; Ochiai et al., 1996, for instance).

The geogrid tensile strength values obtained from those tests with high normal confinement pressure (75 kPa and 100 kPa) were lower than the nominal reference value provided by the manufacturer. This may be due to the fact that the geogrid elements experienced some localized damage during such tests, as it was observed that the material confinement worked as a jaw-type clamp. This probably generated a concentration of stresses in some regions of the geogrid, causing early failure of the elements in such regions.

Figure 11 shows the pull-out resistance envelopes for all tests performed using 200 mm-wide geogrids. It was observed that the highest pull-out resistances increased with the applied normal confinement pressure in those scenarios where the geogrid pull-out mechanism occurred. The stabilisation, observed for the highest normal confinement pressures, revealed that the geogrids were submitted to a condition similar to that of a conventional tensile test in isolation. Test results carried out with NS presented a higher value of pull-out resistance, even for the lowest normal confinement pressure. Regarding the performance of all the fill materials, three distinguished patterns were observed: i) pull-out without detachment of elements, ii) partial deformation zone with displacement of

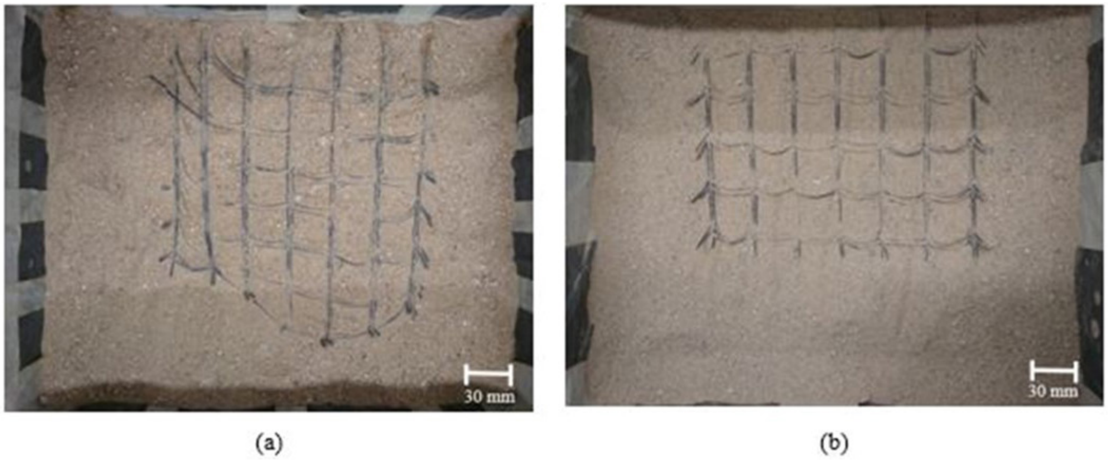


Figure 8. Exhumation of the geogrids used in the pull-out test (σ = 12.5 kPa): (a) NS and (b) PGRS-200-D.

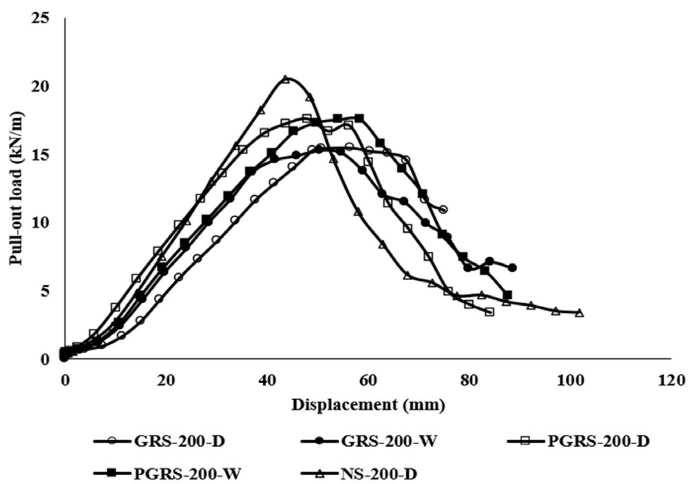


Figure 9. Pull-out test with normal stress equal to 50 kPa. Note: GRS = grey recycled sand; PGRS = produced grey recycled sand; NS = natural sand; 200 = two-hundred-millimetre width of the geogrid sample; W = optimum moisture; D = hygroscopic moisture.

Figure 10. Exhumation of the geogrids used in the pull-out test (*σ* = 50 kPa): (a) NS and (b) GRS-200-D.

the geogrids and detachment of their elements and iii) no pull-out, with damage to the geogrid elements near the external frontal face of the box. The investigated materials revealed the pull-out mechanism for different normal confinement pressure ranges, where the recycled sands (limits defined by the black dashed lines) presented a wide range compared to natural sand (limits defined by grey dashed-dotted lines).

3.1.2 Interface strength coefficient analysis

Tests revealed a tendency for the interface resistance coefficient values (*f*) to stabilise as the normal confinement pressure value increases (Figure 12), particularly under large confining stresses when tensile failure of the reinforcement prevails. This tendency was observed in other studies (Lopes & Ladeira, 1996). When testing the extensible geogrid, higher tangential stresses are generated along the soil-geogrid interface near the point of application of the pull-out force, and lesser mobilisation of these stresses occurs at the back of the reinforcement.

For normal confinement pressure below 37.5 kPa – at this value, the geogrid elements were detached – different values of *f* were found for the investigated materials. For higher normal confinement pressures, there was a tendency for the values of *f* to come closer because of tensile failure of the reinforcement. For normal confinement pressure equal to 100 kPa, they were practically the same regardless of the material and the moisture condition – at this normal confinement pressure, the rupture of the geogrid was observed. When reinforcement pull-out prevailed, higher values of interaction coefficients were obtained in tests with NS compared to those obtained with recycled sands, and this was observed mainly for the lower values of normal confinement pressure (Figure 12).

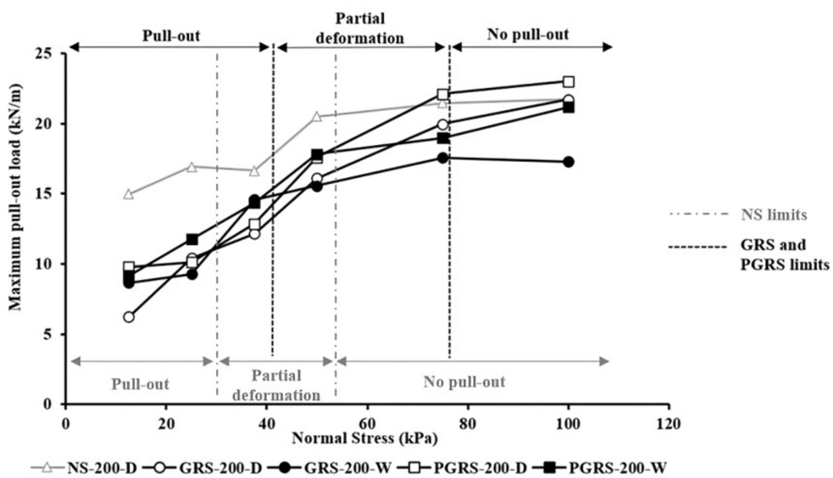


Figure 11. Soil-inclusion interface resistance envelope (pull-out tests performed using 200 mm-wide geogrid samples) and pull-out mechanism limits.

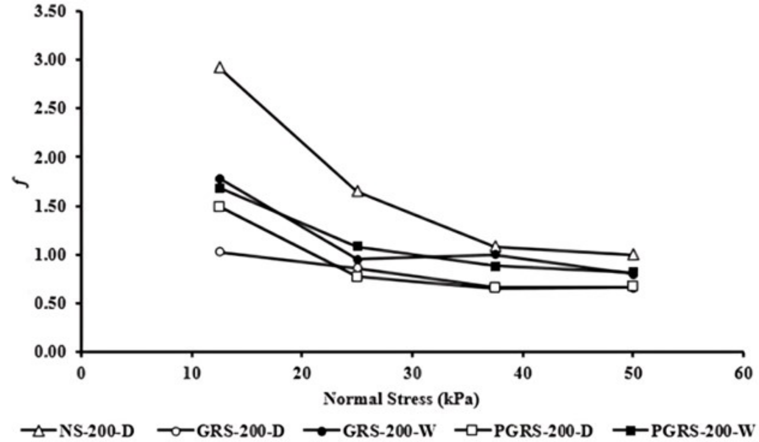


Figure 12. Variation of the interface coefficient (*f*) with normal confinement pressure. Where: $f = (\tau)/(\sigma_n.\text{tg}\phi)$; τ = tangential stress on the interface; σ_n = normal stress on the interface; ϕ = internal friction angle of the soil.

Table 3. Strength parameters for the tests with waste varying in moisture content.

Material	ϕ (degrees)	c (kPa)	δ (degrees)	a (kPa)
GRS-200-D	44	2.40	45	13.50
GRS-200-W	38	7.32	40	21.97
PGRS-200-D	46	0.00	40	24.22
PGRS-200-W	41	24.81	42	24.48

Note: GRS = grey recycled sand; PGRS = produced grey recycled sand; 200 = two-hundred-millimetre width of the geogrid sample; W = optimum moisture; D = hygroscopic moisture; ϕ = internal friction angle of the soil; c = cohesion; δ = interface friction angle; a = adhesion.

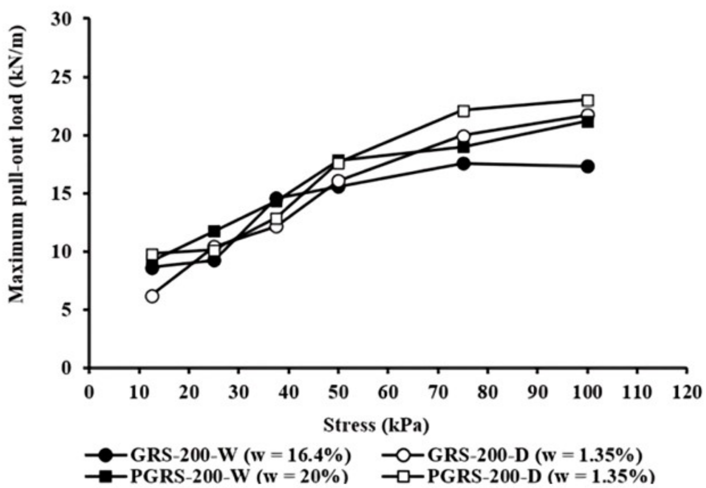


Figure 13. Maximum pull-out strength versus confining stress from tests with fill materials at different moisture contents.

PGRS presented slightly higher f values compared to GRS, either at optimum or hygroscopic moisture content. In general, for each recycled sand (GRS and PGRS), the tests performed at optimum moisture content showed slightly higher values than those performed at hygroscopic moisture. Values greater than one are due to the effect reported by Palmeira (1987) in tests with short grids with few bearing members.

3.1.3 Effect of moisture variation on the interface strength

The interface friction angles (δ) presented the same trend as the internal friction angles of the sands (ϕ), as it was observed that under dry and wet states, similar values were obtained. The lubrication between the grains at the interface contact with the geogrid elements was not sufficient to interfere with these values. Regarding adhesion (a), it is important to note that there was a significant increase in the wet conditions (at optimum water content). However, further studies on such aspects are needed. Table 3 shows the parameters obtained from the strength envelopes for the recycled sand-geogrid interfaces under pull-out (normal stresses of 12.5 kPa and 25 kPa) and the shear strength parameters of the recycled sand obtained from direct shear tests.

Figure 13 shows that the maximum pull-out force was higher for GRS and PGRS when they were at the optimum moisture content. When the sands are compared at the same moisture content, it can be seen that PGRS presented higher values of pull-out strength, although the values for both materials (GRS and PGRS) were very close. In general, it was observed that for the range of values tested moisture content did not present significant impacts on the pull-out force for the investigated systems, especially for those where the geogrids were completely pulled out.

4. Conclusions

This paper investigated the interaction between geogrids and recycled sands by mean of pull-out tests. The tests were carried out on natural sand, grey recycled sand (as provided by the recycling plant) and laboratory-produced recycled grey sand (with the same grain size distribution in the natural sand), for varying moisture conditions. Based on the results obtained, the main conclusions are presented below.

1. There is a variability of the geotechnical characteristics of the recycled sands tested, but this would not prevent the application of this non-conventional material as backfill in GRS structures. After adequate characterisation, its grain size distribution can be adjusted to attend gradation limits recommended by technical standards;
2. The results of geogrid pull-out force versus displacement showed that the pull-out condition

was observed only for lower normal confinement pressures at the sample top. For very high pressure, the pull-out box worked as a clamp, preventing the geogrid from being pulled out and yielding to its tensile failure;

3. Based on the effect of the normal confinement pressures adopted in the tests, behavioural zones were identified for different mechanisms. This conclusion encourages the use of the small box in pull-out tests as a way to obtain preliminary qualitative results, particularly when investigating the potential use of a non-conventional fill material in RSS. However, results from larger equipment should be used for design purposes;
4. The recycled sands tested at optimum moisture showed higher values of pull-out strength (considering the normal stress range in which full grid pull-out occurred).

Therefore, compared to the behaviour of natural sand, the recycled sands showed good strength properties, mechanical behaviour and interaction with a geogrid under a pull-out condition that encourages further studies on the use of such environmentally friendly material in RSS.

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Declaration of interest

The authors have no affiliation with or involvement in any organisation 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 content 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

Priscila F. S. Oliveira: methodology, investigation, validation, writing – original draft preparation. Eder C. G. Santos: conceptualisation, methodology, supervision, validation, funding acquisition, writing – reviewing and editing. Ennio M. Palmeira: supervision, validation, writing – reviewing and editing.

Data availability

Research data available upon request.

List of symbols and abbreviations

a	Adhesion
c	Cohesion
e_{max}	Maximum voids index
$e_{mín}$	Minimum voids index
f	Interface resistance coefficient
w	Water content
w_{op}	Optimum water content
Al	Aluminium
Al_2O_3	Alumina
Ca	Calcium
CaO	Calcium oxide
C_C	Soil curvature coefficient ($C_C = D_{30}^2 / D_{10} \cdot D_{60}$)
CDW	Construction and demolition waste
C_U	Soil coefficient of uniformity ($C_U = D_{60} / D_{10}$)
CV	Coefficient of variation
D	Diameter of the particle (mm)
D	Hygroscopic moisture
DC	Degree of compaction (%)
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)
EDS	Energy-dispersive X-ray spectroscopy
Fe_2O_3	Ferrous oxide
GRS	Grey recycled sand
GRS-01	Grey recycled sand (sample 01)
GRS-02	Grey recycled sand (sample 02)
GRS-03	Grey recycled sand (sample 03)
GRS-04	Grey recycled sand (sample 04)
GRS-05	Grey recycled sand (sample 05)
GRS-06	Grey recycled sand (sample 06)
GRS-06-D	Dry grey recycled sand (sample 06)
GRS-06-W	Wet grey recycled sand (sample 06)
GRS-200-D	Dry grey recycled sand sample with two-hundred-millimetre width of the geogrid sample
GRS-200-W	Sample wet grey recycled sand with two-hundred-millimetre width of the geogrid sample
G_S	Specific gravity
K_2O	Potassium oxide
MgO	Magnesium oxide
NCMA	National Concrete Masonry Association
NS	Natural sand
NS-D	Dry natural sand sample
NS-200-D	Dry natural sand sample with two-hundred-millimetre width of the geogrid sample

PGRS	Produced grey recycled sand
PGRS-06-D	Dry produced grey recycled sand (sample 06)
PGRS-06-W	Wet produced grey recycled sand (sample 06)
PGRS-200-D	Dry produced grey recycled sand sample with two-hundred-millimetre width of the geogrid sample
PGRS-200-W	Sample wet produced grey recycled sand with two-hundred-millimetre width of the geogrid sample
RCDW	Recycled construction and demolition waste
RSS	Reinforced soil structures
SEM	Scanning electron microscopy
Si	Silicon
SiO_2	Silica
SP	Poorly graded sand
SP-SC	Poorly graded sand with clay
TCP	Total pressure cell
TSC	Total stress cell
USCS	Unified Soil Classification System
γ_{dMax}	Maximum dry unit weight (kN/m^3)
δ	Interface friction angle
σ	Normal confinement pressure
σ_n	Normal stress on the interface
τ	Tangential stress on the interface
ϕ	Internal friction angle of the soil

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