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Review

A Review of the Characteristics of Recycled Aggregates and the Mechanical Properties of Concrete Produced by Replacing Natural Coarse Aggregates with Recycled Ones—Fostering Resilient and Sustainable Infrastructures

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Abstract

The construction industry is responsible for 50% of mineral resource extraction and 35% of greenhouse gas (GHG) emissions. In this context, concrete stands out as one of the most consumed materials in the world. More than 30 billion tons of this material are produced annually, resulting in the extraction of around 19.4 billion tons of aggregates (mainly sand and gravel) per year. Therefore, it is urgent to develop strategies that aim to minimize the environmental impacts arising from this production chain. Currently, one of the most widely adopted solutions is the production of concrete through the reuse of construction and demolition waste. Thus, the objective of this research is to conduct a systematic literature review (SLR) on the use of recycled aggregates in concrete production, aiming to increase urban resilience by reducing the consumption of natural aggregates. An extensive search was performed in one of the most respected scientific databases (Scopus), and after a careful selection process, the main articles related to the topic were considered eligible through the PRISMA protocol. The selected manuscripts were then subjected to bibliographic and bibliometric analyses, allowing us to reach the state-of-the-art on the subject. The results obtained on the replacement rates of natural aggregate by recycled aggregate indicate that the recommendations vary from 20 to 60%, and these rates may be higher as long as the recycled aggregate is characterized, and may reach up to 100% as long as the matric concrete has a minimum compressive strength of 60 MPa. The specific gravity of most recycled aggregates ranges from 1.91 to 2.70, maintaining an average density of 2.32 g/cm^3. Residual mortar adhered to recycled aggregates ranges from 20 to 56%. The water absorption process of recycled aggregate can vary from 2 to 15%. The mechanical strength of mixtures with recycled aggregates is significantly reduced due to the amount of mortar adhered to the aggregates. The use of recycled aggregates results in a compressive strength approximately 2.6 to 43% lower than that of concrete with natural aggregates, depending on the replacement rate. The same behavior was identified in relation to tensile strength. The modulus of elasticity showed a reduction of 25%, and the flexural strength was reduced by up to 15%.

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Academic Editor: Youssef Diab

Received: 18 June 2025
Revised: 30 July 2025
Accepted: 8 August 2025
Published: 14 August 2025

Citation: Junior, G.A.F.; Leite, J.C.T.; Mendez, G.d.P.; Haddad, A.N.; Silva, J.A.F.; da Costa, B.B.F. A Review of the Characteristics of Recycled Aggregates and the Mechanical Properties of Concrete Produced by Replacing Natural Coarse Aggregates with Recycled Ones—Fostering Resilient and Sustainable Infrastructures. *Infrastructures* **2025**, *10*, 213. https://doi.org/10.3390/infrastructures10080213

Keywords: recycled concrete; aggregates; construction industry; PRISMA protocol; sustainability; environmental impacts

1. Introduction

The preservation of natural resources and the reduction of greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), are priorities for the construction industry [1]. In contrast, this is one of the economy sectors that has shown exponential growth in recent decades [2], being responsible for 40% of global energy consumption [3], 50% of the extraction of natural mineral resources, 30% of water consumption, one-third of global waste production [4], and 35% of greenhouse gas emissions [5].

Currently, one of the most used products in the construction sector is concrete [6], being the most manufactured artificial resource in the world [7]. Its production method is recognized for using the largest amounts of non-renewable natural resources and causing greenhouse gas emissions, with consumption and generation rates in the range of 30% and 8%, respectively [8–10].

In this context, coarse and fine aggregates are elements that constitute around 75% of the concrete mass [11–15]. The remainder is composed of water and cement [16], with coarse aggregates representing more than 50% of the volume, strongly influencing the properties of the concrete [17]. Therefore, research on recycled concrete has focused on replacing natural coarse aggregates with recycled elements.

Industrial and social development programs in the planning phase around the world indicate a clear trend of evolution in the consumption of this material [18]. This increase was already evident in the period between 1950 and 2020, where in 2020, concrete consumption increased from 900 million tons to 30 billion tons [19], confirming a correlation with the demand of 4.0 billion tons of cement per year, as shown in Figure 1 and 19.4 billion tons of aggregates [20], with growth expected until 2050, mainly in countries that are in the process of development [21,22].

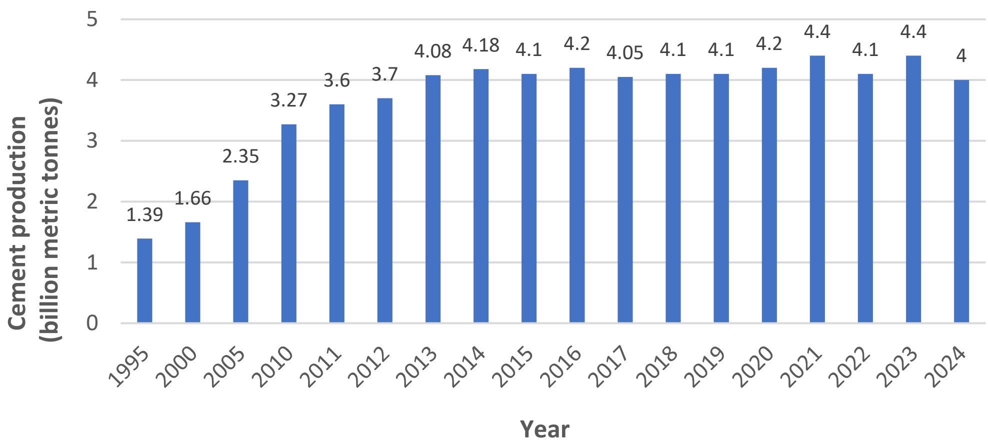

Figure 1. Global cement production (1995–2024) [23,24].

Concrete production directly impacts the emergence of numerous adversities, such as climate change and environmental pollution. This is because aggregates are non-renewable natural resources extracted mainly from rivers, where the high need for extraction causes ecological transformations and rainfall erosion [25,26]. The extraction of natural resources to be used as aggregates in concrete production is expected to exceed 500 billion tons by 2100 [27–29]. In addition to the adverse conditions for extracting natural resources, the construction sector is also responsible for generating construction and demolition waste

(CDW), with 95% of the amount generated being sent to landfills or discarded on riverbanks and urban perimeters [30]. Research indicates that up to 90% of this waste could be reused or recycled [31].

Globally, the amount of CDW produced is on the order of 2.4 billion tons in China [32], 850 million tons in the European Union [33], 600 million tons in the United States [34], and 45 million tons in Brazil alone [35]. Concrete waste alone accounts for 85% of all CDW generated in the United States. In Australia and China, for example, this proportion is 81% and 45%, respectively [36]. Therefore, it is necessary to seek solutions to minimize the extraction of natural resources and environmental impacts and to manage, reuse, or recycle CDW [24], in addition to meeting the needs of countries that already have a shortage of natural aggregates, such as the United States and France [37]. The most widely used solution currently is the production of concrete through the reuse of CDW as a partial or total replacement for natural aggregates [38], called recycled concrete [39] or Green Concrete, which is concrete produced through the use of recycled aggregates from construction and demolition waste (CDW) [40], with the aim of meeting sustainability goals [2].

Although the topic has been widely discussed in the international literature in recent years, it is clear that there is no congruence in relation to the results obtained by the various studies, considering the different variables to be considered in the dosage and production of recycled concrete. Therefore, the objective of this research is to conduct a systematic literature review (SLR) on the characterization of recycled aggregates, addressing the production process, treatment, replacement rates in relation to natural aggregate, specific mass, residual mass, water absorption, and abrasion resistance. Furthermore, the mechanical properties of compressive strength, tensile strength, flexural strength, durability, and modulus of elasticity were addressed. These are essential properties for evaluating the performance, quality, and suitability of concrete for various applications, which can boost its use in civil construction and promote sustainability.

2. Materials and Methods

A systematic literature review (SLR) is recognized as the most appropriate methodology to ensure that the most influential research on a given topic is verified and to identify gaps in the field of knowledge [41]. This is conducted through a mixed analytical approach, i.e., bibliometric and bibliographic. The combination of these two techniques is essential to obtain the state of the art on the topic under study.

2.1. Bibliometric Analysis

Bibliometric analysis can be defined as a set of methods used to study or measure texts and information, especially in the form of large data sets [42]. It is widely recognized as a well-established research technique in science for assessing research performance, particularly because it offers a way to map and visualize the evolution of the literature in each field [43].

This quantitative analysis model is used to describe, evaluate, and monitor published research, identifying the most reliable and popular sources of scientific publication, recognizing the main scientific actors such as authors and institutions, distinguishing future academic collaborators, pointing out the appropriate institutes to obtain their academic titles or carry out joint research, detecting emerging research interests, and predicting the future success of research within a given area of knowledge [44–46].

Therefore, it has the potential to introduce a systematic, transparent, and reproducible review process, highlighting the historical progress and quantitative trends of research publications within a specific topic, thus allowing users to analyze the internal relationships of the literature based on their bibliographic data [43,47].

To achieve this, it is necessary to use a well-defined protocol that, together with other analysis tools, allows the identification, screening, inclusion, and evaluation of documents selected for review. In this manuscript, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [48] protocol was selected for data acquisition, ensuring the levels of transparency and quality required by the systematic review, being applied in conjunction with the Excel and VOSviewer 1.6.20 software, developed in the Centre for Science and Technology Studies (CWTS) of Leiden University located in the city of Leiden, in the Netherlands.

2.1.1. Application of the PRISMA Protocol for Data Collection

The PRISMA protocol is a widely recognized, evidence-based approach to conducting reviews and meta-analyses, ensuring the transparency, accuracy, and reliability of the process [48,49].

This protocol is frequently used due to its specific adaptation for structured reviews, which ensures a clear and concise outline of crucial aspects of the review, such as research objectives, eligibility criteria, data collection methods, and analysis plans [48].

The protocol is structured in three stages: identification, screening, and inclusion. The first is responsible for collecting documents, while the screening stage allows for selecting the most relevant and appropriate studies to effectively meet the research objectives. Finally, the inclusion stage indicates the articles that will be analyzed in full by the authors.

Identification

The identification stage involves outlining the search strategy for document retrieval. This process requires defining a series of parameters that allow for obtaining the first set of documents. At this stage, the Scopus scientific database was selected. It is widely recognized for its broad coverage across all disciplines, offering a diverse range of studies and publications relevant to research. Its widespread use facilitates access to a vast body of literature, while advanced search functionalities allow for the accurate retrieval of relevant research articles, increasing the efficiency of the research process.

The parameters used to obtain the articles to be analyzed are defined in Table 1, with a collection date of 1 April 2024.

Table 1. Parameters and settings table.

Parameter	Settings
Keyword	"recycled concrete"
Year	2019–2024
Document type	Article
Publication Stage	Final
Source	Journal
Language	English

The initial parameters applied resulted in 2081 documents being obtained, which moved on to the next stage.

Screening

Due to the large number of records found, it was necessary to establish well-defined exclusion criteria that could be applied in a staggered manner, in order to gradually eliminate documents considered to be of little relevance to this research, as demonstrated in Figure 2.

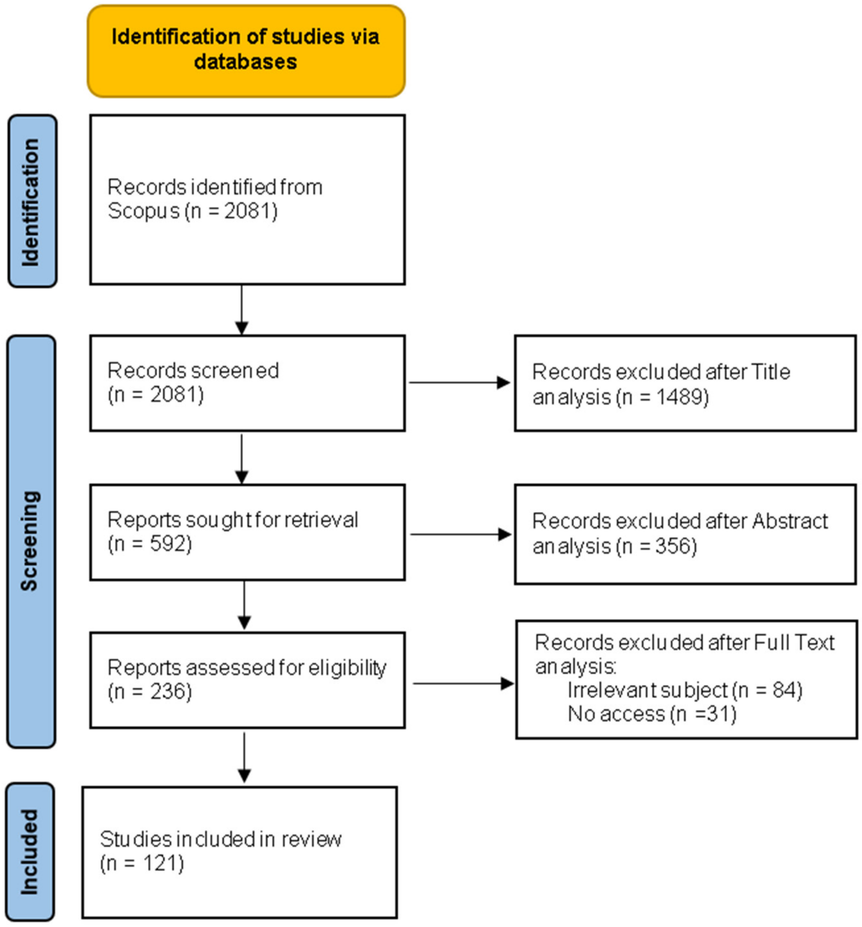

Figure 2. Application of the PRISMA protocol.

The systematic approach employed in this report increases the reliability and validity of the results in order to facilitate a comprehensive and unbiased review of the available literature.

2.2. Bibliographic Analysis

Bibliographic analysis qualitatively investigates academic sources, such as scientific articles, dissertations, and theses, among others. The objective is to identify, compile, and discuss the results of the most recent research published in the international literature, where the information found will contribute to the development of a solid theoretical basis on the topic under analysis.

3. Results and Discussion

3.1. Bibliometric Analysis Results

Considering the articles analyzed in the bibliometric stage of this research, 66% addressed experimental programs, 18% conducted simple bibliographic reviews, and 15% were dedicated to comparative data analysis, while only 1% performed systematic bibliographic reviews, that is, developed according to a well-defined protocol. This demonstrates that, despite being a well-established field of research, there is a lack of studies that aim to analyze and compare the results between the various manuscripts already published. This gap is intended to be filled with this massive review manuscript.

3.1.1. Analysis of Publications by Year

The number of publications over time on a given research topic is an important indicator of its relevance in the academic field. In this case, the growing interest in the topic in recent years may be related to a greater understanding by society of the need to minimize the extraction of natural resources and the emission of greenhouse gases, preserving the environment for future generations.

The publication of the manuscripts that constitute the sample of this research indicated a sudden growth from 2019 to 2020 and, from then on, presented a more linear trend, demonstrating a constant interest of the academic community in the topic, as shown in Figure 3.

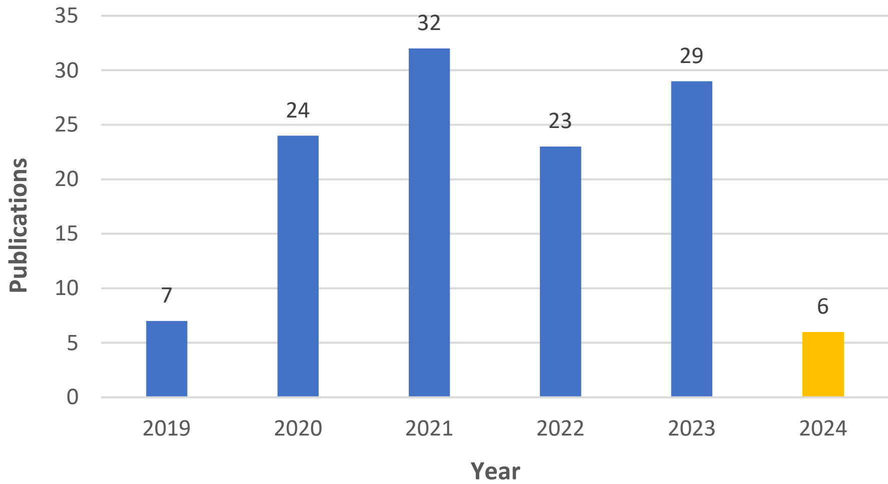

Figure 3. Number of publications per year.

The column referring to the year 2024 is represented by a different color and has few articles, as the data obtained considers only the first three months of the year.

3.1.2. Analysis of the Most Influential Studies

This analysis presents the 10 documents with the highest number of citations received in Scopus. The number of citations of an article is an indication of the academic impact of the research in a given field of knowledge.

The paper "Experimental investigation on the variability of the main mechanical properties of concrete produced with coarse recycled concrete aggregates", authored by Pacheco et al. [50], is the most cited article in the sample, with 177 citations. However, considering only the total number of citations (TC) can confuse the assessment, since older articles have had more time to be read and cited. Therefore, together with the analysis of the total number of citations, it is necessary to measure the average number of citations per year (CPA), which will indicate, in a normalized way, the documents with the greatest citation tendency. In this context, the paper "Towards Circular Economy through Industrial Symbiosis in the Dutch construction industry: A case of recycled concrete aggregates", authored by Yu et al. [51], has the highest average number of citations (26.25 citations per year), having been published two years after the leading document in total citations, as shown in Appendix A, which presents the name, authors, number of citations, number of citations per year, year of publication, and publication journal of the 10 most cited articles.

To confirm the results obtained in Appendix A, the data were submitted to VOSviewer to create a publication network based on direct citations. The use of direct citation is a recognized form of measurement to identify the most influential studies in a research field. This method differs from simply counting the number of citations obtained by the document, as shown in Appendix A, as the software establishes that the relationship of the items is determined based on the number of times they are cited. In other words, this is a very effective method for checking the influence of articles in the international literature.

VOSviewer is capable of creating distance-based network maps, which indicate the proximity between studies. The font size and the area represented by each study also differentiate the concentration of citations, where larger fonts show a higher level of citations for a study. The minimum number of citations for a paper was set to 20 to return a sample of highly influential studies on the topic. Thus, 37 studies reached the limit to be included in the network, as illustrated in Figure 4. Therefore, it can be seen that the work of Pacheco et al. [50] really stands out from the others.

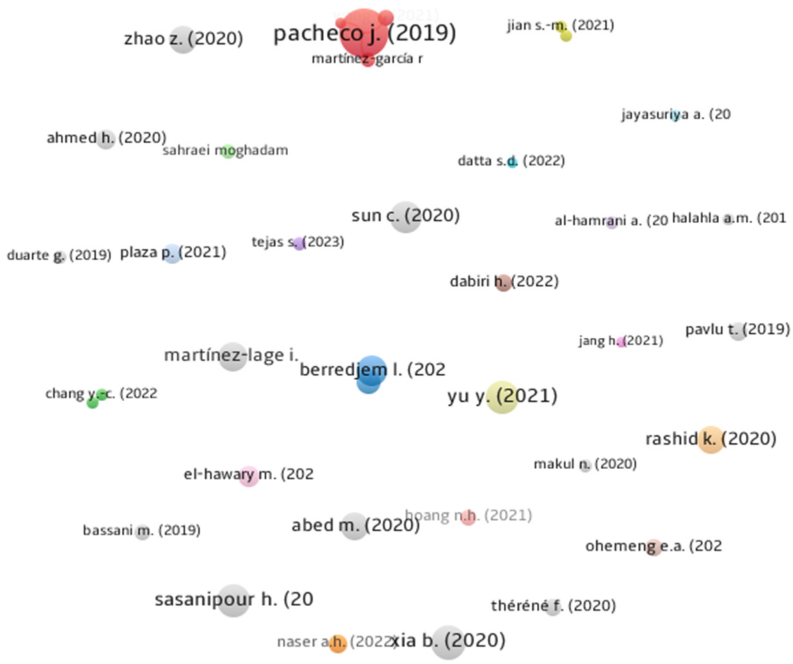

Figure 4. Total number of citations.

3.1.3. Analysis of the Most Productive Authors

The number of documents published by each author and the respective number of citations are often considered important indices for measuring the influence and impact of an author in an area of knowledge. According to the research results, the 121 selected articles were written by 437 authors. The eighth most productive authors in the sample, based on the number of articles published on the topic in the period 2019 to 2024, are presented in Table 2.

Table 2. Most productive authors.

Rank	Author	Documents	Total Citations	Citation per Document
1	De brito, J.	4	331	83
2	Xiao, J.	4	329	82
3	Abed, M.	3	91	30
4	Li, J.	3	83	28
5	Nemes, R.	2	91	46
6	Kumar, R.	2	73	37
7	Kumar, V.	2	73	37
8	Singh, R.	2	73	37

De Brito, J., is the author who published the most (four documents) and had the most citations (331), followed by Xiao, J., who published four documents and received 329 citations.

3.1.4. Co-Authorship Mapping

The articles that constitute this sample are predominantly multi-authored, indicating the general need for multiple contributions on this topic. In this context, it becomes convenient to understand how co-authorship relationships occur between authors, especially the most influential ones. The data was then fed to VOSviewer to create a co-authorship network based on co-authorship analysis, so that the software can establish the relationship of items based on the number of co-authored documents.

The minimum number of documents from an author was defined as one, and it was decided to establish a minimum number of citations per author of 10 citations, ensuring that only authors with a certain authority in this area of knowledge were selected. Thus, 222 authors reached the limit to be included in the network, as shown in Figure 5.

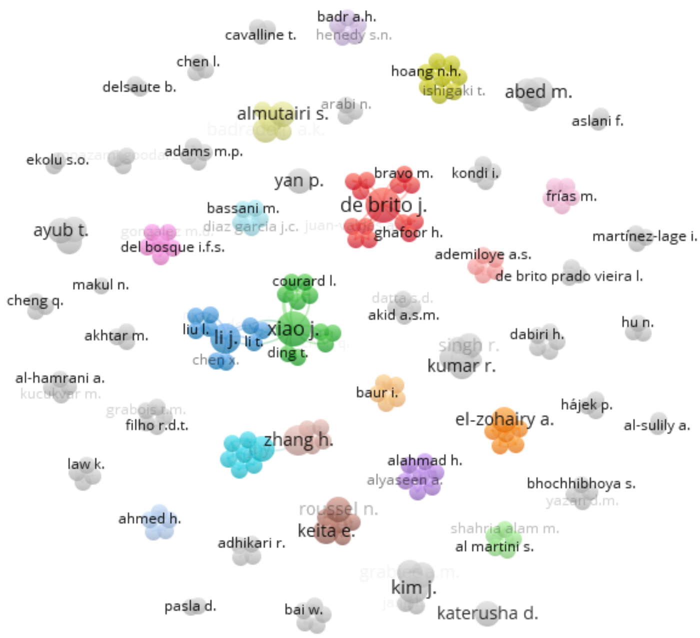

Figure 5. Co-authorship clusters.

This is an important result, as the broad connection between the authors indicates a relevant international contribution to research on the topic, where the clusters show the number of grouped items and the strength of the connection of each item, allowing the visualization of internal relationships, that is, whether there are robust interrelationships between the subgroups of guarantors.

Analysis of Figure 5 allows for the rapid identification of three main groups, with 14, 10, and 11 authors, respectively. Cluster 1 (red) is led by De Brito J., Cluster 2 (green) is led by Xiao J., and Cluster 3 (blue) is led by Li J., where the cluster colors are intended to visually identify the authors belonging to each cluster. It is interesting to note that there is a predominance of Chinese authors in the clusters.

3.1.5. Most Influential Countries

Analyzing publication patterns by country provides interesting insights into a research field, as author affiliation gives an indication of countries active in research on a given topic. The articles incorporated into this review came from 53 different countries.

China is the most prolific country, with 22 publications (18.18%) and 572 citations, followed by Spain, with 12 publications (9.91%) and 238 citations, as shown in Table 3.

Table 3. Most influential countries.

Rank	Country	Documents	Citations
1	China	22	572
2	Spain	12	238
3	India	10	150
4	USA	9	211
5	Polonia	8	118

3.1.6. Keyword Analysis

Keywords are the basic units of a specific field of study and can provide information about the structure of knowledge and research trends. Thus, to provide deeper insight, VOSviewer's text mining capability was utilized to create a keyword co-occurrence network. Each node in the network represents a keyword, and the link between nodes represents the co-occurrence of the keywords. The more often the two keywords appear together, the thicker the line between them will be. Additionally, distance-based networks created by VOSviewer show the affinity of terms by their distance in the network. Smaller distances between two terms show a stronger relationship between the terms based on their co-occurrences in published studies. The co-occurrence count is then normalized to determine the strength of each link. Since clustering determines the most used keywords and similarity, it provides indications of the most concentrated topics in the search field. This network can also be used to analyze the connection between different approaches to the topic.

A total of 1036 keywords were detected by the software in the sample. Due to the large number of words identified, it was decided to select only those with at least 10 occurrences. The most prominent keywords were "recycling" with 85 occurrences and "concrete aggregates" with 78 occurrences. Thus, 33 keywords met the stipulated criteria and composed the map presented in Figure 6.

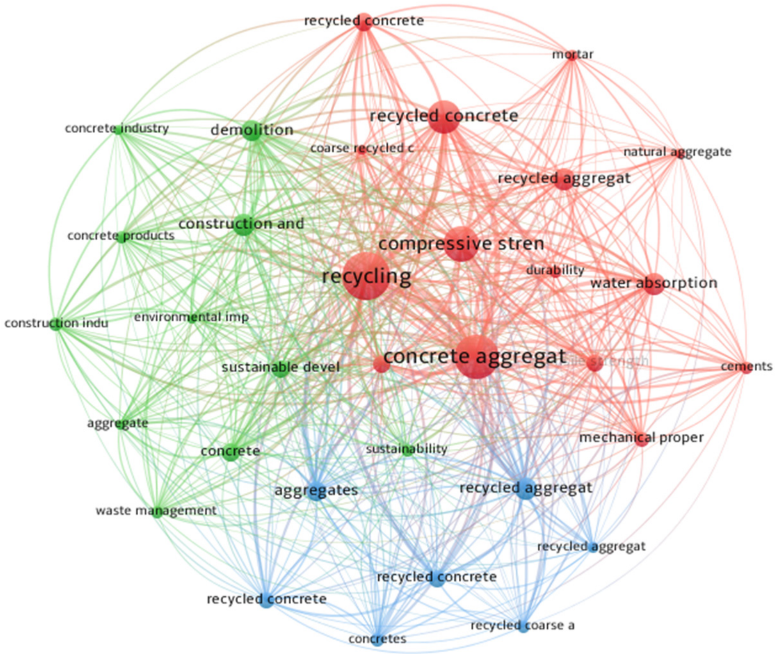

Figure 6. Keywords coocurrence.

Other keywords that were listed most frequently by the authors were "compressive strength", with 57 occurrences, and "recycled concrete aggregates", with 53 occurrences. This confirms the relevance of compressive strength tests in the study of recycled concrete and also the trend of using recycled aggregates as a way of reducing the environmental impact of this material.

3.2. Bibliographic Analysis Results

At this stage of the research, the aim is to qualitatively evaluate the results obtained by the various articles published on recycled concrete, in order to reach the state-of-the-art on the subject. Thus, in addition to the articles considered in the bibliometric analysis stage, a large number of other studies considered relevant to understanding this area of knowledge were added. This resulted in extensive analysis work, in which more than 300 articles were meticulously examined. Figure 7 illustrates the topics to be covered, separated into categories. Each of the items illustrated in the figure below will be discussed based on the existing literature, in order to obtain the state of the art on the subject, and also identify possible inconsistencies between the results of similar research.

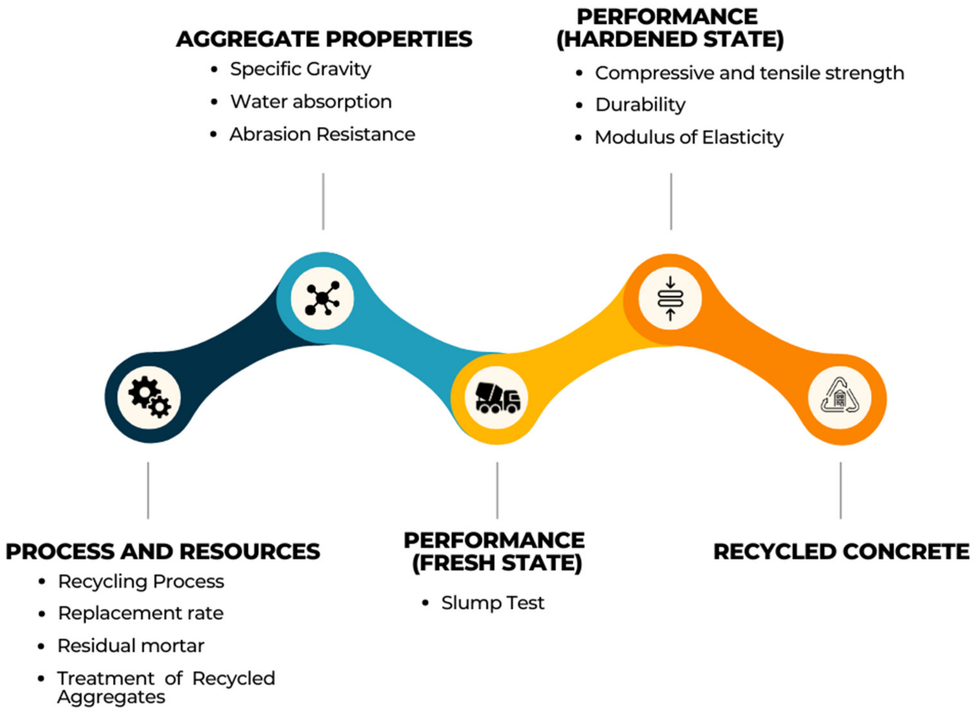

Figure 7. Categories addressed in the literature review.

3.2.1. Recycled Concrete

Recycled concrete is produced through the use of recycled aggregates from construction and demolition waste (CDW), which have undergone the process of crushing, screening, cleaning, and classification, partially or totally replacing the natural aggregate [52,53]. However, it is worth noting that the source and crushing process of the recycled coarse aggregate significantly affect the quality of the concrete produced [54].

The use of CDW in the manufacture of concrete called recycled began in the 1970s, in the United States, after the demolition of old roads and buildings, where this kind of concrete was used for non-structural purposes, beginning research into the viability of replacing natural aggregate with recycled aggregate [55]. Although the use of recycled aggregates was first reported in Europe after World War II [56]. Currently, CDW is widely used as a coarse aggregate comparison to fine aggregate [57]. This occurs because the amount of mass adhered to the coarse aggregate is less than that of the fine aggregate [58].

The production of recycled concrete provides the preservation and reduction of the extraction of natural resources, minimizing the generation of waste [59,60], meeting the sustainability goals established in the Sustainable Development Goals (SDGs) [61]. The goal is to reduce greenhouse gas emissions by 35%, energy consumption by 42%, and the extraction of natural resources by 50% [62].

Despite providing greater efficiency and useful life to landfills [2,63], the implementation of the circular economy [64], and other benefits, recycled concrete is little used in civil construction due to its unfavorable financial viability [65], the lack of government support [66], and the absence of research on its durability and technical characteristics [67].

The economic perspective regarding the recycling of construction waste and the use of recycled aggregates in concrete production is evaluated by some researchers [68–73], but in a general context, research addresses, in a limited way, the factors that influence the price of concrete. Therefore, the economic viability of using recycled concrete is considered unfavorable due to the price of this material, being higher than that of concrete with natural aggregates [74], in the range of 10% in Australia, for example [75]. In this context, the creation of government measures that encourage the recycling of CDW and the use of green products [76] could provide price equality.

Advances in research on the properties of recycled concrete may allow for its widespread use in structural projects [77–80], since it is currently used mainly in pavements and landfills [81,82], due to the lack of standardization regarding the production of this type of mixture [83]. This occurs because aggregates from CDW present heterogeneous characteristics due to variations in particle morphology, quantification of adhered mortar, and crushing technique, which can influence and result in inconsistent data regarding the mechanical properties and durability of concrete, compared to identical concrete mixtures that use natural aggregates, restricting their use [58,84–89].

Previously published studies mention that the quantity and quality of the adhered mortar are characterized by the quality of the matrix concrete, the production method, and the size of the aggregate. However, most of them do not mention exactly whether the strength of the matrix concrete directly influences the characteristics of the recycled aggregates [90,91]. Some studies [92–95] mention that recycled aggregates from low-strength concretes present lower water absorption due to the smaller amount of mortar. While other authors state that aggregates from high-strength concrete have greater absorption capacity [58,96–98]. There are also those who indicate that aggregates from high-strength concrete have lower water absorption [93,99,100]. This confirms the lack of agreement regarding the results of different studies, which makes it difficult to develop objective guidelines on the subject.

Regarding specific gravity, Liu et al. [93] state that as the strength of the matrix concrete increases, the specific gravity also increases. However, other studies disagree with this result [90,92]. Therefore, several studies converge on the essentiality of characterizing recycled aggregates [76,92,99,101–105], mainly regarding their composition, water absorption, unit, and specific mass. This occurs because they present greater porosity [106,107] and an interfacial transition zone (ITZ) of weak adhesion between the aggregate and the mortar [108], due to the quantity and quality of the adhered mortar [79,104,109–111]. Furthermore, this need is also justified because the matrix concrete has already been put into service, undergoing numerous transformations, such as carbonization, physical extrusion, chemical corrosion, and temperature variation, among others [57].

3.2.2. Recycling Process

The crushing process of recycled aggregates does not differ significantly from that used in common aggregates. It starts with primary crushing, typically using horizontal impact crushers or jaw crushers, where recycled aggregate samples are reduced to fragments below 100 mm [112]. The comminuted elements can then be collected according to the procedures described by ASTM C702 [113], EN933-11 [114], and characterized by TSEN933-1 [115] and EN206 [116] standards.

The quality of recycled aggregate is assessed using an index called flakiness, according to ASTM D3398 [117] and TSEN933-3 [118] standards, where the texture and shape of the aggregate are taken into account. Aggregates with smooth and long surfaces are considered to be of low quality, as they reduce the strength of the concrete, in addition to requiring an increase in the amount of cement [119]. Coarse aggregates must have a flakiness index of less than 35%, with the index of natural aggregate being 5 to 9% higher than that of recycled aggregate [92,95].

3.2.3. Replacement Rate

The current literature indicates that partial replacement rates of natural aggregates by recycled aggregates in structural concretes (above 20–25 MPa) need to be limited to a maximum of 25% by mass. However, when the recycled aggregate has a low porosity and a water absorption of less than 3.5%, its use as a replacement for natural aggregate cannot exceed 20% [120–128].

Tam et al. [81], in their review article on the subject, found that most countries limit recycled concrete made with recycled coarse aggregates to 20% in structures. In contrast, environmentally progressive countries allow the use of recycled aggregates, up to 30%, for application in structural concrete [129], in agreement with some researchers who mention that this substitution rate produces the same compressive strength of concrete in relation to the reference concrete, consisting only of natural aggregates [130].

According to the national RECYBETON recommendations (NF EN 206 + A2/CN), concrete mix designs containing recycled aggregates are limited between 20 and 60% [116]. This recommendation converges with other research, which mentions that the maximum levels of recycled aggregates should be kept below 50% [131,132]. On the other hand, Machado et al. [133] recommends that, when the replacement content exceeds 50% of the mass, it is essential to carry out characterization tests on the recycled aggregates (such as composition, water absorption, and density), in accordance with ASTM C136/C136M standards [134], in order to ensure less variation in the properties of the recycled aggregate concrete and in its prediction by modeling. From another perspective, Andreu and Miren [99] state that it is possible to replace 100% of natural coarse aggregates with recycled ones, generating concrete with considerable mechanical properties, as long as the recycled aggregate matrix concrete has a minimum compression of 60 MPa.

3.2.4. Specific Gravity

The specific density of recycled aggregates is an essential classification criterion and can be determined using several standards, such as BS 812 [135–137], ASTM C127 [138], EN1097-6 [139], ASTM C12715 [138], and EN1097-6 [139], with emphasis, according to [102,140], on ASTM C138 [141] and ASTM C33 [142]. Its relevance is directly related to the presence of impurities adhered to the aggregate, such as cement and residual mortar, which is the portion of mortar that remains adhered to the recycled aggregate, resulting from the crushing process. This characteristic influences the water absorption capacity and the chemical composition of the recycled aggregate, causing changes in the properties and behavior of the concrete, in the fresh and hardened phases [10,143–150].

Recycled aggregates have greater porosity [105], lower apparent density, and lower dry saturated surface density [82,92,105,151–155]. This is due to the presence of the residual mortar mentioned above, which has a lower density than natural aggregate, and also to the presence of microcracks [156–158].

The specific density of most recycled aggregates according to the ASTM C128 [159] standard ranges from 2.40 to 2.90, i.e., values close to those cited in other databases, which range from 2.13 to 2.68 [160]. These values are also close to those cited by Verian et al. [143], according to which the recycled aggregate has a low specific density ranging from 1.91 to 2.70.

Skocek et al. [112] performed analyses on 300 samples of recycled aggregates, finding an average density of 2.32 g/cm^3. The results differ from those established by the ASTM C29 standard [161], in which the recycled coarse aggregate must have an apparent density of 1200 kg/m^3 to 1750 kg/m^3, determined by the TSEN1097-3 standard [162].

3.2.5. Residual Mortar

Residual mortar adhered to recycled aggregates is considered one of the most influential factors in the performance of this kind of aggregate in concrete production, where its quantification is an important factor in assessing its quality [163–166]. The research investigated converges regarding the amount of mortar adhered to the recycled aggregate, which varies between 20% to 47% [149] and 20% to 56% [90,167–172]. Furthermore, according to Olofinnade and Oyawoye [173], it is possible to remove or modify this mortar, with the aim of improving the physical–mechanical properties of CSW, in terms of water absorption capacity, specific gravity, and porosity.

3.2.6. Treatment of Recycled Aggregates

Several methods are used to quantify or remove mortar adhered to recycled aggregates [174]. These processes result in better performance in the properties of recycled concrete, improving the adhesion of the aggregate–cement matrix [85,175]. The methods found in the current literature are the addition of nanomaterials [87,176–178], carbonation [179], coating with cementitious materials [108], embedding in epoxy [180,181], immersion in sodium sulfate [182] and the application of freeze–thaw cycles [170], grinding using the effects of rolling vibration of ball mills [183,184], autogenous cleaning [185], heat treatment [186], ultrasonic cleaning [187], immersion in acidic solutions (e.g., hydrochloric, sulfuric, phosphoric) [173,188,189], and treatment with pozzolans [174,184,190–194].

The characteristics and execution processes of each of the various treatment methods mentioned in this manuscript were not addressed in this research, as they are mostly described in articles that specifically address the treatment of recycled aggregates, and are not the focus of this review.

3.2.7. Water Absorption

Water absorption is a commonly used durability indicator, as it provides a measure of porosity, which is strongly associated with durability [195–197]. Porosity and water absorption tests can be performed according to ASTM C1585 [198], ASTM C127 [138], and EN1097-6 [139] by microstructural evaluation using scanning electron microscopy (SEM) [199], using micro-CT analysis, or according to ASTM C830-00 [198].

The texture and microstructure of recycled aggregates often influence the porosity and water absorption capacity of concrete [200–203]. This occurs because the presence of residual mortar adhered to recycled aggregates provides higher water absorption rates compared to natural aggregates [52,92,143,152,154,204].

Research by Safiuddin et al. [205] and Bao et al. [206] shows a tendency for the degree of water absorption in a concrete mix to gradually increase as the amount of recycled aggregate used to replace natural aggregate increases. Shobeiri et al. [160] developed a database on the water absorption of recycled aggregates, indicating that it can be up to 12%, similar to other studies [69–71,120,207–211] that present a variation of 2% to 15%. This absorption rate was also demonstrated by Machado et al. [133], where several types of recycled aggregates showed more than 10% of water absorbed.

Plaza et al. and Silva et al. [212,213] mention an absorption range of 3.9 to 9.6%, while the results of Skocek et al. [112], in turn, indicate an average water absorption of 5%. This index is very close to that found by Zheng et al. [151], which was 4.5% and 5.5% for aggregates with granulometries of 8/15 mm and 3/8 mm, respectively, and by Hosseinnezhad et al. [214], which presented a variation of 5.32% to 7.26%.

Fellah et al. [215] presented a proportion of water absorption of recycled aggregates in relation to natural aggregates. The former presented values five times higher than the latter. This result is justified based on the presence of residual mortar fixed in the natural aggregate and highlights that the use of recycled aggregates for structural concrete applications limits the water absorption values of recycled aggregates to less than 7% [216].

Aiming to minimize the effects caused by the greater water absorption of recycled aggregates, experimental programs sought a relationship between the water absorption of the aggregate, the change in the water–cement ratio of the mixture, and the effect caused on the hydration of the cement [217], since the recycled aggregate absorbs water from the cement paste, causing a change in the water–cement ratio of the mixture [218]. Therefore, it is of great importance to take into account the effective hydration of the cement paste, mitigating the occurrence of inconsistent results.

Furthermore, aiming to preserve the stability and consistency of the fresh phase of the mixture [219–223], studies suggest a pre-saturation of the recycled aggregate of around 60% to 90%, in the period of 24 h [220,224,225], causing the aggregate to lose the capacity to absorb water from the cement paste [226]. Another method recorded in the literature is the addition of water during the mixing process [223,227], also called water absorption compensation, which is performed by adding an extra amount of water to the mixture [228]. In both methods, the Chinese standard GB/T 14685-2011 [229] mentions that the amount of water added or pre-saturation of the aggregates should be conducted according to their water absorption capacity during the 24 h period. The EN206 [116] standard mentions that the absorption rate of coarse aggregates can be obtained after a period of 1 h of immersion in water. In any case, the process must be carried out with caution, because if the total amount of extra water is not absorbed by the recycled aggregate, this will cause an increase in the water–cement ratio and in the interfacial transition zone [230,231], which will influence the compressive strength values of the recycled aggregate [232,233].

Amario et al. [234] tested different water absorption saturation rates, where only the 50% rate for 24 h showed similar strength and workability rates in relation to the reference concrete. Conversely, Leite et al. [225] consider the ideal rate to be 80% to 90% of water absorption during the 24 h period. The hypothesis is corroborated by Mefteh et al. [219], who consider a water absorption rate of 80% as ideal, and Agrela et al. [235], who recommend a rate of 92%.

There is clearly no consensus regarding the use of this technique to compensate for water absorption by recycled aggregate, as highlighted by Poon et al. [220], since its use for concretes with different water–cement ratios is not generally recommended. This occurs because the hydration process of the cement paste and the absorption of water by the recycled aggregate occur simultaneously, making it difficult to analyze absorption due to the long hydration process of the cement part and the distribution of non-grouped water after the concrete-setting process. Therefore, the calculation of water absorption by recycled aggregates used in previous techniques may not represent reality [236].

In view of this situation, a method called LF-NMR was developed to quantify the hydration process of the cement paste and analyze the moisture distribution of the materials [237], as described by She et al. [238] and Leech et al. [239].

3.2.8. Abrasion Resistance

Los Angeles abrasion resistance is a way of determining the resistance of coarse aggregate to surface wear [240]. It is a very important test for the production of concrete [119], especially recycled concrete, as it can suffer fractures, thus losing its strength and durability. The results are normally influenced by the porosity of the aggregate, which can be determined by ASTM C131/C131M-20 [241]. Most natural coarse aggregates are more resistant, while for recycled aggregates, the resistance of the matrix concrete increases, and the abrasion loss of recycled aggregates decreases, thus being dependent on the matrix concrete [92,240,242]. High-strength matrix concretes have a resistant mortar in their composition, which will bind the recycled aggregate with the new cement paste, resulting in a lower probability of breakage.

However, there are studies that claim there is no relationship between the increase in abrasion resistance of recycled aggregate and the increase in the strength of the matrix concrete [243–249].

3.2.9. Slump Test

Slump is a test used to determine the consistency of concrete by measuring the slump value under its own weight, which can be assessed according to European Standard EN 12350-2 [250,251], ASTM C143 [252], Chinese Standard for Performance Test Method for Concrete [248], and BS EN 12350–2 [199].

The use of recycled aggregates negatively affects the workability of recycled concrete compared to concrete with natural aggregates [203,220,224,225,253–255], making it difficult to achieve the workability required by the project [256], with the workability of concrete being an indicator of its ease of preparation, application, compaction, and finishing [257].

According to Caroline et al. [258], replacing up to 25% of natural aggregates with recycled ones does not significantly affect the condition of fresh concrete. However, with the additional increase in recycled aggregate, a significant decrease in workability and a change in the consistency of the concrete in the fresh phase are observed, presenting low slump values [259–261]. Younes et al. [261] state that the slump values of fresh concrete with up to 50% replacement of recycled aggregate were within the standard limits for international codes, where concrete is considered fluid for a slump of 100 to 150 mm and of liquid consistency between 160 to 200 mm, both being suitable for civil construction [262]. The slumps found in recycled aggregate concretes are generally between 135 and 200 mm [263].

3.2.10. Compressive and Tensile Strength

The mechanical strength of mixtures with recycled aggregates is significantly reduced due to particle packing and the mortar content adhered to the aggregates [2,54,73,85,87,207,209,217,264–271]. The reduction in resistance occurs due to the interfacial transition zone [272] and the type and quality of the recycled aggregate, the latter being related to the water absorption capacity [273,274]. Several studies show a gradual decrease in the compressive strength of a concrete mix as the replacement of natural aggregates with recycled ones increases [173,190,193,199,275,276].

Compressive strength tests are well-documented in the international literature [277,278], as are tensile strength tests [277,279,280]. Thus, there is a consensus in the literature that concretes containing recycled aggregates have a compressive strength around 10% to 30% lower than concretes with natural aggregates, using the same water–cement ratio. However, according to Mohammed et al. [281], replacing 50% of the natural aggregates with recycled aggregates results in a 30% reduction in compressive strength, reaching a 43% reduction when the replacement rate reaches 100%. These data are widely questioned in the literature, where some researchers indicate that these values can be improved in concretes with a lower water–cement ratio [184,282–287], while others argue the opposite. That is, as the water–cement ratio increases, recycled concrete presents characteristics similar to the reference concrete [288].

According to Fellah et al. [215], the replacement of natural aggregates by recycled ones at rates of 25% and 75% resulted in decreases in compressive strength of 2.6% and 8.44%, respectively. These results are in agreement with other research that states that mixtures containing high rates of recycled aggregates show greater reduction in compressive strength [289–291]. In contrast, Tabsh et al. [292] and Li [293] state that the use of recycled aggregates with a replacement rate of up to 20% has no significant impact on compressive strength. Meanwhile, other researchers claim that the ideal replacement rate to maintain concrete quality is 30% [40,287,294,295].

Younes et al. [261], on the other hand, state that compressive strength values are practically the same for mixtures with natural aggregates and for mixtures with replacement of up to 50% recycled aggregate. However, the same authors emphasize that, for replacements equal to or greater than 75%, the average compressive strength achieved was much lower, limiting its application to non-structural purposes only. Studies that applied the total replacement (100%) of natural coarse aggregates by recycled ones found a reduction of between 25 and 45% in compressive strength, depending on the water–cement ratio and the condition of the recycled aggregate [296–300].

Few studies, however, report situations in which recycled concrete obtained higher compressive strength values than traditional concrete [57]. In these cases, the presence of particles with smaller and more heterogeneous granulometry, originating from the crushing process with a jaw crusher, provided greater efficiency in the connection between the aggregate and the cement paste.

Regarding the tensile strength of concrete, Abdelgader and Ben-Zeitun [301] indicate a proportion of approximately 8% to 12% of the achieved compressive strength, which is in agreement with the behavior of traditional concrete. In this context, similarly to other properties already analyzed in this manuscript, there are divergences in the literature, where some research indicates that a rate of up to 30% replacement of natural aggregates by recycled ones does not affect their resistance [92,127,295,302,303]. Meanwhile, other researchers record a marked reduction in tensile strength with the total replacement of natural aggregate with recycled aggregate [285].

3.2.11. Durability

The durability properties of concrete containing recycled aggregate depend on the porosity and distribution of its pores [304], the presence of contaminants [143], and the condition of the residual mortar adhered to the aggregate [305]. It was found that some research reported that the durability of concrete decreased with the increase in replacement of natural aggregate with recycled aggregate, including resistance to chloride ion penetration, acid attack and absorption [97,263,306,307], shrinkage, and carbonation [282].

The drying shrinkage process is the viscoelastic response to the capillary tension of water imposed by the loss of external and internal moisture due to cement hydration. Recycled aggregate is expected to lead to larger shrinkage deformations as the paste content increases and the aggregate stiffness decreases [291,308,309].

According to Skocek et al. [112], mixtures with recycled aggregates obtained results comparable to mixtures with natural aggregates, where the drying shrinkage process of the former maintained the same evolution as the latter during the first year. However, the trend, as reported by Silva et al. [158] and González-Fonteboa et al. [310], is for the retraction to increase up to 0.1 mm. Still, the differences were considered small in absolute value, remaining within expectations. Other studies, however, indicate that shrinkage increases as the use of recycled aggregate increases, and can reach 50% shrinkage in the case of total replacement [157,158,213,311].

Regarding the analysis of concrete resistance to chloride permeability, ASTM C1202 [312] establishes a protocol with the purpose of indicating the electrical capacity of concrete with regard to the penetration of chloride ions. Penetration is classified as low in the range of 1000 to 2000 Coulomb, moderate in the range of 2000 to 4000 Coulomb, and high when more than 4000 Coulomb occurs [313]. The results found in the research analyzed regarding the penetration of chlorine ions showed great variation, depending on the type of cement used [314–317], and according to the replacement rates of recycled aggregates [305,318,319]. Furthermore, concretes with aggregates presenting high porosity showed an increase in permeability to chloride ions [313,320].

Ojha et al. [321] mention that concrete produced with recycled coarse aggregate presents lower resistance to the penetration of chloride ions in relation to the reference concrete. However, both concretes can be included in the same permeability class, and concrete produced with a 100% replacement of natural aggregate by recycled aggregate presents unfavorable performance in relation to the reference concrete. Ariningsih et al. [322] demonstrated that the use of recycled aggregate did not interfere with chloride diffusion during a 5-month exposure period.

Quan et al. [248] mention that the resistance to chloride ion penetration is related to the fractal dimensions of the aggregates. On the other hand, Gómez-Cano et al. [323] state that the negative effects on permeability are more evident in concretes produced with recycled fine aggregates compared to recycled coarse aggregates, due to the surface area of the aggregate, concluding that the decrease in permeability of recycled concrete is related to the size of the recycled aggregates, with these data also mentioned by Pedro et al. [319] and De Brito et al. [324].

Carbonation is a physicochemical process where CO_2 penetrates the cement paste and reacts with Portlandite, producing calcite and consequently reducing the pH of the concrete, where the concrete carbonation rate is influenced by its permeability and humidity [56,305], leaving the steel reinforcement unprotected against corrosion, which occurs when there is the presence of oxygen and water [56].

Sáez del Bosque et al. [325] mentions that the average carbonation depth is greater in concretes with replacement rates of 25% and 50% of natural aggregate by recycled aggregate compared to the reference concrete, and that the concrete made with the 25% rate statistically presented a similar carbonation depth to the reference concrete, similar to the study [318,326] where a rate of 30% was used.

The literature highlights that the carbonation thickness varies from 1.0 to 2.5 when natural coarse aggregates are replaced by recycled ones [56]. This information partially coincides with other studies, which state that carbonation in concretes containing recycled aggregates reaches depths 1.3 to 3.2 times greater than that in the reference concrete [305,327,328]. However, this conclusion is not unanimous, as there are studies whose results indicate that this depth can reach five times, depending on the increase in the water–cement ratio of the concrete [55,329–331]. This is due to the intrinsic properties of recycled aggregates, such as water absorption, density, and porosity [305,306,332].

In this context, it is stated that, to improve the durability of concrete containing recycled aggregate, to meet a certain requirement, the water–cement ratio can be reduced. Meanwhile, others indicate that both the addition of mineral additives, fly ash, and slag, and the selection of recycled aggregate particle size, can improve the quality of recycled coarse aggregate [194,333–336].

3.2.12. Modulus of Elasticity

The modulus of elasticity of the concrete mix can be determined by the ASTM C469M-22 standard [337], being basically influenced by its porosity [338], which, according to the literature, the greater it is, the lower the modulus of elasticity. The modulus of elasticity of concrete depends on the modulus of elasticity of the cement paste and the aggregate, in addition to their respective volumes in the mix [39,292,339,340]. Furthermore, the presence of mortar adhered to the surface of the recycled aggregate results in a lower modulus of elasticity. This occurs because mortar has a lower modulus of elasticity than concrete [307,341].

Studies indicate that, as the replacement rates of natural aggregates increase, the modulus of elasticity shows a reduction of up to 25% [127,302,326,342]. On the other hand, other research indicates that there is no tendency for concrete to lose elasticity as the replacement of natural aggregates increases [99,307,343].

3.2.13. Flexural Strength

Flexural strength is an important parameter in the design and definition of the serviceability of structures such as bridges, slabs, and others. Flexural strength tests should be in accordance with IS 516 Part 1/Section 1 [344].

The study by Zhu et al. [345] conducted experiments that showed that, as replacement rates of natural aggregates with recycled aggregates increased, the flexural strength was reduced by up to 15%, in agreement with Cui et al. [346], who mention a reduction in flexural strength as recycled aggregate rates increased.

In contrast, Kefyalew et al. [347] cite data showing that the use of recycled aggregates at 100% replacement rates caused a 7% reduction in flexural strength, and the absorption property of the structure was found to be reduced by 22%.

4. Conclusions

The use of recycled coarse aggregates in concrete production can provide preservation and reduce the extraction of natural resources, minimizing the generation of waste and favoring the useful life of landfills. Furthermore, it is an initiative that meets the Sustainable Development Goals (SDGs) of the United Nations (UN).

However, due to the divergence in the results obtained by research regarding the characterization data of recycled aggregates and concrete mixtures, recycled concrete has been used predominantly in paving works or in applications with low structural demand. Therefore, unfortunately, the use of this material on a commercial scale does not yet appear to be viable, as this divergence between scientific studies makes establishing standards difficult and time-consuming. It is suggested that the categories identified in Figure 7 be used as a starting point for a recycled concrete standardization roadmap.

Given this scenario, it is considered of great relevance to conduct this massive systematic review in search of the state-of-the-art on the subject, so that researchers can take it as a reference when proposing their experimental protocols and comparing their results with those of their peers.

Due to the large amount of information and data presented throughout this manuscript, it was decided to highlight the main conclusions obtained through bullet points:

- The CDW recycling process is typically conducted using horizontal impact crushers or jaw crushers;

- Replacement rates of natural aggregate by recycled material vary, with limits between 20 and 60%. There are also researchers who advocate the possibility of 100% replacement, as long as the matrix concrete has a minimum compressive strength of 60 MPa;
- The specific density of most recycled aggregates varies from 1.91 to 2.70, maintaining an average density of 2.32 g/cm^3;
- Most research mentions that the amount of adhered mortar varies from 20% to 56%;
- The treatment of recycled aggregates can be performed through the addition of nanomaterials, carbonation, coating with cementitious materials, immersion in sodium sulfate, autogenous cleaning, heat treatment, ultrasonic cleaning, and treatment with pozzolans;
- The water absorption process of recycled aggregate varies from 2% to 15%;
- The abrasion resistance of most natural coarse aggregates in Los Angeles is greater than that of natural ones;
- The slump test demonstrates that the use of recycled aggregates negatively affects the workability of recycled concrete compared to concrete with natural aggregates, making it difficult to achieve the workability required by the project;
- The use of recycled aggregates results in a compressive strength approximately 2.6% to 43% lower than that of concrete with natural aggregates, depending on the replacement rate. The same behavior was observed in relation to tensile strength. However, there is still considerable discrepancy between the results obtained in the various studies analyzed;
- Studies mention that, as replacement rates of natural aggregates with recycled ones increase, the flexural strength is reduced by up to 15%;
- The durability properties of concrete containing recycled aggregate depend on the porosity and pore distribution of the aggregates, which decrease with increasing replacement of natural aggregate by recycled aggregate;
- The modulus of elasticity of the concrete mix is primarily influenced by its porosity and the modulus of elasticity of the cement paste. As natural aggregate replacement rates increase, the modulus of elasticity decreases by 25%.

Therefore, it is concluded that practically all topics on the characterization of recycled aggregates and the fresh and hardened stages of recycled concrete present varied information, which differs from research to research, due to the type and characteristics of the recycled aggregate used. As mentioned previously, the CDW characterization step is essential to ensure the quality of the concrete, which makes its large-scale production difficult. This study was essential to gather information on the characteristics of recycled coarse aggregates and information on the strength of concretes using recycled aggregates. Furthermore, this research stands out in relation to that previously published, as it identifies a new gap in knowledge, which is the need for further development in the use of predictive methods and tools that aim to predict the performance of recycled concrete. Considering that most of the dosing processes for this type of concrete are empirical, the establishment of protocols based on advanced tools is essential for its use to be commercially promoted. Some of the tools already used for this purpose are multicriteria modeling applied to decision-making, finite-element modeling, the application of multivariate adaptive regression splines (MARS), and the use of linear/non-linear regression models, among others.

Therefore, as a suggestion for future research, it is recommended to conduct a systematic review of the literature regarding the use of multicriteria decision modeling. This method is being used by Shouny et al. [348] and by Moro [349] to evaluate and select a more suitable sustainable concrete. Another interesting modeling for future research is the use of finite elements, which was used by Lin et al. [350] to evaluate the effects of residual mortar on the mechanical properties of recycled concrete. This is in addition to the application of MARS, which was applied by Naser et al. [351] to predict the compressive strength of recycled concrete.

As another suggestion for future research, it is recommended to carry out a systematic review of the literature focused on the treatment methods of recycled aggregates, as this can provide an improvement in their characterization indices and, consequently, improve the characterization of the concrete mix in the fresh and hardened phases.

Despite the extensive review performed in this research, we understand that, due to the broad knowledge on the subject, not all mechanical indicators related to recycled concrete could be adequately addressed. We identify this fact as a limitation of our research, especially due to some of the following factors:

- Articles on the topic may have been excluded from the sample obtained by the PRISMA protocol during the screening stage;
- No articles were identified that addressed these indicators under study applied directly to recycled concrete;
- Articles on the topic may have been identified but were not included in the sample because the authors did not have access to their content, as it was closed access.

Therefore, we also suggest that future research involve conducting a new review, specifically looking for items that were not addressed in this research.

Author Contributions: Conceptualization, G.A.F.J., B.B.F.d.C., and J.C.T.L.; methodology, G.A.F.J., B.B.F.d.C., and J.C.T.L.; software, G.A.F.J., B.B.F.d.C., and A.N.H.; validation, G.d.P.M., J.A.F.S., B.B.F.d.C., and A.N.H.; formal analysis, G.A.F.J., B.B.F.d.C., and J.C.T.L.; investigation, G.A.F.J.; resources, G.A.F.J. and B.B.F.d.C.; data curation, G.A.F.J., B.B.F.d.C., and J.C.T.L.; writing—original draft preparation, G.A.F.J. and B.B.F.d.C.; writing—review and editing, G.d.P.M., J.A.F.S., J.C.T.L.; B.B.F.d.C., and A.N.H.; visualization, G.A.F.J. and B.B.F.d.C.; supervision, B.B.F.d.C.; project administration, B.B.F.d.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to acknowledge the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), which helped in the development of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Top 10 most cited articles, 2019–2024.

Rank	Manuscript Title	Authors	TC [1]	CPA [2]	Journal
1	Experimental investigation on the variability of the main mechanical properties of concrete produced with coarse recycled concrete aggregates	Pacheco et al. (2019) [50]	177	16.09	*Construction and Building Materials*
2	Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study	Xia et al. (2020) [352]	111	18.5	*Waste Management*
3	Towards Circular Economy through Industrial Symbiosis in the Dutch construction industry: A case of recycled concrete aggregates	Yu et al. (2021) [51]	105	26.25	*Journal of Cleaner Production*
4	Durability properties evaluation of self-compacting concrete prepared with waste fine and coarse recycled concrete aggregates	Sasanipour & Aslani (2020) [353]	105	21	*Construction and Building Materials*
5	Mechanical and durability properties of concrete based on recycled coarse and fine aggregates produced from demolished concrete	Berredjem et al. (2020) [354]	100	20	*Construction and Building Materials*
6	Utilization of waste concrete recycling materials in self-compacting concrete	Sun et al. (2020) [355]	99	19.8	*Conservation and recycling*
7	Multi-criteria optimization of recycled aggregate concrete mixes	Rashid et al. (2020) [356]	87	17.4	*Journal of Cleaner Production*
8	Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: Technical, economic and environmental analysis	Martínez-Lage et al. (2020) [357]	87	17.4	*Waste Management*
9	Use of recycled concrete aggregates from precast block for the production of new building blocks: An industrial scale study	Zhao et al. (2020) [358]	84	16.8	*Conservation and recycling*
10	Properties of self-compacting high-strength concrete containing multiple use of recycled aggregate	Abed et al. (2020) [132]	84	16.8	*Journal of King Saud University—Engineering*

Note: TC [1] is the total number of citations; CPA [2] is the average number of citations per year

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