Recycling of crushed concrete and steel slag in drainage structures of geotechnical works and road pavements

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Abstract
A crushed concrete aggregate, processed from construction and demolition waste and a siderurgical aggregate, processed from electric arc furnace steel slag, were selected based on their very high availability worldwide and known technical feasibility to be used in construction works. Given the association of their presence to the possibility of reducing the drainage capacity of unbound granular layers of road pavements and drainage structures which they may be associated with, there are studies and regulations that do not recommend their use. The causes that are at the origin of restrictions are mainly the possibility of formation of tufa and recementation phenomena. This behaviour has also hampered their recycling in drainage structures of geotechnical works. Therefore, it was considered that it would be relevant to investigate the drainage capacity of those recycled aggregates, using a leachate produced in a municipal solid waste landfill and tap water. To reference their behaviour, two natural aggregates, a basalt and a limestone, were also studied under identical test conditions. The results obtained showed no reduction in the drainage capacity of the recycled aggregates, similarly to what was observed with the natural aggregates. The possibility of building drainage structures with the tested aggregates is verified.

Keywords
Construction and demolition waste · Steel slag · Recycling · Hydraulic conductivity · Drainage layers

Abbreviations
BAS Basalt
CDW Construction and demolition waste
ISAC Inert steel aggregate for construction
k Hydraulic conductivity
kg Kilogram
L Leachate
LCRL Leachate collection and removal layer
LIM Limestone
Mg Megagram (ton)
MSW Municipal solid waste
Pe Porosity accessible to water
PVC Polyvinyl chloride
RCA Recycled concrete aggregate
RSSA Recycled steel slag aggregate
SS Steel slag
W Water
w max Maximum water absorption under vacuum conditions
ρb Bulk density
ρr Real density

Introduction
In 2015, the United Nations (UN) adopted the 2030 Agenda for Sustainable Development. One of the goals within the plan is Goal 11: “Make cities inclusive, safe, resilient and sustainable”, which states that half of humanity—3.5 billion people—lives in cities today and 5 billion people are projected to live in cities by 2030 [1]. Considering that cities already account for between 60 and 80% of energy consumption and generate as much as 70% of human-induced greenhouse gas emissions, a sustainable urbanization is central to the realization of the UN Sustainable Development Goals [2]. The current Coronavirus pandemic crisis further
highlights the urgent need to address the environmental challenges, benefiting not only the environment, but also our society’s health and well-being [3]. A large majority of our society has finally realized that neither the pandemic nor destructive climate change are a natural disaster; they are, largely, the result of our behaviours and actions.

It is known that the construction industry is one of the sectors that generates more waste in the world, both in volume and in weight [4, 5]. According to Kaza et al. [6], the world average generation of construction and demolition waste (CDW), is 1.68 kg/capita/day, which means a world production of about 4.8 billion Mg/year, which is more than the 3 billion Mg/year estimated by Akhtar and Sarmah [7]. In the European Union (EU-27), for example, in 2018, CDW accounts for 36% of all waste generated, which means about 834 million Mg [8]. On the other hand, construction industry consumes 40% of the materials entering the global economy [9, 10], which in Europe means consuming 12 to 18 million Mg/year of new construction materials [11]. Therefore, it is natural the general concern with, not only, reducing the quantity of CDW removed to landfills, the carbon footprint and the energy consumption in this industry, but also with the availability of natural aggregates and where to find, in the future, new aggregate sources [12], in particularly, regarding sands [13]. This framework has highlighted the need to find alternative materials.

It is in this context, and with the prospect of economic recovery after COVID-19, that the construction industry will have to accelerate the transition to a greener and more sustainable economy, as exemplified by the joint declaration of the EU and China on September 14, 2020 [14].

Concrete waste, which represents the largest percentage of CDW in many countries, and was estimated at 67% in the United States of America (USA) by Akhtar and Sarmah [7], and steel slag (SS), a by-product of steel and iron production, whose world production in 2018 reached about 600 million Mg [15], are, probably, ideal materials to replace natural crushed aggregates, given their fast production, high cost-efficiency of production in comparison to generating natural aggregates, great financial savings due to the elimination of the need to send them to landfill, as well as, their engineering and environmental properties that make them potentially suitable for applications in civil engineering, and particularly, in geotechnics.

Both recycled concrete aggregates (RCA) and recycled steel slag aggregates (RSSA) have been used in construction since the early 1980s; mainly in the construction of unbound granular layers of road pavements (RCA: [16–22]; RSSA: [23–29]). Nevertheless, there are several studies (RCA: [21, 27–35]; RSSA: [27–29, 35]), who report the possibility of this recycling contributing to the reduction of the drainage capacity of the unbound granular layers, as well as the drainage structures (e.g., subdrains, catch basins and spillways) that may be associated with them [27]. The main cause for this may be the formation of tufa, a precipitate of insoluble calcium carbonate, and the recementation of cementitious materials that are not completely hydrated. Due to this behaviour, their use is not recommended, or it is even forbidden, in some states of the USA [36, 37]. However, there are also some studies concluding that tufa formation and recementation are not significant, especially if the percentage of fines is limited to a small percentage [19, 31, 32, 38, 39].

Given the restrictions, or even prohibitions, on the use of RCA and RSSA in unbound granular layers of road pavements, very few studies have been carried out to assess their behaviour as drainage materials [16, 19, 32, 38], which has limited their recycling in drainage structures of geotechnical works (e.g., rainwater drainage layer in landfills, vertical sand drains, and back drainage of earth retaining walls) and road pavements (e.g., longitudinal edge drains, transverse and horizontal drains, permeable bases, and underdrains/deep drains).

In this context, and considering that Freire et al. [40] and Gomes Correia et al. [41] showed that the two recycled aggregates selected for the study presented in this paper, respectively RCA and RSSA, do not release hazardous substances for public health and the environment, and have physical and mechanical properties that allow their recycling in unbound granular layers of road pavements and earth fills, it was considered opportune to assess their drainage capacity with the aim to use them in drainage structures of geotechnical works and road pavements. In addition to evaluating their drainage capacity to tap water, their behaviour to a leachate collected in a municipal solid waste (MSW) landfill, acidified in laboratory from pH 8.2 to 5.5, was also studied. To the authors’ best knowledge, the study of the performance of these recycled aggregates in contact with MSW landfill leachate has not yet been developed. Therefore, another important objective of this study was to assess the feasibility of using these recycled aggregates in the construction of the leachate collection and removal layer (LCRL) of the MSW landfills.

The drainage capacity of RCA and RSSA to water and MSW landfill leachate was compared with that of two natural aggregates, a basalt, and a limestone. Despite studies carried out by Niemann and Hatheway [42] and Bennett et al. [43] concluded that typical landfill leachates would not dissolve significant amounts of carbonate minerals and their use is allowed in some countries, e.g., by the United Kingdom Environmental Agency [44], it continues to be forbidden in others, e.g., by the Portuguese Environment Agency [45] and South Australia Environment Protection Authority [46], or to be limited to a certain percentage, e.g., less than 8.5% in total weight by the Western Australian Environmental Protection Authority [47]. Although hard evidence that carbonate materials are truly unsuitable is lacking [48], there
is a surprising paucity of research concerning the suitability of carbonate aggregate as drainage stone. Therefore, another goal of this study was to evaluate the drainage capacity of the limestone aggregate in contact with the acidified MSW landfill leachate.

The study of the durability of these four aggregates in contact with tap water and the acidified MSW landfill leachate carried out by Roque et al. [49], showed that all of them belong to the “very high” durability class of the classification of Gamble [50].

Materials

Recycled and natural aggregates

The recycled aggregates studied coming from CDW and electric arc furnace SS. The CDW were produced by the Demotri company, of the Ambigroup Group, and their processing in a mobile recycling plant has produced the RCA used in this study. The SS are produced by the two iron and steel plants that exist in Portugal. Together, both plants generate around 250 thousand Mg of SS per year. The recycled aggregate that comes from SS processing is traded under the name Inert Steel Aggregate for Construction (ISAC). Figure 1 shows the RCA and ISAC sampling sites.

The selected natural aggregates were collected in a basalt quarry (BAS), exploited by the Alves Ribeiro company, and a limestone quarry (LIM), belonging to the Agrepor company. The locations of both quarries are also indicated in Fig. 1.

The sampling of recycled and natural aggregates was carried out taking into account, on one hand, the dimensions which they were produced with, and, on the other hand, the required grain-size distributions for carrying out the study. For the RCA, concrete blocks with dimension less than 100 mm were sampled. At the laboratory, these blocks were crushed and sieved to produce the following grain-size fractions: 0.25/0.5 mm, 0.5/1 mm, 1/2 mm, 2/4 mm, 4/12.5 mm, 12.5/16 mm and 16/20 mm (Fig. 2). ISAC was collected in grain-size fractions of 0/6 mm and 0/40 mm (Fig. 2). For the BAS, five grain-size fractions were sampled, as follows: 0/4 mm, 4/12 mm, 10/16 mm and 12/20 mm (Fig. 2). LIM was collected in two grain-size fractions: 0/4 mm and 0/32 mm (Fig. 2).

Samples of the four aggregates were transported to the laboratory in nylon bags and stored at room temperature until the correspondent specimens were prepared to carry out the permeability tests.

According to the macroscopic description of the four aggregates presented in Roque et al. [49], RCA is a heterogeneous and multiphase material, composed by natural aggregates of coarse-grained and fine-grained sizes,
surrounded by a cementitious matrix, which is porous (presence of some pore ≤ 3 mm, dispersed heterogeneously) and light grey in colour; ISAC is a dense material, which presents a vesicular texture, a rough surface, small iron particles and has a black colour; BAS is a compact and melanocratic rock, with aphanitic texture; and LIM is a compact oolithic rock, yellowish to white in colour and contains veins and spherical nodules of calcite. The detailed description of the microscope examination of the four aggregates can be found by Roque et al. [49].

The density (bulk density—\( \rho_b \), and real density—\( \rho_r \)), porosity accessible to water (\( P_e \)) and maximum water absorption under vacuum conditions (\( w_{max} \)) of recycled aggregates (RCA and ISAC) and natural aggregates (BAS and LIM), obtained by Roque et al. [49], are shown in Table 1. According to Roque et al. [49], RCA is the least dense, the most porous and with the highest water absorption capacity, ISAC is the densest, BAS is the least porous and with the lowest water absorption capacity and LIM presents intermediate results compared to the other three aggregates.

### Table 1 Physical properties of the recycled and natural aggregates (adapted from [49])

| Material | \( \rho_b \) (Mg/m\(^3\)) | \( \rho_r \) (Mg/m\(^3\)) | \( P_e \) (%) | \( w_{max} \) (%) |
|----------|-----------------|-----------------|-------------|-----------------|
| RCA      | 2.58            | 2.14            | 16.88       | 7.89            |
| ISAC     | 3.77            | 3.28            | 12.40       | 3.83            |
| BAS      | 3.02            | 3.00            | 12.40       | 0.14            |
| LIM      | 2.72            | 2.58            | 5.40        | 2.20            |

\( \rho_b \) bulk density, \( \rho_r \) real density, \( P_e \) porosity accessible to water, \( w_{max} \) maximum water absorption under vacuum conditions

The main chemical elements of the recycled aggregates, for which it was assessed the feasibility of their use in drainage structures of geotechnical works and road pavements, are included in Table 2.

### Aqueous solutions

The aqueous solutions selected for the experimental program were water (W) from the Lisbon public supply...
network and a leachate (L) from a MSW landfill, operated by the Amarsul Company (AdP Group). Figure 1 shows the MSW landfill location and Table 3 presents the main chemical components of the leachate. Until the performance of the permeability tests, the L was stored in a cold room, at a temperature of about 4 °C.

**Methods**

**Preparation of recycled and natural aggregates**

From the grain-size fractions of each aggregate two mixtures were produced. One in the grain-size range of sand (0.25–2 mm) and the other in the grain-size range of fine gravel (2–20 mm). The plots of the gradation curves and the corresponding percentages of the different grain-size fractions for sand and fine gravel mixtures are shown in Fig. 3. These gradation curves are representative of the gradation curves used in the LCRL of the Portuguese MSW landsfills. The maximum grain-size used was 20 mm to ensure a ratio of about 5 with the diameter of the column used in the permeability tests. According to the Unified Soil Classification System [51], the sand aggregates correspond to a SP poorly graded sand, and the fine gravel aggregates to a GP poorly graded gravel.

The selection of these two grain-size ranges (sand and fine gravel) also allowed to evaluate the influence of the grain-size on the hydraulic performance of the aggregates, in particular of the two recycled aggregates, which has been evaluated in other works [12, 19, 30–32].

### Table 2 Main chemical elements of the recycled aggregates

| Chemical element          | RCA (%) | ISAC (%) |
|---------------------------|---------|----------|
| Aluminium oxide (Al₂O₃)   | 1.2     | 5.8      |
| Calcium oxide (CaO)       | 54.2    | 35.2     |
| Iron oxide (Fe₂O₃)        | 0.7     | 4.4      |
| Magnesium oxide (MgO)     | 0.2     | 0.03     |
| Phosphorus oxide (P₂O₅)   | 2.3     | 15.7     |
| Silicon oxide (SiO₂)      | 0.5     | 0.7      |

### Table 3 Main chemical elements of the MSW landfill leachate

| Chemical element         | Unit | Value |
|--------------------------|------|-------|
| pH                       | –    | 8.2   |
| Electric conductivity    | mS/cm| 34.6  |
| Ammoniacal nitrogen      | g/l  | 4.6   |
| Total nitrogen           | g/l  | 3.6   |
| Biochemical oxygen demand (BOD) | g/l | 1.6 |
| Chemical oxygen demand (COD) | g/l | 10.0 |
| Total organic carbon (TOC) | g/l | 1.86 |
| Phenols                  | mg/l | 0.96  |
| Total phosphorus         | mg/l | 44.0  |
| Bicarbonate (HCO₃⁻)      | g/l  | 21.0  |
| Chloride (Cl⁻)           | g/l  | 4.9   |
| Fluoride (F⁻)            | mg/l | 1.5   |
| Nitrate (NO₃⁻)           | mg/l | 5.0   |
| Nitrite (NO₂⁻)           | mg/l | <0.015 |
| Sulphate (SO₄²⁻)         | mg/l | 360.0 |
| Sulphide (S²⁻)           | mg/l | 6.4   |
| Aluminium (Al)           | mg/l | 2.28  |
| Calcium (Ca)             | mg/l | 34.0  |
| Iron (Fe)                | mg/l | 7.0   |
| Magnesium (Mg)           | mg/l | 43.0  |
| Potassium (K)            | g/l  | 3.13  |
| Sodium (Na)              | g/l  | 3.1   |

### Fig. 3 Grain-size distribution curves of sand and fine gravel used in the preparation of specimens
Specimen preparation

The sand and fine gravel aggregates used in the preparation of the specimens to be used in the permeability tests were dried in an oven at 60 °C, before being poured into a polyvinyl chloride (PVC) column, with the aid of a spoon. The dimensions of the column are, 9 cm in inner diameter and 25 cm in height, which correspond to the dimensions of the tested specimens. The filling of the column with the aggregates was accompanied by blows with a wooden mallet, applied to the upper ring of the wooden structure that supported the column. This procedure is intended to promote the rearrangement of the aggregates’ particles and the densification of their particulate medium. After the column filling was completed, the assemblage of aggregate and column was weighed, and the dry weight of added aggregate was recorded. For each aggregate, two specimens of sand and two specimens of fine gravel were prepared, in a total of 16 specimens. Figure 4 shows the column tops of the sand and fine gravel specimens obtained for the recycled aggregates RCA and ISAC.

Table 4 shows the dry unit weight of the tested specimens. The values varied between 14.9 and 15.2 kN/m³ for RCA, between 21.7 and 24.2 kN/m³ for ISAC, between 17.2

| Material | Influent     | Dry weight of specimen (g) | Dry unit weight (kN/m³) |
|----------|--------------|----------------------------|-------------------------|
| RCA      | Sand         | 2363.3                     | 15.1                    |
|          | Leachate     | 2361.4                     | 14.9                    |
| Fine gravel | Water     | 2349.7                     | 14.9                    |
|          | Leachate     | 2392.7                     | 15.2                    |
| ISAC     | Sand         | 3799.3                     | 24.2                    |
|          | Leachate     | 3769.8                     | 24.0                    |
| Fine gravel | Water     | 3409.8                     | 21.7                    |
|          | Leachate     | 3490.6                     | 22.5                    |
| BAS      | Sand         | 2693.4                     | 17.2                    |
|          | Leachate     | 2828.1                     | 18.0                    |
| Fine gravel | Water     | 3079.5                     | 19.6                    |
|          | Leachate     | 3105.5                     | 19.8                    |
| LIM      | Sand         | 2813.0                     | 17.9                    |
|          | Leachate     | 2805.6                     | 17.8                    |
| Fine gravel | Water     | 2818.6                     | 17.9                    |
|          | Leachate     | 2874.0                     | 18.3                    |

Volume of specimens: 1539.1 cm³

Fig. 4 Top of sand and fine gravel specimens of the recycled aggregates, RCA and ISAC (scale ruler in cm)
and 19.8 kN/m³ for BAS, and between 17.8 and 18.3 kN/m³ for LIM. The ISAC’s dry unit weight was the highest and that of the RCA the lowest. These results were already expected and are attributed to the iron particles present in the constitution of the ISAC aggregates [25, 52], and the mortar adhered to the RCA aggregates [13, 53, 54].

**Leachate preparation**

The pH of L collected at the MSW landfill was 8.2. To test the aggregates under chemically more aggressive conditions, the collected L was acidified in the laboratory, until reaching a pH value of 5.5. This value for the pH was defined considering the possibility that the pH of MSW landfill leachate can reach values of this order of magnitude during the operation period [55, 56].

The acidification of L was achieved by adding 10 ml increments of a 50% hydrochloric acid (HCl) solution. For each litre of MSW landfill leachate, it was necessary to add, on average, about 100 ml of that solution.

**Permeability testing**

Permeability tests were carried out in a rigid-wall permeameter, at a controlled room temperature of about 20 °C. A constant head permeability test was adopted, as it is more suitable than a variable head permeability test for testing coarse soils or aggregates [38]. At the top and bottom of the specimens, previously prepared in the PVC column, a Perspex porous plate was placed. In the sand specimens, on the porous plate, a nylon net was also placed to minimize the migration of the finest particles. Each set was confined between a cover and a base, also in PVC. Both the cover and the base were equipped with two valves. Figure 5 shows the schematic of the setup used in the laboratory permeability tests to generate data for the experimental analyses for this study.

The methodology adopted in the permeability tests intended to approximate the conditions existing in the laboratory to those existing in the MSW landfills, having been defined three distinct test phases. At Phase 1, a minimum volume of about 250 l of W or L percolated through the specimens should be collected. This volume is about three times greater than the volume that would be collected in a LCRL of a MSW landfill, considering an area equivalent to that of the test specimens. For this calculation, it was assumed that the annual production of L in a Portuguese MSW landfill is around 1 m³/m², and that the operation period, up to closure, is projected for 12–15 years. At Phase 2, the permeameter was removed from the test device showed in Fig. 5, and placed in an oven, at a temperature of 45 °C, for a minimum period of 7 days. The placement of the permeameter in the oven at the temperature of 45 °C aimed to simulate the temperature that can be reached in a MSW landfill [57]. After removing the permeameter from the oven and before restarting the permeability test, it was allowed the necessary time for the specimens to reach room temperature. At this stage, a minimum volume of about 30 l of W or L percolated through the specimens should be collected. At Phase 3, which was limited to the four sand specimens percolated with L, the specimens remained in static contact with L for a minimum of 45 days. This phase aimed to promote the reactions between the sand aggregates and L, and to simulate the periods in which it is not possible to collect
L due to the reasons associated with the operating conditions of the MSW landfills. At this last phase, a minimum volume of about 10 l of L percolated through the specimens should be collected.

All permeability tests were carried out until the hydraulic conductivity \(k\) was approximately constant and with a hydraulic head of 0.30 m, which is usually regulated as the maximum height of L above the bottom clay liner of landfills [58, 59]. The permeability tests with this hydraulic head, which correspond to a hydraulic gradient of 2, also contributed to minimize the entrainment of finest particles of the aggregates.

During the permeability tests, the effluent pH was monitored. At the end of the tests, the permeameters were drained and the aggregates placed on trays to dry in an oven at a temperature of 60 °C for 24 h. The dry material was weighed and submitted to grain-size distribution tests, according to the specification E 195 [60].

**Results and discussion**

**Hydraulic conductivity of the aggregates**

Figure 6 shows, on a semi-log scale, the variation of \(k\) as a function of the volume of W or L percolated through the sand and fine gravel specimens of the two recycled aggregates and two natural aggregates. Table 5 presents, for the 16 tested specimens, the values for \(k\) obtained at the different test phases (Phase 1: before oven, Phase 2: after oven, Phase 3: after prolonged static contact with L) as well as the total test time and the total volume of effluent collected.

In all permeability tests performed with the fine gravel specimens, percolated with W or L, the \(k\) value remained approximately constant at Phases 1 and 2. BAS was the most permeable fine gravel aggregate and LIM the least permeable fine gravel aggregate. At the two phases of the test, the following sequences were obtained:

- BAS > RCA > ISAC > LIM, with W;
- BAS > ISAC > RCA > LIM, with L.

In the permeability tests carried out with the sand specimens, the \(k\) values obtained did not show the regularity that was observed in the fine gravel specimens.

When percolated with W, the most significant variations were registered for BAS (Fig. 6c) and LIM (Fig. 6d) sand specimens. For BAS sand specimen, \(k\) value increased from about 140 l of collected effluent. For LIM sand specimen, \(k\) value decreased from about 120 l of collected effluent, which became more accentuated after placing the specimen in the oven. For the recycled aggregates, it was only at the beginning of Phase 2 that there was a change in the \(k\) value for the ISAC specimen, which decreased from around 2 × 10^{-4} m/s to about 0.5 × 10^{-4} m/s. In these tests, the sequence obtained was the same at the two phases, and equal to that obtained in the fine gravel specimens percolated with the same influent (W):

- BAS > RCA > ISAC > LIM.

In the permeability tests carried out with the sand specimens using L as influent, there was only a relevant change for \(k\) value in the BAS specimen, which decreased from around 7 × 10^{-4} m/s to about 1.5 × 10^{-4} m/s at the end of Phase 2 (after oven). In this case, the sequences at the three phases of the permeability tests were as follows:

- Phase 1: BAS = LIM > ISAC = RCA;
- Phase 2: LIM > ISAC = RCA > BAS;
- Phase 3: LIM > ISAC = RCA = BAS.

Figure 7 compares, also on a semi-log scale, the hydraulic performance of the sand and fine gravel aggregates percolated with W (Fig. 7a) or L (Fig. 7b). The value of \(k\) in the fine gravel specimens was always higher than in the sand specimens, consistent with what was expected. It should also be noted that the difference between the values of \(k\) obtained in the sand and fine gravel specimens percolated with W was greater than in the specimens percolated with L.

Figure 8 shows the influence of the influent, W or L, in the hydraulic performance of the aggregates of sand (Fig. 8a) or fine gravel (Fig. 8b). In sand specimens (Fig. 8a), \(k\) values in the permeability tests carried out with L tend to be higher than the ones performed with W. However, in the fine gravel specimens (Fig. 8b), the opposite is observed. It should be noted, additionally, that the extreme values of \(k\) in the fine gravel specimens are much closer (between 9 × 10^{-4} m/s and 28 × 10^{-4} m/s) than in the sand specimens (between 0.2 × 10^{-4} m/s and 18 × 10^{-4} m/s).

Given that \(k\) values remained practically constant for the fine gravel recycled aggregates during the permeability tests, neither tufa formation nor recementation phenomena were observed, which can significantly reduce the drainage capacity of structures that incorporate them or that are adjacent to them, according to different studies carried out in the laboratory and in the field. In the tests carried out with the sand recycled aggregates, \(k\) values did not remain constant throughout the permeability tests; however, the observed changes are also not attributed to tufa formation or recementation. Indeed, on one hand, variations of \(k\) values were more frequent and more accentuated in natural aggregates than in recycled aggregates. On the other hand, the gradation curves of the aggregates obtained at the end of the permeability tests were very similar to the respective reference gradation curves (Fig. 9). If there had been relevant recementation, larger particles would also have formed [39].

To maintain the drainage capacity of the unbound layers built with recycled aggregates coming from crushed concrete and SS, the experience acquired, both at the laboratory and in the field, recommends reducing the percentage of fines [19, 30, 32–34, 38] and proper processing [19], namely,
Fig. 6 Hydraulic conductivity of sand and fine gravel aggregates to tap water and MSW landfill leachate: a RCA; b ISAC; c BAS; d LIM
### Table 5  Hydraulic conductivity of the recycled and natural aggregates

| Material | Influent | Influent Time (day) | Effluent volume (l) | Hydraulic conductivity, $k$ ($\times 10^{-4}$ m/s) |
|----------|----------|---------------------|---------------------|-----------------------------------------------|
|          |          | Phase 1 (before oven) | Phase 2 (after oven) | Phase 3 (after prolonged static contact)      |
| RCA      | Sand     | Water 42            | 310                 | 4                                             |
|          |          | Leachate 73         | 298                 | 4                                             |
|          | Fine gravel | Water 28          | 300                 | 25                                            |
|          |          | Leachate 31         | 290                 | 13                                            |
| ISAC     | Sand     | Water 41            | 285                 | 2                                             |
|          |          | Leachate 73         | 300                 | 4                                             |
|          | Fine gravel | Water 28          | 310                 | 19                                            |
|          |          | Leachate 31         | 290                 | 13                                            |
| BAS      | Sand     | Water 48            | 315                 | 9                                             |
|          |          | Leachate 75         | 305                 | 6                                             |
|          | Fine gravel | Water 28          | 310                 | 28                                            |
|          |          | Leachate 31         | 290                 | 19                                            |
| LIM      | Sand     | Water 46            | 213                 | 0.5                                           |
|          |          | Leachate 75         | 308                 | 6                                             |
|          | Fine gravel | Water 28          | 307                 | 17                                            |
|          |          | Leachate 31         | 290                 | 11                                            |

**Fig. 7**  Hydraulic conductivity of sand and fine gravel of recycled and natural aggregates: a permeated with tap water; b permeated with MSW landfill leachate
the removal of free lime in the SS [28] and the exposure of crushed concrete to atmospheric conditions for an extended period [30, 38].

Regarding the behaviour of LIM percolated with L, the variation of \( k \) values throughout the permeability tests does not indicate that the carbonate minerals have been dissolved, confirming the results obtained in previous studies [42, 43]. The control of the dry mass of the LIM specimens also allowed to verify that their reduction had very little significance at the end of the permeability tests (between 0.10% and 0.69%), and it was comparable with the loss of mass obtained in the remaining specimens (RCA: 0.24–1.35%; ISAC: 0.07–0.81%; BAS: 0.07–0.50%). These results can be explained by the fact that the natural chemical conditions favourable to the karstification (or chemical dissolution) of limestone and dolomite (\( \text{CO}_2 + \text{H}_2\text{O} + \text{CaCO}_3 \leftrightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \)) do not exist in the LCRL of landfills to promote their dissolution. On the other hand, the time required for the formation of karst areas from the dissolution of carbonates it is much longer than the useful lifetime designed for landfills.

**Fig. 8** Hydraulic conductivity of recycled and natural aggregates: a sand permeated with tap water and MSW landfill leachate; b fine gravel permeated with tap water and MSW landfill leachate

**Fig. 9** Grain-size distribution curves of sand and fine gravel of recycled (RCA; ISAC) and natural (BAS; LIM) aggregates, before and after permeability tests
pH monitoring of the effluent

The initial pH value of the influent W, which was around 8.2, increased significantly in the effluents collected in the permeability tests carried out with recycled aggregates. Table 6 shows that effluent pH values between 10.55 and 11.72 were obtained. These high alkalinity values were also mentioned in other studies (RCA: [19, 30, 34, 39, 61]; RSSA: [62]). According to Barca et al. [63], the high alkalinity of RSSA is due to the existence of reactive calcium oxides. In the case of RCA, Nam et al. [19] have considered that it is due to the dissolution of calcium, sodium, and potassium hydroxides, which exist in the mortar. During the performance of the permeability test, the pH value of the collected W decreased very slightly in all specimens, with the most accentuated decrease, of 2.2 units, to be verified at the RCA fine gravel. In the remaining specimens, the decrease in pH was between 1.08 and 1.53 units. Similar evolution was also observed in other studies with RCA [31, 32, 34]. Regarding the RSSA, no reference was found to the variation in pH with the volume of effluent collected, in the literature reviewed. In natural aggregates, the pH value of the W collected was much lower than the effluent pH of the recycled aggregates, and it was only slightly higher than the initial pH value of the influent W, except in the case of BAS sand. During the permeability tests, the decrease in effluent pH varied between 0.34 and 1.62 units, being, therefore, less accentuated than in recycled aggregates.

For permeability tests carried out with influent L, where the initial pH was 5.5. Table 6 shows that only the effluent collected in recycled aggregates (RCA and ISAC) showed alkaline characteristics. However, during the permeability tests carried out on these aggregates, the effluent pH decreased until it presented acidic characteristics. In recycled aggregates, the effluent pH decreased between 2.29 and 3.17 units, and in natural aggregates, between 0.40 and 0.74 units.

The set of results obtained with recycled aggregates shows that the pH of the effluent is higher in sand aggregates than in fine gravel aggregates, which is consistent with the smaller size of the sand particles and the increase in its specific surface. In natural aggregates, the pH of the effluent is approximately the same in sand and gravel aggregates.

### Practical geotechnical applications

The $k$ value typically required for the LCRL landfills is equal to, or greater than, $1 \times 10^{-4}$ m/s [45, 59, 64]. Figure 7b shows that both sand and fine gravel aggregates percolated with L fulfilled the minimum requirement of $k \geq 1 \times 10^{-4}$ m/s, although compared to most of the grading envelopes required [65], the grain-size fractions of the tested specimens are finer.

Under normal conditions, in all other geotechnical applications and in the drainage layer of the final cover of landfills, the aggregates only contact with W at room temperature. Therefore, the $k$ values obtained at Phase 1 of the permeability tests were taken into account to analyse the technical feasibility of using the tested aggregates, in particular the RCA and ISAC.

Considering that the $k$ required for the drainage layer of the final cover of landfills is typically similar to that required for their LCRL, it is noted that both grading fractions for all tested aggregates fulfilled the foreseen requirement. The exception in it is the LIM sand. It is important to reemphasize that the $k$ values were obtained with finer grading fractions than those usually required, so that the existing specifications will be, in some way, conservative.

For drainage layers of road pavements, the required values for $k$ are typically equal to, or greater than, $1 \times 10^{-3}$ m/s [66, 67]. For these applications, only the fine gravel aggregates have $k$ values with the required order of magnitude. Considering, however, that the nominal grain-sizes usually required [66–69] are larger than those of the tested fine gravel, it can be considered that their empirical designing is conservative for obtaining $k \geq 1 \times 10^{-3}$ m/s.

At the inside face of retaining walls, the material with drainage functions should typically present $k > 1 \times 10^{-5}$ m/s [70] and nominal grain-sizes of 20 mm. In this case, whatever the grading fraction of the tested aggregates, the minimum requirement is fulfilled.

For vertical sand drains, no references were found on the values required for $k$, only grading envelopes, corresponding
to clean sands. According to IDOT [71] and IP [72], these materials should have a percentage of fines (≤ 0.075 mm) less than 3% and 6%, respectively. FHWA [73] specified a percentage less than 4% for particles with an equivalent diameter less than or equal to 0.106 mm. The grading characteristics of the tested sand specimens and the obtained k values allow us to consider that the studied sand aggregates are suitable for building vertical sand drains.

By the exposed, the presence of fines in aggregates to be applied in drainage structures should be very low, as they increase the possibility of tufa formation, the development of recementation phenomena, and clogging. Considering that RCA is very susceptible to the production of fines during storage, transport, and application [19], its handling should also be guided to minimize them.

It should be pointed out, finally, that the two recycled aggregates are potentially corrosive to aluminium or galvanized iron pipes placed in direct contact with them, due to their high alkalinity [62]. In Germany, for example, aggregates applicable to road pavements must have a pH ≤ 10–13 [62]. Despite the high alkalinity of these recycled aggregates, the environmental hazard of the effluents generated from them is unlikely and restricted to a small region near the applied material, due to the usual natural dilution [34].

Conclusions

The results of the study of the drainage capacity of two recycled aggregates and two natural aggregates, percolated with a leachate coming from a municipal solid waste (MSW) landfill (acidified to pH 5.5) and tap water, are presented. The recycled aggregates, a recycled concrete aggregate (RCA) and an inert steel aggregate for construction (ISAC), respectively, coming from the processing of construction and demolition waste (CDW) and electric arc furnace steel slag (SS), and the natural aggregates, respectively, from basalt (BAS) and limestone (LIM) quarries. Considering that the main goal is to promote the use of recycled aggregates in the construction of drainage structures for geotechnical works and road pavements, the analysis of the results focused mainly on the hydraulic performance of recycled aggregates, supported in comparison to the hydraulic performance of natural aggregates.

Contrasting to what has been observed in several published studies, there were no decreases in the hydraulic conductivity of the two recycled aggregates (RCA and ISAC), which presented a hydraulic performance similar to that of natural aggregates (BAS and LIM). On the other hand, the maintenance of the drainage capacity of recycled aggregates during the development of permeability tests confirms the conclusions of other studies referenced in this paper. According to those studies, it is important to eliminate, or reduce, the percentage of fines and reactive elements responsible for the formation of tufa and the development of the phenomena of recementation and clogging. It follows that a proper processing and handling of these recycled aggregates are crucial to their adequate hydraulic performance. In the results obtained, there is also no evidence of the inadequacy of the drainage capacity of the limestone aggregate for the construction of leachate collection of removal layer (LCRL) of the MSW landfills, as it is admitted in several countries, due to the possibility of dissolution of carbonate minerals. It was also observed that with finer grading ranges than those required by the regulations, hydraulic conductivity values equal to, or higher than those defined for these were obtained, indicating that the grain-size distributions or grading envelope required, mostly based on empirical principles, could be conservative.

Considering the hydraulic performance obtained for the studied recycled aggregates (RCA and ISAC), complemented by the results obtained on their environmental, physical, and mechanical characteristics in previous Portuguese studies, it is concluded that under the laboratory-tested conditions, they will be suitable for the construction of drainage structures of geotechnical works (e.g., LCRL and stormwater drainage layers of landfills, vertical sand drains, and drains at the inside face of retaining walls) and road pavements (e.g., longitudinal edge drains, transverse and horizontal drains, permeable bases, and underdrains/deep drains). The study carried out also allows us to conclude that the LIM aggregate could be used in the construction of LCRL of MSW landfills.

The results obtained in this study, by enabling the applicability of recycled concrete aggregates (RCA) and recycled steel slag aggregates (RSSA) in the drainage structures of geotechnical works and road pavements, will contribute to the preservation of natural resources and for the reduction of the disposal of CDW and SS in landfills, that is, for a more sustainable construction.

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References

1. UN (2018) Sustainable cities: Why they matter. United Nations (UN), New York (NY), USA. https://www.un.org/sustainabledevelopment/wp-content/uploads/2018/09/Goal-11.pdf. Accessed 16 Feb 2021
2. UN (2019) The strategic plan 2020–2023. United Nations (UN), New York (NY), USA. https://unhabitat/sites/default/files/
1. EEA (2020) COVID-19 measures have mixed impacts on the environment. European Environment Agency (EEA), Copenhagen, Denmark. https://www.eea.europa.eu/highlights/impact-of-covid-19-lockdown. Accessed 16 Feb 2021

2. Akhtar A, Sarmah AK (2018) Construction and demolition waste management in Australia: a mini-review. Waste Manag Res 34:1872–1–13

3. Rodriguez C, Parra C, Casado G, Miñano I, Albaladejo F, Benito F, Sánchez I (2016) The incorporation of construction and demolition wastes as recycled mixed aggregates in non-structural concrete precast pieces. J Clean Prod 127:152–161. https://doi.org/10.1016/j.jclepro.2016.03.137

4. Kaza S, Yao L, Bhada-Tata P, Van Woerden F (2018) What a waste 2.0. A global snapshot of solid waste management to 2050. Urban Development Series, International Bank for Reconstruction and Development / The World Bank, Washington (DC), USA. file:///C:/Users/Aroque/Downloads/9781464813290.pdf. Accessed 20 Jan 2021

5. Asif M, Muneer T, Kelley R (2007) Life cycle assessment: a case study of a dwelling home in Scotland. Build Environ 42(3):1391–1394. https://doi.org/10.1016/j.buildenv.2005.11.023

6. Ceylan H, Kim S, Gopalakrishnan K (2014) Use of crushed/recycled concrete as drainable base/subbase & possible future plugging of pavement systems. Institute for Transportation, Iowa State University, Ames (IA), USA. https://www.extension.iastate.edu/registration/events/conferences/ascegeotech/presentations/Ceylan%20-%202014%20ASCE%20Iowa%20Geotechnical%20Engineering%20Conference.pdf. Accessed 7 June 2020

7. Evangelista L, Guedes M, de Brito J, Pereira MF (2015) Physical, chemical and mineralogical properties of fine recycled concrete aggregates made from concrete waste. Constr Build Mater 86:178–188. https://doi.org/10.1016/j.conbuildmat.2015.03.112

8. Cecozi (2014) Resource efficiency in the building sector. Cecozi, Rotterdam, the Netherlands. https://ec.europa.eu/environment/eussd/pdf/Resource%20Efficiency%20in%20the%20Building%20Sector.pdf. Accessed 7 June 2020

9. Hurd JO (1988) Effect of unbound crushed concrete bases on PCC pavement drainage. Transp Res Rec 1192, National Academy of Sciences, Washington (DC), USA, pp 79–84. http://onlinelibs.trb.org/OnlineLibs/trr/1994/1434/1434-002.pdf. Accessed 3 Feb 2021

10. Hurd JO (1988) Effect of slag type on tufa precipitation formation. Transp Res Rec 1192, National Academy of Sciences, Washington (DC), USA, pp 79–84. http://onlinelibs.trb.org/OnlineLibs/trr/1994/1434/1434-002.pdf. Accessed 3 Feb 2021
64. Koerner RM (1993) Collection and removal systems. In: Daniel DE (ed) Geotechnical practice for waste disposal. Chapman & Hall, London, pp 187–213
65. Jones DRV, Hall DH (2002) Landfill engineering: leachate drainage. Collection and Extraction Services, R&D Technical Report P1–39/7, Environment Agency, Bristol, UK
66. CDOT (2019) Seepage & Groundwater. In Drainage Design Manual, Colorado Department of Transportation (CDOT), Denver (CO), USA. https://www.codot.gov/business/hydraulics/drainage-design-manual. Accessed 10 Feb 2021
67. FHWA (2006) Geotechnical aspects of pavements. Reference Manual/Participant Workbook. Report FHWA NHI-05–037, Federal Highway Administration (FHWA), United States Department of Transportation, Washington (DC), USA. https://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05037.pdf. Accessed 11 Feb 2021
68. HA (2021) Drainage and service ducts. In Manual of Contract Documents for Highways Works, Highways Agency (HA), London, UK. https://www.standardsforhighways.co.uk/ha/standards/mchw/vol1/pdfs/MCHW%20Vol%201%20Series%205000%20web%20PDF.pdf. Accessed 11 Feb 2021
69. MRWA (2019) Sub-soil drains (Specification 403). Main Roads Western Australia (MRWA), Perth, Australia. https://www.mainroads.wa.gov.au/globalassets/technical-commercial/technical-library/specifications/400-series-drainage/specification-403-sub-soil-drains.pdf. Accessed 5 Feb 2021
70. DTMR (2018) Reinforced soil structures. Transport and Main Roads Specifications, MRTS06, Department of Transport and Main Roads (DTMR), Queensland, Australia. file:///C:/Users/Aroque/Downloads/MRTS06%20(1).pdf. Accessed 4 Feb 2021
71. IDOT (1976) Evaluation of different types of sand drains. Illinois Department of Transportation (IDOT), Springfield (IL), USA
72. IP (2009) Earthwork: Material’s characteristics. Technical specifications – 14.01 (in Portuguese). Infraestruturas de Portugal. https://www.infraestruturasdeportugal.pt/sites/default/files/cet/14_01_fev_2009.pdf. Accessed 10 Feb 2021
73. FHWA (1986) Prefabricated vertical drains. Engineering Guidelines. Report FHWA RD-86/168, Federal Highway Administration (FHWA), United States Department of Transportation, Washington (DC), USA. file:///C:/Users/Aroque/Downloads/dot_25323_DS1.pdf. Accessed 9 Feb 2021

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