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Review

Steel Slag and Recycled Concrete Aggregates: Replacing Quarries to Supply Sustainable Materials for the Asphalt Paving Industry

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Abstract: Various researchers are developing efforts to integrate waste and by-products as alternative materials in road construction and maintenance, reducing environmental impacts and promoting a circular economy. Among the alternative materials that several authors have studied regarding their use as partial or total substitutes for natural aggregates in the asphalt paving industry, the steel slag aggregate (SSA) and recycled concrete aggregate (RCA) from construction demolition waste (CDW) stand out. This paper reviews and discusses the characteristics and performance of these materials when used as aggregates in asphalt mixtures. Based on the various studies analyzed, it was possible to conclude that incorporating SSA or RCA in asphalt mixtures for road pavements has functional, mechanical, and environmental advantages. However, it is essential to consider some possible drawbacks of these aggregates that are discussed in this paper, to define the acceptable uses of SSA and RCA as sustainable feedstocks for road paving works.

Keywords: steel slag aggregate; recycled concrete aggregates; waste products; asphalt mixture; sustainable materials

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1. Introduction

The European Community aims to contribute to a radical increase in the construction sector sustainability through a paradigm shift that implements the circular economy principles [1].

A pavement's sustainability is highly influenced by the proper selection of the materials used [2]. The material circularity principle for a cleaner production of asphalt mixtures aims to completely or partially replace traditional aggregates and fillers with wastes or by-products, which can also be used on asphalt binder modifications. Adapting asphalt mixtures to incorporate waste materials reduces the consumption of naturally mined materials, minimizing the carbon footprint and pavement industry's impact on the environment. Furthermore, the use of waste materials minimizes landfills and deposition in piles and limits the disposal of enormous volumes of waste produced from various sources [3–5].

Previous research works have demonstrated the advantages of applying new recycled materials in the granular or asphalt layers of road pavements. Steel slags and construction and demolition waste are among the alternative materials that several authors have studied as partial or total substitutes for natural aggregates in asphalt mixtures [2,6–12].

Formerly considered waste material, steel slag has become a valuable by-product used as a raw material for many industries and is almost fully utilized in some countries [13]. Steel slag aggregates (SSA) can replace natural aggregates in asphalt and cement-based road construction, lowering the environmental impact by reducing the consumption of natural and non-renewable aggregates and the quantity of steel slag deposited on landfill sites [14].

The rapid development of the construction engineering sector has led to a massive and unsustainable production with an excessive consumption of natural resources. Moreover, Menegaki and Damigos state that around 35% of the global construction and demolition waste (CDW) is disposed of directly in landfills without treatment [15]. These landfills are detrimental to a significant land area and bring major environmental concerns, such as global warming and soil and water pollution [16]. Excess construction and demolition waste puts a massive strain on the environment. Therefore, recovering CDW as aggregates for the partial substitution of natural aggregates in asphalt or concrete cement roads minimizes this effect and the consumption of new materials.

Concrete is the primary waste source in CWD. This concrete can be reused as recycled concrete aggregate (RCA), prepared through the crushing and grading of waste concrete, which can be wholly or partially used as a raw material in new concrete mixtures [17]. Because the high volume of RCA produced exceeds the amount placed back into the construction cycle, finding alternative applications for RCA is essential to maintain the construction industry as globally sustainable. Hence, utilizing recycled aggregates for highway pavement construction offers tangible environmental and economic benefits [18].

Several studies and reviews [13,15,19–25] have recently focused on the technical and economic feasibility of using recycled concrete and steel slag aggregates to produce new asphalt concrete mixtures. This topic became essential for the current and future development of the road paving industry.

Therefore, this review paper thoroughly identifies and evaluates innovative, efficient, and sustainable alternatives for the current uses of SSA and RCA in asphalt mixtures, thus promoting the circularity of road paving materials. It also aligns with the sustainable development goal twelve defined by the United Nations, i.e., responsible consumption and production [26]. This paper shows that SSA and RCA are the two main by-products capable of substituting significant amounts of natural aggregates in producing asphalt mixtures, either separately or together, as "alternative quarries".

After a brief description of steel slag and recycled concrete from construction and demolition wastes, the legal and environmental aspects of using these wastes or by-products are discussed using different approaches. Then, the mechanical properties of steel slag and the main treatments of recycled concrete were the main points focused on for each alternative aggregate. Finally, the current research on the various applications of these wastes as road paving materials is presented, demonstrating their potential and efficient use as new aggregates for asphalt mixtures.

A greater demand for environmental and legal requirements in the construction industry is expected soon, and this article aims to stimulate the use of eco-efficient building materials in road construction.

2. Steel Slag Aggregates Applications in the Asphalt Paving Industry

2.1. Steel Slag Properties and Their Application in Road Pavements

2.1.1. Steel Slag Types and Main Properties

Steel slag is a synthetic aggregate produced as a by-product in the steel production process, recycled in many countries worldwide for decades. This by-product is one of the most used materials, and it can be considered a green resource because it has a great potential to substitute natural aggregates and reduce the environmental impact of virgin resources quarrying [27–29].

There are many possibilities for using steel slag in building and transport infrastructure construction [30]. Material researchers and civil engineers studied its use in construction applications. They concluded that this material could be used in broad areas, such as a raw material for blended cement manufacturing, aggregates for asphalt mixture production, or granular material for a road pavement base or subbase courses [19,31].

As mentioned by Skaf et al. [20], there are currently five main types of metallurgical slags: the iron-making slag of a Blast Furnace (BF), steel slag divided into Basic Oxygen Furnace (BOF) slag (sometimes referred to as Linz–Donawitz slag), the Electric Arc Furnace (EAF) slag, and secondary refining slag that are the Ladle Furnace (LD) and the stainless steel slag.

The BOF and EAF steel slags from different sources within Europe are generally comparable, but the properties may differ based on the steel produced and the furnace. Compared to EAF, the main problem with BOF is the excess quantity of its free lime and magnesia contents [32,33]. Although EAF steel slag aggregate (Figure 1) is the most common type used in road construction [34,35], some researchers [36–46] have developed research on applications of BOF steel slag aggregates in asphalt mixtures.

Figure 1. Steel slag aggregates from electric arc furnaces (EAF SSA).

The EAF steelmaking process is essentially a steel scrap recycling process. Therefore, the chemical composition of EAF slag depends significantly on the source and properties of recycled steel, and its chemical composition can vary from one batch to another. The main chemical components of EAF steel slag are lime (CaO), magnesium oxide (MgO), iron oxides (FeO, Fe_2O_3), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3). Therefore, the CaO–MgO–SiO_2–FeO–Al_2O_3 system can represent the steel slag. The FeO, CaO, SiO_2, Al_2O_3, and MgO contents of EAF slags are typically 10–40%, 22–60%, 6–34%, 3–14%, and 3–13%, respectively. EAF slags also contain free CaO and MgO and other complex minerals and solid solutions of CaO, FeO, and MgO [20,31,47,48].

2.1.2. Characteristics of Steel Slag Aggregates Relevant for Road Pavements

Zumrawi and Khalill [49] state that particular attention has been directed at investigating the possible use of SSA as a substitute for natural mineral aggregates to produce asphalt mixtures. The steel slag has been utilized as a coarse or a fine aggregate in asphalt pavements and had a reliable response [50]. Numerous researchers have found that the angular shape, the rough-textured surface, and the high specific gravity of steel slag provides a high skid resistance, mechanical interlocking, better stability, a high-temperature deformation resistance, and a low-temperature cracking resistance [47,51,52]. Moreover, steel slag aggregates (SSA) have shown excellent polishing resistance, meaning surface courses with SSA will keep their friction properties over time. This result was confirmed in field studies reporting that sections made with SSA have equal or better skid resistance and macrotexture than sections made with conventional asphalt mixtures produced with natural aggregates [53].

The mechanical performance of EAF slags when they replace natural coarse aggregates in asphalt mixtures has been evaluated in-depth, obtaining excellent results. Steel slag's mechanical and physical properties productively meet high-class material requirements, making it an alternative high-quality aggregate compared to the natural aggregate. A comparison of some properties of steel slag with natural aggregate is shown in Table 1. Moreover, according to several authors, the asphalt mixtures with SSA have excellent workability, durability, permeability, stability at high temperatures, fatigue and thermal cracking resistance, abrasion resistance, and increased stiffness [30,32,47,54,55].

Table 1. Technical properties of EAF steel slag against granite natural aggregates adapted from [2,13].

Characteristics	EAF Steel Slags	Granite
Bulk density (g/cm^3)	3.4–3.5	2.5–2.7
Shape—thin and elongated pieces (%)	<10	<10
Impact value (wt.%)	18	12
Crushing value (wt.%)	13	17
Micro-Deval Coefficient (wt.%)	10	15
Polished stone value, PSV (%)	51–61	48–52
Water absorption (wt.%)	0.7–1.3	0.5–0.7
Resistance to freeze-thaw (wt.%)	<0.5	<0.5
Binder affinity (%)	50–65	10–15

Steel slag has also been reported to retain heat considerably longer than natural aggregates. The heat retention characteristics of SSA can be beneficial for hot mix asphalt (HMA) production, as less energy can be used to heat aggregates in the asphalt plant being maintained for more extended periods during the asphalt paving works [20,52].

Another property that makes steel slag an excellent aggregate for asphalt mixtures is its strong affinity with bitumen. EAF slag aggregates are tough and dense, but they have excellent adhesion with bitumen due to their high alkali character. This property of steel slag helps to resist bitumen stripping and minimizes potential moisture damage to asphalt mixtures [20,32,56,57].

In general, using EAF steel slag to substitute part of the natural aggregates improves the mechanical performance of the resulting asphalt mixtures. This tendency is stated in the literature for skid resistance, Marshall stability, indirect tensile strength, stiffness, resistance to permanent deformation, fatigue, and low-temperature cracking resistance [29,34,58,59]. Table 2 summarizes previous research on SSA incorporation in different HMA and warm mix asphalt (WMA) mixtures and the corresponding advantages.

Table 2. Research work developed with the incorporation of SSA in different asphalt mixtures.

Reference	Type of Mixture	Improved Properties with SSA
Kavussi and Qazizadeh [59]	HMA	Fatigue cracking resistance
Maharaj et al. [47]	HMA	Marshall stability and surface characteristics
Pasetto and Baldo [30]	HMA	Stiffness modulus, fatigue and rutting resistance, and indirect tensile strength
Abd Alhay and Jassim [28]	HMA	Marshall stability and temperature susceptibility
Shiha et al. [29]	HMA	Marshall stability and fatigue cracking resistance
Masoudi et al. [34]	WMA	Marshall stability, stiffness, resilient modulus, and indirect tensile strength
Ameri et al. [58]	WMA	Marshall stability, tensile strength, resilient modulus, moisture resistance, and rutting resistance
Ziaee and Behnia [60]	WMA	Indirect tensile strength, resilient modulus, and dynamic creep
Keymanesh et al. [61]	Microsurfacing	Abrasion resistance, curing time, bleeding, and vertical displacement

However, the incorporation of SSA in asphalt mixtures can have some restrictions due to its chemical and physical characteristics. According to Swathi et al. [62], three of the most discussed issues associated with the use of SSA in asphalt mixtures are failures due to volume instability, increased bitumen demand due to its texture and porous structure, high air void contents, and voids in mineral aggregate (VMA) of the corresponding asphalt mixture. However, the lack of volume stability of steel slag can be improved with a pre-treatment or aging treatment [63].

Although many factors influence the stability of the EAF steel slag, there seems to be an agreement that the hydration reactions of free lime and periclase of SSA are responsible for its expansive behavior [20]. In contact with water, free MgO and CaO in steel slag will react to hydroxides. Depending on the free lime or free MgO rate, this reaction causes a slag's volume increase, mostly combined with a loss of strength and partial disintegration of the slag pieces [33]. In the free lime hydration, there may be an increase in the volume of 99%, and in the case of hydration of free magnesium oxide, the volume may increase by 119% [64,65].

The bitumen and air voids contents are the two most crucial mix design control indexes [66]. Asphalt mixtures with high steel slag aggregate contents tend to have more voids, and the optimum bitumen content can be excessive and lead to binder drainage [20]. The higher air voids content in 100% SSA asphalt mixtures can be attributed to the difference in the specific gravity of the coarse and fine fractions of SSA. Adopting the weight-based grading envelopes for asphalt mix design without considering the difference in the specific gravity, for a unit volume of the asphalt mix, few coarse aggregates may be obtained than the mixture with natural aggregates with similar specific gravity. The consequence is that the asphalt mixture with SSA tends to have more fine aggregates than the corresponding mixture with natural aggregates of a similar specific gravity, resulting in a higher VMA [62].

He et al. [63] stated that using steel slag in an asphalt mixture benefits the environment and saves cost. Nonetheless, the critical points of mix design of asphalt mixtures with SSA include the ratio of NA substitution, the gradation correction, the determination of effective relative density, and the optimum binder–aggregate ratio. The same authors mentioned that the main limiting factors (i.e., large density, poor volume stability, and the increasing binder content) had not been fundamentally resolved, and the long-term performance and quality control system of pavements with SSA should be further researched.

2.2. Legislation on the Use of Steel Slag

Despite the general use of steel slag in construction, there has been an ongoing legal argument about classifying steel slags as waste or by-products. The classification of steel slags is not uniform within the European member states. Some steel slag types are considered by-products in several countries and waste in others [67].

According to the European Waste Directive 2008/98/CE, later amended by Directive (UE) 2018/851, steel slag is initially classified as waste, leaving this condition after processing, meeting technical criteria, and proving no risks to health and the environment. Thus, the SSA is a by-product obtained from various stages of steel slag beneficiation, has a well-defined market and demand, and meets the legislation, technical standards, and criteria so that its intended applications do not cause adverse impacts on the environment or human health. Therefore, it aligns with Article 5 of the European Waste Directive concepts and can be legally framed as a by-product by meeting the following conditions:

(a) further use of SSA is certain;
(b) SSA can be used directly without any further processing other than regular industrial practice;
(c) SSA is produced as an integral part of a production process; and
(d) further use of SSA is lawful, fulfilling all the requirements for its specific use without causing adverse environmental or human health impacts.

The same waste framework directive (WFD) also introduced the end of waste status in Article 6 for wastes undergoing recycling or recovery operations but falling outside the definition of by-products according to Article 5. Therefore, the waste must be applied with specific objectives and assure a market or demand. Furthermore, it should also fulfill the technical requirements and applicable legislation without compromising the environment or human health.

Figure 2 shows the different classifications of steel slag according to Articles 5 and 6 of the European Waste Directive 2008/98/EC, later amended by Directive (UE) 2018/851.

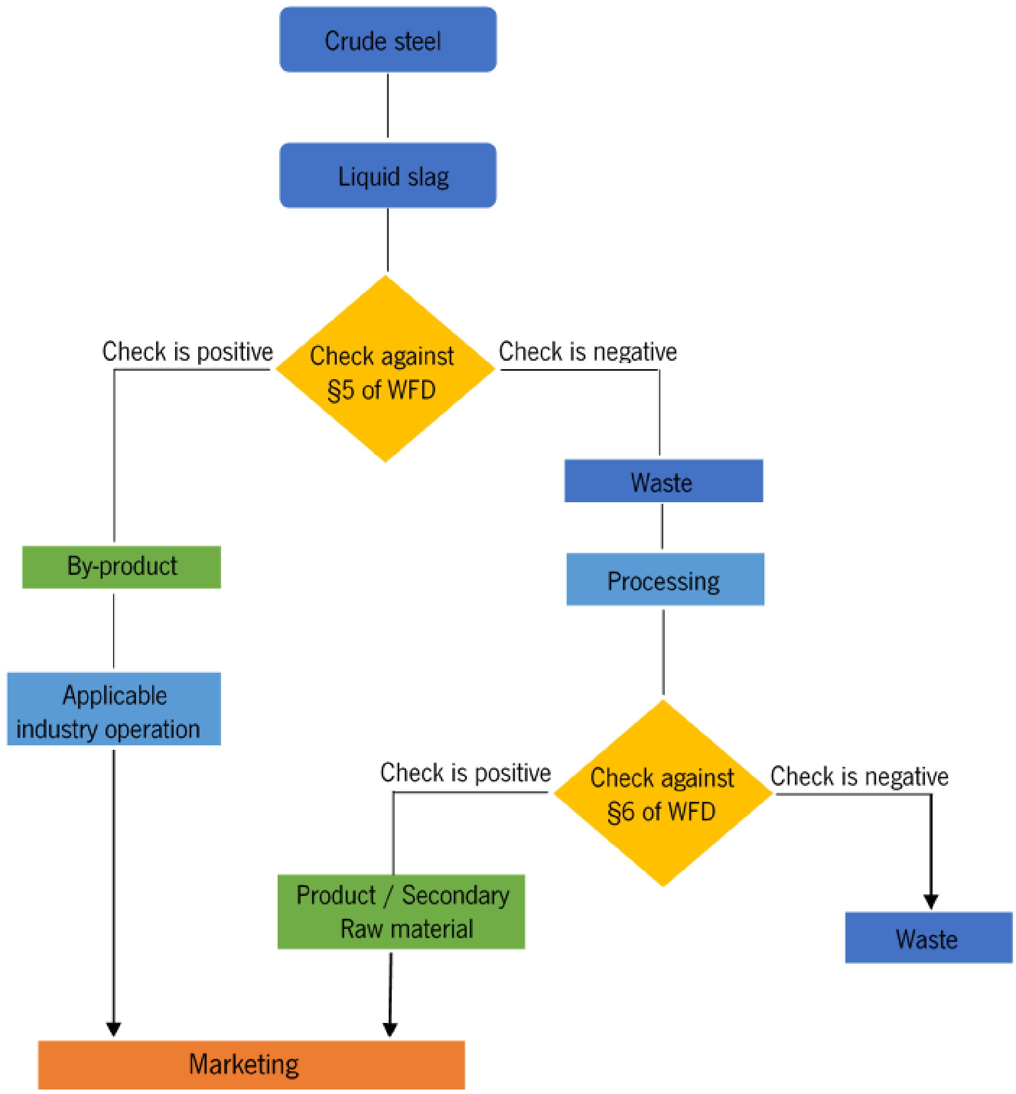

Figure 2. Different classifications of steel slag according to Articles 5 and 6 (§5 and §6) of the European Waste Directive 2008/98/EC, amended by Directive (UE) 2018/851 adapted from [68].

The same Directive mentions a list of waste (LoW) in Article 7, created to identify wastes from various activities, called the European list of waste. The list consists of 20 chapters, numbered from 01 to 20, which groups waste that concerns a specific activity area that generates waste. The term steel slag has two references in the LoW, being considered a waste from thermal processes in the steel industry, identified by code 10 02 01 (wastes from the processing of slag) and 10 02 02 (unprocessed slag). However, the existence of several stages for the processing of steel slag automatically excludes them from item 10 02 02, once it is processed, becoming a new material with economic value. Moreover, such materials cannot be classified under code 10 02 01 since they are classified as by-products according to Articles 5 and 6. Thus, it can be inferred that the European waste list does not cover the steel slag aggregates that have undergone further processing steps and, therefore, should not be classified as waste [69].

2.3. Environmental Evaluation of Steel Slag Aggregates

Replacing natural aggregates with wastes and by-products has several environmental benefits. On the one hand, it reduces the production of raw materials, the consumption of water, electricity, diesel, and the emission of noise and dust. On the other hand, waste disposal in landfills is avoided, extending the landfill's life, and reducing emissions. Besides, this solution represents considerable cost reductions for both generators and consumers since the industries, in most cases, do not intend to make profits through the commercialization of steel slag aggregates precisely because they are not their main product [69,70].

The mechanical performance of asphalt mixtures incorporating EAF steel slags to replace natural coarse aggregates has been evaluated in-depth, obtaining excellent workability, stiffness, fatigue and rutting resistances, and moisture damage performance. However, the environmental aspects of this solution have not been studied in such detail [70].

According to Mombelli et al. [71], the use of EAF SSA in construction is limited by some polluting chemical elements in their composition, such as chromium [72], barium, and vanadium, which can be dangerous to humans and the environment. Nevertheless, Motz and Geiseler [33] state that the assessment of aggregates' environmental compatibility as a building material is not determined by the content of environmentally relevant elements in the solid material but by the potential leaching behavior.

Gan et al. [73] studied the risk of leaching of heavy metal elements during the steel slag stockpiling process and after paving asphalt mixtures. They concluded that the leaching concentration of heavy metals (particularly Cu) from steel slag increased rapidly due to the acid rain effect. Increasing the specific surface area and decreasing pH value will increase the leaching risk of heavy metals in SSA. The leaching risk of SSA was significantly reduced after being introduced into asphalt mixes. Another work [74] focused on the leaching behavior study of EAF slag to assess its suitability as a construction material because it contains toxic metals that can leach and affect the eco-system. It was found that toxic metals were not leached beyond the permissible limits for pH values between 4.0 and 8.5. By applying different leaching test methods, these authors concluded that the leaching of hazardous heavy metals from EAF slag is negligible or within permissible limits, confirming it can be used as an eco-friendly construction material.

Moreover, Li et al. [75] stated that steel slag is alkaline in an aqueous solution due to its basic oxide components. They studied the pH value of the short-term and long-term deposited slag leaching solution and concluded that it was below the specifications and, hence, was not considered as hazardous waste. However, the specification limit was exceeded for ground steel slag, highlighting the importance of adequate storage of SSA.

A few studies quantified the environmental performance of incorporating EAF steel slag as an aggregate in asphalt mixtures using the Life Cycle Assessment (LCA) methodology. Esther et al. [70] analyzed the environmental impact of replacing high-quality coarse aggregates with EAF SSA. The researchers performed an LCA on three asphalt mixtures containing different aggregates, one ophite, and two steel slag types. The results showed the importance of the aggregate absorption rate and the humidity, and steel slags can replace natural aggregates even when located up to 144 km from the asphalt plant.

Another study analyzed the environmental impact of using EAF SSA in road pavements compared with the natural materials used in road construction. The authors verified that some of the most relevant environmental impacts, such as carbon footprint, ozone layer depletion, abiotic depletion, and photochemical oxidation, depend highly on the road construction technologies used. Moreover, they concluded that significant environmental benefits could be obtained from using SSA in road construction [14].

Mladenovič et al. [76] carried out an LCA to compare the environmental impacts of asphalt surface course construction in two scenarios: a conventional scenario (using siliceous aggregates) and an alternative scenario (using SSA). The Life Cycle Assessment results (based on consequential modeling) showed that the alternative scenario is more sustainable than the conventional one if the following impact categories are considered: acidification, eutrophication, photochemical ozone creation, and human toxicity. The impacts are reduced by approximately 80% in the above indicators compared to the conventional scenario. The authors found that the alternative scenario is more sustainable even when considering long SSA delivery distances (around 100 km) and minimal delivery distances of the siliceous aggregate. Nevertheless, LCA results changed when the delivery distance exceeded 160 km due to the high SSA density.

2.4. Case Studies of Steel Slag Aggregate Incorporation in Asphalt Mixtures or Road Pavements

2.4.1. Incorporation of Steel Slag Aggregate in Conventional HMA

The initial steel slag applications occurred in the late 1960s when Canada and the United States constructed the first test roads using steel slag to evaluate the pavements' stability. From the 1970s to the middle 1980s, Baltimore City, in the United States, paved many sidewalks with steel slag asphalt mixtures. From 1990 to 1995, the total steel slag asphalt mixtures applied in New York reached about 250 thousand tons. Furthermore, it is reported that steel slag aggregates have been produced and used successfully as a road construction material in various European countries due to their advantageous technical properties [77].

Motevalizadeh et al. [78] successfully employed different EAF steel slag types containing coarse and fine aggregates to substitute mineral aggregates in asphalt mixtures. Rohde [79] also studied the possibility of using steel slag from electric arc furnaces in different layers of road pavements. The study results showed that EAF SSA could be used as an aggregate in asphalt mixtures, presenting no risks to the environment and public health when adequately treated. The same author found that a 40 cm layer of graduated basalt gravel has elastic deformations equivalent to a 25 cm base layer with EAF SSA. Thus, the economic advantage of reducing the granular base layer by 15 cm when using steel slag aggregates was demonstrated while maintaining the mechanical characteristics.

Ahmedzade and Sengoz [80] determined the influences of steel slag utilization as a coarse aggregate on the HMA properties. Four different asphalt mixtures containing two binders and coarse aggregates (i.e., limestone, steel slag) were produced to obtain Marshall specimens and determine the optimum bitumen content. The mechanical characteristics of all mixtures were evaluated by Marshall stability, indirect tensile stiffness modulus, creep stiffness, and indirect tensile strength tests. The researchers observed that steel slag used as a coarse aggregate improved the mechanical properties of asphalt mixtures.

A more comprehensive study on this topic also evaluated the effectiveness of using SSA to improve the engineering properties of asphalt mixtures. For this purpose, thirteen mixtures were tested containing steel slag in a portion of fine or coarse aggregates or all the portions. The effectiveness of the SSA was judged by the improvement in Marshall stability, indirect tensile strength, resilient modulus, and fatigue life of the asphalt mixtures samples. It was found that replacing 50% of the limestones coarse or fine aggregates with SSA improved the mechanical properties of the mixtures [50].

Kavussi and Qazizadeh [59] evaluated the fatigue behavior of asphalt mixtures containing EAF SSA. Asphalt mixture samples were produced, replacing various coarse limestone aggregate fractions (greater than 2.36 mm) with EAF SSA. Fatigue testing was performed in a controlled stress mode at various stress levels to characterize the fatigue behavior of the asphalt mixes. The results showed that incorporating EAF SSA in asphalt mixtures considerably improved the fatigue life of tested samples.

Pasetto and Baldo [30] verified the possibility of using EAF steel slags to substitute the natural aggregates (NA) in the composition of surface course asphalt mixtures for flexible pavements. The researchers evaluated the asphalt mixtures' performance through gyratory compaction, permanent deformation, stiffness modulus tests at various temperatures, fatigue, and indirect tensile strength tests. The asphalt mixtures with EAF SSA have generally presented better mechanical characteristics than those of the corresponding mixtures produced with natural aggregates.

Kim et al. [81] compared the behavior of HMA containing SSA or natural aggregates. They observed that the dynamic modulus of mixtures with SSA remained higher than that containing natural aggregates because of a favorable SSA interlock due to its high strength and the suitable grain shape. Sorlini et al. [54] and Zumrawi and Khalill [49] also evaluated the use of SSA as a substitute for NA in the production of HMA and observed that the incorporation of SSA significantly improves the properties of HMA.

A group of researchers from Germany [82] carried out a comprehensive investigation of the performance-based properties of different asphalt mixtures produced with 100% Linz–Donawitz slag aggregate compared to conventional mixtures with NA. They concluded that, in most cases, mixtures produced with this type of SSA perform better than conventional ones, making them suitable for flexible pavement construction.

2.4.2. Incorporation of Steel Slag Aggregate in WMA Mixtures

Several researchers also recommend using EAF SSA to produce WMA mixtures. Ameri et al. [58], Goli et al. [83], and Masoudi et al. [34] developed laboratory studies using coarse EAF SSA aggregates in WMA mixtures. In all studies, the authors verified that using coarse SSA in WMA mixtures enhances the mechanical performance of the mixture, including Marshall stability, tensile strength, resistance to moisture damage, resilient modulus, and resistance to permanent deformation. Furthermore, WMA mixtures containing SSA as the coarse portion of aggregates have a better fatigue performance than HMA mixtures. The authors concluded that WMA mixtures containing EAF steel slag aggregates are recommended as eco-friendly, economical, and suitable mixtures for road paving industries.

Ziaee and Behnia [60] investigated the use of EAF steel slag as a substitute for coarse aggregates in WMA mixtures, replacing 0%, 25%, 50%, and 75% of natural coarse limestone with EAF SSA. The authors concluded that replacing 25% to 50% of the natural coarse aggregates with EAF steel slag can optimize the WMA mechanical properties.

2.4.3. Evaluation of Different Incorporation Ratios of Steel Slag Aggregate

The literature review shows no standard rule for the proportion of steel slag used as a natural aggregate substitute, but satisfactory results are found for replacement rates between 20% and 100% [32]. Several studies investigated the ideal percentage of natural aggregate substitution for steel slag aggregate.

Asi et al. [84] studied the replacement of 0%, 25%, 50%, 75%, and 100% of the coarse limestone aggregate by SSA in asphalt concrete mixtures. The authors verified an improved mechanical performance of the asphalt mixtures when SSA replaced up to 75% of the coarse limestone aggregates. Kasaf and Prastyanto [85] studied HMA mixtures with steel slag ratios of 0%, 50%, 80%, and 100% as coarse aggregates. The best Marshall stability results were obtained using 80% steel slag as coarse aggregates.

Abd Alhay and Jassim [28] applied SSA with percentages of 10–40% of the weight of the asphalt concrete mixtures produced. The results revealed improved mechanical properties mainly when adding 30–40% SSA percentages, increasing Marshal stability from 8 to 15 kN. Behiry [57] studied the effect of using different ratios of steel slag combined with limestone aggregates to improve the mechanical properties and the resistance to failure factors of unbound layer mixtures. The author verified that the highest density and strength of the subbase layer were obtained for a blend of 70% SSA to 30% limestone aggregates. Moreover, the resistance to the deformation of the mixture increased proportionally to the steel slag content.

Studies were also developed to evaluate the possibility of producing asphalt mixtures incorporating 75% SSA. Rodrigues [86] concluded that steel slag could replace up to 75% of the natural aggregates used in asphalt mixtures but reduced the fatigue cracking resistance, implying a slight increase in the pavement thickness. Nascimento et al. [87] and Moura et al. [2] evaluated the mechanical performance of asphalt mixtures with 75% SSA. They concluded that mixtures incorporating steel slag might present slightly higher air void contents due to their lower workability. Nevertheless, those mixtures showed higher moisture and rutting resistance than conventional ones with natural aggregates, confirming the feasibility of using SSA as an alternative aggregate for asphalt mixtures.

2.4.4. Combined Use of Steel Slag Aggregate with Other Waste or By-Products

Some researchers have also combined SSA with other waste or by-products to develop more sustainable asphalt mixtures following a circular production system. Chen et al. [88] stated that it is worth further studying the addition of two types of recycled materials or by-products in asphalt mixtures to meet the mix design requirements (e.g., substituting coarse or fine aggregates or filler). Oluwasola et al. [35] investigated the rutting potential and skid resistance of HMA incorporating EAF SSA and copper mine tailings. Four different mixtures containing different proportions of copper mine waste and EAF steel slag were investigated. The results showed that the mixture with 20% copper mine tailings and 80% EAF steel slag had the highest skid number, intermediate texture depth, and the lowest rut depth.

Viana [89] studied the feasibility of producing asphalt mixtures using high amounts of SSA and reclaimed asphalt pavement (RAP). The excellent performance of those asphalt mixtures, assessed with laboratory tests (water sensitivity, wheel tracking, fatigue), revealed that the joint incorporation of SSA and RAP is a viable and successful solution for producing sustainable asphalt mixtures. Pasetto and Baldo [90] analyzed the rutting and moisture susceptibility of asphalt concrete mixtures incorporating RAP and EAF SSA, using these materials to partially substitute limestone aggregates at different proportions (up to 70% of their weight). The experimental results were highly satisfactory for all the asphalt mixtures produced with SSA and RAP regarding fulfilling technical acceptance requisites (i.e., air voids, ITS) for road paving applications. Furthermore, these mixtures were characterized by low water damage and a high permanent deformation resistance, demonstrating their good durability.

Fakhri and Ahmadi [53] investigated the effects of using SSA and RAP in warm asphalt mixtures. Therefore, six WMA asphalt mixtures with two contents of coarse steel slag aggregates (0% and 40%) and three contents of fine RAP material (0%, 20%, and 40%) were produced. Overall, the authors concluded that simultaneous use of SSA and RAP materials in WMA mixtures was an environmentally and economically friendly option with a comparable or even better performance than conventional WMA mixtures produced with natural aggregates.

Crisman et al. [72] researched the influence of using recycled crumb rubber (CR) when producing asphalt mixtures with SSA. The asphalt mixture was modified using the "dry" method for CR incorporation. The results indicated a significant stiffness increase at high temperatures (up to 30%), a slight reduction at low temperatures (up to 8%), and a reduction in permanent deformation under cyclic loads after incorporating CR in the mixtures with SSA. The authors stated that SSA has a higher bulk specific gravity than natural aggregates and a highly porous surface that permits a distinct interaction with the bitumen and the crumb rubber compared to natural aggregates. These factors justify the improved performance of the asphalt mixtures with SSA when modified with CR.

2.4.5. Incorporation of Steel Slag Aggregate in Other Types of Asphalt Mixtures

Steel slag has also been used as aggregates in other asphalt mixtures. Some authors [66,72,91,92] explored the feasibility of using steel slag as aggregates in Stone Mastic Asphalt (SMA) and concluded that SSA improves the characteristics of SMA mixtures. The authors state the performance is superior to that of SMA mixtures only with natural aggregates, highlighting the high stiffness, excellent friction resistance, better volumetric characteristics, and dynamic stability in situ with twice the value of a mixture with natural aggregates. SMA mixtures with steel slag used in an in-service pavement also presented excellent surface characteristics, including roughness and British Pendulum Number.

Another study was conducted using two open-graded aggregate gradations to investigate the use of SSA in porous asphalt (PA) mixtures. Those mixtures were tested for the resilient modulus, the rutting resistance, and permeability and were later compared with similar mixtures with natural aggregates. The resilient modulus and the rutting test results were significantly different, with the PA mixture with steel slag aggregate performing better. However, in this study, the porous asphalt mixture produced with conventional aggregates had higher permeability values than the PA mixture with steel slag [52].

Keymanesh et al. [61] studied the feasibility of using steel slag rather than conventional filler materials for a microsurfacing mix design to improve the mixture's ultimate performance. Microsurfacing mixtures were prepared with five compositions containing EAF steel slag filler at 0%, 25%, 50%, 75%, and 100% as the replacement filler (passing the 0.075 mm sieve). The tests showed that the mixtures with EAF steel slag satisfied the standard requirements and were compatible with the bitumen emulsion, thus obtaining the desirable mechanical, chemical, and physical properties. Furthermore, the authors verified that the mixture containing 50% EAF steel slag filler obtained the best performance among all studied mixtures.

Several authors [93–97] recently evaluated the incorporation of SSA in dense or porous asphalt mixtures to promote induced crack healing per induction or microwave radiation heating. These works with SSA demonstrated the importance of taking advantage of specific features of this by-product (e.g., electromagnetic capacity) to obtain new multifunctional products. In these solutions, steel slag will work as aggregate and healing/heating promoter in the asphalt mixtures.

3. Recycled Concrete Aggregates Applications in the Asphalt Paving Industry

3.1. Characteristics of Construction and Demolition Waste

The construction sector is associated with almost 36% of waste production volume in Europe and close to 67% in the United States [21], with the corresponding potential environmental impacts. This reality represented the production of around 924 million tons of CDW in the European Union in 2016 and 2.36 billion tons only in China in 2018 [98].

In addition to the very significant quantities of CDW produced, these materials have other characteristics that make their management and recycling difficult, as typified in Figure 3, primarily due to:

- A heterogeneous constitution with fractions of several size gradings and levels of hazard;
- Scattered origins in terms of geography;
- Occasional or temporary production at each place of origin considering the construction works' temporary nature.

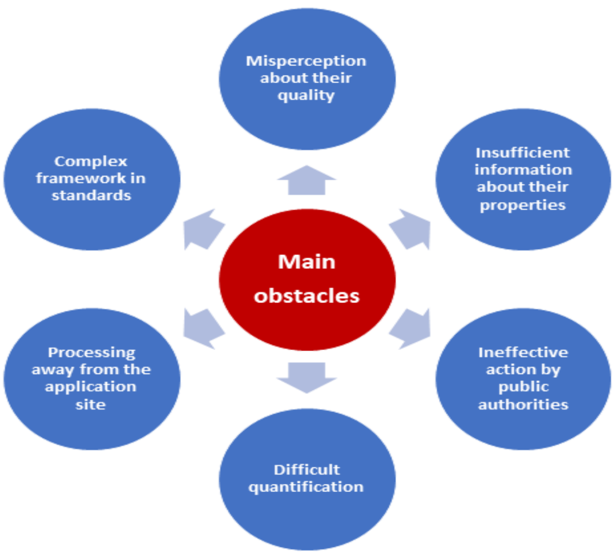

Figure 3. Some of the difficulties that CDW recycling has faced.

These problems lead to problematic quantification, frequent uncontrolled deposition, and systems supported by end-of-line treatments promoted by the low exploitation of mineral resources and landfill costs. This situation is challenging to revert and has very high environmental, social, and economic impacts, such as the environmental and visual impacts of illegal disposal and the costs to eliminate them [99]. However, some advantages and benefits of possible CDW recycling, such as those mentioned in Table 3, will contribute to the increased use of more sustainable materials and a cleaner environment.

Table 3. Advantages/benefits and drawbacks of CDW recycling adapted from [22].

Advantages	**Benefits**
It prevents the depletion of natural resources	Protection of natural habitats
Minimizing dependency on raw materials	Minimization of consumption of natural resources Prioritize ready-to-use materials
Reduction in necessary financial resources	Reduction in energy costs used in the extraction, processing, and transport of natural materials
Elimination of waste deposits	Minimization of greenhouse gas emissions Reductions in water and air pollution
Minimization of disposal expenses	Decrease in transport and disposal costs
Environmental protection	Contribution to climate change mitigation
Drawbacks	
Heterogeneity in the CDW composition Difficulties in pre-screening CDWs It may have contamination Uncertainties about the standards to be met Processing and crushing equipment may not be suitable Lack of incentives from some public entities	

3.2. Properties and Treatments of Recycled Concrete Aggregates Applied in Road Pavements

3.2.1. Properties of Recycled Concrete Aggregates Applied in Road Pavements

Concrete is globally the second most widely used material, after water, with an annual global production estimated at 25 billion tons in 2009 [100,101]. This situation generates significant impacts on the environment and society in general. One of the problems is cement production, which accounts for 4.4% of global annual industry emissions. Another problem is the end-of-life of concrete materials and structures since these materials are landfilled after demolition, generating large amounts of CDW—more than 850 million tons/year in the European Union [22]. Therefore, one way to minimize this problem is to incorporate RCA into paving materials to produce sustainable asphalt mixtures [102].

Several researchers have been pointing out some ways to process and incorporate recycled concrete aggregates (Figure 4) in different types of asphalt mixtures during the last decade, namely in hot mix asphalt [103–106], warm mix asphalt [107,108], stone mastic asphalt [103], foamed asphalt mixtures [109], and emulsified asphalt mixtures [110].

Nowadays, the main concepts involved in the comprehensive waste management process should prioritize strategies favoring implementing the most recent 7 R's rule: Rethink, Redesign, Reuse, Repair, Remanufacturing, Recycling and Recover [111]. These principles may also explain why incorporating recycled concrete aggregates in asphalt mixtures or other layers for flexible pavements, or even in other types of work, has also been recently described in several articles and technical documents [112].

Figure 4. Recycled concrete aggregate (RCA) resulting from CDW processing.

A suitable way to accomplish the goals mentioned above is to reuse RCA in asphalt mixtures. However, recycled concrete aggregates usually have a high porosity and water absorption, which has been reported as the main reason for increasing bitumen content in asphalt mixtures. Meanwhile, some recycled aggregate fractions usually have many angular and rough-textured particles. Thus Marshall stability tends to increase, and Marshall flow tends to decrease [113].

Considering the general requirements listed in the relevant standards, the adequacy of these recycled concrete aggregates resulting from construction and demolition waste processing shall be evaluated to be used in asphalt mixtures. The selection and assessment of RCA quality must be made for each type of asphalt mixture and layer to offer the best mechanical and functional performances; namely, regarding the quality of asphalt, the resistance to raveling and stripping, the resistance to weathering, the resistance to freezing and thawing, the bitumen absorption, the skid resistance, the compaction, the strength and stability, and the resistance to fragmentation [114]. In order to ensure adequate performance levels in these tests, Martinho et al. [115] reported that different natural, artificial and recycled aggregates could be combined and used in more sustainable asphalt mixtures.

Table 4 shows some of the relevant properties of recycled concrete aggregates for their incorporation in asphalt mixtures [109,116–120].

Table 4. Some RCA properties reported by several authors.

Properties	References						
	[116]	[109]	[108]	[119]	[117]	[118]	[120]
Flakiness index, FI (%)	3.4	-	-	6.0	-	4.5	34.0
Sand equivalent, SE (%)	-	-	62	30	-	77	67
Los Angeles fragmentation, LA (%)	19	28	-	43	-	38	34
Micro-Deval abrasion loss, M_{DE} (%)	-	-	-	-	24	-	-
Bulk specific gravity, G (Mg/m^3)	2.52	2.28	2.50	2.30	2.30	2.64	2.63
Water absorption, WA_{24} (%)	4.8	5.8	1.0	6.1	5.9	7.0	6.1
Flat and elongated particles (%)	-	-	-	-	2.9	-	-
Porosity, ϕ (%)	-	-	-	-	13.6	-	-

Đokić et al. [121] analyzed the mineralogical–petrographic and physical–mechanical properties of RCA, the natural aggregate (dolerite), and their combination (RCA rates between 15% and 60%). They confirmed that the granular mixtures presented good wearing and fragmentation resistance (M_{DE} 14–15%, LA 22–27%) and an acceptable Polishing Stone

Value (PSV) of 55–57. They concluded that RCA could be used in asphalt mixtures or flexible pavement layers and several traffic loads.

Moreover, as Galan et al. [104] reported, among other differences in using RCA in HMA, a 50 % higher duration on the mixing time is required until a 100% bitumen coating is reached, and the HMA compaction is more difficult due to greater internal friction on the aggregate. However, these authors also concluded that using RCA rates up to 60% improves the mechanical performance of the HMA.

The recycled concrete aggregates also tend to improve the rutting resistance of asphalt mixtures, but some works analyzed by Pasandín and Pérez [122] mention that this parameter can decrease when high percentages of RCA are used.

Regarding the resistance to fatigue cracking, using these recycled concrete aggregates usually slightly reduces the performance of HMA mixtures [123], even though this tendency was not observed in some studies mentioned by Pasandín and Pérez [122].

3.2.2. Treatments of Recycled Concrete Aggregates for Road Pavement Application

The RCA is included in the European Waste Catalogue (EWC) under code number 17 01 07 and, in general, has lower quality when compared with other natural aggregates. Therefore, many treatments [22,106,122,124] have been considered to avoid the consequences of using RCA material with inferior properties on asphalt mixtures. Table 5 presents some of the treatments studied and proposed by different researchers and their effects.

Table 5. Some treatments for RCA and their effects adapted from [22,122].

Treatments	Effects	Ref.
Double coating with cement slag paste and "Sika Tite-BE"	Decrease in water absorption and a marked increase in stiffness and moisture resistance	[125]
Microbial carbonate precipitation	Compressive strength increases (up to 40%), and water absorption decreases (up to 27%)	[126]
Pre-soaking with hydrochloric acid, nitric acid, and sulfuric acid	Increase in the compressive strength	[127]
Coating with bitumen emulsion (5%)	Improvement in stripping resistance	[128]
Coating with waste plastic bottles	Reduces water absorption and improves its mechanical behavior	[124]
Activation by organic silicon resin	Improvement in the dynamic stability of asphalt treated base	[129]
Curing at 170 °C in the oven	Improvement in moisture resistance	[130]
Modification by calcium carbonate bio deposition	A decline in water absorption	[131]
Modification with liquid silicone resin	Improved low-temperature flexibility and higher moisture and rutting resistance	[132]
Precoating with cement slag paste	Resulting in high pore contents, absorption of water, and asphalt content	[133]
Calcination process	Transform RCA calcium carbonate into lime	[134]
Silica fume solution and ultrasonic cleaning	Increase in compressive strength	[135]
Carbonation and hydrochloric acid	Significantly reduced RCA porosity	[136]

3.3. Legislation on the Use of Recycled Aggregates from CDW

The first European Directive (2008/98/EC) regarding the use of construction and demolition waste already defined a minimum threshold increase to 70%, by 2020, in respect of preparation for reuse, recycling, and other forms of material valorization for non-hazardous CDW (except natural materials as defined in the category 17 05 04 of the EWC).

In this regard, the situation in Europe remains very heterogeneous, with the CDW recovery rate ranging from less than 10% to more than 90% [137]. Therefore, these authors claim that it is essential to create conditions for secondary materials generated from the recycling of CDW to be effectively integrated into the market and used in high added value applications, dynamizing this market and promoting a circular economy in the construction sector.

Thus, the European Commission prepared a protocol in 2016 [138] to strengthen the confidence in the CDW management and the quality of recycled materials obtained. The Commission thought that this objective would be achieved as follows:

- Improving the identification, separation of the origin, and collection of waste;
- The improvement of waste logistics;
- The advance in waste processing;
- Quality management;
- The appropriate policy and framework conditions.

In particular, the importance of improving the identification, separation of the origin, and collection of CDW have been highlighted by several authors as one of the most relevant features affecting the general acceptance and use of these alternative materials [139–143].

In 2018, the European Directive 2018/851 amended the Waste Framework Directive 2008/98/EC. Among other changes, this new document replaced the concept of a "European recycling society" with that of a "European circular economy", and a new disposition was introduced to promote selective demolition. Consequently, hazardous substances must be safely removed, and selective reuse and high-quality recycling be facilitated by establishing a sorting system for CDW, including mineral fractions (e.g., concrete, bricks, tiles, ceramics, and stones). This objective's fulfillment is expected to contribute to obtaining RCA with better quality in the future.

Nowadays, recycled aggregates obtained from the CDW can also have the CE mark under the Regulation EU No-305/2011 of the European Parliament and Council because they can be used in different civil construction activities, replacing natural aggregates extracted from quarries.

Nonetheless, there is still an urgent necessity to implement measures to promote new applications of these recycled materials by all private and public owners that should contemplate the mandatory incorporation of a minimum percentage of recycled aggregates in the works' technical specifications. Thus, national environmental agencies have prepared guides that allow municipalities and companies to improve CDW streams' management and effectively fulfill their legal obligations [144–146].

3.4. Environmental Evaluation of Recycled Concrete Aggregates from CDW

Sun et al. [147] studied the workability and fracture toughness of natural aggregate and recycled concrete aggregate combined with a blowing agent through an environmental study. The acceptability of these materials was investigated and discussed based on their mechanical, micro-mechanical, and ecological performance evaluation through compressive strength, flexural strength, X-ray diffraction (XRD), scanning electron microscope (SEM), and CO_2 emission tests. The results indicated that natural aggregates (NA) have better compressive strength performance, while recycled concrete aggregates have improved flexural strength. Finally, the CO_2 emission per unit of NA was higher than RCA, indicating that using recycled concrete aggregate over other conventional resources will reduce energy consumption and meet the goal of being environmentally friendly.

Another approach to evaluate the viability of using recycled aggregates in asphalt mixtures consists of their LCA [148,149]. The work of Nwakaire et al. [149] on the use of RCA for sustainable highway pavement applications included a complete diagram with the life cycle phases to be considered for their use in road pavements (Figure 5). The authors concluded that RCA could be fully used in pavement lower layers and is a sustainable substitute for natural aggregates for highway pavements.

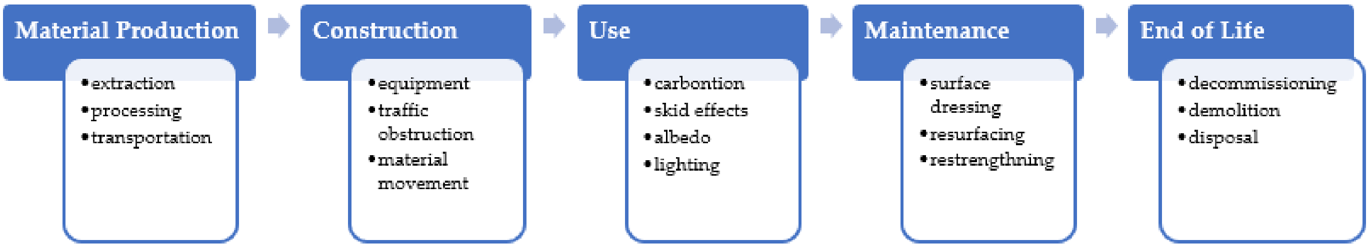

Figure 5. Life cycle phases for road pavements and factors/processes considered (adapted from Nwakaire et al. [149]).

Another example considered a cradle-to-laid LCA method to evaluate the prospective environmental impacts related to the use of RCA in an HMA for a binder course [148]. This study identifies the main processes and the system boundaries, taking into account the following four life cycle phases:

- The aggregates production and transportation to the asphalt plant;
- The production at the asphalt plant;
- The asphalt mixture transportation to the construction site;
- The pavement construction.

These authors defined three percentages of RCA replacements, ranging from 15% to 45%, and used data collected from Colombian contractors to model the foreground system. Next, they used the SimaPro software for modeling the processes, and all the life cycle inputs and outputs related to the functional unit were considered for potential impacts studied with the TRACI v.2.1 impact assessment methodology. According to their conclusions, the HMA with 15% and 30% RCA can be considered eco-friendly alternatives to the HMA with NA. However, the HMA with 45% RCA presented a lower environmental performance. Nevertheless, this work demonstrated the advantages of using recycled concrete aggregates processed from CDW in new asphalt mixtures [148].

3.5. Case studies of Recycled Concrete Aggregates Incorporation in Asphalt Mixtures or Road Pavements

3.5.1. Incorporation of Recycled Concrete Aggregate in Conventional HMA

As already well recognized, one possible approach for using recycled concrete aggregates processed from CDW is to use them as an alternative to natural aggregates, particularly in hot asphalt mixtures.

As concluded in the final report of the IRCOW project [150], the main reasons that have led many European public authorities to pay more attention to the CDW problem were the following:

- CDW is an essential source of waste in the EU and can be reused or recycled;
- Directive 2008/98/EC, from 2008, amended by Directive (UE) 2018/851, already indicated a target of 70% for the reuse of these materials by 2020;
- Recycling and reusing CDW saves natural resources and energy and can be cheaper than natural aggregates.

Another worthy effort to encourage the reuse of recycled aggregates was given by the DIRECT-MAT project, developed between 2009 and 2011 and involved twenty partners from fifteen European countries [151].

Many projects and research studies have followed this CDW recycling or reuse principle, resulting in numerous reports and technical articles over the last two decades. Since one of the materials being addressed in this review paper is recycled concrete aggregate, the main conclusions of some of the most recently released studies conducted by different authors on diverse RCA applications are presented below.

Sánchez-Cotte et al. [17,152] evaluated the incorporation of RCA of two different origins (CDW of a building; CDW of a rigid pavement) on HMA mixtures, assessing the RCA's physical and chemical properties and comparing the performance of the mixtures produced with both RCA and NA aggregates. They used different techniques to evaluate these aggregates and their influence on HMA: X-ray fluorescence, XRD, UV spectroscopy, and atomic absorption spectrometry. They replaced NA with RCA at 15%, 30%, and 45% for each coarse fraction. The mineralogical tests showed that the potential reactions in asphalt mixtures by nitration, sulfonation, amination of organic compounds, and reactions by alkaline activation in the aggregates could be neglected. These authors concluded that coarse RCA could be used in asphalt mixtures without affecting their chemical stability.

Furthermore, the laboratory test results showed that the HMA with and without RCA offered a similar behavior. However, RCA promotes more significant environmental benefits and potential cost savings. Nevertheless, the authors also stated that the HMA performance is strongly associated with the RCA source and dosage. Finally, similarly to other authors' conclusions, they note that HMA with RCA induces a higher optimum binder content (OBC) than NA.

Pasandín and Pérez [122] published an extensive and comprehensive review of the properties of HMA with RCA. These authors found that the laboratory results had significant variations, probably due to RCA's different origins. These aggregates include cement mortar, promoting a higher water/bitumen absorption, and a lower mixture quality. Most of the analyzed studies also reported a high tendency for stripping on mixtures with RCA. As previously mentioned in Section 3.2, some treatments were also identified which minimize this problematic characteristic and increase the moisture resistance of mixtures. However, other aspects need to be analyzed, including their economic and environmental impacts and practical feasibility at the asphalt mixing plant. These authors also documented the costs of using RCA in asphalt mixtures (e.g., with a higher bitumen consumption, lower density, and lower environmental impacts) and the lack of technical specifications as two critical aspects to take into account.

Regarding the specifications, the Marshall method can underestimate HMA properties because compaction can break some RCA particles and some countries use the same limits for natural aggregates in this test. Pasandín and Pérez [122] also mentioned that some studies point out that RCA can be used on the pavements of low-traffic roads and favor sustainable growth. Thus, they have concluded that new specifications must frame RCA's use in asphalt mixtures to increase the application success in trial sections, defining the type of roads and heavy traffic categories suitable to each use.

Tahmoorian and Samali [114] highlighted that asphalt mixtures include more than 65% coarse aggregates, and the large quantities of RCA available in different construction sites turn their use in asphalt mixtures to almost mandatory. In their laboratory work, they assessed the suitability of RCA and basalt to be incorporated in asphalt mixtures as coarse aggregates. In the tests performed, these authors [114] confirmed that, compared to basalt, the RCA provides better workability, compaction, and permanent deformation resistance to the asphalt mixtures. The test results also revealed that the RCA exhibits more absorption and wet/dry resistance variation than conventional aggregates and that the RCA still complies with aggregate requirements for asphalt mixtures in the remaining tests.

Gopalam et al. [153] also developed an experimental study to evaluate the influence of the binder type on the performance of dense graded asphalt mixtures that included RCA replacing NA in the HMA coarse fraction. They produced different Marshall samples of dense asphalt macadam (DBM) mixtures under the Indian technical specifications, using three binders, conventional VG 30 and VG 40 bitumen's, and a crumb rubber modified binder (CRMB), all of them with RCA or NA. Then, they evaluated the Marshall characteristics, indirect tensile strength, moisture sensitivity, resilient modulus, and permanent deformation resistance. Based on the results, they confirmed that, in general, all the mixtures fulfilled the requirements for the Marshall and moisture susceptibility characteristics. The CRMB and the VG40 binders offered the best performance with RCA or NA, although the latter showed slightly better results.

The need for recycling CDW (as RCA) for use in road pavement construction was also studied by Kanoungo et al. [154]. They compared some of RCA's available treatment methods; namely, acid treatment, thermal treatment, and asphalt emulsion, to define what would be the best method. Using these treatments, they produced DBM mixtures with RCA and analyzed the Marshall characteristics and moisture sensitivity. The results pointed to the asphalt emulsion treatment of RCA as the most suitable method.

The possible use of fine and coarse RCA as NA substitutes in nine asphalt mixtures for base course layers was also studied by Radević et al. [155]. These researchers assessed the influence of the RCA rate (up to 45 wt.%) on the physical and mechanical properties of an AC 22 base 50/70 mixture and compared the results with those obtained in a reference mixture produced with NA. They found that RCA's addition needs a higher binder content (up to 1%), which resulted in lower stiffness and higher fatigue cracking resistance of the asphalt mixtures, while their low-temperature resistance was slightly inferior. In conclusion, it is possible to use up to 45% RCA in asphalt mixtures without significantly reducing the mechanical performance.

Nwakaire et al. [149] claimed that more unanimous standard guidelines should be developed to guarantee excellence and sustainability when using RCA in HMA. These authors stated that more studies are needed on the use of RCA for porous and SMA mixtures and rigid pavements. Moreover, other essential research areas are assessing the actual field performance of in-situ RCA pavements, surveying the professional's perspectives on the challenges of using RCA, and identifying all feasible utilization potentials for RCA based on different circumstances and scenarios using LCA methods. Regarding the mix design of RCA mixtures, it is necessary to harmonize the binder requirement for RCA mixtures, develop an innovative asphalt binder with an improved affinity with RCA, adjust the particle size requirements of the conventional HMA for RCA mixtures, and adjust the solution to the sources and nature of RCA used.

3.5.2. Incorporation of Recycled Concrete Aggregate in WMA Mixtures

The use of RCA in WMA was evaluated by other authors [107,108,119,156] to assess the influence of these alternative aggregates (processed from CDW) on the performance of WMAs. Martinho et al. [108] selected three WMA mixtures with RCA considering different laboratory results, optimizing them before being produced in an asphalt plant, and then compacted under real conditions in several pavement trial sections. A dense-graded AC 20 base mixture was used as a reference mixture. Using up to 60% RCA was possible because its grading curve (Figure 6) matches the selected AC 20 base mixture gradation. The RCA characteristics were also evaluated according to EN 933-11, mainly comprising concrete (84%), unbound natural aggregates (9%), masonry elements of clay materials (5%), and traces of asphalt material and other CDWs (respectively, 0.7% and 0.6%).

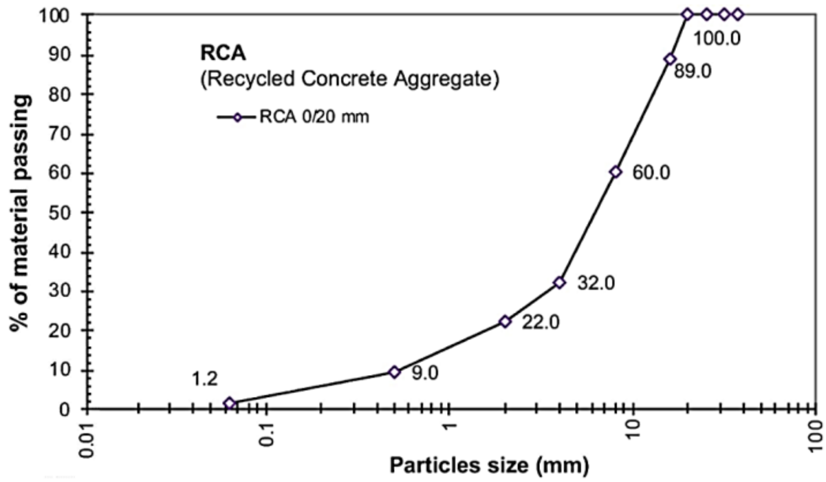

Figure 6. Grading curve of the RCA used in a WMA, adapted from Martinho et al. [108].

The results obtained in that study, supported by the literature (up to that date), led to the conclusion that the general performance of WMA with 60% of RCA was good; namely, when using an organic wax as the WMA additive. The use of a chemical additive reduced the rutting resistance compared to the wax. The alternative aggregates slightly reduced the stiffness modulus and water sensitivity results of the WMA mixtures, although the results are still satisfactory for a conventional base/binder layer. The fatigue life of WMA with RCA was adequate and close to the performance observed for the HMA and WMA mixtures used as references. Although conventional equipment was used to build the experimental pavement sections, no specific problems were observed in the field for the WMA mixtures with RCA in any of the necessary operations: mixing, transport, laying, and compaction.

Abass and Albayati [157] investigated the possibility of using RCA in WMA, testing five replacement rates (ranging from 0% to 100%) for the coarse fraction of natural aggregates, using untreated RCA and RCA treated with hydrated lime slurry or hydrochloric acid. The binder contents were obtained with the Marshall mix design method, and the WMA performance was assessed by moisture damage, resilient modulus, and permanent deformation tests. The untreated RCA mixes presented a higher binder content than treated RCA mixes. The moisture susceptibility of treated RCA was improved by nearly 10% compared to untreated RCA. However, the resilient modulus and rutting resistance for mixtures with 100% RCA were lower than those obtained with natural aggregates.

Another innovative paving technique toward a circular economy model was promoted by Neves et al. [158], studying the properties of an AC 20 WMA mixture composed of 60% RCA and a modified binder (4.5%). After assessing the aggregate-bitumen affinity, Marshall properties, moisture sensitivity, stiffness, rutting, and fatigue resistance, the authors concluded that the WMA with RCA shows adequate performance for base course layer use, comparable to equivalent WMA or HMA mixtures with natural aggregates.

In several case studies, Polo-Mendoza et al. [156] have examined WMA mixtures with various RCA contents. This study developed a trade-off methodology based on the LCA technique and statistical analysis to determine the maximum incorporation rate of RCA in WMA without generating increasing environmental impacts due to the higher binder content of those mixtures.

In a different type of WMA mixture, Zou et al. [109] reported that using RCA in foamed asphalt mixtures (FAM) does not affect the binder curing time, but the mixture performance is influenced when the processed aggregates include redbrick. These authors also concluded that FAM fulfills technical requirements for the strength and moisture resistance of base and subbase course with 100% RCA. The inclusion of redbrick in RCA weakens the FAM performance (a redbrick content limit of 5% is suggested in FAM with RCA), but the addition of 0.5% to 1.5% cement content increases the indirect tensile strength (ITS) and wet/dry indirect tensile strength ratio (ITSR) of FAM. These authors also recommended using harder bitumen's in foaming, as they include more asphaltenes and offer a higher viscosity.

Monu et al. [159] investigated the optimum proportion of hydrophobic RAP and hydrophilic RCA (separately and combined) for the production of FAM mixtures. The incorporation of RCA affected FAM performance but delayed the hydration of residual cement grains, which could enhance the performance of FAM. FAM mixtures with 20% RCA, 40% RAP, or a blend of 30% RCA and 10% RAP satisfied the specified requirements for pavement applications.

3.5.3. Evaluation of Different Incorporation Ratios of Recycled Concrete Aggregate

Different amounts of fine and coarse RCA (from 20% to 60%) were integrated by Daquan et al. [160] in an AC 20 HMA to evaluate their effect on mechanical performance. The authors concluded that the OBC increased, and the bulk density of mixtures decreased for higher amounts of RCA. Besides, they observed that fine RCA had higher OBC than coarse RCA, and mixtures with 50% coarse RCA or more had reduced moisture resistance.

Furthermore, all mixtures presented good low-temperature properties, but the rutting resistance of asphalt mixtures with RCA was lower than that of HMA with natural aggregates. The decrease in RCA content led to an increased resilient modulus and extended fatigue life (particularly when reducing coarse RCA). The mixtures with 20–40% fine and coarse RCA generally showed the best performance.

Galan et al. [161] studied the influence of RCA percentage on binder content, curing time, and temperature by studying the stiffness of HMA samples. The asphalt mixtures were produced with different percentages of RCA (0%, 5%, 10%, 20%, and 30%) and bitumen (3.5%, 4.0%, and 4.5%). The samples were cured for 0 h, 2 h, or 4 h before being tested at different temperatures (0 °C, 10 °C, and 20 °C). This study concluded that temperature was the most influential factor in decreasing the stiffness modulus. Conversely, the percentage of RCA was not very relevant to changing the stiffness modulus.

Zhang et al. [162] produced a dense-gradated AC 16 HMA incorporating RCA processed from low strength concrete [163] as a partial substitute for NA at different rates: 30%, 50%, and 75% by weight of NA. Compared with NA, this RCA presented higher wearing and fragmentation values, a lower apparent relative density, a higher water absorption, and a more inadequate bitumen adhesion. The water sensitivity of the mixture decreased up to 50% with the increase in RCA content. Nevertheless, the authors concluded that HMA incorporating up to 50% RCA could be satisfactorily used in road construction.

Finally, after reviewing the available literature on RCA uses in sustainable flexible and rigid pavement applications, Nwakaire et al. [149] presented a summary of several studies where different rates of RCA (15% to 100%) were incorporated in HMA (Table 6).

Table 6. RCA replacement levels in asphalt mixtures, adapted from Nwakaire et al. [149].

References	Type of Mixture	%RCA Included	Conclusions
Paranavithana and Mohajerani [164]	HMA	100	Volumetric properties and stability similar to other mixtures
Lee et al. [133]	HMA	100	Satisfactory mechanical performance, including the rutting resistance and moisture sensitivity
Mills-Beale and You [165]	Asphalt mixtures	75	Satisfactory mechanical performance, including the rutting resistance and moisture sensitivity
Zulkati et al. [166]	HMA	60	Satisfactory rutting resistance
Al-Bayati et al. [117]	HMA	60	Above 60%, the requirements for volumetric properties and stability were not met
Rafi et al. [167]	HMA	50	Above 50%, it did not meet the Marshall requirements (stability and flow)
Zhang et al. [168]	HMA	50	Shows a considerable reduction in the flexural tensile strength and the stiffness modulus
Wong et al. [134]	HMA	45	Adequate performance based on creep resistance and stiffness modulus
Pérez et al. [120]	HMA	40	Satisfactory rutting resistance
Pasandín and Pérez [130]	HMA	30	Satisfactory fatigue life and rutting resistance
Pasandín and Pérez [122]	HMA	30	Satisfactory water sensitivity, fatigue life, and rutting resistance
Dhir et al. [169]	Asphalt mixtures	30	Satisfactory stiffness modulus, rutting resistance, and fatigue life
Qasrawi and Asi [170]	HMA	25	Did not meet the requirements for volumetric properties above 25%
Ossa et al. [99]	Surface HMA	20	Above 20% caused moisture damage
Kowalski et al. [171]	Asphalt mixtures	15	Above 15% caused moisture damage

3.5.4. Combined Use of Recycled Concrete Aggregate with Other Waste or By-Products

Most studies combining RCA with other waste or byproducts to produce new road paving materials include RAP [9,172–174]. Nevertheless, it should be noted that some examples of the simultaneous use of RCA and SSA are presented in Section 3.6.

Abedalqader et al. [172] studied the temperature influence on the performance of asphalt mixtures with RAP and coarse RCA, concluding that the mechanical properties of these asphalt mixtures decreased as RAP and RCA incorporation levels increased for the same test temperature.

Another work was developed to obtain a 5–10 mm RCA and RAP aggregate fraction to substitute natural aggregates in hot mix asphalt [173]. The results show the possible combination of both wastes in RCA/RAP ratios equal to 25/75 or 50/50 to obtain a coarse aggregate fraction meeting the specifications and great environmental benefit due to the reduced use of natural resources.

Coban et al. [174] investigated recycled aggregate base layers for road pavements with two different RCA materials with different gradations and a blend of RCA and RAP materials, compared to the conventional solution with natural aggregates. After performing lab tests (resilient modulus) and field tests (falling weight deflectometer), they concluded that all the recycled aggregate base layers had satisfactory performance.

The fatigue cracking and moisture resistance of HMA mixtures produced with 0%, 35%, and 42% RCA and 10% waste tire rubber modified bitumen were evaluated by other authors [175,176]. This investigation showed the beneficial effect of simultaneously using RCA and crumb rubber on fatigue life, although crumb rubber increased the water sensitivity of the RCA mixture. Nevertheless, these solutions have adequate properties for medium-traffic roads.

Giri et al. [177] explored combining waste materials such as coarse RCA and waste polyethylene in asphalt paving mixtures. They observed that all the developed mixtures satisfy the Marshall and moisture susceptibility specified requirements. The use of waste PE chiefly improves the engineering properties at higher temperatures.

3.5.5. Incorporation of Recycled Concrete Aggregate in Other Types of Asphalt Mixtures

Nwakaire et al. [116] studied the performance of an SMA 14 mixture after replacing 20% to 100% of natural coarse aggregates with RCA. They also used a control SMA with 100% granite. The effect of RCA replacement on SMA quality was assessed through volumetric properties, Marshal stability, indirect tensile strength (ITS), moisture susceptibility, resilient modulus, fatigue and rutting performance, abrasion, and skid resistance. The SMA with RCA performed worse than the control SMA in the ITS and resilient modulus tests, contrary to the remaining tests. Nevertheless, the authors recommended an optimum replacement of 40% RCA because the SMA with RCA requires higher binder contents for optimum performance. The skid resistance of all SMA mixtures was satisfactory, and the rutting resistance of the SMA with RCA was lower than the control SMA at the initial cycles but was better at the end of the test.

The incorporation of RCA in cold asphalt mixtures was studied by Zou et al. [110] by investigating the feasibility of using RCA from CDW to replace natural aggregates in emulsified asphalt mixtures (EAM). Their work was based on the laboratory's assessment of the optimum moisture and emulsified asphalt contents of some EAM samples that included different RCA rates. They also evaluated the RCA EAM in-service performance after adding cement, including the moisture sensitivity and high and low-temperature performance. This work found that RCA increased the high-temperature performance and reduced the low-temperature performance and moisture damage resistance of EAM mixtures. Moreover, the addition of cement enhances the in-service performance of EAM so that RCA can substitute NA in EAM mixtures when combined with cement.

Chen and Wong [178] evaluated mechanically and functionally PA mixtures made of 100% RCA. Drain down, Cantabro, Marshall, permeability, and aging tests were used to assess the performance of three PA designs: 100% RCA; 100% RCA with enhanced asphalt binder; and control PA with granite aggregates. The results for PA made of 100% RCA assured the essential drainage function, although it is necessary to use enhanced binders to fulfill the Marshall criteria for regular highway applications. The results suggest the possible application of 100% RCA in PA.

Another study incorporated several RCA fractions in semi-dense asphalt (SDA) mixtures. Mikhailenko et al. [18] replaced 100% and 50% of the natural aggregates with three fractions of RCA (coarse, sand, and filler) and evaluated the mixtures' volumetric properties, water sensitivity, ITS, fracture energy, and rutting resistance. The results confirmed that coarse RCA absorbed higher amounts of binder and reduced the workability. The RCA mixtures presented increased ITS results and brittleness, reducing crack resistance. Higher aggregate replacements significantly affected the moisture susceptibility of the mixtures and decreased the fracture energy (mainly when replacing sand fraction). The incorporation of recycled concrete aggregates enhanced the SDA's rutting resistance, especially when replacing the coarse fraction. In general, RCA's use in SDA can be incorporated in limited amounts, and replacement by volume is recommended.

3.6. Case Studies of SSA and RCA Simultaneous Incorporation in Asphalt Mixtures

This paper presents a comprehensive literature review on two alternative by-products or secondary materials (i.e., SSA and recycled concrete aggregate) arising among the principal substitutes of natural aggregates in asphalt mixtures to fulfill the circular economy model. Various studies evaluated the potential use of these two alternative materials in asphalt mixtures separately. However, only a few studies assessed asphalt mixtures with the simultaneous incorporation of SSA and RCA, being presented in this section.

Martinho et al. [108] compared the mechanical performance of several warm asphalt mixtures with recycled concrete aggregate, EAF steel slag, or both by-products as partial substitutes for the natural aggregates. Initially developed in the laboratory, this study selected asphalt mixtures later applied in road pavement trials. Conventional HMA and WMA mixtures without by-products were used as references. The research evaluated aggregate substitution rates of 60% RCA, 30% EAF SSA, or a blend of 40% RCA and 35% EAF SSA. The authors concluded that using EAF SSA or RCA in WMA mixtures increases Marshall stability and could increase or decrease the rutting resistance. The results also showed that the water sensitivity and the stiffness modulus are slightly reduced, and the fatigue resistance does not change significantly. The overall performance of WMA mixtures with RCA or SSA was satisfactory, and the best results were obtained with 60% RCA.

Arabani and Azarhoosh [179] developed a study to determine the mechanical properties of asphalt mixtures produced simultaneously with recycled concrete and SSA. Six different asphalt mixtures containing three types of aggregate (dacite, recycled concrete, and steel slag) were produced to obtain Marshall specimens and determine the optimum binder content. Marshall stability, indirect tensile resilient modulus, dynamic creep, and indirect tensile fatigue tests evaluated the mechanical characteristics of the asphalt mixtures. The results indicated that the asphalt mixture with the best performance contains steel slag coarse aggregates and recycled concrete fine aggregates.

Roque et al. [180] evaluated the concurrent incorporation of RCA processed from construction and demolition waste and a steel slag aggregate in granular drainage layers of road pavements. Considering the high durability and permeability of the granular materials prepared with these by-products, the authors concluded that these materials could be used together in the drainage base or sub-base layers of transport infrastructures.

After presenting a comprehensive literature review on SSA and RCA aggregates' use in asphalt mixtures, including their combined use described in this last section, these alternative aggregates' main advantages and drawbacks are summarized in Table 7.

Table 7. Advantages and drawbacks of SSA and RCA in asphalt mixtures.

Aggregate	Advantages	Drawbacks
SSA	• Minimizes depletion of natural resources • Reduces consumption of natural aggregates • May reduce the production costs • Reduces waste landfill • Presents excellent wearing and polishing resistances • Can replace high amounts of NA • Increases the mechanical performance of asphalt mixtures regarding water sensitivity and rutting resistance • May be used as a self-healing promoter	• Increases the transportation costs due to its higher density • Reduces the mixture workability and increases air void and binder contents due to its rough and porous surface • Untreated SSA may leach heavy metals, increase the eluates' pH values, and present long-term expansion problems • Shows higher variability depending on steel slag origin and treatment • Demands new specifications • Increases equipment wearing and production complexity
RCA	• Minimizes depletion of natural resources • Reduces consumption of natural aggregates • Shows a mechanical performance similar to natural aggregates when the mixture is adequately designed • Minimizes the impacts of material transportation when reused on-site • May reduce the production costs • Reduces environmental liabilities	• Increases the heterogeneity due to different concrete origins • Shows higher processing variability • May present low fragmentation resistance and high water absorption • Demands new and specifically developed standards • Lacks trust from public authorities • Unknown long-term evolution of mixtures with these aggregates

4. Conclusions

This review paper showed that it is possible to use steel slag aggregates and recycled concrete aggregates from CDW to substitute significant amounts of natural resources used to produce asphalt mixtures. This substitution is especially relevant in the current situation of very high energy costs and shortages of natural aggregates. Moreover, these alternative aggregates improve the mixtures' mechanical performance, durability, and long-term sustainability in most cases.

The mechanical properties of SSA, such as roughness, shape, angularity, hardness, polishing resistance, and wear resistance, make it suitable for use as aggregates in different asphalt mixtures. Consequently, the mechanical behavior of mixtures with steel slag aggregate was generally better than that of mixtures with natural aggregates.

Different rates of SSA incorporation were observed in the literature, with values between 20% and 100%, without compromising the performance of asphalt mixtures. Nevertheless, several authors have noted that the best results were obtained when replacing up to 75% of natural aggregates with SSA.

However, some studies concluded that mixtures with SSA require a higher bitumen content than natural aggregates. In addition, some authors report difficulties in assuring the specified air voids contents due to the lower workability of these mixtures. It is also essential to pay special attention to the high density of SSA during the mix design phase, highlighting the need to use a volumetric approach.

Regarding the recycled concrete aggregates processed from CDW, different solutions have been presented for their use in asphalt mixtures as a natural aggregates replacement. Nevertheless, since RCA properties have limitations (e.g., lower wearing resistance and higher water absorption), several treatment methods were mentioned to improve its quality, and different binders can be incorporated. Different asphalt mixtures have also been produced with a wide range of RCA incorporation rates (between 15% and 100%), substituting different fractions (coarse, medium, or fine) of the natural aggregates.

Both alternative aggregates addressed in this paper allow various combinations (e.g., individual or simultaneous use of different byproducts) in replacing natural aggregates in several asphalt mixtures (e.g., HMA, WMA, SMA, foamed mixtures, cold mixtures, and recycled mixtures). This range of solutions demonstrates the importance of appropriately selecting, in each actual case, the composition that can maximize the performance and sustainability of the alternative asphalt mixtures.

Thus, researchers and engineers should continue to investigate this type of sustainable asphalt mixture to understand and evaluate its long-term mechanical and environmental performance.

The sustainability of replacing natural aggregates with SSA or RCA in asphalt mixtures is the inspiration of several research studies mentioned in this review, and it was proven using LCA techniques in some of those studies. Nevertheless, the environmental advantages depend on the amount of SSA or RCA replacement and the scenarios and boundaries considered.

In conclusion, this comprehensive literature review on incorporating steel slag and recycled concrete aggregates in asphalt mixtures for road pavements showed an adequate mechanical and environmental performance. A few restrictions of these solutions were identified, which can be corrected with an appropriate mix design. Therefore, these byproducts can be widely used to replace quarries in supplying alternative and sustainable aggregates for the asphalt paving industry.

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Abbreviations

The following abbreviations are used in this manuscript:

BF	Iron-making slag of Blast Furnace
BOF	Basic Oxygen Furnace
CDW	Construction Demolition Waste
CR	Crumb Rubber
CRMB	Crumb Rubber Modified Binder
DBM	Dense asphalt macadam
EAF	Slag and Electric Arc Furnace
EAM	Emulsified Asphalt Mixtures
EWC	European Waste Catalogue

FAM	Foamed Asphalt Mixtures
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
LD	Ladle Furnace
LCA	Life Cycle Assessment
LoW	List of Waste
NA	Natural Aggregates
OBC	Optimum Binder Content
PA	Porous Asphalt
PSV	Polishing Stone Value
RAP	Reclaimed Asphalt Pavement
RCA	Recycled Concrete Aggregate
SDA	Semi-Dense Asphalt mixtures
SEM	Scanning Electron Microscope
SMA	Stone Mastic Asphalt
SSA	Steel Slag Aggregate
VMA	Voids in Mineral Aggregate
WFD	Waste Framework Directive
WMA	Warm Mix Asphalt
ITSR	Wet/dry Indirect Tensile Strength Ratio
XRD	X-ray diffraction

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