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Review

A Literature Review on the Use of Recycled Construction and Demolition Materials in Unbound Pavement Applications

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Abstract: The construction industry is one of the biggest sectors of economic activity in the European Union, consuming more energy and natural resources than any other industrial activity. Additionally, construction and demolition (C&D) waste is the most common waste produced throughout the European Union. A more efficient and effective use of natural resources and the attenuation of environmental impacts provoked by their extraction could be accomplished if correct construction and demolition waste management and recycling policies were implemented. The use of recycled C&D waste in road pavement layers is a solution with economic and environmental benefits that has been widely studied in recent decades. This paper provides a literature review on the relevant engineering properties of different types of recycled aggregates coming from C&D waste, a comparison with the properties of natural aggregates, and how these recycled aggregates perform in the long-term when used in unbound pavement applications. An analysis of the current status of C&D waste generation and recovery practices in the European Union is also presented. The aim of this review is to further encourage the use of recycled materials coming from C&D waste, particularly in unbound pavement applications, since, in general, research conducted worldwide has proven their good performance in the short and long-term.

Keywords: environmental sustainability; construction and demolition waste; recycled aggregates; long-term behaviour; unbound pavement applications

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1. Introduction

The construction industry produces large amounts of waste resulting from various activities, such as the cleaning of construction sites, leftovers and waste materials from construction, demolition and maintenance, conservation and rehabilitation of structures and infrastructures. At the same time, the construction industry consumes large quantities of natural resources.

Reducing the exploitation of non-renewable natural resources has long been one of the constant concerns associated with preserving the environment. The significant consumption of natural resources, around 14.0 ton/year per capita in the European Union (7.1 ton/year per capita are non-metallic minerals, making up half of the total) [1], makes it necessary to promote significant changes in patterns of consumption. It is therefore fundamental to promote studies and applications involving alternative materials.

Nearly all human and industrial activities generate some kind of waste, and the increasing accumulation of this is the cause of serious economic and environmental concern all over the world. In 2020, the total waste generated in the European Union (EU) was 2151 million tonnes [2]. Demolition and construction activities (798 million tonnes, 37.1% of the total) and quarrying and mining activities (504 million of tonnes, 23.4% of the total) are the main economic sectors that generated waste in 2020 (Figure 1). It is worth mentioning that 96.5% of the total waste produced by these two sectors were soils or mineral waste (waste rocks, excavated earth, construction and demolition waste, road construction waste, dredging spoil, tailings, and others). The amount of rare mineral waste in relation to the total waste generated was 64.0% [2].

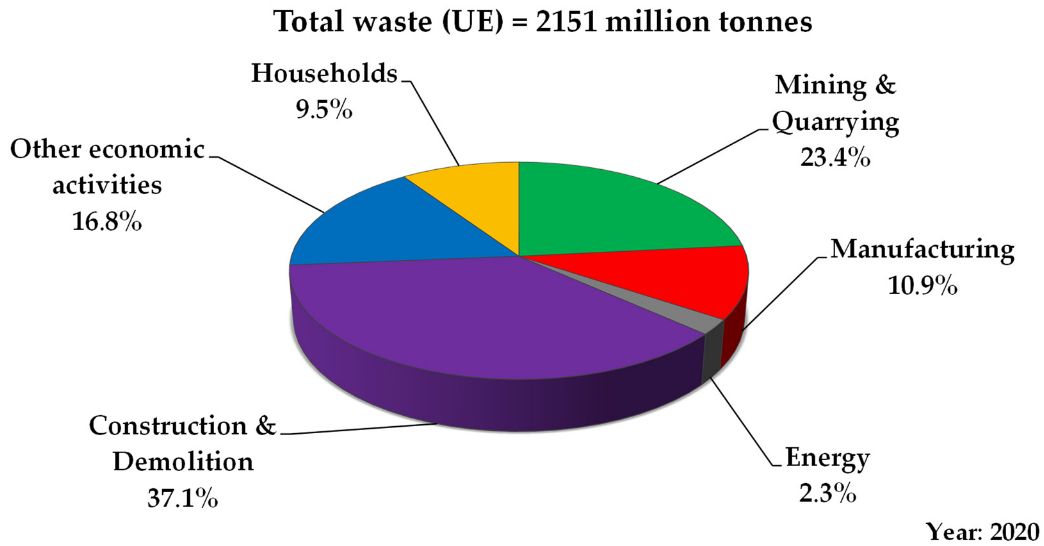

Figure 1. Distribution of waste generated in 2020 by domestic consumers and economic activities in the European Union (data from [2]).

Construction and demolition (C&D) waste is a huge and voluminous waste stream, representing around 35% of all waste generated in the EU, four times more than the total household waste produced. C&D wastes are composed of various materials, such as bricks, concrete, glass, wood, metals, gypsum, plastics, excavated soils, solvents, and asbestos, many of which have the potential to be recycled. C&D wastes arise from a wide range of activities, including the construction, maintenance, rehabilitation and demolition of buildings, and civil engineering infrastructures.

C&D waste, dumped illegally in ravines and open areas, contaminates soil and can cause underground water pollution and forests fires. The illegal dumping of C&D waste can cause risks to human health and to the environment, including transportation obstacles leading to accidents, impact on the urban landscape, air pollution, soil and groundwater contamination, degraded infrastructure, and waste of land [3,4].

The recycling of C&D waste is an antique practice, conducted by Ancient Egyptians, Greeks, and Romans. In the 20th century, after World War II, it began to find expression during the reconstruction of buildings in Europe [5].

In recent years, the circular economy concept has attracted increasing attention. Its goal is to offer an alternative method to dominant traditional models of consuming natural resources. It focuses on three main approaches: reduction, re-use, and recycling.

The use of recycled C&D wastes reduces natural resources' consumption and avoids the landfilling of inert materials. Despite these advantages, some developed countries have very low recycling rates of C&D waste [6].

Geotechnical design and construction, which are often placed at the beginning of a civil engineering project, can significantly contribute to improving overall sustainable development by incorporating sustainable practices, including the use of unconventional, environment friendly materials and the reuse of waste materials such as the C&D waste [7–9]. In Europe, around 40% of natural aggregates are consumed in unbound layers of transportation infrastructures [10]. This suggests that the dependence on natural aggregates in geotechnical works is high, and that the inclusion of recycled aggregates can significantly contribute to the perseveration of the environment.

In recent decades, several studies have been carried out showing the possibility of using recycled aggregates from C&D waste in concrete [11–14], pipe bedding and backfilling [15,16], and in base and sub-base layers of transportation infrastructures [17–24].

However, there are very few studies regarding the long-term behaviour of recycled C&D materials, particularly in geotechnical applications. Being unconventional materials, it is fundamental to enable their wide application gain the confidence of the construction industry, by providing evidence of their suitable long-term performance.

A more extensive use of recycled aggregate in transportation infrastructures is key to meeting the ambitious targets of the EU circular economy action plan.

As a framework of this theme, this paper presents, first, an overview on the legislation and C&D waste recycling rates in the European Union. Thereafter, a literature review on the research and application of recycled aggregates from C&D waste, with an emphasis mainly on their use as a filling material for embankments and as base and subbase layers for transportation infrastructures, is pointed out. Physical, mechanical, and geotechnical properties of recycled C&D materials have been studied by researchers all over the world. Their main findings are described and discussed herein. The paper ends with some case studies on the use of recycled aggregates in unbound pavement layers.

The goal of this review is to further encourage the use of recycled aggregates coming from C&D waste, particularly in unbound pavement applications, since, in general, research conducted worldwide has proven their good performance in the short and long-term.

2. State of Play in the European Union

2.1. European Union Legislation on C&D Waste

In the EU, there is currently no specific legislation for C&D waste. This waste stream is regulated by the Waste Framework Directive [25], which institutes the legislative framework for waste management in the community. In this Directive, there are two important references concerning C&D waste. One is related to the exclusion from the scope of the Directive uncontaminated soil and other naturally occurring excavated materials (subparagraph (c) of Article 2: "uncontaminated soil and other naturally occurring material excavated in the course of construction activities where it is certain that the material will be used for the purposes of construction in its natural state on the site from which it was excavated shall be excluded"). The other one refers to the recycling target to be reached by 2020 (subparagraph (b) of Article 11: "by 2020, the preparing for re-use, recycling and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste (. . .) shall be increased to a minimum of 70% by weight").

In the EU, some countries took measures way before Directive 2008/98/EC, creating various regulations and initiatives to encourage proper C&D waste management. For instance, in the Netherlands, there have been a variety of initiatives since 1993 which led to a C&D waste recycling rate of 90% in 1999 [26]. The main factors used to achieve this high recycling rate were the separation at source of various types of C&D waste, a healthy market for recycled products, and prohibition of the landfill of recyclable C&D waste. Since 2000, most landfills have obtained an exemption from the C&D waste landfill ban, due to insufficient capacity to recover or incinerate these waste streams [26]. However, landfilling this fraction is not attractive because of the high landfill fee (€122 per tonne).

Another example of best practice in the management of C&D waste is Denmark, where C&D waste recycling is a common practice. The target of achieving, in 2004, a recycling rate of 90% was reached in 1997, and it has remained at this level since then [26]. Until the 1980s, Denmark still relied heavily on landfills. The move from landfills was precipitated by concerns about groundwater pollution, particularly because all of Denmark's drinking water comes from groundwater [26]. In 1985, the Danish Environmental Protection Agency began to regulate the reuse of asphalt. In 1990, it allowed the reuse, without prior approval, of clean stone materials, unglazed tile materials, and concrete in building and construction works [27]. Later, local councils were tasked with the duty of drafting regulations on C&D waste in order to increase its recycling. Regulations should cover provisions that mandate separation at source when the total C&D waste from a building or construction project exceeds 1 tonne [27]. The waste tax for landfilling C&D waste, one of the highest in the EU, has also proved to be an effective tool to increase the recycling of C&D waste.

However, there are still many EU countries where the management of C&D waste is at an early stage, needing to go a long way in order to achieve the success of countries with higher levels of development. This is the case of Portugal and Spain, whose governments only passed a national decree to regulate the production and management of C&D waste in 2008.

It is also important to mention that the European Commission developed the EU Construction and Demolition Waste Protocol [28], published in 2016, aiming at the proper management of this waste stream, which can bring considerable benefits to the construction and recycling sectors.

The EU Construction and Demolition Waste Protocol contains a relevant set of guidelines aimed at improving the identification, separation and collection at source, logistics, processing, and quality management along the entire line of C&D waste management, boosting recycling and confidence in the quality of recycled materials.

2.2. Composition of C&D Waste

The constitution of C&D waste depends largely on the type of construction site. For instance, a road construction generates a large quantity of excavated soils and rocks that, should it not be possible to use them afterwards, will become waste. Depending on the region of the globe, a huge amount of concrete waste or mixed waste (concrete, mortar, brick masonry, ...) is produced in a building demolition site. Therefore, the diversity of construction activities makes it hard to establish reliable consumption standards or waste generation rates per capita, per work, or per square metre of construction. In a benchmarking exercise, various researchers have sought to establish quantitative ranges of C&D waste generation rates depending on the construction techniques, structure type, and traditional practices [26]. These rates tie the construction activity and the quantity of waste per unit of built, rehabilitated, or demolished area to indicators of C&D waste, for different types of techniques, structures, and practices. For example, precast structures generate less C&D waste because the fabrication process is very controlled and currently specific for each construction. In the meantime, the expected volume of C&D waste and its constitution is substantially different if reinforced concrete structures or timber are used. New buildings' construction generates 18 to 33 kg per m^2 of built-up area of concrete waste with the use of concrete structures, while timber-based structures produce 10 times less waste [26]. The demolition of residential buildings can produce up to 840 kg of concrete waste per m^2 demolished, whereas the demolition of timber-based structures can generate up to 300 kg per m^2 [26].

Table 1 offers a summary of the range of components of C&D waste across the EU [6]. C&D waste is generally composed of large amounts of inert materials with smaller quantities of other components.

The European Commission has published a comprehensive list with specific codes for the wastes arising from different economic activities, usually referred to as the European List of Waste (LoW), stipulated by the Commission Decision 2000/532/EC [29] and amended by the Commission Decision 2014/955/EU [30]. Chapter 17 of the LoW refers to C&D wastes, providing a specific code (with six digits) for the main types of wastes produced by the construction industry.

The variety in the composition of C&D waste is due to factors such as construction time, origin of production, and local construction practices. This variability conditions its recovery, so an adequate sorting and selection of the appropriate preparation process becomes a basic requirement for consideration in the production of recycled aggregates of quality and added value.

Selective demolition, also known as "construction in reverse" or "deconstruction", consists in a sequence of demolition activities that allow the separation and sorting of building components and valuable building materials such as metals, windows, doors, tiles, bricks, plasterboards, and so on [28].

Selective demolition is normally carried out in two phases. The first is characterized by the rigorous dismantling of construction materials used to fill the buildings, and is carried out using mainly manual techniques that involve the use of small equipment, such as pneumatic hammers [31]. The second concerns the demolition of the main structure of the building, separating the materials that constitute it. The separation of materials is carried out according to their characteristics, in a safe and efficient way, minimizing dust, noise and vibrations [31].

Table 1. Ranges of composition of C&D waste by waste category for European countries (according to [6]).

Waste Category	Minimum Percentage (% *w*/*w*)	Maximum Percentage (% *w*/*w*)
Concrete and Masonry (Total)	40.0	84.0
Concrete	12.0	40.0
Masonry	8.0	54.0
Asphalt	4.0	26.0
Others Mineral Waste	2.0	9.0
Wood	2.0	4.0
Metal	0.2	4.0
Gypsum	0.2	0.4
Plastics	0.1	2.0
Miscellaneous	2.0	36.0

Selective demolition allows for the implementation of systems for the selective collection of waste at the place of its production with a view to its maximum recovery. From a general point of view, selective demolition has several advantages over the traditional one, which are [31,32]:

- Increased diversion rate of C&D wastes from landfill and consequent land use preservation;
- Valorisation of waste as secondary raw materials consequently reducing the need for primary raw materials;
- Enhanced environmental protection both at the local and global scale by reducing waste landfilling and the use of new materials;
- Reduction in overall demolition costs through landfill charge savings and revenues from the sale of secondary raw materials.

All these aspects lead to the perception of selective demolition as absolutely essential for a sustainable built environment.

2.3. Recovering Rates of C&D Waste

The term "recycling" is difficult to apply coherently to C&D waste across countries, as there is a wide range of recovery and recycling activities carried out. Recovery can, to a small extent, be incineration of waste with energy recovery, but generally the term recovery is used as "material recovery", namely backfilling operations using waste to replace other materials.

C&D waste was identified as a priority waste stream by the EU, and thus, the European Commission approved the Waste Framework Directive 2008/98/EC [25] which promotes waste recovery and sets a specific target for C&D waste recovery.

It should be noted that the 70% recovery target for non-hazardous C&D waste in the Waste Framework Directive [25] includes "preparing for re-use, recycling and other material recovery including backfilling operations [. . .]". Furthermore, the definition of recycling unequivocally excludes "[. . .] the reprocessing into materials that are to be used as fuels or for backfilling operations".

Figure 2 illustrates the different recovery levels of C&D waste using a colour scale. A very high recovering rate is represented by a dark green colour and an orange colour indicates a low recovering rate (<70%). Dark blue identifies the countries that have a 100% C&D waste recovery rate.

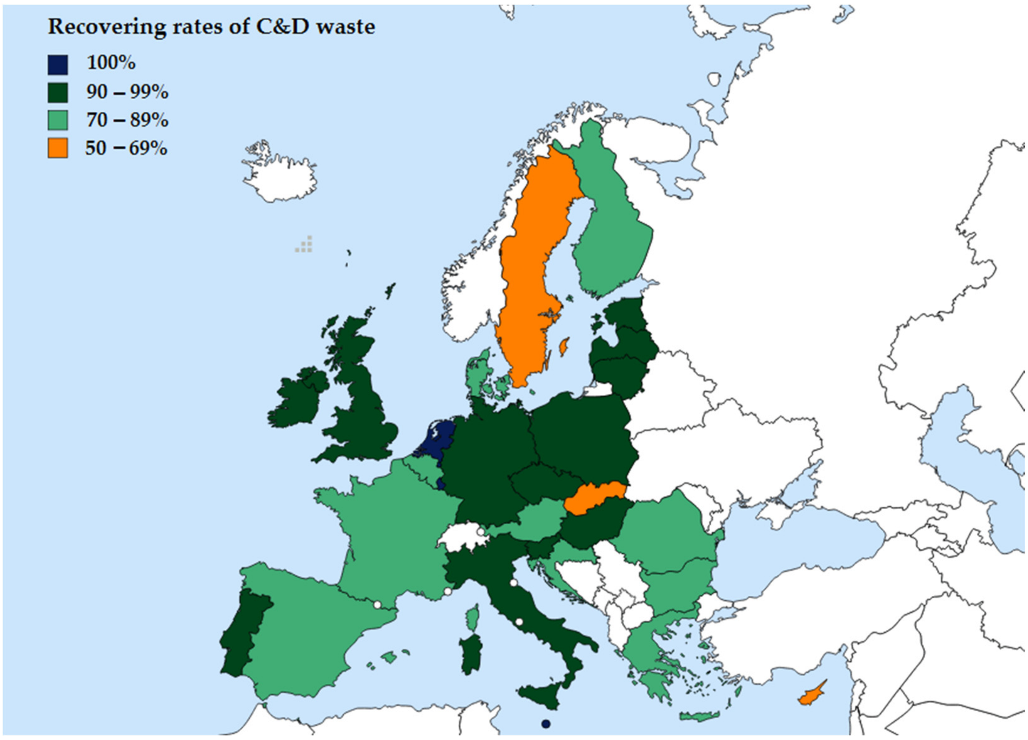

Figure 2. EU recovering rates of non-hazardous C&D waste in 2018 (data from [33]).

According to European Environment Agency [29], in 2018, the EU generated around 393 million tonnes of no-hazardous C&D waste (Table 2). The recovery rate of non-hazardous C&D waste is generally high in EU countries (Figure 2). Most countries in 2018 already meet the Waste Framework Directive target [25] to prepare for reuse, recycling, or other material recovery, including backfilling operations, 70%, by weight, of non-hazardous C&D waste.

Table 2 and Figure 2 show that there are three EU countries (Luxembourg, Malta, and the Netherlands) which in 2018 have reporting 100% recovery rates. In these countries, it three main factors encouraging high levels of C&D waste recycling can be found: limited availability of raw materials; difficulty finding places for landfill installation; and economic and legal measures that promote recovery. In contrast, there are other countries where the recycling rate is below 70% (Cyprus, Slovak Republic, and Sweden) (Table 2). The average recovery rate of C&D waste in EU was 88%. It is important to note that there are some uncertainties around the reporting of C&D waste treatment by EU countries.

The low recovery rates of C&D waste in some EU countries can mainly be attributed to the following reasons:

- Landfill prices are low and the penalties for contravention are generally small or non-existent;
- Available raw materials offer sufficient quality at a moderate cost, and therefore, the recycled C&D materials industry is not really established in the market (low-cost of raw materials is a fierce competition with recycled materials);
- Inadequate C&D waste management models. Although some countries have introduced preventive measures for the recovery of waste materials, several years ago, the C&D waste generated in some EU countries was still dumped in legal or illegal landfills.

By contrast, countries with high recovery rates have high prices for waste disposal and strong financial incentives when the construction firms separate the C&D waste in different fractions before its disposal.

Table 2. Statistics of the quantities of non-hazardous C&D waste generated and recovery in the EU (according to [33]).

Country	Total Weight C&D Waste Generated (Million Tonnes)	% Recovery (Recycled and Backfilling)
Austria	11.43	88
Belgium	22.28	84
Bulgaria	0.16	89
Croatia	0.64	75
Cyprus	0.33	57
Czech Republic	7.47	92
Denmark	4.61	89
Estonia	1.21	97
Finland	1.72	84
France	73.37	70
Germany	90.73	91
Greece	1.44	88
Hungary	3.50	99
Ireland	0.73	96
Italy	46.29	98
Latvia	0.39	98
Lithuania	0.82	97
Luxembourg	0.59	100
Malta	1.91	100
The Netherlands	22.22	100
Poland	7.37	91
Portugal	1.67	97
Romania	0.74	85
Slovak Republic	0.82	53
Slovenia	1.08	98
Spain	14.70	79
Sweden	3.40	60
United Kingdom *	71.29	96
EU	392.92	88

* The UK is currently outside the EU.

The Waste Framework Directive [25] targets backfilling as "a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials". Backfilling is classified as recovery under the Waste Framework Directive [25], but the definition of recycling excludes its use for backfilling operations. Backfilling can be regarded as low-quality recovery, being lower in the waste hierarchy than recycling [33].

Nonetheless, some countries (Croatia, Czech Republic, Estonia, Ireland, and Portugal) have achieved high recovery rates due to backfilling, while recycling rates in these countries are low (Figure 3); for example, in Malta, in 2018, backfilling accounted for 100% of the recovery, whereas 24% was recycled. Backfilling was a determining factor for some EU countries to meet the EU 2020 target.

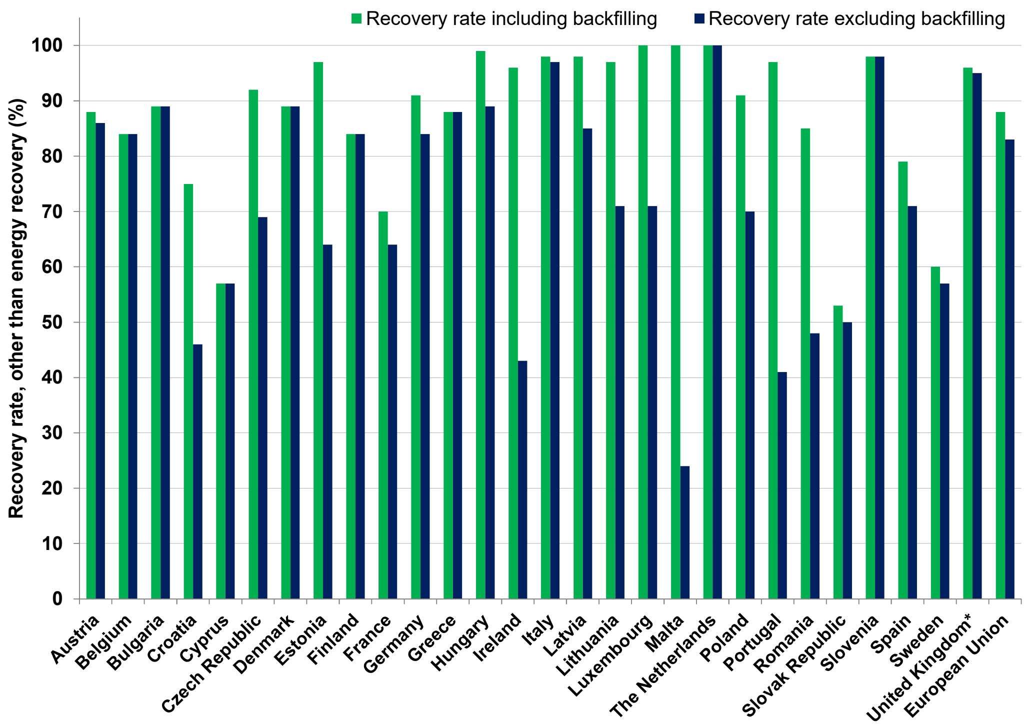

Figure 3. Recovery rates from C&D waste in the EU in 2018—including and excluding backfilling (data from [33]).* the UK is currently outside the EU.

The amount of C&D waste generation and recycling varies significantly from one country to another. This difference has been discussed in several studies, which conclude that the great disparity of data is due to differences in terms of the constructive tradition of the country, lack of control and C&D waste data reporting, lack of common definitions, C&D waste categories, or even different management alternatives [6].

2.4. Use of C&D Waste towards a Circular Economy in the Construction Industry

The circular economy represents a fundamental alternative to the linear economic model (“take, make, consume, and dispose”) that still prevails. This linear model is based on the supposition that natural resources are available, abundant, easy to obtain, and cheap to dispose of. Nevertheless, the linear model is unsustainable, as the world is moving towards (and in some cases exceeding) environmental boundaries.

The circular economy is restorative by nature and aims to maintain the usefulness of products, components, and materials for as long as possible while preserving their value. Thus, it minimises the need for new inputs of energy and virgin materials, while reducing environmental pressures related to emissions, resource extraction, and waste management. This goes beyond just waste and requires efficient and sustainable management of natural resources throughout their lifecycle [34].

The principal phases of a circular economy model are presented in Figure 4. Each of these phases offers different opportunities to decrease costs and the dependence on natural resources, to boost new business models, as well as to reduce the production of waste and emissions for the environment. All of these phases shall be interlinked, aiming to reduce the resources that escape the circle.

The key advantage of the circular economy systems is that the added value of the products and services shall be maintained for as long as possible, and the production of waste eliminated. The resources are kept within the economy when the product reaches the end of its life, so that they can be reused more efficiently and therefore create more value. The transition to a circular economy requires systematic and innovative changes in society, technologies, policies, and financial methods.

According to Baldassarre et al. [35], the transition to a circular economy requires the establishment of a framework supported on three strategies: closing the loops, slowing the loops, and reducing/narrowing the loops. Closing the loops refers to generating a circular flow of resources arising from the usage phase and considered generally as waste. Slowing loops consists of extending the product's lifetime and reusing it through operations such as remanufacture, refurbishment, and repair. Narrowing the loops means reducing the need for resources and simultaneously maximizing the efficiency of the production processes.

Figure 4. The main phases of a circular economy model (adapted from [36]).

Extending the product life use can be a very effective strategy to reduce the utilisation of resources. Long-life product design shall be sustained by design for trust and attachment (often referred to as emotional durability), physical durability, and reliability. Designing or extending product life can be facilitated by designing for repair and maintenance; upgrading and upgradability; compatibility and standardization; and disassembly and reassembly [37].

One of the major design strategies used to slow resource loops is long-life product design. During the design process, the use of the products for a long period should be guaranteed, and durable materials should be selected.

In 2014, the EU published the Communication "Towards a circular economy: A zero waste programme for Europe" (COM/2014/0398) [36], followed in 2015 by the Communication "Closing the loop. An EU action plan for the circular economy" (COM/2015/0614) [38]. These two documents are part of the "Circular Economy Package", where several legislative proposals and action plans highlighting each stage of the value chain (production, consumption, waste management and secondary raw materials) are presented. Five important sectors: critical raw materials, plastics, construction and demolition waste, food waste, and biomass and bio-based products are also identified.

In the demolition and construction industry, the circular economy is a tool to pro-mote more efficient C&D waste management and to reduce resource and emission leaks from the loops.

Table 3 presents an overview of the most important strategies and initiatives developed in the EU regarding C&D waste management and circular economy in demolition and construction industries.

Table 3. Overview of current EU circular economy initiatives in the C&D waste sector.

Circular Economy Initiatives	Highlights/Goals
Towards a circular economy: A zero waste programme for Europe COM/2014/0398 [36]	• C&D waste is a priority waste stream. • The importance of improving the secondary materials market, to raise C&D waste recycling rates. • Establish a framework for assessing the environmental performance of buildings as described in COM/2014/0445-Resource efficiency opportunities in the building sector. In particular: • Including actions aimed at pre-construction stage (specifically design) to improve the management of C&D waste and increase the recyclability and recycling content in construction materials. • Definition of a series of measures such as the application of economic mechanisms (for instance, higher landfill taxes) and additional separation obligations at the construction site and end-of-life stages.
Closing the loop: An EU action plan for the circular economy COM/2015/0614 [38]	• C&D waste is considered a priority stream, with focus on pre-construction stages. • Three potential measures are established to secure resources for the recovery and adequate management of C&D waste, and to facilitate environmental assessment of buildings: • Guidelines for evaluation of pre-demolition/deconstruction; • Formulation of a protocol for recycling; • Design of a framework of key indicators for environmental assessment of buildings and development of incentives for their use.
EU Construction & Demolition Waste Management Protocol [28]	• Part of the actions of COM/2014/0398. • Framed within the Circular Economy package. • With the main objectives of increasing the user confidence in recycled materials and improve C&D waste management practices. • Provides a framework of guidelines to produce efficient management plans of C&D waste before and during construction. • Comprises measures and specifications to improve identification, segregation, collection, site logistics and treatment practices of C&D waste.
EU Waste Audit Guideline [39]	• Part of the actions of COM/2015/0614. • Describes the waste audit process and elements to be included in it. • The waste audit should result in an inventory of materials and components arising from (future) demolition, deconstruction, or refurbishment projects, and provides options for their management and recovery.
Level(s)-European framework for sustainable buildings [40]	• Part of the actions of COM/2015/0614. • A tool for designing and constructing sustainable buildings. • It is a voluntary reporting framework to improve the sustainability of buildings; it includes indicators reducing environmental impacts and for creating healthier and more comfortable spaces for their occupants.

Reverse logistics has a strong relationship with the circular economy regarding technical cycle (restoration and circularity of materials), and both are associated with the concept of sustainability [41].

Reverse logistics encompasses all of the logistic activities from used products which are no longer required by the users for products again usable in a market. Within the environmental context, reverse logistics has been successfully applied for the recovery, recycling and reuse of end-of-life electrical and electronic equipment [41]. Figure 5 presents the basic activities or processes in the reverse logistics system.

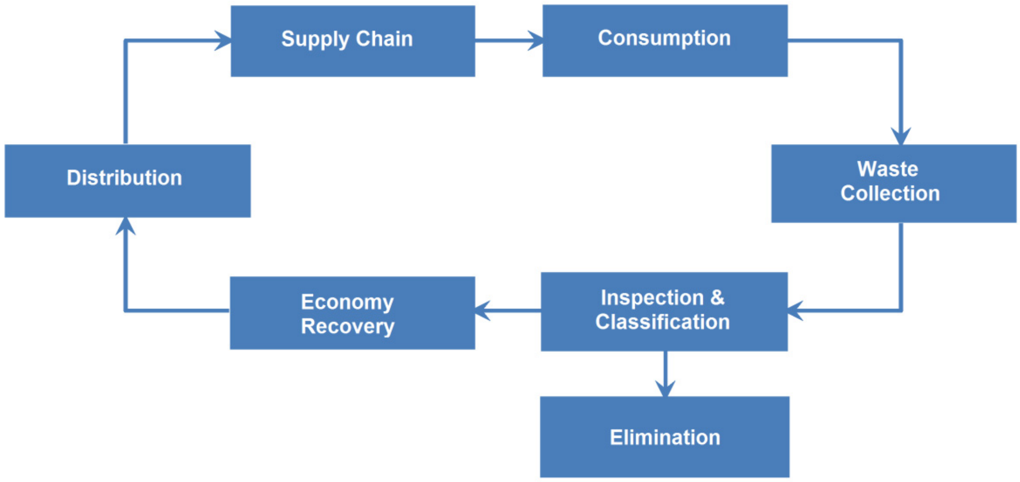

Figure 5. Basic activities in a reverse logistics system (adapted from [41]).

Well-planned and well-executed reverse logistics in recycling and reuse are a useful alternative to traditional construction management [42]. Reverse logistics can improve the environmental efficiency in the construction industries through the planning and implementation of effective cost control, as well as through ensuring an efficient flow of the raw materials, inventory processing, finished products, and related information required for recapturing or creating value or proper waste disposal [43].

Reverse logistics should follow a systemic approach for the efficient management of resources in the construction lifecycle. This involves the collection, separation, sorting, treatment, and reuse of C&D waste in accordance with rules, construction standards, laws, and an efficient waste management plan [42].

Reverse logistics can facilitate waste management, selective demolition, and the use of recovered materials for construction, reinforcing responsible and sustainable behaviour [42,43].

3. Applications and Relevant Properties of Recycled C&D Materials

3.1. Main Applications

The use of recycled C&D materials in civil engineering applications represents social, economic, and environmental benefits. Common recycled C&D materials used in civil engineering applications include recycled concrete aggregates (RCA), recycled masonry aggregates (RMA), mixed recycled aggregates (MRA), and reclaimed asphalt pavement (RAP).

The recycling of C&D materials is recognized as having the potential to preserve natural resources and to reduce the consumption of energy in the production processes. Replacing natural aggregates with recycled aggregates, partially or totally, has been studied in several research and application works. Studies can be found in the literature related to the use of recycled aggregates in structural and non-structural concretes [44–46], in base and sub-base layers of transportation infrastructures as unbound materials [47–49] or as stabilised alternative material [50,51], in geosynthetic-reinforced structures [52–55], in pipe backfilling [15,16], or in seawall foundations [56].

In this study, the literature review was carried out using the content analysis method as presented by [57]. The literature review was carried out using five keywords (“environmental sustainability”, “construction and demolition waste”, “recycled aggregates”, “long-term behaviour” and “unbound pavement applications”) in order to search in different databases. After defining the keywords, the next step was to search for articles and reviews in the following databases: Science Direct, Scopus, and Web of Science. These databases are multidisciplinary, display a high citation index, and provide access to a vast number of publications provided by prestigious publishers such as Elsevier, Springer, and other platforms such as Google Scholar. The exclusion criteria used were articles published in languages other than English.

In the following section, the use of recycled C&D waste in unbound base layers of transportation infrastructures will be analysed, emphasizing the physical, mechanical, and geotechnical properties, the durability performance, and environmental behaviour.

3.2. Physical, Mechanical, Chemical and Geotechnical Properties of Recycled C&D Materials

In this section, a compilation of the main physical, mechanical, chemical, and geotechnical properties reported in the literature and with relevance to unbound granular layers of transportation infrastructures is presented and discussed. Table 4 summarizes the information collected, reporting the range of values for the specific gravity, flakiness index, Los Angeles (LA) abrasion loss, Micro-Deval (MDE) abrasion loss, maximum dry unit density, optimum water content, Californian Bearing Ratio (CBR), angle of internal friction, cohesion, water-soluble sulphates, and hydraulic conductivity.

Table 4. Physical, mechanical, chemical and geotechnical properties of recycled and natural coarse aggregates (data from [10,15,18,20–23,48,49,58–97]).

Properties	RCA	RMA	MRA	RAP	Natural Aggregates
Specific gravity	2.05–2.85	1.67–3.08	1.92–2.62	1.90–2.47	2.42–3.11
Flakiness index (%)	6.0–21.0	10.0–28.5	5.90–40.0	5.0–23.0	8.0–18.0
LA abrasion loss (%)	18.0–42.0	30.4–43.0	27.0–51.5	34.1–43.1	13.1–30.1
Micro-Deval (%)	10.0–34.0	18.0–23.5	16.0–20.3	7.5–25.0	6.6–22.0
Maximum dry density (kN/m^3)	17.1–21.1	16.4–20.1	17.3–20.8	18.4–20.0	18.0–23.3
Optimum water content (%)	8.6–15.8	10.7–15.4	8.7–21.5	2.1–8.1	5.2–7.1
CBR (%)	19–215	45–157	26–150	19–39	36–170
Cohesion (kPa)	0–155	0–88	10–20	0–60	-
Friction angle (°)	40–66	42–58	42–52	33–60	30–60
Water-soluble sulphates (%)	<0.38	< 0.93	<3.93	<0.20	<0.20
Hydraulic conductivity (m/s)	8.0×10^{-9}–2.0×10^{-6}	0.5×10^{-9}–6.5×10^{-6}	6.5×10^{-9}–2.0×10^{-5}	5.0×10^{-8}–7.0×10^{-6}	$<10^{-8}$—clay (impermeable) 10^{-8}–10^{-7}–silt (poor drainage) 10^{-7}–10^{-6}—silty sand (poor drainage) $>10^{-6}$—fine sand (good drainage)

The recycled materials' properties can be affected by the chemical composition of the original materials and the recycling process [10]. The geotechnical, physical, and mechanical characteristics of different types of recycled aggregates from the literature are presented in this section [10,15,18,20–23,48,49,58–97].

Most of these characteristics can be used for the classification of recycled aggregates which can contribute to the CE marking of the materials if European Standards are used for the tests. As for the chemical characterization of these materials, most of the local regulations require specific tests on the waste product in order to assess their potential effects on the environment.

As shown in Table 4, the specific gravity of recycled aggregates ranges from 1.67 to 3.08. The low specific gravity of recycled aggregates can be attributed to the existence of cement paste of porous nature adherent to the aggregate particles, bituminous coating (with density frequently lower than 1.10 kg/m^3 in RAP [10]), or lightweight materials (particularly in MRA). Due to the abovementioned factors, the specific gravity of the recycled aggregates is lower to that of virgin aggregates.

The flakiness indexes of all types of recycled aggregates range from 6.0–40.0% (Table 4). In general, recycled aggregates resulting from primary and secondary crushing processes tend to have a low flakiness index [20]. As usual, they have a low flakiness index, with the exception of the slate in nature. According to Look [98], the flakiness index of the aggregates for use in sub-base layers should not exceed 40%. All the types of aggregates characterized in Table 4 meet this basic requirement.

The resistance of an aggregate to fragmentation or mechanical breakage due to impact and wearing can be evaluated through the Los Angeles (LA) abrasion test. Table 4 illustrates that the LA abrasion values of MRA, RMA, and RAP are very similar and higher than those of RCA. However, the LA abrasion values of recycled aggregates are generally higher than those of virgin quarried materials. This suggests that recycled aggregates are less resistant to abrasion (due to traffic loading) and degradation (due to compaction).

The internal angle of friction of recycled aggregates is usually between 40° and 50°; the recycled aggregates cohesion generally does not exceed 100 kPa, and in some cases it is non-cohesive.

The optimum moisture content of MRA, RCA, and RMA is generally above 10%, while RAP exhibits a smaller optimum moisture content close to that of virgin aggregates.

Although the CBR of the recycled aggregates is lower than that of natural aggregates (Table 4), the material still fulfils the requirements for use in base and sub-base layers. RCA presents the highest CBR value among the recycled aggregates.

Table 4 also shows values of the hydraulic conductivity of recycled aggregates reported by various researchers, as well as those of typical soil and drainage classification as provided by [99]. It should be mentioned that most of the results refer to samples tested using a falling head permeability apparatus, compacted to their optimum water content, and at 98% of maximum dry density.

Due to its interconnected voids which facilitate water drainage, poorly graded recycled aggregates have higher hydraulic conductivity. Although the particle size distribution of the tested samples of RCA, RMA, MRA, and RAP corresponds to a mixture of sand and gravel, the hydraulic conductivity values exhibited by these materials were similar to those of silts (poor drainage) and clay deposits (almost impermeable). According to [9], this may result from the breakage of the adhered cement paste or bitumen residue during compaction, producing smaller particles that fill the voids and makes the material less permeable.

C&D wastes are very heterogeneous and if a selective demolition is not carried out, it is very hard to obtain recycled aggregates of good quality to be used, for instance, in concrete production. Most of the recycled aggregates coming from C&D waste produced in Portugal are mixed recycled aggregates, including concrete, ceramics, mortars, masonries, and natural stones, since the selective demolition is not really implemented. In particular, the fine grain portion of these mixed recycled aggregates is commonly not considered suitable for concrete production or road construction applications, being landfilled instead of reused.

Recently, some studies have been conducted to assess the suitability of replacing the soils typically used in the construction of geosynthetic-reinforced structures (steep slopes and retaining walls) by fine-grain recycled C&D materials [52,54,55,100–103]. Fine-grained C&D waste, in addition to being able to be applied to geosynthetic reinforced structures, can also be applied to capping layers of transport infrastructure [104].

The physical, mechanical, and geotechnical properties of the fine-grain C&D waste from the different studies are listed in Table 5.

Table 5. Properties of fine recycled mixed aggregates used in geotechnical applications (data from [52,54,55,100–103]).

Properties	Data Range
D_{10} (mm)	0.01–0.032
D_{50} (mm)	0.65–2.1
Particles density	2.58–2.72
Methylene blue value (g/kg)	1.0–3.2
Maximum dry density (kN/m^3)	17.8–20.1
Optimum water content (%)	6.6–12.5
Friction angle (°)	34.4–45.9
Cohesion (kPa)	6.0–29.7
pH	7.8–8.9

D_{10}, D_{50} are characteristic grain diameters.

The distribution of particles of fine recycled aggregates from C&D waste may be different based on the source type and composition, on the procedure of demolition, and on the planned application of the material. D_{50} is the corresponding particle size when the cumulative percentage reaches 50%. Since the studied C&D wastes were fine grained, the D_{50} value is low, between 0.65 mm and 2.1 mm.

The specific gravity of natural materials commonly used in geotechnical and paving applications can vary depending on the material type, and it ranges between 2.60 and 2.75 or more on average [104]. The specific gravity of fine C&D wastes is within the range 2.58 to 2.72.

Clay minerals can be found in microfine materials (<0.063 mm). The assessment of fines is usually performed through methylene blue tests carried out on the 0/2 mm size fraction. An increase in the amount of clay material increases the methylene blue value. The value obtained of 3.2 g/kg of methylene blue for some fine mixed recycled aggregates is directly related to the higher content of fine plastics resulting from the disintegration of clay masonry units.

Some engineering properties of soil or other unbound paving materials, such as shear strength, internal friction, and water drainage, improve by reducing the volumetric ratio between the voids and the particles due to rearranging and repacking of grains with mechanical compaction. Several types of assessments such as standard Proctor and modified Proctor tests are used to evaluate the compactability of soils. The maximum dry unit weight of the studied C&D waste is between 17.8 kN/m^3 and 20.1 kN/m^3, and the optimum water content value is between 6.6% and 12.5%. These values are within the range of typical quarry and fine-grained recycled aggregates.

The recycled C&D wastes studied revealed a friction angle between 34.4° and 45.9° and cohesion between 6.0 kPa and 29.9 kPa. Soils with high levels of fines content have cohesive strength. All of the fine recycled aggregates showed an alkaline pH.

3.3. Durability of Recycled Aggregates

Durability is the capacity to last a long time without significant deterioration and requiring minimal maintenance. It is an important factor to assess the sustainability of a material. A durable material has a lower impact on the environment, as it contributes to resource conservation and waste reduction.

In pavements, recycled aggregates coming from C&D waste can be used as substitutes for virgin quarried materials. In the case of structural layers, the recycled material should present suitable shear strength and guarantee adequate drainage and anti-freeze characteristics. A good hydraulic behaviour is also important to ensure appropriate durability.

The degradation of unbound pavement layers can occur due to the increase of pore water pressure. When unbound pavement layers have low permeability, water retention tends to occur, and the interstitial pore water pressures developed under repeated dynamic loads reduce the shear strength and stiffness of the layer. Since the materials in pavement layers are commonly coarse materials, they are not expected to expand upon wetting. However, if the recycled material is not dense enough and becomes wet under load, it may collapse due to breakage of the constituent material and rearrangement of its fragments [105]. Breakage depends on the toughness of the particles; therefore, the properties of each particle are important to understand its resistance.

Pavement performance can be adversely affected by the accumulated deformations caused by freeze–thaw cycles. Therefore, an adequate permeability of the pavement layers is important in order to guarantee that water does not accumulate, but suitable freeze–thaw resistance of the aggregates is also relevant.

The chemical resistance (soundness) of the aggregates is also important in order to ensure that the pavement has the necessary resistance to environmental or chemical degradation agents. In the case of particle breakage caused by these effects, localized deformation cannot be avoided, and the pavement performance is jeopardised.

3.3.1. Permeability

The permeability of the unbound layers is also a fundamental property for the prevention of rigid pavements' pumping. The permeability of aggregate mixtures with different proportions of RCA and RAP has been studied by Bennert and Maher [106]. Table 6 summarises the permeability and the quality of drainage (in accordance with AASHTO [107]) of sub-base layers prepared with natural and recycled aggregates. Bennert and Maher [106] found that the use of RCA up to 75% resulted in permeability values similar to those of natural aggregates. This result was expected, since similar particle size distribution was embraced, and the dry unit weight derived from the laboratory testing was similar for both types of aggregates.

Table 6. Permeability and quality of drainage of sub-base prepared with natural aggregates, RCA and RAP (data from [64,106]).

Authors/ Reference	Material & Mixture	Permeability ($\times 10^{-3}$ cm/s)	Quality of Drainage [107]
Bennert and Maher [106]	100% Coarse natural aggregate	27.0–60.0	Fair/Good
	75% Coarse natural aggregate/25% RCA	27.0	Fair
	50% Coarse natural aggregate/50% RCA	23.3	Fair
	25% Coarse natural aggregate/75% RCA	23.0	Fair
	100% RCA	0.1	Poor
	75% RCA/25% RAP	0.4	Poor
	50% RCA/50% RAP	1.8	Poor
	25% RCA/75% RAP	0.2	Poor
	100% RAP	6.0	Fair
Poon et al. [64]	100% Natural aggregate	229.0	Good
	100% RCA	267.0	Good

Table 7 provides some details on the quality of drainage of pavement layers following the guidance of AASHTO [107].

Table 7. Quality of drainage according to AASHTO [107].

Quality of Drainage	Minimum Permeability ($\times 10^{-3}$ cm/s)	Time for Pavement to Drain
Excellent	352.8	2 h
Good	30.0	1 day
Fair	3.9	1 week
Poor	0.2	1 month
Very Poor	0.007	Water will not drain

Table 6 shows that the permeability decreased when RAP aggregates were used, and in these cases, the mixtures were classified as having poor- to fair-quality drainage. The lower permeability can be explained by the presence of impermeable bituminous particles and the potential linking effect of these soft particles during compaction.

Poon et al. [64] also compared the permeability of sub-base layers constructed with natural aggregates and RCA. These authors concluded that RCA samples exhibited higher permeability than that of natural aggregate samples. Furthermore, both materials demonstrated good-quality drainage.

According to Seferoğlu et al. [108] the interlocking between the asphalt-coated aggregates in RAP and the natural aggregate particles decreases the air voids and results in the low permeability of the aggregates. As shown in Figure 6, the permeability of RAP blends decreased as the percentage of RAP material in the blend increased. The reduction of permeability might be due to the aggregation of RAP particles as a result of compaction, since the asphalt in RAP could form a bond between particles.

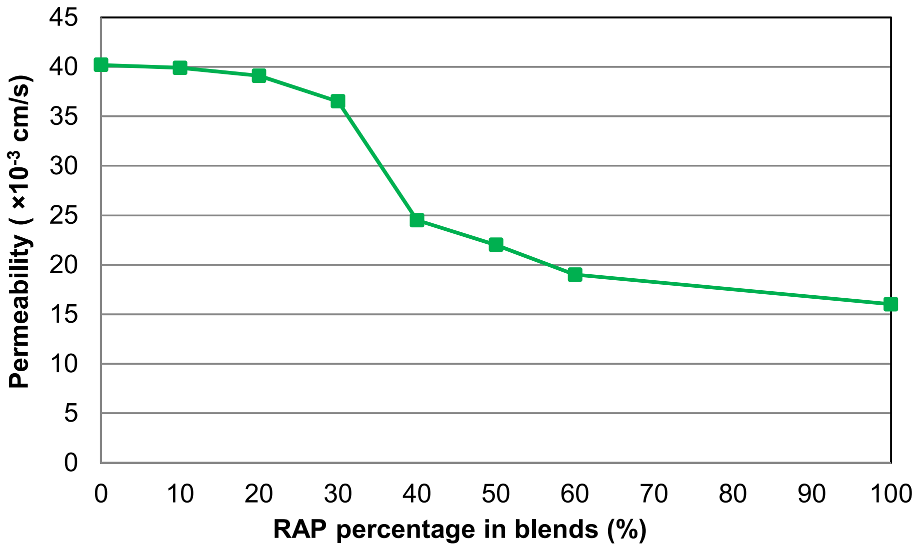

Figure 6. The permeability test results of RAP/natural aggregate blends [108].

3.3.2. Soundness

The durability of an aggregate is often evaluated using sulphate soundness tests. This laboratory test is carried out by the repeated immersion of the aggregate in a saturated solution of sodium sulphate or magnesium sulphate followed by a drying phase to induce the dehydration of the salt precipitated in the pores.

Data obtained by several authors [18,78,89–91,93] for the weight loss of recycled aggregates RCA, MRA, RPA, and natural aggregates are illustrated in Figure 7. The sulphate soundness value of natural aggregates is usually very low and not more than 3%, except in the case in which the magnesium sulphate soundness of limestone was 17% [78]. Alternatively, the sulphate soundness test result for RCA had a tendency to be higher than that of natural aggregates due to the presence of weak and porous cement paste adhered to the RCA. However, most of the samples from recycled aggregates had a sulphate soundness value inferior to 20% (Figure 7), indicating that the material had good weathering action resistance. Figure 7 also shows that MRA had the highest loss of mass values in the sulphate soundness test. This is because the material consists of 25% to 50% crushed clay bricks and has completely fragmented after testing [18]. The results of the laboratory tests in Figure 7 suggest that the recycled aggregate RCA is more suitable for use in unbound mixes for road pavements; however, this will only be possible if the content of weak elements, such as adhered cement paste, is relatively low.

The soundness of two recycled aggregates (RCA and RMA) was compared by Bazaz et al. [109] after being subjected to 5 cycles of immersion in sodium sulphate solution followed by drying in an oven. In this study, the weight loss ranged between 65.9–38.5% for RCA and from 10.9–4.9% for RMA. The results obtained by [109] suggested that the performance of RCA regarding the soundness results is inferior to that of RMA, since sulphate has a destructive effect on cementitious materials such as concrete and mortar.

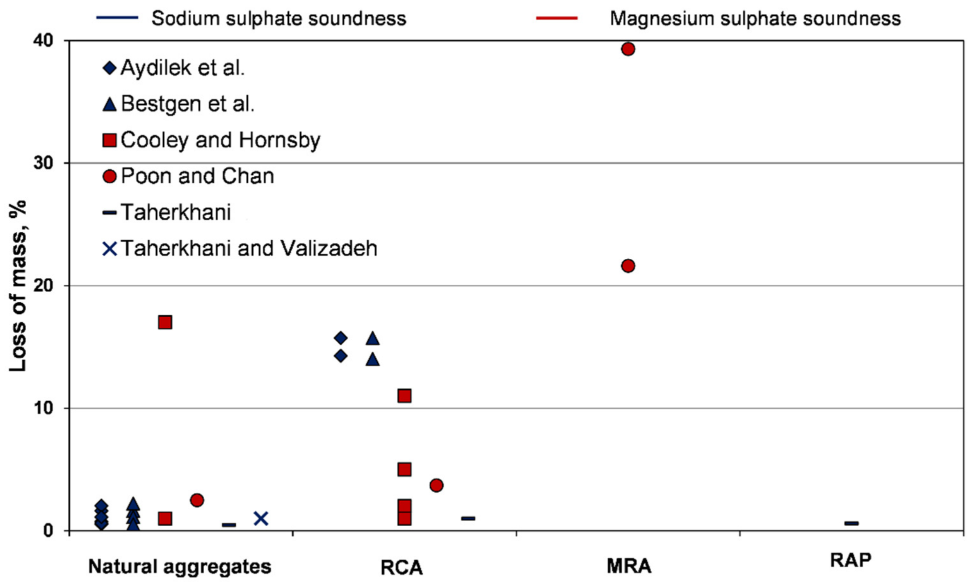

Figure 7. Sodium sulphate and magnesium sulphate soundness of natural and recycled aggregates (RCA—recycled concrete aggregate; MRA—mixed recycled aggregate; RAP—reclaimed asphalt pavement) [18,78,89–91,93].

3.3.3. Freeze–Thaw Resistance

The simulation of the expansive freezing action of water in the pores of aggregates can be achieved by carrying out sulphate soundness tests; however, there are freeze–thaw tests to assess this physical deterioration.

Freeze–thaw resistance is a relevant property for the good performance of pavements, particularly in places where the climate permits freeze–thaw cycles. The negative impacts caused by freeze–thaw cycles are important, regardless of the degree of saturation of the layer. The increase in the volume of water that invades the pores of the particles, due to freezing, leads to the creation of considerable tensile stresses that can lead to fragmentation of the aggregated particles if they present low freeze–thaw resistance.

The presence of salt reduces the surface tension of water and makes the penetration of water into small pores easier. Parameters such as particle strength, the number of voids, and the size of voids inside the particles interfere with the freeze–thaw resistance. However, only water-accessible pores are involved in this process, so it should not be assumed that all porous materials have low freeze–thaw resistance.

Table 8 summarises freeze–thaw test results for recycled and natural aggregates from various authors [63,70,79,92,110]. Results from Asthiani and Saeed [79] showed that the freeze–thaw resistance of RAP is superior to that of RCA, due probably to the higher porosity of RCA compared to RAP.

The results reported by Diagne et al. [110] showed that the reduction in constrained modulus is higher when the content of porous clay brick in MRA increases. Thus, the freeze–thaw resistance of MRA is lower than that of RCA. However, it should be noted that the crushing of RCA during its processing can generate micro cracks which can in turn can reduce its resistance to freeze–thaw attack [70].

The effect of the number of freeze–thaw (F-T) cycles on the resilient moduli of three different RAP materials and one RCA was studied by Soleimanbeigi et al. [92]. Their results showed that, while the RAP specimens exhibited a reduction of around 30% in the resilient modulus after 20 F-T cycles, the reduction on the control specimen (natural aggregate) was only 20%. Regarding the RCA specimens, although a similar reduction in the resilient moduli to that of the control samples has been recorded after 5 F-T cycles, after 20 cycles, the resilient moduli increased to between 28% and 36%, depending on the RCA source.

The better performance of the RCA samples after 20 F-T cycles might be a result of the self-cementing properties of unhydrated cement particles present in RCA.

Table 8. Freeze–thaw resistance data of recycled aggregates coming from C&D waste.

Authors/ Reference	Recycled Aggregates	Procedures	% Loss of Mass and Other Mechanical Performances
Blankenagel [63]	RCA	Samples were cured for 7 days; Standard: ASTM D560 [111]. Freeze-thaw cycles: 13.	RCA loses 35% of its stiffness.
Chidiroglou et al. [70]	RCA RMA	Standard: EN 1367-1 [112]; Freeze-thaw cycles: 10.	RCA found a 10–15% reduction in ACV and AIV *; RMA showed a decrease in ACV and AIV by 11% and 8%, respectively *.
Ashtiani and Saeed [79]	RCARMA	Samples were immersed in 3% NaCl solution for 24 h prior to testing; Freeze-thaw cycles: 5.	RCA experienced 22–25% weight loss; RAP experienced a weight loss of 0.7–9.5%; Natural aggregates lose less than 1% of weight.
Diagne et al. [110]	RCA MRA	Standard: Modified ASTM D6035 [113]. Freeze-thaw cycles: 20.	RCA found a 7% reduction in constrained modulus. MRA showed a greater reduction in modulus than RCA and the reduction increased with increasing clay brick content.
Soleimanbeigi et al. [92]	RCA RAP	Samples were compacted to 95% $\gamma_{d,max}$. Standard: ASTM D6035 [113]. Freeze-thaw cycles: 20.	RCA resilient modulus decreases after 5 cycles, beyond which it increases about 28–36% more than its original value. Approximately 30% reduction in the resilient modulus of RAP Approximately 18% reduction in the resilient modulus of natural aggregates

* ACV: aggregate crushing value; AIV: aggregate impact value; $\gamma_{d,max}$.: maximum dry density.

The effects of the compaction process and freezing actions on the resilient modulus of three MRA collected from different recycling plants were investigated by Bassani and Tefa [114]. Partially saturated samples of MRA (W_{opt} and at $W_{opt} \pm 2\%$) were prepared in a gyratory shear compactor with 30 and 100 gyrations. The samples were also subjected to 0, 4, and 8 freeze–thaw cycles. Each cycle lasted for 2 days with temperatures ranging from −18 °C to +20 °C. Their study showed that the brittle/weak components of MRA (crushed concrete bricks) generate fine particles in the first part of the compaction process (in the first 30 gyrations). The MRA specimens compacted at W_{opt} and W_{opt} + 2% increased their resilient modulus at the end of the freeze–thaw cycles. A similar trend was observed in the resilient modulus of the natural aggregate under similar moisture conditions, while both MRA and natural aggregate showed a slight reduction for some samples prepared at $w_{opt}-2\%$.

Domitrović et al. [115] evaluated the effect of freeze–thaw cycles on the resilient modulus and permanent deformation modulus of mixtures of natural aggregates and RAP, for the construction of unbound base layers. Triaxial repeated load tests were performed on mixtures of RAP and crushed limestone on standard samples and samples exposed to 14 freeze–thaw cycles. The percentages of replacement of crushed limestone by RAP studied by [115] were 0%, 20%, 35%, and 50% of the dry mass.

Freeze–thaw conditioning resulted in a decrease in the resilient modulus and an increase in permanent deformation. This trend was more pronounced in the crushed limestone sample (0% RAP). Mixtures containing 35% RAP showed a stable resilient behaviour and less change in permanent deformation accumulation after freeze–thaw conditioning. As the RAP content increases, the sensitivity of the mixtures to freeze–thaw cycling regarding the resilient and permanent deformation behaviour was reduced.

3.3.4. Other Studies Related with Long-Term Behaviour of Recycled Aggregates

The wetting and drying process, often occurring due to weather phenomena, is an important process in aggregates' dissolution and slacking.

Diagne et al. [110] presented a laboratory investigation of mixtures of RMA, coming from C&D waste and RCA, as an unbound base course in roadway construction. The hydraulic behaviour of mixtures with 100% RMA, 30% RMA, 15% RMA, 5% RMA, and 100% RCA was evaluated using a rigid-wall hydraulic conductivity test and multi-step outflow. Results showed that the drainage was faster as the percentage of RMA increased due to enlarged pores. The effects of weathering through wet–dry (W–D) and freeze–thaw cycles and abrasion through Micro-Deval (MDE) and Los Angeles (LA) tests were performed to determine the change in stiffness per number of cycles and the effects of abrasion on particle degradation of the samples.

Their results revealed that MDE and LA coefficients increased with the percentage of RMA in the mixture due to the low particle density and high porosity compared to those of natural aggregates (Figure 8). The durability of the aggregates was affected by the number of W–D cycles and an increase in the percentage of fine content was observed.

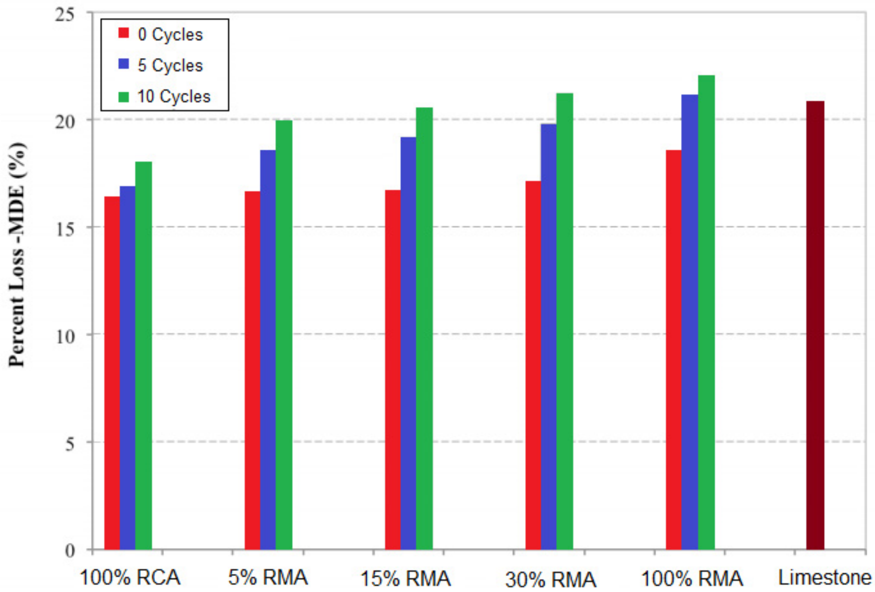

Figure 8. Percent loss of the Micro-Deval coefficient of the natural and recycled aggregates submitted to different number of W–D cycles (adapted from [110]).

Pereira et al. [116] studied the change to the physical, mechanical, and chemical properties of a mixed recycled aggregate (MRA) due to degradation agents simulated through 10 W-D cycles. In this study, each W–D cycle consists of placing the sample into an electric oven under a temperature of 60 °C for 7 days, and then moving it to a humidity chamber at 20 °C and a relative humidity close to 100% for another 7-day period.

The results showed that after 10 W–D cycles under controlled conditions, the amount of particles smaller than 14 mm increased due to the disaggregation of bigger particles. However, the changes in the size range 14–31.5 mm were not relevant (Figure 9). The effects of W–D cycles on LA coefficient and water-soluble sulphate content were almost negligible.

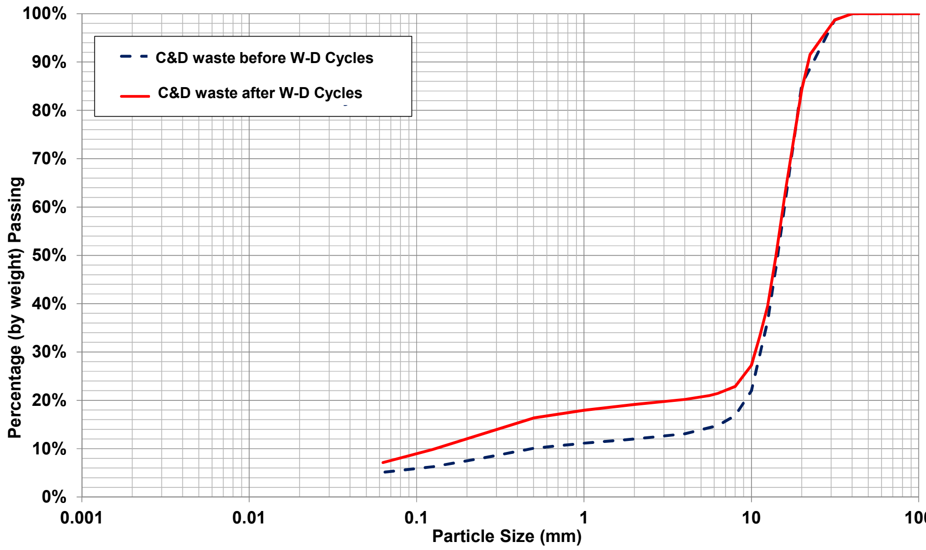

Figure 9. Grain size distribution for recycled C&D aggregate before and after W–D cycles (adapted from [116]).

Li et al. [117] carried out laboratory creep tests and field subgrade settlement measurement in order to study the long-term deformation characteristics of recycled construction waste (35% recycled brick; 40% recycled concrete; 15% recycled mortar; 10% others).

The creep tests were performed for approximately 500 days on the prototype illustrated in Figure 10. The samples were placed in the steel sheath and then immersed by adding water to the steel sheath. After 48 h, the dial indicator was installed, and the load was applied to the loading platform. To simulate the load at different subgrade depths, 5 load levels were considered.

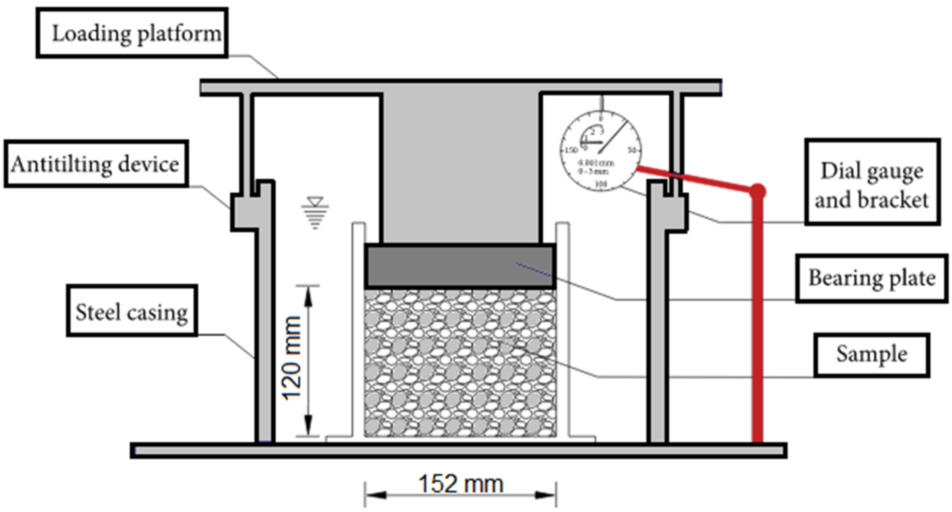

Figure 10. Creep loading tests apparatus used by Li et al. (adapted from [117]).

Li et al. [117] found that as the load increases, the breakage of particles and the instantaneous deformation also increase. The instantaneous strains were higher than 80% of the total strain, so to reduce the settlement of the subgrade, the compaction during construction should be closely monitored.

The percent of particles smaller than 2 mm significantly increased after the creep tests, and the plastic deformation was around 95% of the total deformation. The main reason for the high deformations was attributed to the breakage of particles.

The measurement of settlement in the field was obtained by placing sensors on the upper and lower surfaces of the subgrade in a road section. Settlements of the upper surface of the subgrade and of the foundation were monitored separately; through these two components, it is possible to obtain the settlement of the subgrade layer. The subgrade settlement at different measurement points was lower than 40 mm, and the maximum variation between them was around 6 mm.

The calculated subgrade settlement based on the creep test was significantly higher than the measured settlement in situ.

3.4. Environmental Risk

C&D waste arises from the construction, renovation, repair, and demolition of structures, such as houses, buildings, roads, and bridges. As seen in Section 2.2, the composition of these wastes is strongly dependent on the type of structure or infrastructure that gives rise to the waste and the type of construction used. Due to this heterogeneity, C&D wastes can also contain hazardous materials or components unsuitable for use in construction, such as organic compounds, plaster, and metals [80].

Chemical analyses on RCA, RMA, MRA, and RAP for the release of harmful elements such as Arsenic (AS), Barium (Ba), Chromium (Cr), Copper (Cu), Molybdenum (Mo), Nickel (Ni), Antimony (Sb), Selenium (Se), and Zinc (Zn) have been conducted by Barbudo et al. [77] and Galvin at al. [80] using laboratory leaching tests carried out in accordance with EN 12457—3 [118]. The concentrations of all elements emitted from recycled aggregates are well below waste acceptance criteria levels for inert waste in the EU, with the exception of a few samples of RMA and MRA which had high Cr levels.

Vieira et al. [46] reported results of laboratory leaching tests carried out on MRA and also concluded that the limits of the above-mentioned harmful elements were lower than waste acceptance criteria limits for inert waste. However, the sulphate value and the total dissolved solids (TDS) exceeded the levels stipulated by the EU legislation for inert wastes.

4. Field Studies of Unbound Pavement Applications

4.1. Case Studies

Table 9 compiles a series of studies on the suitability of introducing recycled aggregates into unbound base and sub-base layers of transportation infrastructures, considering their performance in the field [48,65,67,119–121]. Most of the recycled aggregates used in these studies are high-quality RCA that meet the natural aggregates' requirements for unbound pavement applications. In general, the performance of the pavement layers was evaluated through roughness and surface deflection.

Table 9. Studies on the suitability of using recycled aggregates into unbound base and sub-base pavement layers.

Authors/Reference	Most Relevant Conclusions
Arm [119]	The FWD tests showed that the RCA sections demonstrated equivalent performance to the natural aggregates section.
Park [48]	The deflection of the RCA section was similar to that of the natural aggregates section.
Lancieri et al. [65]	Section built with MRA showed an improvement in performance over time compared to sections built with natural aggregates, due to their self-cementing properties.
Ho et al. [67]	The base course produced with RCA had lower deflection values than the base course produced with natural aggregate.
Lee et al. [122] & Lee et al. [120]	The results of the IRI and deflection showed that the road sections made of RCA had similar performance to the sections made of natural aggregates.
Jiménez et al. [121]	The deflection of the section built with RCA was slightly higher than that of the section built with natural aggregates.
Neves et al. [21]	In situ loading tests revealed that recycled materials (MRA and RAP) behave differently than natural aggregates, but it could be admitted that, in general, all the recycled materials showed acceptable performance.

4.2. International Roughness Index

Roughness is a relevant measure of the condition of the road surface, because it affects the quality of the course and the operating and maintenance costs. The value of the International Roughness Index (IRI) is commonly used around the world to quantify the roughness of a road surface. This index can be obtained from longitudinal profile measurements (ASTM E1926-08 [123]) or by the static level method (ASTM E1364-95 [124]).

In the case study presented by Ho et al. [67] (Table 9), two 140 m-long road sections were constructed using RCA as base course material, and another road section was built using a natural aggregate. The IRI values of the two stretches were similar, varying between 1 m/km and 4 m/km, over the course of 3 months of monitoring. Other field measurements suggested that, when compared with the base course produced with granite, the base course produced with RCA exhibited similar rut depth but less deflection. The results reported by Ho et al. [67] showed that RCA has a high potential to be considered as an alternative material in base course construction.

In the same way, Lee et al. [122] also compared the IRI of pavements constructed with RCA and natural aggregates. After five months of road service, the average IRI values for the section with RCA as base course materialwas about 2.4 to 2.5 m/km, while for the section with granite as base course material, the IRI values ranged from 4.1 to 4.5 m/km. For the same traffic volume and pavement age, the base course produced with RCA showed less deformation, leading to lower IRI values than the base course produced with granite.

Jiménez et al. [121] assessed the performance and the environmental impact of RCA as a surface layer material for an unpaved road. Their results showed that the initial values of IRI for superficial layers constructed with RCA were similar to those of superficial layers built with natural aggregates (between 2.5 m/km and 6.0 m/km). over the course of 2.5 years of monitoring, the IRI values for the surface layer of the natural aggregate increased significantly, while those for the surface layer of RCA were augmented only slightly. The results reported by Jiménez et al. [121] show that RCA can be considered as a viable alternative to natural aggregate as a surface layer material for unpaved roads, and that it can also improve their long-term performance.

4.3. Deflection

The falling weight deflectometer (FWD) test is non-destructive and used to evaluate the subsurface properties, to assess load transfer efficiency, and to determine the presence of voids under the pavement slabs. It consists of dropping a known weight on the pavement surface, measuring the deflection by sensors (geophones or force-balance seismometers) placed around the circular load plate.

The study developed by Lee et al. [122] (Table 9) showed that the base course section constructed with RCA exhibited lower deflections than those of the base course section built with natural aggregate. For the base course section constructed with RCA, the deflection was approximately 0.2 mm (on average), while the average deflection was approximately 0.5 mm for the base course constructed with natural aggregate. This evidence results, probably, from the greater roughness of the RCA, which allows high interparticle friction and, therefore, a more uniform redistribution of loads. RCA are also more prone to breakage, which can cause higher densification of the layers and, as a consequence, lower deflection.

The results obtained by several authors [48,65,92,119] in recent years have shown that RCA and MRA can be considered suitable alternative aggregates for base and sub-base layers without significantly modifying the pavement deflection.

The field study conducted by Lancieri et al. [65] showed, interestingly, that the deflection of pavement constructed with MRA was lower than expected. An improvement in the elastic modulus of pavement after 8 years of service was recorded, being attributed to the self-cementing properties of the recycled material.

Neves et al. [21] used MRA, RAP, and a natural limestone (as reference material) in a 300 mm thick granular base layer of distinct experimental roadway sections. FWD tests carried out over these roadway sections showed that the stiffness of the layers built with recycled materials (MRA and RAP) is equal to or only slightly lower than that of the layers constructed with the natural aggregate.

5. Conclusions

The implementation of the Sustainable Development Goals proposed by the United Nations is nowadays an imperative to the prosperity of the planet. The construction industry can contribute to these goals in a variety of ways, among which is the use of recycled aggregates (Goal 12—Ensure sustainable consumption and production patterns).

The total or partial replacement of virgin quarried materials by recycled aggregates can foster mitigation of the high environmental impacts caused by the construction industry, and thus, make it more sustainable.

From the literature review on the relevant engineering properties of different types of recycled aggregates and their long-term performance when used in unbound pavement applications presented in this paper, the following main conclusions can be drawn:

- In general, recycled aggregates are suitable alternatives to natural aggregates in unbound pavement layers and other geotechnical applications.
- When RAP is used, the permeability tends to decrease, possibly due to the presence of impermeable bituminous particles.
- RCA tends to show a lower resistance to freeze–thaw cycles than natural aggregates; however, this resistance is strongly dependent on the quality of the RCA.
- The use of RCA in pavements may not be allowed where very low temperatures are expected, as their performance (shear strength and stiffness) can be affected.
- The performance of RCA is commonly lower than that of natural aggregates regarding the exposure to environments with high sulphate concentrations.
- The IRI deflectometer tests have shown that the performance of sub-base and base layers built with RCA can be equal to or even better than that of the layers constructed with natural aggregates. It was also found that, over time, natural aggregate surface layers tend to show higher IRI increases than those of RCA surface layers, which means that RCA may provide a longer pavement structural life.

As a general conclusion, it can be stated that studies developed over recent years have shown the feasible use and appropriate performance of C&D waste as recycled aggregate. The use of different types of C&D materials (RCA, RMA, MRA, and RAP) in the base and sub-base layers of transportation infrastructures can be seen as a viable alternative to natural aggregates without significant compromise on infrastructure performance. The present literature review will allow recycled aggregates from C&D waste, traditionally destined for landfills, to be used sustainably as a base/sub-base material for pavements, which is important from an engineering, economic, and environmental point of view.

Finally, it is important to highlight that despite the increasing number of studies carried out over recent decades, some of them presented herein, those regarding long-term behaviour are still limited.

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