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Review

Sustainable Solutions with Geosynthetics and Alternative Construction Materials—A Review

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Abstract: Geosynthetics have proven to provide sustainable solutions for geotechnical and geoenvironmental problems when used with natural materials. Therefore, the expected benefits to the environment when geosynthetics are associated with unconventional or alternative construction materials will be even greater. This paper addresses the use of geosynthetics with wasted materials in different applications. The potential uses of alternative materials such as wasted tires, construction and demolition wastes, and plastic bottles are presented and discussed considering results from laboratory and field tests. Combinations of geosynthetics and alternative construction materials applied to reinforced soil structures, drainage systems for landfills, barriers, and stabilisation of embankments on soft grounds are discussed. The results show the feasibility of such combinations, and that they are beneficial to the environment and in line with the increasing trend towards a circular economy and sustainable development.

Keywords: geosynthetics; wastes; tires; CDW; PET bottles

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1. Introduction

The preservation of the environment as a whole and specifically of its natural resources is of utmost importance for current and future generations. In this context, geosynthetics can provide sustainable engineering solutions for geotechnical and geoenvironmental problems, reducing the consumption of natural materials and causing less impact to the environment [1–4]. Geosynthetics can perform different functions in an engineering project, such as drainage, filtration, barrier, separation, reinforcement, and protection. Frischknecht et al. [1] showed reductions greater than 70% of some environmental impact parameters such as water consumption, renewable and non-renewable energy consumption, emissions of gases that contribute to global warming, etc. in some applications of geosynthetics in comparison with conventional geotechnical solutions. Significant reductions in energy consumption and CO_2 emissions were obtained by Damians et al. [2] when the environmental impacts caused by geosynthetic reinforced retaining structures were compared to those from conventional concrete retaining walls. Heerten [3] also presented two examples of construction infrastructures where the use of geosynthetics showed lower environmental impacts due to significant reductions of cumulated energy demand and CO_2 emissions. Touze-Foltz [4] presented several other examples of the environmental benefits of using geosynthetics in geotechnical and geoenvironmental works.

The benefits brought by the use of engineering solutions with geosynthetics discussed above were obtained using conventional soils as construction materials. When geosynthetics are combined with materials commonly considered wastes, solutions involving geosynthetics will be expected to be even more beneficial to the environment, since they will avoid or reduce the utilisation of good-quality natural materials (which are increasingly scarce and expensive in several regions) and reduce their exploitation, with positive repercussions for the environment. These are the cases of combinations of different geosynthetic products with wasted tires, plastic objects, and construction and demolition wastes, for instance. However, one must bear in mind that some of these wastes can be harmful to the environment. Thus, due care must be exercised when using wastes in construction to avoid ground contamination due to the degradation of the waste with time or the presence of pollutants. In this context, the use of such wastes may still be feasible if appropriate geosynthetic barriers (geomembranes or GCLs) are employed.

Very little can be found in the literature on the combination of geosynthetic products and alternative/waste construction materials in geotechnical and geoenvironmental works. The same comment applies to the use of wastes to produce low-cost alternative geosynthetics. This paper presents the properties and relevant characteristics of some waste materials, treated hereafter as alternative construction materials, that can be combined with geosynthetics in geotechnical and geoenvironmental works. Advantages, limitations, and examples of such combinations are presented and discussed.

2. Some Examples of Alternative Construction Materials Commonly Used in Engineering Projects

2.1. Wasted Tires

Over the years, population growth has led to higher volumes of wastes, requiring large areas for disposal. One material that has been pointed out as an environmental hazard is discarded tire. Used tires have approximately 75% voids and, in some countries, there are several specific stockpile areas for their disposal. Therefore, these materials can generate an environmental problem due to the growing demand for space for their disposal. In geotechnical engineering applications, tires can be utilised as lightweight material after they are shredded to small pieces.

Tire stockpiles present large groundwater contamination potential once they are overall composed of rubbers, carbon black, metals, antioxidants, and polymers [5]. Besides the risk of ground contamination, there is also the possibility of combustion when the wasted tires are disposed in large areas (Figure 1a). Humphrey [6] reported self-heating reactions of tires in Washington and Colorado. Another occurrence of this type took place in Hagersville, Ontario, Canada (Figure 1b), where a large tire stockpile fire burned for days [7]. The huge amount of wasted tires is a global environmental concern and the related risk of either soil/groundwater contamination or stockpile fire poses the need to recycle and reuse these materials.

(**a**)

(**b**)

Figure 1. Environmental hazards produced by wasted tires [7]: (**a**) tire stockpile disposal; (**b**) tire stockpile fire in Canada in 1990 [7].

According to the United States Tires Association (USTA) [8], 303.5 million rubber tires were produced in 2019. The United States has made an effort to recycle these materials as much as possible and, in 2019, almost 76% of scrap tires were recycled to be used in rubber-modified asphalts, the manufacturing of automotive products, mulch for landscaping, and tire-derived fuel. The USTA also reported that tires are now one of the most recycled products in the U.S., but end-of-life markets are not keeping pace with their annual generation [8]. On the other hand, the Canadian Association of Tire Recycling Agencies reported that 82% of the 421,184 tires collected were recycled in 2019 [9]. In 2020, Brazil recycled 42 million scrap tires with a produced total amount of 59.5 million [10,11]. However, despite the efforts to recycle these materials, there are still tons of scrap tires discarded throughout the country.

Based on the above information, there is a need to recycle wasted tires as much as possible in order to reduce the environmental impacts caused by their disposal, and one way to tackle this problem is by mixing them with soil. Many applications of mixtures of wasted tires in geotechnical applications can be found in the literature. It is possible to find investigations involving laboratory and field tests with different types of soils and rubbers for different applications [6,12–26]. Despite the relevance of such mixtures, the present paper focuses on combinations of some wastes, including rubber, with geosynthetics in geotechnical and geoenvironmental applications.

2.2. Recycled Construction and Demolition Wastes (RCDW)

Important studies have been conducted for decades on raw source material conservation. The relevance of such studies is even more evident today, as human-made mass has exceeded all living biomass [27]. In 2020, the sub-groups of concrete and aggregates were estimated to represent approximately 80% of the total amount of anthropogenic mass—inanimate solid objects made by humans that have not been demolished or taken out of service. Nowadays, it is imperative to investigate solutions to improve the use of construction and demolition wastes (CDW).

The need for materials for future construction and renovation of buildings and/or infrastructure brings recycling as a fundamental strategy, once it can provide a material with a low-carbon footprint, hereafter called "recycled construction and demolition waste" (RCDW). Bearing in mind that over 10 billion tons of CDW are generated per year [28], recycling could significantly reduce the volume of this waste currently destined to final disposal in landfills. At the same time, it could also reintroduce RCDW into construction works at a very low cost and reduce the environmental impact since it could mitigate the demand for natural raw material supply.

Due to the introduction of various legislative measures and the adoption of several waste management strategies, CDW has been investigated in several disciplines, including phenomenology, environmental science and environmental engineering, material science and engineering, the industrial ecology perspective, management science, architecture, the construction and operation of buildings [28], pavement engineering, and geotechnical engineering. However, the applications of RCDW are mainly focused on the use of recycled aggregate in road pavements and concrete, but this is a consequence of the methods usually adopted by the recycling plants and some economic aspects.

With the potential for consuming a large amount of RCDW, investigations on the application in pavements have shown geotechnical properties equivalent or superior to those of typical quarry granular coarse base and subbase materials [29,30]. Laboratory tests have revealed that the use of recycled concrete aggregate in hot-mix asphalt for base courses is promising, given that the bitumen absorbed by the aggregate makes its whole surface be coated by the binder, reducing the porosity and, therefore, the sensitivity to moisture [31,32]. The adoption of new concepts when designing a cold asphalt mixture with recycled concrete aggregate may allow the application of such recycled products [33]. Regarding the potential environmental impacts of RCDW, field-site leaching from crushed concrete was measured after 10 years of exposure in a road subbase and the simplified risk assessment showed that the released trace elements did not exceed the pre-defined acceptance criteria for groundwater and fresh water [34].

Given that some countries classify soil as CDW, this material may correspond to a significant volume received by some recycling plants. Considering those regions where measures to promote an efficient on-site sorting process are not developed yet, the CDW will consist of a mixture of soils (from excavation), inert and non-inert materials, and materials from site clearance activities (organic matter and other debris). This fraction of the CDW, composed of soil, is not desirable for producing aggregates for concrete and pavements due to poor-quality properties. However, the recycling processes usually carried out by the recycling plants (sorting of non-inert material, crushing, and sieving) can enable the RCDW to be used as backfill material for geosynthetic reinforced soil structures (GRS). This use may allow the construction of such structures in places where natural materials are scarce, reducing the exploitation of new and far quarries and, consequently, their economic and environmental costs.

2.3. Plastic Bottles

Plastic wastes can also be combined with geosynthetics to fulfil different functions in geotechnical works. Despite its enormous advantages for society in different areas, when not properly disposed or confined, plastics can cause damage to the environment as well as serve as a habitat for organisms that are hazardous to public health. It is estimated that over 1,000,000 plastic bottles are sold every minute [35], with still a limited amount of recycling in most countries. In addition, it may take over 450 years for a plastic bottle to completely degrade in the environment. Plastic bottles may end up in rivers (Figure 2) [36], beaches, and even far out in the oceans, forming huge floating masses, or accumulating on remote islands and coral atolls [37], with evident harm to marine fauna. Thus, it is important to develop and encourage other uses for plastics in general, particularly for polyester (PET) bottles. As far as geosynthetics are concerned, PET bottles can be used as a drainage medium associated with a geotextile filter, for instance, as will be seen later in this paper, as well as being processed to produce recycled geosynthetics.

Figure 2. Plastic bottle accumulation in Tietê River, Brazil [36].

3. Some Combinations of Geosynthetics and Alternative Construction Materials

3.1. Recycled Construction and Demolition Wastes in Geosynthetic Reinforced Structures—Concerns and Relevant Properties

Some properties and characteristics of RCDW must be evaluated when considering the use of such material in geotechnical works. Below, some of these characteristics are described and discussed.

- Particle Crushing

Even when processing a homogenous CDW, the procedures adopted by the recycling plant may determine several of the properties of RCDW. Gomes et al. [38] investigated the influence of three different comminution and sizing processes (simple screening, crushing, and grinding) on the composition, shape, and porosity characteristic of a recycled concrete aggregate (obtained from concrete block wastes). The results revealed products with different chemical and mineralogical compositions, grain size distribution, particle shapes, and porosity. This case highlights the importance of considering the application of RCDW with commonly considered undesirable fractions (soil and powder) in works where material selection is technically more tolerant.

The compaction process, usually carried out during the construction of a GRS, improves the backfill material strength and promotes better interaction with the reinforcing element (e.g., geogrid or geotextile). However, this construction procedure may also cause additional crushing and breakage of RCDW particles, changing its grain size distribution. In a laboratory investigation, Leite et al. [29] found that the physical changes caused by compaction (changing grain size distribution and increasing the percentage of cubic grains) contributed to a better densification of the RCDW aggregate and consequently improved its bearing capacity, resilient modulus, and resistance to permanent deformation.

The degradation of aggregates and soils during shearing, when subjected to monotonic or cyclic stresses, has always been a concern for researchers and engineers even for natural materials such as decomposed granite soil [39], silica sand [40], and latite basalt [41]. When dealing with RCDW, this concern deserves special attention given that these materials present a very heterogeneous composition due to having different origins. According to Sivakumar et al. [42], cyclic direct shear tests on recycled aggregate revealed a reduction in friction angle due to particle crushing (from 43° to 38° for crushed concrete, and from 43° to 39° for crushed brickwork). Although special attention is needed for the construction and maintenance of some geotechnical works, the reported reduction in friction angle would not prevent the use of RCDW in most geosynthetic applications.

Domiciano et al. [43] conducted a laboratory investigation on RCDW with different grain size distributions—three products from a local recycling plant—subjected to static loading (ranging from 150 to 600 kPa). The RCDW more susceptible to particle breakage when subjected to the static loading process was the one presenting two main characteristics: (i) uniform grain size distribution and (ii) a composition marked by a significant presence of ceramic components. The RCDW products that were composed of concrete components showed a low occurrence of grain breakage. In general, the results revealed the occurrence of significant changes in the grain size distribution curves, but no abrupt particle breakage was noticed. It was observed that particles larger than 9.5 mm were the ones most affected by loading, showing a smooth surface (less rough) caused by the removal of fines particles around them.

- Interface Shear Strength

Soil–geosynthetic interaction is of utmost importance for the design and performance of GRS structures, and this interaction can be very complex depending on the nature and properties of the reinforcement and the soil [44]. The need to understand the interaction mechanisms in a GRS structure has encouraged researchers to develop new tests and to modify some classical ones, such as (i) a direct shear test with the geosynthetic specimen at the shear plane [45,46], (ii) a direct shear test with the geosynthetic specimen inclined to the shear plane [45,47,48], (iii) a confined tensile test [49,50], and (iv) a pull-out test [45,46]. Several studies have been performed using such testing apparatuses with different types of soils and geosynthetics, revealing all the main factors (e.g., boundary condition and scale factor) that may affect the test results. However, due to the few studies carried out with RCDW, such influencing factors will not be discussed in this paper.

A study conducted by Touahamia et al. [51] investigated the shear strengths of three waste materials (building debris, crushed concrete, and quarry waste). The tests were carried out using a medium-size shear box (305 mm × 305 mm) and considered different conditions of moisture content (dry or wet), the presence of reinforcement (reinforced or non-reinforced), and contamination (clean or smeared with clay slurry—a condition investigated only for concrete and quarry wastes). The waste materials were prepared in the laboratory with grain sizes between 20 and 40 mm. The contaminated condition was achieved with the addition of kaolin slurry (20% of kaolin powder by dry weight of the tested material; powder–water relation of 1:1.5). The results revealed that building debris presented friction angle values (dry, 37°; wet, 35°) and behaviour similar to those observed for crushed concrete. The presence of reinforcement (geogrid specimen at the box central plane) increased the dry friction angle by 12°. Among the wastes investigated, the increase in friction angle due to the presence of reinforcement was more pronounced for building debris.

Materials obtained from the demolition of single-family houses and the cleaning processes of land with illegal deposition of CDW were recycled and tested by Vieira et al. [52]. The RCDW was subjected to geotechnical characterisation, a leaching test, and direct shear tests with and without reinforcement. The grain size distribution revealed that the material was composed of fine particles (smaller than 20 mm) and the short-term contaminant release investigation revealed that the RCDW fulfils the acceptance criteria for inert landfills. The direct shear test results for the unreinforced RCDW showed values of peak friction angle and cohesion equals to 44.1° and 17.3 kPa, respectively. The reinforced condition presented values of peak friction angle and apparent adhesion equal to 35° and 12.6 kPa, respectively, for an extruded geogrid made from high-density polyethylene (ultimate tensile strength of 68 kN/m, and 16 × 219 mm aperture size). The tests with an extruded geogrid made of polyester (ultimate tensile strength of 80/20 kN/m, and 30 × 73 mm aperture size) revealed values of peak friction angle and apparent adhesion equal to 36.6° and 19.7 kPa, respectively.

The use of RCDW as backfill in a GRS structure was investigated by Santos and Vilar [53], who performed geotechnical characterisation and shear and pull-out tests. The RCDW was obtained from a local recycling plant and consisted of a mixture of a crushed material (consisting mainly of soil, bricks, and small particles of concrete). Two other materials were used as reference: (i) river sand (in accordance with the U.S. Federal Highway Administration—FHWA) and (ii) local soil (sandy clay soil). The RCDW presented low variability in its geotechnical properties (grain size distribution, specific gravity, unit dry weight, and moisture content) and an alkaline extract (mean pH = 9.1) that allowed its use with the PET geogrid tested (ultimate tensile strength, T_{ult}, of 61 kN/m × 30 kN/m, machine x cross-machine direction; 30 × 20 mm aperture size). The results of the pull-out tests showed that the RCDW presented a higher interface strength than that of the river sand and the values of the adherence factor—the ratio between the RCDW–geogrid interface strength and the RCDW shear strength—in a range (0.52 to 1.30) observed by other studies for conventional soil–geogrid interfaces.

- Geosynthetic Damage

The reduction in ultimate tensile strength (T_{ult}) caused during the installation process has been pointed out as the most critical mechanism affecting the short-term durability of geosynthetics [54]. Besides the intrinsic characteristics of a geosynthetic (e.g., geometry, shape, and polymer) that affect its durability, the backfill material composition and installation procedures influence the occurrence and severity of damages. Bearing in mind the proposal of using RCDW in GRS structures, the damage mechanisms may be influenced by the physical and chemical characteristics of such new backfill material.

To investigate the factors affecting the short-term damages of a polyester (PET) geogrid (T_{ult} of 20 kN/m at machine direction) and of a polypropylene (PP) non-woven geotextile (T_{ult} of 19 kN/m and mass per unit area of 300 g/m^2), Santos [55] simulated the construction procedures used to build two large-scale wrapped-face geosynthetic reinforced walls with RCDW as backfill material (classified as sand with gravel, pH equal to 8.84 at 25 °C). The criteria adopted to indicate the occurrence of damage was based on the mean value of the tensile strength for virgin specimens (T0) (not submitted to the installation procedure) and a level of confidence of 98% calculated using Student's t-distribution—given that only five specimens were tested for each scenario, characterising a small sample size. For scenarios where the mean tensile strength (Ti) presented values outside the confidence interval, the occurrence of damage was assumed and the reduction factor (RF) was calculated. The scenarios investigated were (i) compaction by a lightweight roller, (ii) a hand tamping plate, and (iii) compaction by a lightweight roller and burial in RCDW for 450 days. The results revealed that the PP geotextile tested was stronger than the PET geogrid and that more severe damages were observed for the specimens left in contact with RCDW. The results for the geogrid revealed the influences of compaction energy and contact with the RCDW. Table 1 presents the values of RF for all the scenarios investigated.

Table 1. Reduction factor (RF) for geosynthetics with RCDW backfill material [55].

Scheme	Nonwoven Geotextile	Geogrid
Lightweight roller	1.00	1.12
Hand tamping plate	1.00	1.28
Lightweight roller + 450 days burial	1.64	1.20

An extensive study on geogrid mechanical damage due to contact with RCDW was carried out by Fleury et al. [56] considering several factors of influence: (i) RCDW dropping height H (0.0, 1.0, and 2.0 m, and 2.0 m over a RCDW protection layer of 50 mm) and (ii) a compaction method (no compaction—to isolate the influence of dropping height, vibratory roller, and hand tamping plate) and geogrid type (polymer-T_{ult}: PVA-35 kN/m, PET-35 kN/m, and PET-55 kN/m). The RCDW (mainly composed of soil, concrete, mortar, and ceramic) was obtained from a local recycling plant and the final compacted layer was 200 mm thick. The combination of the influencing factors totalled 36 scenarios, with five specimens been tested for each scenario. The results of the tensile tests (wide strip specimens) were obtained according to ASTM D-6637 [57], and the method for determining damage occurrence followed the one presented by Santos [55]. The results showed that (i) the RCDW presented variability in its geotechnical properties, (ii) the dropping process caused slight damages and the increase in the dropping height showed limited influence in the damage intensity (RF = 0.94 to 1.21), (iii) the adoption of fine-grained RCDW can be seen as an attractive alternative as a protective layer, (iv) the compaction method was the most important factor for geogrid installation damage (RF = 0.98 to 1.22) once the severity of the damage seemed to be directly associated with the compaction degree reached during the tests, and (v) the multiplication of individual RF values for the investigated factors (dropping height and compaction method) was conservative. The study conclusions highlight the importance of obtaining RF for specific situations when RCDW is used, the complexity of damage mechanisms, and the positive technical, economic, and environmental aspects of using such non-conventional backfill material in GRS structures. Testing the same geogrids, Domiciano et al. [43] reported no influence of damage (RF = 1.0) on T_{ult}. The tests were carried out by subjecting the specimen to different values of static loading (ranging from 150 to 600 kPa) and using RCDW with different compositions and grain size distributions. However, Domiciano et al. [43] showed different RF values for other parameters of interest (strain at failure, ε_{rup}; stiffness at 2%, $J_{2\%}$; and stiffness at 5%, $J_{5\%}$).

3.2. Recycled Construction and Demolition Wastes in Unpaved Roads

Recycled construction and demolition wastes (RCDW) can be effectively used as fill materials in environmentally friendly solutions for unpaved roads. Góngora [58] carried out a series of large-scale tests on unreinforced and geosynthetic reinforced unpaved roads on a weak subgrade. Figure 3 shows the characteristics of the equipment used in these tests, which consisted of a rigid steel tank (750 mm diameter, 550 mm high). A rigid circular platen (200 mm diameter) applied the repeated loading (frequency of 1 Hz) on the fill surface. Geogrids were used as reinforcement, whose main properties are listed in Table 2. The secant tensile stiffness at a 5% strain of the geogrids tested varied between 130 kN/m and 1500 kN/m, with varying aperture sizes. The subgrade soil consisted of a fine-grained soil (Table 3) with a California Bearing Ratio (CBR) value of 4.2%. Two materials were investigated as fill for the roads. The first one was a natural gravel with an average particle diameter (D_{50}) equal to 10.5 mm, which served as a reference fill material. The other fill material was a recycled construction and demolition waste (RCDW) with an average particle diameter of 34 mm. The main geotechnical properties of the soils tested are presented in Table 3. Additional information can be found in Góngora [58] and Góngora and Palmeira [59].

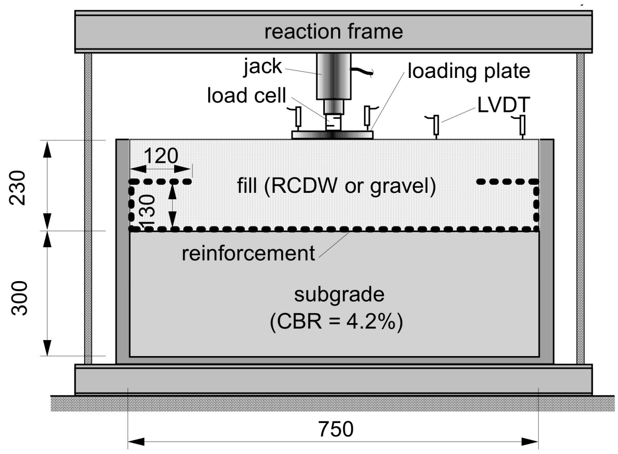


Figure 3. Equipment used in the tests on unpaved roads [58].

Table 2. Reinforcement properties.

Property [1]	G1	G2	G3
Aperture dimensions (mm)	30 × 30	20 × 20	40 × 40
Percentage of grid open area (%)	33	73	84
Tensile stiffness at 5% strain	1500	260	130
Tensile strength (kN/m)	200	35	17.5
Aperture stability modulus (N-m/deg.) [2]	1.54	0.029	0.019

Note: [1] Data from manufacturers' catalogues. Geogrids manufactured with polyester fibres protected by a PVC cover; [2] also known as in-plane torsional rigidity modulus [60,61], obtained at 2 N-m torque, minimum value.

Table 3. Properties of the soils.

Property	Subgrade	Gravel	RCDW [1]
D_{85} (mm) [2]	0.19	16.7	47.4
D_{50} (mm)	0.025	10.5	34
D_{10} (mm)	—	1.6	5.9
Percent of fines (<0.075 mm) (%) [3]	63	1.0	1.0
Soil coefficient of uniformity	—	7.1	6.8
Liquid limit (%)	39	—	—
Plastic limit (%)	29	—	—
Moisture content (%)	27.1	—	—
Dry unit weight (kN/m^3)	14.0	17.6	16.9
Soil particles density	2.68	2.65	2.74
California Bearing Ratio (%)	4.2	—	—
Los Angeles Abrasion Test (%)	—	36.0	56

Notes: [1] RCDW = recycled construction and demolition waste; [2] D_n = diameter for which *n* percent in mass of the remaining particle diameters is smaller than that diameter, coefficient of uniformity of the soil = D_{60}/D_{10}; [3] tests using a dispersing agent for the subgrade soil.

Figure 4 shows the results of tests on unreinforced roads, where the target surface rut depth of 25 mm at the fill surface was reached for close values of a number of load repetitions (N) for both fill materials (N equal to 1630 and 1710 for the gravel and RCDW roads, respectively). However, the presence of reinforcement (geogrid G1) made a significant difference on the road performance, as can be seen in Figure 4. In this case, the 25 mm-deep rut was reached in the reference (gravel) road for a value of N of 24,064, whereas in the case of the reinforced RCDW road it was reached for a value of N of 57,235. It should be noted that up to a rut depth value of 22 mm (N ≅ 11,000) the behaviour of the two fill materials was very similar. As that rut value came closer to the target maximum rut depth, it may be considered that both materials behaved similarly under reinforced conditions, with a TBR (traffic benefit ratio = N_r/N_{unr}, where N_r and N_{unr} are the values of N under reinforced and unreinforced conditions, respectively, for a given rut depth) of the order of 15 at the end of the tests. Similar tests after road surface repair showed the good performance of the reinforced roads (gravel and RCDW fills) in terms of TBR values, particularly for tests with reinforcements less prone to suffering mechanical damage [59].

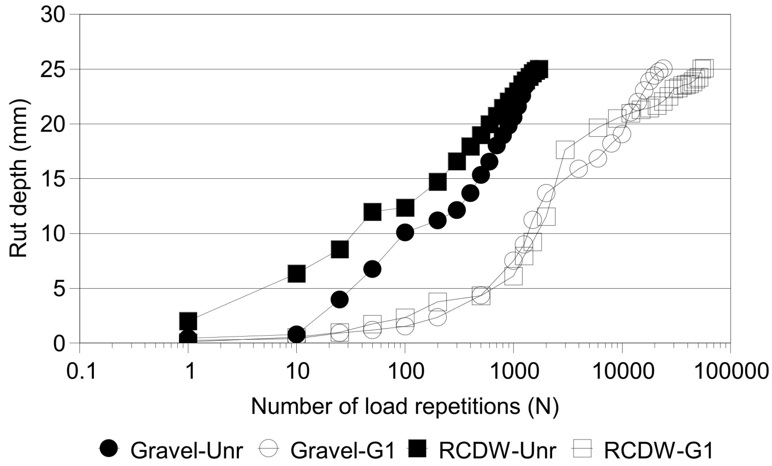


Figure 4. Rut displacement versus number of load repetitions.

Mehrjardi et al. [62] reported the use of construction and demolition wastes as fill materials combined with geocell reinforcement in unpaved roads on compressible subgrade. Figure 5 shows a schematic of the test equipment used in the investigation. A natural aggregate (gravel, USCS classification = GP, D_{50} = 4.6 mm, D_{10} = 0.2 mm and coefficient of uniformity (CU) of 26.3) layer was also used as fill material for comparison purposes. The alternative base materials consisted of a waste soil (fine-grained fraction of the CDW, USCS classification = GW, D_{50} = 1.3 mm, D_{10} = 0.12 mm and coefficient of uniformity (CU) of 19) and a recycled concrete aggregate from CDW (USCS classification = GP, D_{50} = 3.0 mm, D_{10} = 0.21 mm and coefficient of uniformity (CU) of 18). The subgrade soil consisted of the wasted soil with a moisture content of 1.5% and a relative density of 60%. The geocells utilised were manufactured from a heat-bonded nonwoven geotextile made of polypropylene, with cells with equivalent diameter and height of 55 mm and 50 mm, respectively; a mass per unit area of 690 g/m^2; and a secant tensile stiffness at 5% strain of 5.7 kN/m.

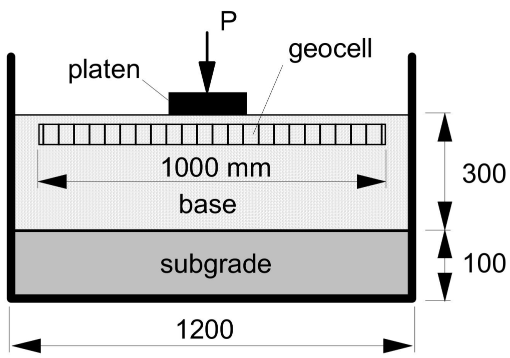


Figure 5. Tests on unpaved roads reinforced with geocells [62], modified.

Figure 6 shows some test results obtained by Mehrjardi et al. [62] in terms of permanent settlement at the fill surface versus number of load repetitions for the tests with the waste soil and natural aggregate. This figure shows that the geocell-reinforced road built with the waste soil performed significantly better than its unreinforced counterpart and presented similar performance to that of the natural aggregate at the end of the test.

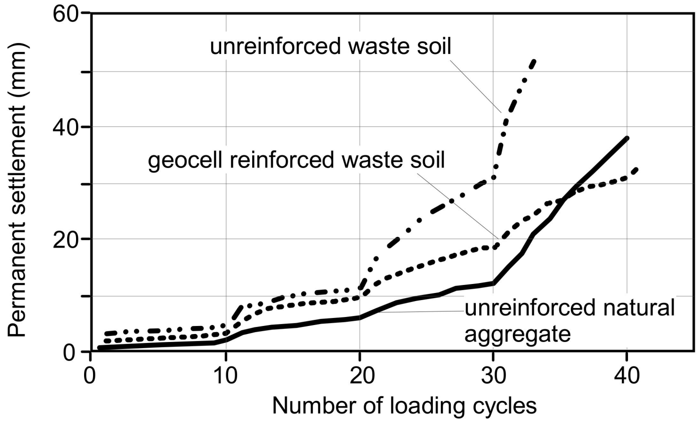


Figure 6. Settlement versus number of loading cycles [62], modified.

The results presented in Figures 4 and 6 show the potential of the use of recycled construction and demolition wastes reinforced with geosynthetics in unpaved roads on poor subgrades. The utilisation of RCDW will avoid or reduce the use and exploitation of more expensive natural materials, with favourable repercussions to the environment.

3.3. Recycled Construction and Demolition Wastes in Geosynthetic-Encased Granular Columns

Alkhorshid [63] investigated the use of geosynthetic-encased columns (GEC) to reduce excessive settlements and failure of embankments built on soft soils (Figure 7a,b). In this type of subgrade, there is low confinement at the upper part of the granular column, reducing its load capacity. A technique that has been applied to increase column lateral confinement is the use of geotextile encasement (Figure 7b). Large scale tests were carried out by Alkhorshid [63] on conventional and geotextile-encased granular columns using a large box (1.6 m × 1.6 m × 1.2 m) to investigate the use of three types of woven geotextile encasements and three types of infill materials, including RCDW. The GEC models were 1000 mm in height and 150 mm in diameter. Sand, calcareous gravel, and recycled construction and RCDW were used as infill materials for the columns. Bentonite (4% in mass) was added to the subgrade soil to increase its plasticity and workability, resulting in a soft subgrade classified as CH by the Unified Soil Classification System (USCS). The properties of the soft soil and filling materials and the geotextile characteristics are presented in Tables 4 and 5. If a scale factor of 4 is considered, the tests would simulate a prototype problem of a 0.6 m-diameter encased column in a soft clay with an undrained strength of 20 kPa. During the tests, monotonically increasing vertical loads were applied to the column top by a rigid steel plate.

(**a**)

(**b**)

Figure 7. Geosynthetic-encased granular columns to stabilise embankments on compressible ground: (**a**) typical differential settlement between an abutment on soft ground and a bridge; (**b**) geosynthetic-encased granular column.

Table 4. Properties of the soft subgrade.

Property	Soil			
	Clay	Sand	Gravel	RCDW
Liquid limit (%)	60	-	-	-
Plasticity index (%)	21	-	-	-
Soil particle density (-)	2.7	2.65	2.66	2.65
Compression index	0.47	-	-	-
Expansion index	0.03	-	-	-
Undrained strength (kPa)	5	-	-	-
Coefficient of uniformity	5.5	3.51	1.6	1.5
Coefficient of curvature	1.05	0.825	0.98	0.92
D_{50} (mm)	0.304	0.50	6.55	6.64
D_{10} (mm)	0.073	0.179	4.44	4.78
D_{30} (mm)	0.175	0.305	5.56	5.64
D_{60} (mm)	0.401	0.63	7.11	7.21
Maximum void ratio	-	0.87	0.74	0.76
Minimum void ratio	-	0.6	0.41	0.45
Friction angle (degrees)	-	41	43	42
Dilation angle (degrees)	-	11	12	12

Table 5. Properties of the geosynthetic encasements.

Property	Geotextile		
	G-1	G-2	G-3
Tensile strength (kN/m)	30	16	8
Maximum tensile strain (%)	22	16	15
Tensile stiffness (k/m)	120	107	53.4

The G-1-encased column (the column using geotextile G-1, Table 5, with the highest tensile strength and stiffness) presented higher bearing capacity and lower settlements than those encased with G-2 and G-3. Moreover, the maximum lateral bulging of the encased columns was observed for the column encased with the most extensible geotextile (G-3), at a depth ranging from 1 to 1.5 times the column diameter. Figure 8 shows values of load capacities of the columns encased by geotextile G1 and with the three different infill materials tested (sand, gravel, and RCDW). This figure also shows the results for the conventional materials (no encasement). A significant increase in column load capacity was observed with the use of geotextile encasement. It is also noticeable that the values of load capacity of the RCDW-encased columns were very similar to those of the traditional natural infill materials, which highlights the potential use of RCDW as infill material in encased granular columns for the stabilisation of embankments on soft soils. Additional information on this type of application of RCDW can be found in Alkshorshid [63] and Alkhorshid et al. [63–65].

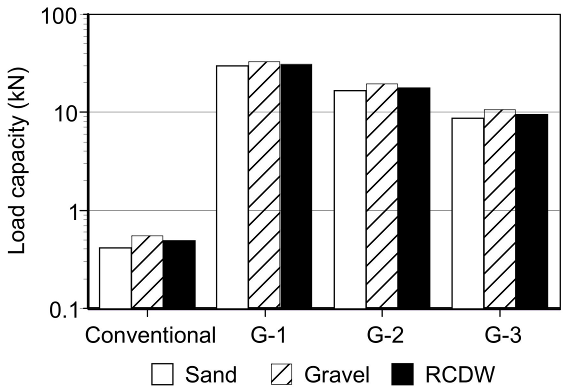


Figure 8. Comparison between load capacities of granular columns [63], modified.

3.4. Reinforced Soil Structures Constructed with RCDW: Performance

As part of a research programme on the combined use of CDW and geosynthetics in geotechnical and geoenvironmental works at the University of Brasília, Brasilia, Brazil, a research project was responsible for the conception, construction, instrumentation, and monitoring of two full-scale GRS structures using RCDW as backfill material. The 3.6 m-high wrapped face walls were constructed over a porous collapsible foundation soil located at the Foundation and Field Investigation Site of the Graduate Programme of Geotechnics of the University of Brasilia. Because the walls were monitored through dry and rainy seasons, it was possible to observe the influence of the properties and performance of the foundation soil on walls deformations, settlements, horizontal earth pressures, and reinforcement strains [55,66,67]. The walls were constructed with different geosynthetic reinforcements (Wall 1: PET geogrid and Wall 2: PP non-woven geotextile) and back-to-back in a reinforced masonry block facility (Figure 9). Three layers of lubricated polyethylene sheets were placed on the internal faces of the facility to minimise the influence of soil-side wall friction on the test results. Tables 6 and 7 present the properties of RCDW and geosynthetics used in these experiments, respectively.

Figure 9. Complete view of the test facili showing the water reservoirs and main reservoir [55].

Table 6. Properties of the RCDW backfill material (Santos [55]).

Property	Value
D_{85} (mm)	15.0
D_{50} (mm)	2.1
D_{10} (mm)	0.032
CU	106
pH of backfill	8.9
Unit weight (kN/m^3)	17.8
Moisture content (%)	6.6
Friction angle (degrees)	41
Cohesion (kPa)	6

Notes: D_n, diameter of particles for which *n*% in mass of the remaining particles is smaller than that diameter; CU, soil coefficient of uniformity (CU = D_{60}/D_{10}).

Table 7. Geosynthetic properties [55].

Property	Geogrid (Wall 1)	Nonwoven Geotextile (Wall 2)
Polymer	Polyester	Polypropylene
Aperture size (mm × mm)	20 × 20	NA [2]
Tensile strength (kN/m)	20 [1]	24 [3]
Secant stiffness (kN/m)	300 at 5% strain [1]	15 at 5% strain [3]
Strain at break (%)	12	70

Notes: [1] In direction of loading (transverse members); [2] NA = not applicable; data from manufacturer's literature unless stated otherwise; tensile properties as per ASTM D6637 [57]; [3] Santos [55].

Besides the expected collapse of the foundation soil due to the natural infiltration of water through the wall face and backfill surface during the rainy season, artificial inundation was also carried out to enhance foundation soil collapse in a controlled manner and thus further investigate its effect on the performance of the walls. To assure the complete infiltration of water into the foundation soil, a granular drainage layer was installed at the base of the walls and water reservoirs were constructed adjacent to the test facility (Figure 9).

Because the walls were built during the dry season, the following rainy season presented a relevant effect on the performance of the walls, mainly during the first 100 days, which resulted in approximately 250 mm of cumulative precipitation. Concerning the horizontal displacements of the wall face, it was noted that after being subjected to the first rainy season or to artificial inundation (the latter for Wall 1) the values measured tended toward stabilisation. The artificial inundation of the foundation soil presented a greater influence on Wall 1 (geogrid) and were shown to be negligible for Wall 2 (nonwoven geotextile wall). Figure 10 presents the normalised horizontal displacements measured (at a normalised elevation of 0.83) at the wall faces from the end of construction up to 587 days after construction. Measures of inward displacement at the crest of both walls were also observed, which may have been a consequence of the compressibility of the foundation soil at the wall toe as reported in other studies not related to the use of RCDW as backfill material [68–71]. Although both walls showed the largest outward displacement at an elevation equal to 3.00 m ($h/H = 0.83$, where h is the elevation and H is the height of the wall), the final values for Wall 2 ($\Delta x/H = 6\%$, where Δx is the face horizontal displacement) were about twice those of Wall 1 ($\Delta x/H = 3\%$). This performance of Wall 2 can be explained by the fact that nonwoven geotextile presents much lower stiffness under the unconfined conditions at and closer to the wall face, where the occurrence of greater reinforcement bulging was marked. The maximum outward post construction movement observed was greater than the values recorded for conventional wrapped-face walls in a database of wall case studies collected by Bathurst et al. [72]. Clearly, the performance of the walls can be attributed to the compressibility of the foundation soil. However, the magnitudes of face displacements recorded by Santos et al. [67] could be acceptable for temporary structures in some jurisdictions (e.g., WSDOT [73]) or even prevented by means of some foundation soil treatment, which could be carried out before or simultaneously to the wall construction.

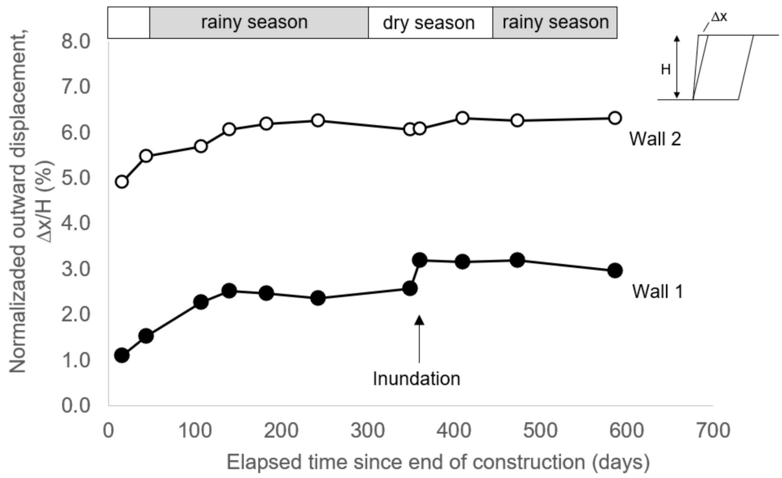


Figure 10. Horizontal outward displacement of the wall face at an elevation of 3.0 m.

The displacement of the wall top was influenced by the first rainy season (following the construction of the walls) in a very significant manner, associated with a value of 250 mm of cumulative precipitation as a trigger to the process. Differences in settlement profiles were observed, which can be attributed to differences in the compressibility of the foundation soil under each wall. The wall crest presented the most significant vertical displacements for both walls, with the highest values observed for Wall 1 (Figure 11). Considering the wall top, for x/B = 0.24, where x is the distance from the wall face and B is the wall base width, the stabilisation of displacements was observed at 261 days after construction, which was associated with approximately 1250 mm of cumulative precipitation. However, the artificial inundation showed that this stabilisation was due to the reduction in precipitation and infiltration of water, because of the dry season's proximity. In a period of just 48 h after the artificial inundation process, the vertical displacement at x/B = 0.24 increased by 45% and 39% for Walls 1 (geogrid) and 2 (nonwoven geotextile), respectively. The effects caused by the artificial inundation continued for approximately 48 days (during the dry season), with increments of 8% and 15% for Walls 1 and 2, respectively. The second rainy season showed no significant influence on the vertical displacements at the wall top up to the end of monitoring of the walls (587 days after the end of construction).

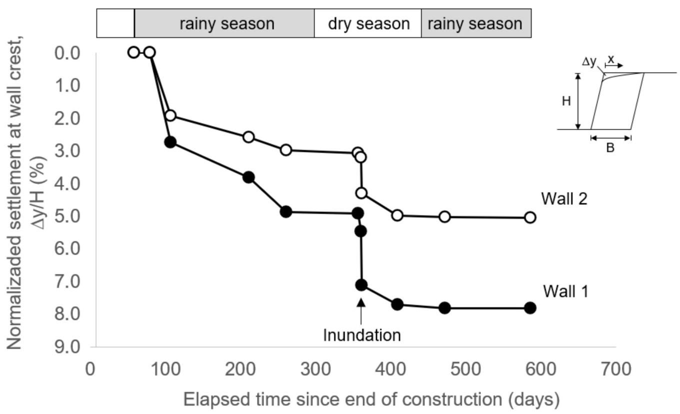


Figure 11. Vertical displacements at the wall top (x/B = 0.24).

Concerning the reinforcement strain, much higher values were observed close to the face of Wall 2 (nonwoven geotextile) compared to Wall 1, particularly for reinforcement layer 5 (elevation of 2.4 m). Maximum strains in this layer in Wall 1 reached 0.23% just before the artificial inundation of the foundation, whereas for the same reinforcement layer in Wall 2 the maximum strain was equal to 12.4%. The maximum reinforcement strains in Wall 1 reveal the viability of using RCDW as backfill material once such values are consistent with the low strain levels reported in databases of monitored geosynthetic soil walls under operational conditions by Miyata and Bathurst [74] and Bathurst et al. [75]. The larger values of strains close to the face of Wall 2 (nonwoven geotextile) are a consequence of the low confinement in that region. Beyond half of the base length, the RCDW provided enough confinement to the geotextile reinforcement and the strains were low (below 1%) in both walls. The effects of the rainy season on reinforcement strains were noted more significantly in Wall 1, with the cumulative precipitation of 250 mm working again as a trigger. On the other hand, the results indicate that reinforcement strain mobilisation in Wall 2 occurred during the construction process, with the rainy season and artificial inundation not causing relevant changes.

4. Combinations between Geosynthetics and Alternative Materials in Waste Disposal

Landfills have plenty of materials that can be reused in civil engineering works and to fulfil some needs of the landfills themselves. This section addresses some combinations of geosynthetics and waste materials for applications in landfills.

Palmeira and Silva [76] carried out tests to investigate the performance of the combination of geotextile filters and alternative drainage materials using large-scale waste containers. The containers were made of steel plates and were 3.5 m long, 2.5 m wide, and 1.0 m high, as shown in Figure 12. A lateral drainage trench allowed the flow of leachate to external tanks for leachate volume and property measurements. The drainage trench in each container was 300 mm wide and 300 mm deep. Perforated pipes at the top of the containers allowed the pluviation of water on the waste under controlled conditions. In cell C1 (Figure 12a) the drainage trench was filled with recycled construction and demolition wastes (RCDW). A nonwoven geotextile layer covered the entire plan area of the container. The main properties of the RCDW are listed in Table 8. In cell C2 the drainage system consisted of a 100 mm-thick layer of shredded wasted tires with a geotextile filter layer on top (Figure 12b). In both containers the geotextile filter was a nonwoven, needle-punched geotextile made of polyester, with a thickness of 2.3 mm and a mass per unit area equal to 200 g/m^2. The mass of domestic waste in each cell was approximately equal to 2.5 tons, with the following composition: 44% organic matter, 26% paper and cardboard, 16% plastics, 4% metal, and 10% other materials. The initial height of the waste was equal to 900 mm and the waste was disposed in a loose state, with a unit weight of 4 kN/m^3 and an initial moisture content of 58%. Figure 13 shows views of the drainage trenches in containers C1 and C2 before the installation of the geotextile filter.

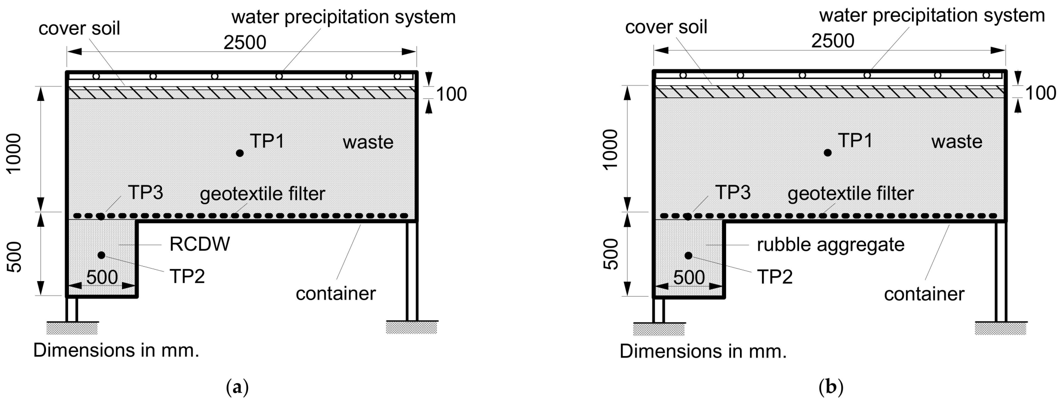


Figure 12. Waste containers: (**a**) container C1; (**b**) container C2 [77].

Table 8. Properties of the drainage materials.

Property	RCDW	Tire Shreds
D_{90} (mm) [1]	33	45
D_{85} (mm)	31	—
D_{50} (mm)	21.4	—
D_{10} (mm)	2.0	—
Coefficient of uniformity	12.5	1.5
Dry unit weight (kN/m^3)	11.13	3.67
Void ratio	0.95	2.19
Permeability (cm/s) [2,3]	10	15
Compression index [2]	1.18	0.79

Notes: [1] D_n = diameter for which *n* percent in mass of the remaining particle diameters is smaller than that diameter, coefficient of uniformity of the soil = D_{60}/D_{10}; [2] from large-scale laboratory tests [77]; [3] from large-scale constant head permeability tests [77].

(**a**) (**b**)

Figure 13. Drainage trenches in containers C1 and C2: (**a**) C1; (**b**) C2.

The water pluviation on the waste started 75 days after the waste disposal in the containers, under pluviation rates of 10 L/week to simulate wet seasons and 2.5 L/week to simulate dry seasons. The instrumentation used allowed the measurement of waste settlements and temperature in the waste mass below the geotextile filter and inside the drainage trench. Effluent volumes were collected for measurements of effluent flow rates as well as chemical analyses such as the determination of pH, chemical oxygen demand, sulphate content, ammonium content, nitrate content, and solids content. Additional information on materials and testing methodology can be found in Paranhos and Palmeira [77], Silva [78], and Palmeira et al. [79].

Figure 14 depicts the variation of cumulative effluent volume from the containers with the cumulative volume of precipitation. The results show a greater discharge capacity of the drainage trench with tire shreds in comparison with that of the RCDW aggregate. Some level of waste heterogeneity may have influenced the different responses of the drainage systems. However, even before the start of the water pluviation on the waste, effluent flow was already noticed in container C2, whereas effluent in container C1 only started after water pluviation. This late response from C1 may also be a consequence of the presence of the horizontal drainage layer in container C2, which was not present in C1, besides the large coefficient of permeability of the tire shreds (Table 8). It can also be noted that after 130 L of water pluviation (approximately 138 days since the beginning of pluviation) the rate of increase in the effluent volume with pluviation volume was very similar for both drainage systems.

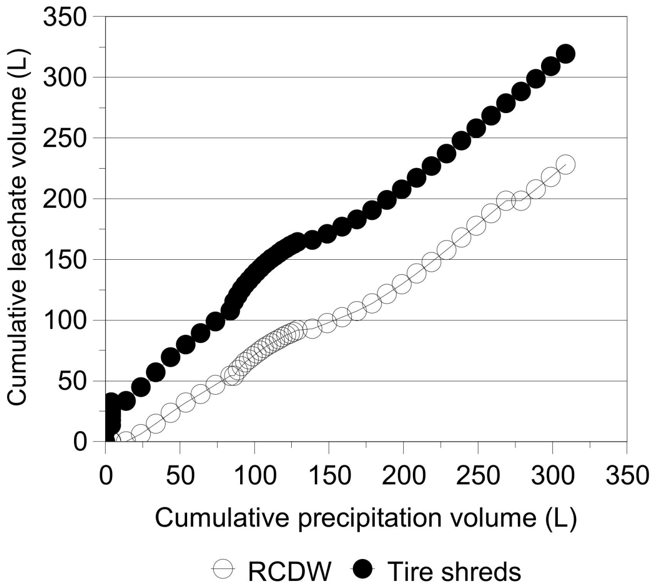


Figure 14. Variation of cumulative effluent volume with cumulative precipitation volume in containers C1 and C2.

Figures 15 and 16 show the variation of chemical oxygen demand (COD) and pH with cumulative precipitation for the two drainage systems investigated. These figures also present the variation in cumulative precipitation volume with time. Significant differences between COD values can be noted, and this may have been due to the influence of the delay in the liberation of leachate from container C1, as mentioned before; the interaction between the particles and leachate, and the better filtering action of the RCDW layer. A significant amount of COD reduction in the effluent from container C1 was noted during the dry season, when the rate of precipitation was smaller, probably due to more favourable conditions for bacterial activity, as well as when water pluviation was stopped on day 600 (Figure 15). At the end of the tests, some level of degradation of the RCDW grains was visually observed, which must be considered when using this type of material in drainage systems under long-term conditions. The initially larger pH values of the effluent from container C1 (Figure 16) was likely due to the interaction between the concrete particles and the leachate. As time passed, the pH values became similar for both containers. The reduction in the pH values with time for container C1 may have been a consequence of the particles of the drainage system having been covered with a layer of leachate, which avoided or minimised continuous direct contact between the leachate and concrete particles. The effluents of both systems presented pH values close to the neutral value at the end of the experiments. Additional information on the behaviour of the drainage systems in the containers can be found in Silva [76] and in Palmeira and Silva [80].

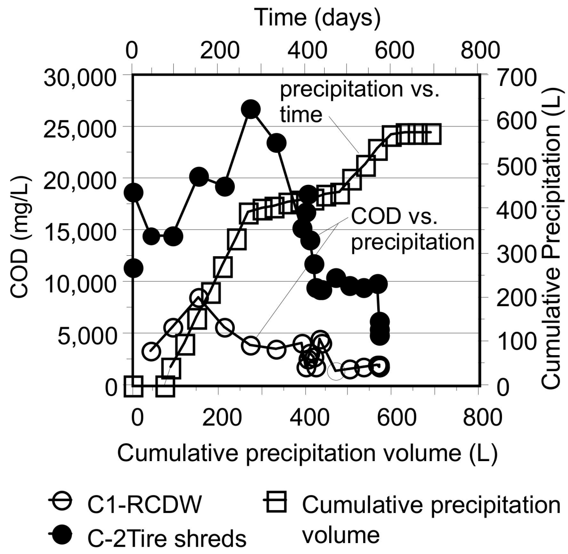


Figure 15. COD variation with cumulative precipitation volume.

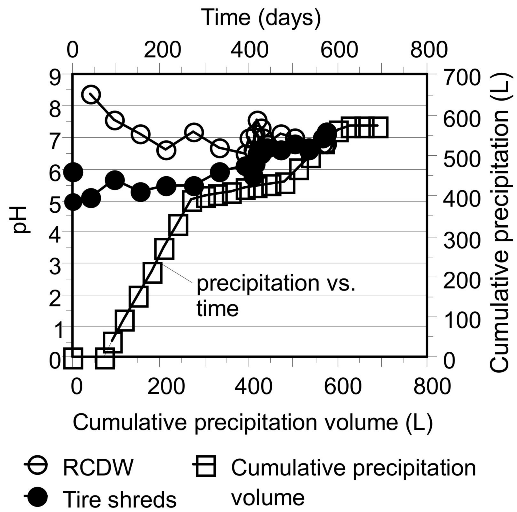


Figure 16. Variation of COD and pH of the effluent with cumulative precipitation volume [78], modified.

Junqueira et al. [16] and Silva [78] described the use of wasted tires as drainage layers in landfills. The authors compared the performance of a conventional gravel layer at the base of an experimental domestic waste cell to an alternative drainage system consisting of a layer of whole wasted tires and a nonwoven geotextile filter. The use of the geotextile filter aimed also to investigate the possibility of its clogging, since clogging of either geotextile or sand filters and even of gravel drainage layers have been observed in landfills. Figure 17 shows the geometrical characteristics of these waste cells, where each cell contained approximately 50 tons of municipal solid waste collected in the Federal District, Brazil. The main properties of the soils and alternative drainage material involved in this study are presented in Table 9. The municipal solid waste in the cells had a composition consisting of 49% (in mass) organic matter, 18% plastics, 22% paper and cardboard, 2% metals, and 9% other materials. The waste had a unit weight of 5.4 kN/m^3. Cell Gr had a conventional drainage layer at its bottom consisting of a gravel layer 200 mm thick (Figure 17). Cell T had an alternative drainage system formed by a layer of wasted tires as the system drainage core with a geotextile filter (nonwoven, needle-punched, 150 g/m^2 mass per unit area, 1.5 mm thick, 2.5 s^{-1} permittivity, and filtration opening size of 0.15 mm). Figure 18 shows images of cell T during construction and filling with waste. HDPE geomembranes were used as barriers at the bottom of both cells to avoid the contamination of the subgrade.

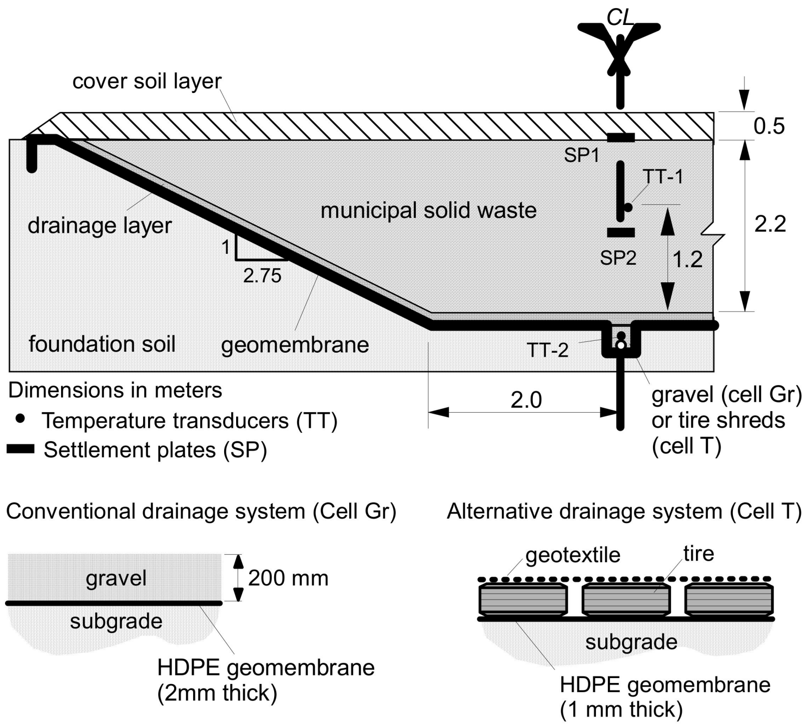
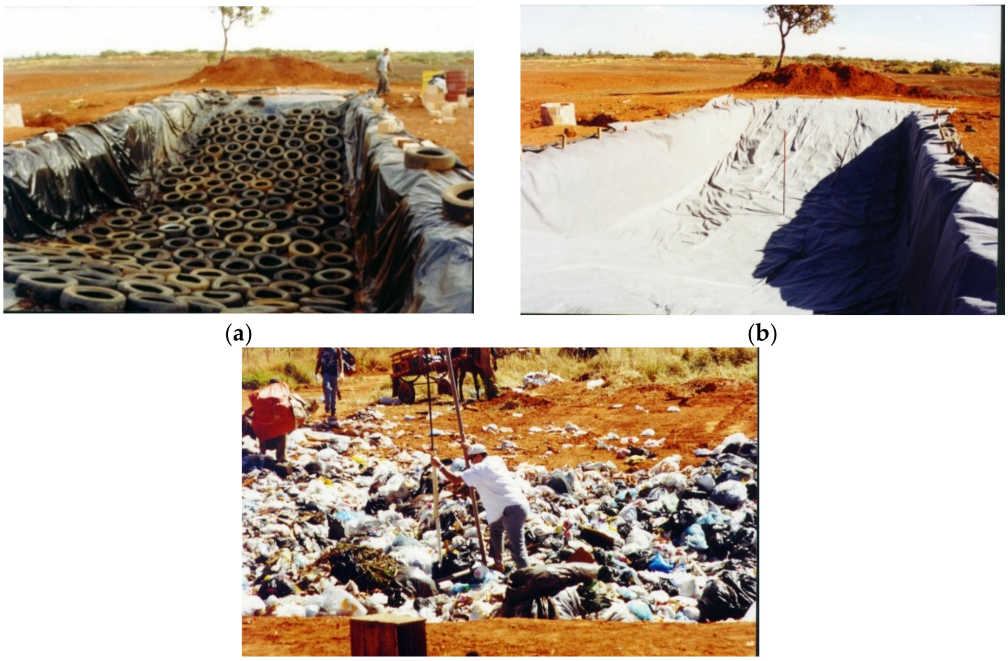


Figure 17. Geometrical characteristics of the experimental waste cells [78], modified.

Table 9. Properties of the materials tested.

	Gravel	Tire Shreds	Cover Soil [3]
D_{10} (mm) [1]	53	NA [6]	NA
D_{50} (mm)	60	NA	NA
D_{85} (mm)	65	41	0.20
CU [2]	1.2	1.5	NA
Dry unit weight (kN/m^3)	19.7	3.67	13.4
Permeability (cm/s) [4]	24 [5]	15 [5]	0.003 to 0.009

Notes: [1] D_n is the diameter for which *n*% in weight of the soil has particles with diameters smaller than that value; [2] CU = soil coefficient of uniformity = D_{60}/D_{10}; [3] 79% in mass with particles smaller than 0.074 mm; [4] from field infiltration [78,81]; [5] from large-scale constant head permeability tests [77]; [6] NA = not applicable.



(**a**) (**b**) (**c**)

Figure 18. Construction and filling of one of the experimental waste cells [78]: (**a**) drainage layer; (**b**) installation of the geotextile filter; (**c**) filling.

The experimental cells were instrumented with settlement plates and temperature transducers for waste mass settlement and temperature measurements, respectively. The variation of the effluent flow rate with time and the pluviometry in the region was also assessed. In should be pointed out that the region has very well-defined wet and dry seasons. The dry season runs from May to September each year, whereas the rainy season runs from October to April. Data acquisition from the instrumentation started in the month of August, during the dry season. Additional information on the experiments can be found in Silva [16] and Junqueira et al. [78].

The variation of cumulative effluent volume with cumulative precipitation volume is presented in Figure 19. It can be observed that the results obtained are very similar, showing the good performance of the alternative drainage system in comparison with that of the conventional one. The rather constant value of effluent volume between months 7 and 14 corresponds to the dry season in the region. Hence, the response of the drainage systems in terms of effluent volumes was directly related to the pluviation in the region. Figure 20 shows the ratio between the effluent volume and the volume of water precipitated on the cells during rainy periods, showing again the similar behaviour of both drainage systems investigated. The rather constant rate between the effluent and precipitated volumes in the first three months of monitoring was due to fact that the initiation of flow took place during a dry season, thus with the effluent from both cells being mainly a consequence of the decomposition of organic matter. Junqueira et al. [16] showed that similar variations of settlement and chemical parameters of the effluent with time were also found for both cells. However, the amount of suspended solids in the effluent from cell T was smaller than that from cell Gr due to the filtering action of the geotextile layer in the former. For the duration of the experiment, there was no indication of clogging of the geotextile filter.

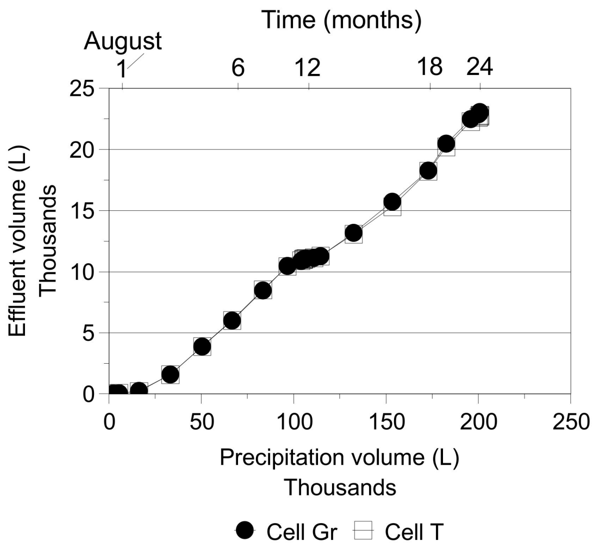


Figure 19. Cumulative effluent volume versus cumulative precipitated volume.

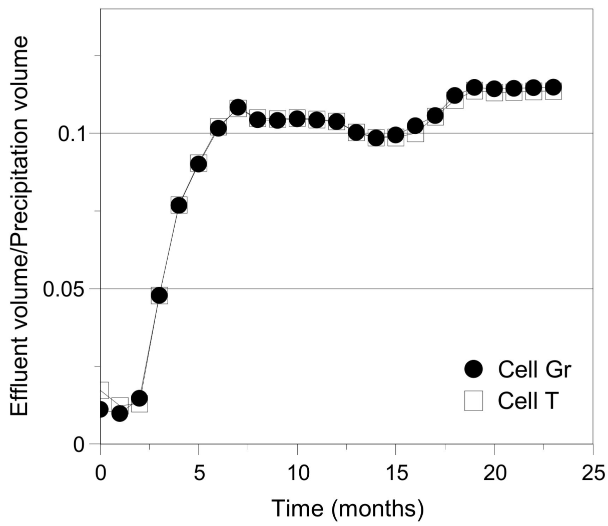


Figure 20. Ratio between effluent and precipitated volumes versus time.

5. Other Sustainable Combinations of Geosynthetics and Alternative Materials

Other waste materials can be combined with geosynthetics to provide sustainable engineering solutions. This is the case for PET bottles, which can be used to form a drainage layer. Figure 21 shows a drainage system consisting of compressed PET bottles enveloped by a geotextile filter. The compressed bottle layer presented high permeability coefficients under low stress levels, even greater than those of conventional granular materials commonly used in drainage systems. Table 10 lists typical values of relevant geotechnical properties of some alternative drainage materials. These results were obtained in large-scale permeability (constant head) and compression tests [77,79]. The coefficient of permeability (50 cm/s) of the compressed PET bottles was of the order of 3.5 to 5 times those of the tire shreds and rubble aggregate tested. However, PET bottles were significantly more compressible (Table 10), and this may be an issue depending on the stress level on the drainage layer.

(a)

(b)

Figure 21. Alternative drainage system with a core of compressed PET bottles (images courtesy of H. Paranhos): (**a**) compressed PET bottles; (**b**) geocomposite for drainage formed by compressed PET bottles enveloped by a geotextile filter in a drainage trench.

Table 10. Properties of some alternative drainage materials [77].

Property	Compressed PET Bottles	Shredded Tires	Rubble Aggregate
Shape	Round	Lamellar	Irregular
D_{90} (mm)	95	45	35
CU	1.0	1.5	2.0
Unit weight (kN/m^3)	92.0	367.0	1113.0
k (cm/s)	50.0	15.0	10.0
e	2.11	2.19	0.95
C_c	4.7	0.79	1.18

Notes: D_{90} diameter for which 90% of the remaining particles have smaller diameters than that value; CU = coefficient of uniformity; k = coefficient of permeability (from large-scale constant head tests); e = void ratio; C_c = compression index (from large-scale compression tests).

Another interesting application of PET bottles is in infiltration trenches for runoff water to avoid or minimise the consequences of floods in urban areas. Figure 22 shows this type of application, where a geotextile filter is associated with whole PET bottles to favour the infiltration of surface runoff water into the ground [82].

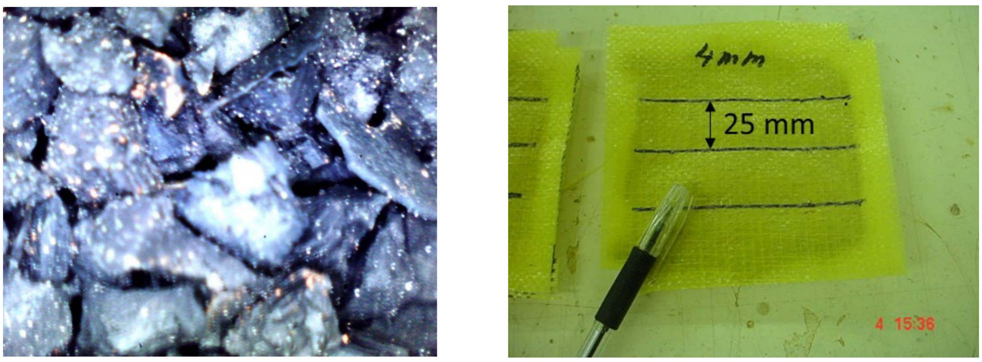
Figure 22. Drainage trench with PET bottles for flood control [82].

Geotextiles can also be combined with alternative drainage materials to produce low-cost biplanar drainage geocomposites. Figure 23 shows alternative geocomposites for drainage consisting of a nonwoven filter layer and drainage cores made of PET bottle caps or rubber strips from wasted tires [83,84]. Transmissivity tests performed on these alternative geocomposites showed values of transmissivity under pressure similar to those of some conventional commercially available products [84].

(**a**) (**b**)

Figure 23. Alternative geocomposites for drainage [83]: (**a**) drainage core consisting of PET bottle caps; (**b**) drainage core consisting of rubber strips from wasted tires.

Rubber grains from wasted tires (Figure 24a) can also be utilised to manufacture low-cost alternative geocomposite clay liners (GCL, Figure 24b). In this case, the rubber grains can be mixed with the bentonite to save bentonite. However, this mixture will swell less than pure bentonite when subjected to moisture content increase. Viana et al. [85] investigated the influence of the amount of rubber grains (D_{85} = 0.6 mm, D_{10} = 0.12 mm, CU = 4.0) from wasted tires on the permittivity and expansibility of an alternative GCL. Figure 25a shows that significant permittivity increased with increasing rubber content. On the other hand, the permittivity decreased with increasing normal stress. The variation of expansion of rubber-bentonite mixtures with vertical stress is depicted in Figure 25b. The results show less expansion of the alternative barrier due to the addition of rubber grains. Despite the increase in permittivity and decrease in expansibility, the use of a low-cost GCL incorporating rubber grains may be interesting as additional barrier layers or as bedding or protective layers underneath geomembranes in landfills, particularly in less critical situations.



(**a**) (**b**)

Figure 24. Alternative GCL [85], modified: (**a**) rubber crumbs; (**b**) alternative GCL.

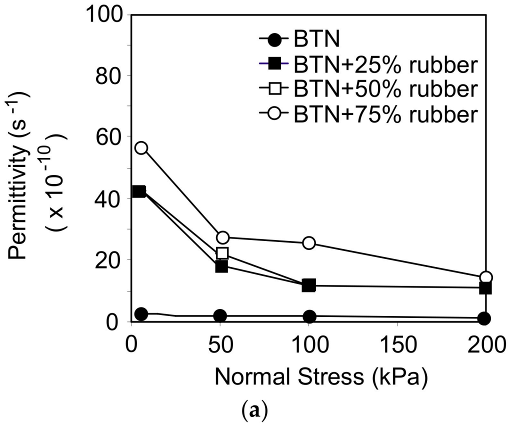


Figure 25. Results of tests on an alternative GCL [85], modified: (**a**) permittivity versus normal stress; (**b**) expansion versus normal stress.

Inert mining wastes can also be used as alternative construction materials if the requirements regarding geotechnical and geoenvironmental properties are fulfilled. Fernandes et al. [86] reported on the use of geogrid-reinforced fine mining waste mixed with local soils in an alternative sub-ballast layer of a railway. Instrumented experimental sections showed the good performance of the alternative geogrid reinforced sub-ballast layer in comparison with the conventional and more expensive material traditionally used in that railway. Some of the benefits brought by the combination of mining waste and geosynthetic reinforcement were less vertical and horizontal strains in the sub-ballast layer, an increase in the track stiffness, and less breakage of ballast particles, with positive repercussions in reducing the maintenance costs of the railway track.

Martins [87] and Gomes and Martins [88] described the use of mining waste as fill material in a 28 m-high retaining structure (Figure 26). The reinforced mass was 18 m high and was constructed using ore mining waste as backfill material. This mining waste had up to 40% fine fraction, with a unit weight of 20.3 kN/m^3, a cohesion of 19.7 kPa, and a friction angle of 39°. Nonwoven and woven geotextiles were used as reinforcement with tensile strengths of 40 kN/m and 70 kN/m, respectively. The reinforced structure is already 24 years old and has behaved very well.

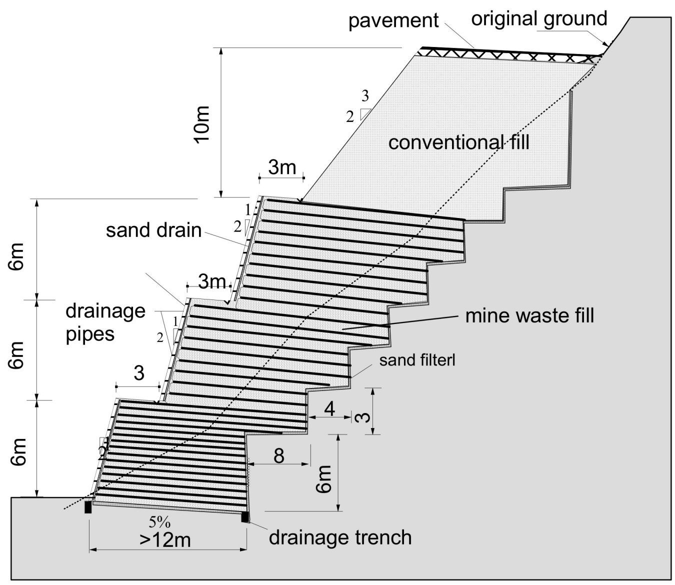


Figure 26. Geosynthetic reinforced structure built with mining waste backfill [87].

6. Conclusions

The preservation of the environment and natural resources is of major importance for current and future generations. Therefore, the concepts of sustainability and circular economy have come to stay, and engineers must be encouraged to propose engineering solutions in line with this new reality. In this context, geosynthetics can already provide sustainable solutions when used in combination with conventional natural materials. Hence, if combined with properly selected wastes and low-grade construction materials, the benefit to the environment will be even more significant. This paper presented a review on the use of wastes as alternative construction materials in geotechnical and geoenvironmental works, with particular emphasis on their combination with geosynthetics. The main conclusions obtained are summarised below.

- Although there are environmental concerns regarding the use of rubber tire waste mixed with soils, this type of mixture has been evaluated over the last decades in different countries and the investigations have shown that the risk of contamination is low for constructions involving low rates of waterflow.
- Rubber tires mixed with soils are considered suitable for different types of granular materials, although the mechanical properties of the mixtures vary depending on the type of soil and the size and shape of the rubber particles.
- The performance of unpaved roads on soft ground where geosynthetic reinforced construction and demolition wastes (CDW) were used as fill materials compared well to the performance of unpaved roads constructed with conventional natural granular fills.
- Recycled construction and demolition wastes, wasted tires, and plastic bottles may also provide low-cost and environmentally friendly solutions for drainage systems in geotechnical and geoenvironmental works, particularly when used in landfills, where these wastes are abundant.
- Wasted tires and plastic elements such as plastic bottle caps can be combined with geotextiles to produce low-cost geocomposites for drainage. The use of recycled plastics to produce geosynthetics should also be encouraged, particularly for less critical and less severe applications.
- Properly selected recycled construction and demolition waste can be a feasible infill material for geosynthetic-encased granular columns.
- The reported studies show the influence of waste origin and recycling procedures on the variability of RCDW geotechnical properties and chemical behaviour. The need for specific characterisation when RCDW is subjected to surcharge (static or cyclic loading) and the influence of its component properties (e.g., concrete, ceramic, mortar, etc.) was observed. However, the results reported in the literature present physical, mechanical, and chemical properties that allow the effective application of RCDW in several geotechnical works involving the use of geosynthetics.
- The compaction method was revealed to be of utmost importance for short-term mechanical damage of geosynthetic reinforcement when RCDW is used as backfill material. Due to the intrinsic complex mechanisms that are involved with geosynthetic damage, it is important to use appropriate values of reduction factors based on the properties of the RCDW, construction site conditions, and reinforced soil structure characteristics to obtain low-cost and safe designs.
- The performance of two full-scale wrapped-face geosynthetic-reinforced soil walls constructed over a collapsible foundation soil revealed the influences of the rainfall regime (dry or wet season), foundation inundation, and geosynthetic type on the behaviour of the walls as a whole (face and top displacements and reinforcement strains). Even under extreme conditions, the walls built with RCDW as backfill material showed satisfactory performance. The proposal of using such a non-conventional backfill material further enhances the recognised advantages of geosynthetic-reinforced walls (cost effectiveness and reduced environmental impacts, for instance) and encourages

the growth of geotechnical engineering practices in accordance with the concept of sustainable development. The same comments apply to the use of mining wastes.

- Mining wastes can also be successfully combined with geosynthetics in reinforced soil structures.

Despite the relevance and benefits to the environment in reusing wastes in geotechnical engineering, one must bear in mind that some of these wastes will degrade with time or can contain substances that may cause ground contamination. Thus, a careful evaluation of such aspects must be carried out before using wastes as construction materials in geotechnical and geoenvironmental works. In this context, geosynthetics such as geomembranes and geocomposite clay liners can be properly specified to provide efficient barriers for such contaminants.

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