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Systematic Review

Recycled Concrete Aggregate in Self-Consolidating Concrete: A Systematic Review and Meta-Analysis of Mechanical Properties, RCA Pre-Treatment and Durability Behaviour

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Abstract

This systematic review and meta-analysis per PRISMA 2020 addresses the use of recycled concrete aggregates as a replacement for aggregates in self-consolidating concrete for structural and non-structural use. It provides a comprehensive evaluation of the available research and offers a synthesised overview of the potential use of recycled concrete aggregate in self-consolidating concrete beyond standardised replacement levels. A total of 256 research papers were obtained from different databases, and after a detailed content review, only 24 unique experimental research studies fulfilled the review criteria. Data were extracted on recycled concrete aggregate source, pre-treatment, replacement ratio, mix proportions, fresh properties, strength, stiffness, and durability. It was observed across all studies that the recycled concrete aggregates originated from precast concrete rejected elements with a low water-to-cement ratio, producing an equal or stronger concrete than the reference concrete in the studies; however, none of the studies included in this research resulted in a higher modulus of elasticity than the corresponding reference concrete. Additionally, moderate aggregate replacement (20–50%) preserved the workability, whereas high replacements (75–100%) affected fresh concrete properties as well as increased shrinkage and creep. The inclusion of fine recycled concrete aggregate in addition to coarse recycled concrete aggregate has a larger effect on lowering compressive strength and stiffness in the concrete. Overall, high-quality coarse recycled concrete aggregate (precast rejects or screened demolition waste)—an aggregate replacement level of around 50%—facilitates the production of sustainable self-consolidating concrete, whereas full replacement requires aggregate pre-treatment and a carefully optimised mix design.

Keywords: Recycled Concrete Aggregate (RCA); Coarse RCA (cRCA); Fine RCA (fRCA); Recycled Precast Concrete Aggregate (RPCA); Self-Consolidating Concrete (SCC)

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1. Introduction

Concrete has become an essential material in modern society. Its production increase is directly linked to rapid urbanization, infrastructure expansion and industrial growth. Being the most used material in the world, its production has quadrupled since the 1980s [1]. The annual global concrete production in 2022 reached 14 billion m^3, as reported by the World Economic Forum [2,3]. China itself accounts for more than half of this production, followed by India, the European Union, and the United States [4,5]. The production of this always-needed material depends greatly on the cement industry, responsible for approximately

8% of the global CO_2 emissions [1], and the extensive extraction of natural raw materials, creating significant environmental damage in recent decades. Given the forecast population growth, especially in Africa and Southeast Asia [6], the transition into a more sustainable and circular concrete is pressing even more.

The extraction of non-renewable natural resources for the production of concrete aggregates like sand and gravel depletes natural resources and damages ecosystems. Moreover, the demolition of ageing infrastructure generates massive construction and demolition waste (CDW) worldwide. Approximately 850 million tonnes of construction and demolition waste per year are generated annually in Europe, representing 38% of all waste in the European Union [7]. In Germany alone, 220 million tonnes of CDW were produced in 2022 [8]. In the United States, 600 million tonnes of CDW were obtained in 2018 [9], per the latest published reports. And in China, 52 million tonnes of CDW were produced in 2022 [10].

The general population, the scientific community, and governments, more specifically the European Commission have expressed great concern in the rising production of construction waste. In fact, the European Commission, has emphasized in its latest report in 2025 that circularity is set to become a central priority for maximizing the EU's scarce resources, reducing external dependencies, and strengthening resilience [11]. In the context of concrete, material circularity can be achieved by using RCA, which is crushed processed concrete rubble obtained from demolition activities, and using it back into new concrete, replacing natural stone aggregates. Many studies [12–17] have evaluated the use of RCA in concrete for decades; as a consequence, many standardized norms for the proper use and the allowable replacement ratio of RCA in concrete have been developed [18]. The broad use of this material comes with many industry challenges, for example, the poor connection between stakeholders, lack of awareness about the potential benefits, lack of circular design guidelines, material cost, and variability of the recycled material [19]. However, many experimental studies indicate that concrete made with recycled aggregates can match, or in some cases surpass, the mechanical performance of concrete produced with virgin aggregates, while also lowering the carbon footprint of new concretes and supporting the attainment of sustainability certifications [20].

Self-consolidating concrete (SCC) has become widely used for precast concrete elements because of its excellent flowability and early strength gain property, being the preferred material for modern construction [21]. The addition of RCA in the production of SCC in larger replacement ratios holds promise for sustainable construction and reduction in CO_2 emissions [21]. However, the use of RCA in SCC differs significantly in behaviour and strength from natural aggregates. RCA shows higher water absorption and porosity due to the old adhered mortar on the natural stone from the primary concrete seen in Figure 1. Because of its high water absorption, it leads to more variability in the concrete mix due to additional water and reduced workability; therefore, it has often been used for non-structural concrete elements [22]. The mechanical properties, such as compressive strength and modulus of elasticity, can also be inferior the greater the RCA replacement ratio in concrete [22]. For this reason some guidelines have limited its use to a maximum of 45% high-quality RCA replacement with no allowable fine recycled aggregate replacement and strongly depend on the exposure class [23]. The high water absorption of RCA requires careful adjustments in added water and admixture dosage to maintain the self-consolidating properties and early strength. Moreover, treatments such as mechanical screening, grinding, and acid washing can be used to remove the adhered mortar and improve the recycled aggregate quality [22].

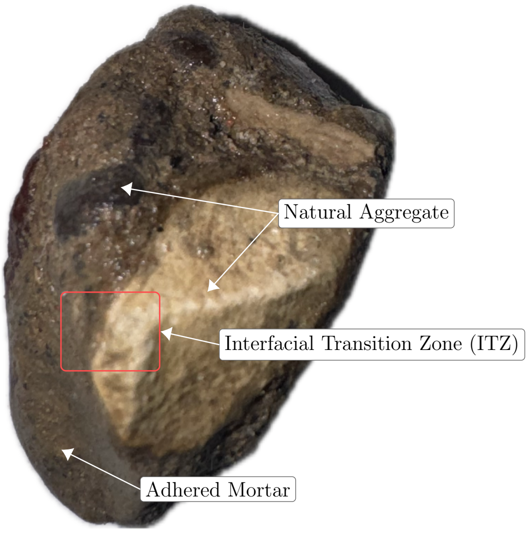

Figure 1. Recycled concrete aggregate.

1.1. Problem Statement

The literature proves that the use, in controlled portions, of RCA in SCC represents no significant loss in the overall concrete performance [24]. However, many gaps still exist in this field. Many studies rely on precast rejects RCA derived from known concrete strength and properties rather than field-sourced recycled aggregates with variable demolition origins [21]. Moreover, research has predominantly studied the 28-day strength, whereas the fresh concrete performance and early-age strength are critical properties of SCC [21]. Limited understanding exists in the appropriate recycled aggregate treatment for SCC use, which can potentially mitigate the negative effect of high RCA replacement [25]. Current guidelines in the EU and the world limit the use of RCA in SCC to conservative levels, with no common methodologies on RCA in SCC mix design for structural purposes [24,26]. Therefore, it is imperative and urgent to find the appropriate RCA pre-treatment and concrete mix proportion for the use of RCA in structural SCC to increase the RCA replacement ratio and increase the material circularity while significantly reducing the natural resource extraction to compensate for the growing concrete demand.

1.2. Research Significance

This systematic review seeks to provide comprehensive guidance on the potential use and challenges of RCA in SCC and to highlight future research directions for advancing sustainable concrete. This research aims to address the gaps existing in the literature by synthesising current knowledge on the use of RCA in SCC beyond standardised levels. The topics to be evaluated are recycled aggregate characteristics and origin, replacement ratios and pre-treatment methods influencing the fresh concrete behaviour, mechanical performance and durability of SCC for both structural and non-structural applications. Particular attention was paid to fresh concrete behaviour, strength requirements for precast elements and the long-term durability of RCA in SCC by critically assessing the evidence and identifying research trends and limitations.

2. Methodology

This research consists of a systematic literature review of available experimental research investigating the use of RCA in SCC written in English. The quantitative investigation of this review includes a meta-analysis of all relevant studies on the use of RCA, from different sources, in SCC for structural and non-structural precast elements. The databases used to extract the studies included in this review were ScienceDirect, Google

Scholar, and Scopus. The keywords used for the search included “recycled concrete aggregates”, “self consolidating concrete” and “precast concrete”. The search was limited to studies published between 2018 and 2025. Additionally, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [27] was used in this review study for a clear replicability of this study. The PRISMA methodology diagram can be seen in Figure 2. The database search, conducted in Scopus, ScienceDirect, and Google Scholar using the predefined keywords, year range (2018–2025), and language restriction (English), initially retrieved 256 records. After removing duplicate entries, review articles, and conference papers, 167 unique studies remained. In the first screening stage, titles and abstracts were examined to assess topic relevance. Studies that investigated non-SCC mixtures, natural aggregates without recycled concrete, or focused primarily on asphalt, polymers, or supplementary cementitious materials were excluded because they did not align with the scope of this review. Additionally, alkali–silica reaction (ASR), e.g., accelerated expansion tests and pore-solution alkali characterisation, were not included in the quantitative synthesis because they were rarely and inconsistently reported across SCC–RCA studies meeting the eligibility criteria. This screening step reduced the dataset to 119 papers.

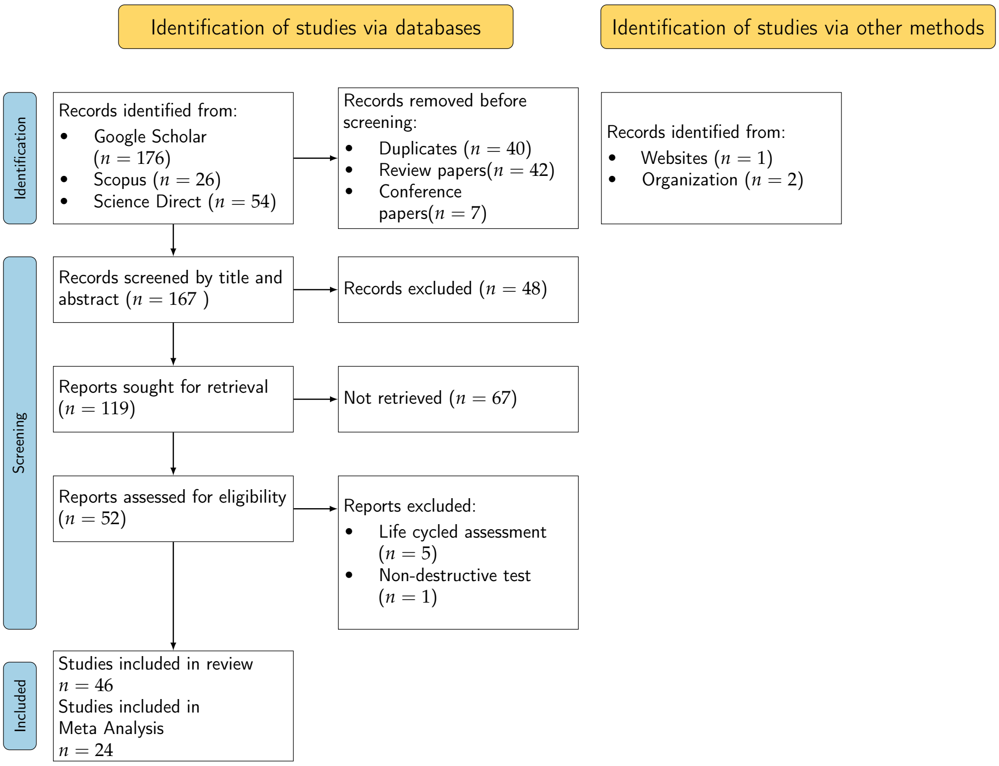

Figure 2. Research paper selection following PRISMA methodology per Page, et al. [27].

The remaining studies underwent full-text assessment based on methodological transparency and material source accuracy. Papers were excluded if they contained insufficient experimental data to support quantitative analysis, presented ambiguity in the origins or composition of the recycled concrete aggregates, or addressed topics outside the defined scope, such as life-cycle assessment (LCA) or modeling studies without laboratory experimentation. After this stage, 24 experimental investigations satisfied all inclusion criteria and were thoroughly evaluated for the meta-analysis. For consistency across studies, only the data corresponding to the highest RCA replacement level in each experiment were extracted and analyzed. The complete meta-analysis and data synthesis are presented in this research and can be seen in the supplementary materials.

The majority of the publications included in the meta-analysis originate from Spain, which accounts for approximately one-third of the total dataset, highlighting its strong research activity in this field. The United States and China follow with equal contributions, while Belgium and Italy show moderate representation. Countries such as Australia, Brazil, France, India, Portugal, and Thailand are each represented by a single publication, indicating a more limited but globally diverse research participation; see Figure 3.

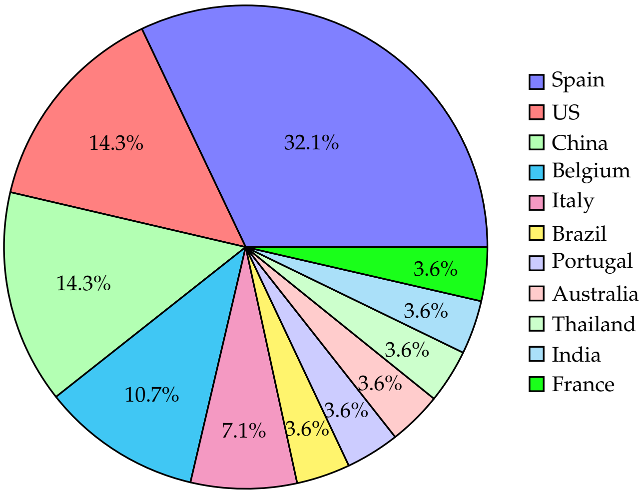

Figure 3. Country distribution of publications.

It is important to mention that the selection of the research papers included in this systematic review has demonstrated the process, sources, methodologies, material and results in each study. These studies can be replicable, and the assumptions taken can be justified. All research studies that did not meet the minimum required criteria were eliminated. This review followed a registered protocol on protocols.io (DOI: 10.17504/protocols.io.3byl46dnrgo5/v1; registered on 14 October 2025). The protocol prespecified eligibility criteria, outcomes, screening/extraction procedures, risk-of-bias criteria, and synthesis plans.

3. Qualitative Analysis

Following the initial screening of the retrieved literature, 46 unique studies published between 2018 and 2025 were found to meet the search criteria. From the 46 research papers selected for the systematic review, only 24 unique research papers were included in the meta-analysis. The publication rate was considered stable, averaging between four and six studies per year, except in 2019 and 2022, when only one study per year was published on the topic of RCA in SCC; see Figure 4A. Authors such as Revilla-Cuesta et al. [28,29] and Fiol et al. [30–32] have more than one publication on this topic, suggesting that they are active researchers in the field, as seen in the collected data shown in the Appendix. All research studies included in the meta-analysis have evaluated the impact of course RCA (cRCA) in SCC. The majority of the studies have used 100% RCA replacement in their experiments, whereas others have evaluated ratios of 50%, 60%, 75%, and 80%, as shown in Figure 4A. The use of fine recycled concrete aggregate (fRCA) was also evaluated in some of these research studies and thus included in the meta-analysis. Different proportions of fRCA were used in a total of six studies over the period from 2018 to 2025: two in 2018 with 50% and 100% replacement [33,34], one in 2019 with 100% [35], one in 2020 with 100% replacement [29], one in 2021 with 50% and 100% within the same study [28], and one in 2024 with 70% replacement [21]. In Figure 4, the first bar chart (A) represents the total amount of reports published per year with the subdivision of different cRCA replacement ratios. In the second bar graph (B), the percentage of papers that used fRCA as an aggregate substitution is also given, given that all studies included in the meta-analysis used cRCA replacement. Given the limited evidence base, the concentration of publications within a few groups, and marked heterogeneity in RCA origin, pre-treatments, replacement ratios, and SCC mix designs, the evidence is at non-trivial risk of publication/selection bias; accordingly, the overall certainty is rated as low to moderate, in line with PRISMA and GRADE [27,36].

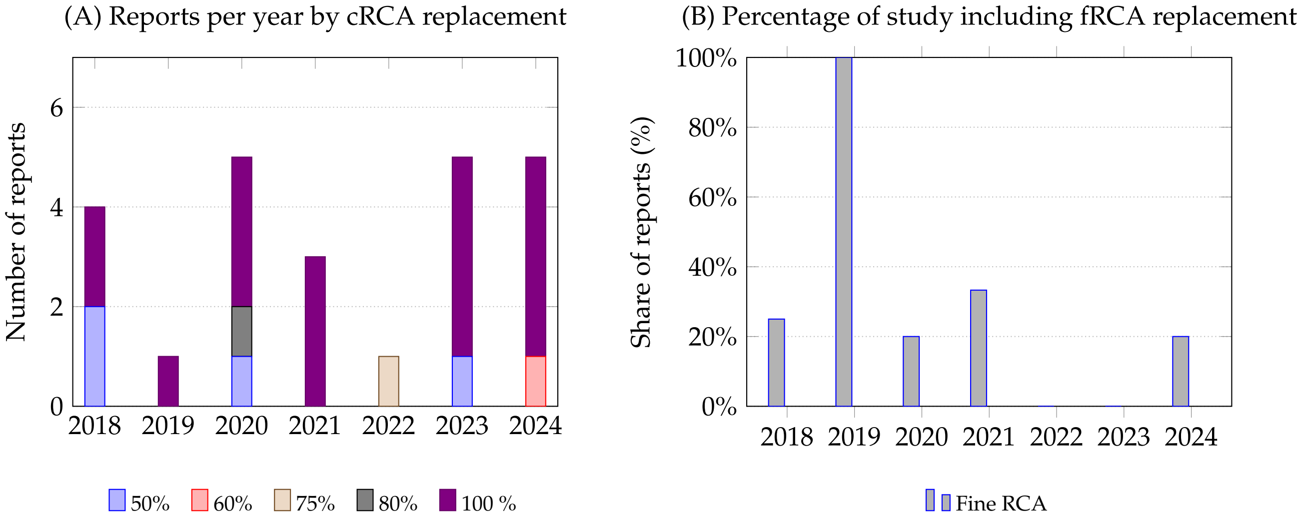

Figure 4. (**A**) Report count and cRCA replacement (**B**) percentage of studies including fRCA in addition to cRCA.

4. RCA Sources and Pre-Treatment

SCC with RCA can meet structural concrete performance when the concrete mix is re-proportioned and the RCA quality is controlled [32]. This is especially true for recycled precast concrete aggregate (RPCA) from rejected precast elements with known strength, which typically shows lower variability and supports high mechanical performance in SCC [30]. By contrast, RCA from mixed construction and demolition waste introduces greater uncertainty due to the adhered old mortar, which increases water absorption and lowers particle density, while the secondary interfacial transition zone (ITZ) can be weaker [37]. The secondary ITZ is the bond between the adhered old mortar and the mortar from the new concrete. This effect is more pronounced with the additional use of fine RCA, which can substantially decrease flowability and compressive strength. This negative effect can be partially mitigated if the effective water demand, fines content, and superplasticizer dosage are carefully managed [29].

The old adhered mortar holds great importance in the use of RCA because it represents from 20 to 70% of the RCA weight, making the recycled concrete underpreform compared to concrete using natural aggregates [38]. The residual old cement paste increases water absorption, reduces density, and weakens the ITZ due to its highly porous nature [37]. This effect is particularly critical for SCC, where flowability and early strength are essential properties of the mix [21]. Over the years, various strategies have been proposed to enhance the performance of RCA in new concrete, which can be broadly categorised into RCA pre-treatments and RCA quality improvement methods [39]. The advantages and disadvantages of these methods have been summarised in Table 1, and they are described as follows:

- RCA Pre-Treatment: These treatments consist in partially removing the adhered mortar attached to the aggregate. As a subcategory can be found the Mechanical Treatment Method (MTM) and the Chemical Treatment Method (CTM).
  Mechanical removal via ball milling or grinding effectively removes the weak old cement paste and reduces water absorption but can induce microcracks in the stone [12,39,40]. Thermal routes such as heating–grinding, known as "heating and rubbing", can detach the cement paste after applying heat followed by mechanical grinding of the RCA. This treatment can improve the quality of the aggregate and give them similar properties to the natural stone [41]. Similarly to the heating method, the microwave heating method creates a differential expansion between the stone and the mortar, inducing thermal stresses that break the paste–aggregate bond [38]. Finally, the ultrasonic cleaning method consists of washing the RCA in an ultrasonic bath to remove the crumbs from the surface of the aggregate, increasing the strength by 7% [42].
  Chemical treatments can also be used to remove the adhered mortar in RCA. This method includes pre-soaking the RCA in acidic solutions. Three acids have been studied, hydrochloric acid (HCL), sulphuric (H_2SO_4), and phosphoric acid (H_3PO_4). The result has shown a reduction in water absorption and improvements in the concrete mechanical properties [43]. Another approach is the impregnation of the RCA using a slurry of pozzolanic materials, such as silica fume. This impregnation of the aggregate has the potential to enhance the quality of the adhered mortar by filling up the pores with the pozzolanic solution. This solution would then react with the calcium hydroxide in the cement paste of the RCA and the CO_2 in the atmosphere, creating $CaCO_3$, thus strengthening the RCA. Studies have shown that using silica fume in this way can increase compressive strength by up to 30% at 7 days and 15% at 28 days [42].
- RCA Surface Quality Improvement: In addition to the RCA pre-treatment to improve the recycled concrete behaviour, some methodologies have been developed to improve the performance of the RCA itself. Accelerated carbonation of the RCA has proven to reduce the water absorption, reduce its permeability, and improve durability [44]. The freeze–thaw method on recycled aggregates consists of inducing cracks in the adhered mortar of RCA. Ice formation within the pores causes the water in the cracks to expand, which facilitates the separation between the mortar and the aggregate [45,46]. Another variant of this method exists, and it includes high-temperature drying after the freeze–thaw cycle. This additional step induces thermal shrinkage differentiation, accelerating the mortar separation without damaging the natural stone [47].

Table 1. Comparison of pre-treatment methods for RCA in SCC.

RCA Pre-Treatment	Advantages	Disadvantages
Mechanical removal (ball-milling or grinding) [12,39,40]	Removes adhered mortar and lowers water absorption	Can induce micro-cracks; energy-intensive; useful for coarse RCA with high attached mortar.
Thermal–mechanical (heating and grinding) [41]	Detaches old cement paste; yields aggregates closer to natural stone	Requires heating equipment; possible thermal damage; suited for demolition-derived RCA when heat and grinding equipment are available.

Table 1. *Cont.*

RCA Pre-Treatment	Advantages	Disadvantages
Microwave heating [38]	Breaks the paste–aggregate bond via thermal stress	Needs specialised microwave reactors currently limited to laboratory or high-value applications.
Ultrasonic cleaning [42]	Cleans aggregate surface and can raise strength by ≈ 7%	Only removes superficial mortar; equipment is expensive; best for small batches of high-quality RCA.
Acid soaking (chemical treatment) [43]	Reduces water absorption and improves mechanical properties	Handling and disposing of acids poses safety and environmental risks; may roughen aggregate; suitable in controlled lab settings or where regulations allow acid use.
Silica-fume slurry impregnation [42]	Fills pores and forms $CaCO_3$, boosting strength up to 30% at 7 days and 15% at 28 days	Adds processing steps and cost; effectiveness depends on penetration and curing; suited for high-performance SCC requiring enhanced strength and durability.
Accelerated carbonation [44]	Lowers water absorption and permeability and improves durability; also stores CO_2	Requires CO_2 supply and controlled conditions; treatment time can be longer; appropriate for sustainable,high-replacement SCC with carbonation facilities.
Freeze–thaw cracking (and freeze–thaw + high-temperature drying) [45–47]	Facilitates mortar separation without chemicals; high-temperature variant accelerates detachment	Time-consuming; may damage natural stone; needs freeze–thaw and drying equipment; mainly for research or low-cost non-chemical treatments.

5. Meta-Analysis Results

Through a systematic review of the available experimental literature on RCA in SCC published between 2018 and 2025, 24 unique experimental studies were identified and included in a comprehensive meta-analysis. Because each study examines specific aspects of RCA-SCC, the meta-analysis focuses on outcomes that are consistently reported across studies. This section synthesises the available data on compressive strength and modulus of elasticity and summarises the durability performance of RCA-SCC as investigated in the majority of the literature.

5.1. RCA-SCC Compressive Strength

The compressive strength of concrete is an important property that must be evaluated in all concrete mixes in all projects. Among the 24 reviewed studies on RCA-SCC, from which some of them evaluated different concrete mixes, compressive strength was the only parameter consistently reported across all experiments, making it the primary basis of comparison in the meta-analysis. Figure 5 presents the relationship between compressive strength and water-to-cement ratio for all experimental studies. To ensure comparability, the compressive strength values are normalised relative to the reference concrete mix used in each respective study. This approach expresses the results as proportional strength values, enabling a more accurate interpretation of the results since the concrete mixes in different studies vary in their design, cement type and content, admixture usage, and water-to-cement ratios.

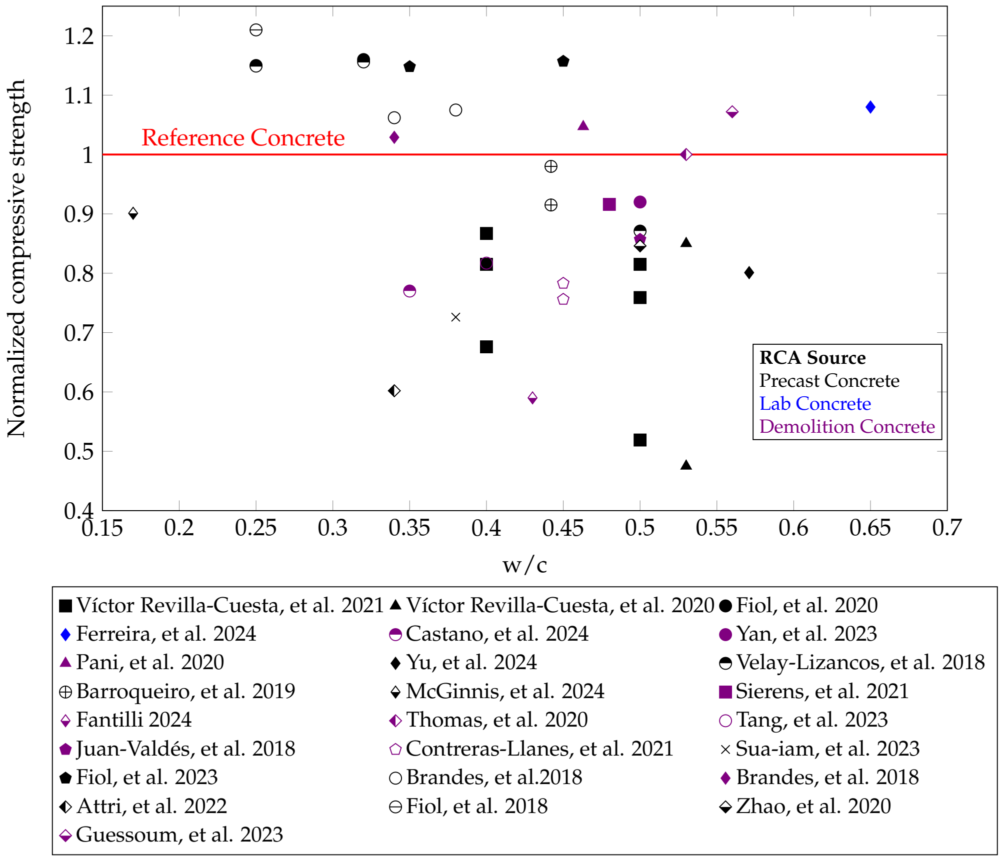

Figure 5. RCA SCC normalized compressive strength. Guessoum, et al. [20], Castano, et al. [21], Tang, et al.[22], Víctor Revilla-Cuesta, et al. [28], Víctor Revilla-Cuesta, et al. [29], Fiol, et al. [30], Fiol, et al. [31], Fiol, et al. [32], Juan-Valdés, et al. [33], Velay-Lizancos, et al. [34], Barroqueiro, et al. [35], Ferreira, et al. [48], Yan, et al. [49], Pani, et al. [50], Yu, et al. [51], McGinnis, et al. [52], Sierens, et al. [53], Fantilli [54], Thomas, et al. [55], Contreras-Llanes, et al. [56], Sua-iam, et al. [57], Brandes, et al. [58], Attri, et al. [59], Zhao, et al. [60].

The influence of the RCA source is illustrated by the color coding in Figure 5. Black belongs to RCA from precast rejects, blue was assigned to RCA as laboratory concrete waste and purple represents the RCA from demolition waste. In most research studies, RCA was derived either from precast concrete rejects with known strengths or from processed demolition concrete. Among the reviewed experiments, 14 mixtures achieved compressive strengths equal to or higher than their respective reference concretes; of these, 10 utilised RCA from precast rejects [30–32,50,58], three from demolition concrete [20,55,58], and one from discarded laboratory-concrete specimens [48]. Notably, 50% of the studies used w/c ratios between 0.4 and 0.5; however, the highest-performing mixes were associated with w/c ratios of 0.25–0.45 and typically incorporated precast concrete rejects as RCA. This highlights the strong effect of the aggregate source on the overall concrete behavior.

5.2. RCA-SCC Modulus of Elasticity

At the same time, 66.6% of the reviewed studies also reported the modulus of elasticity (MOE) of their recycled concrete mixtures. Figure 6 presents the normalized modulus of elasticity as a function of the ratio of water-to-cement. As with the compressive strength results, the modulus of elasticity values were normalized to their respective reference concretes to allow for more meaningful comparisons. In this case, none of the RCA-SCC mixtures exhibited higher stiffness than the corresponding reference concrete. This is due to a weaker bond between the old adhered mortar and the new mortar in the concrete [61]. In Figure 6, a subset of data highlighted within a gray rectangle can also be seen.

This data subset corresponds to the seven mixes that incorporated fine RCA in varying proportions in the recycled concrete. Since the modulus of elasticity is highly influenced by the quality of the bond between the cement paste and the aggregates [62,63], these concretes show significantly lower stiffness compared to studies that evaluated only coarse RCA. Unlike compressive strength, the relationship between the source of RCA and the modulus of elasticity is less evident. However, the use of fine RCA draws a consistent trend in the reduction in stiffness compared to the reference concrete, regardless of the water-to-cement ratio.

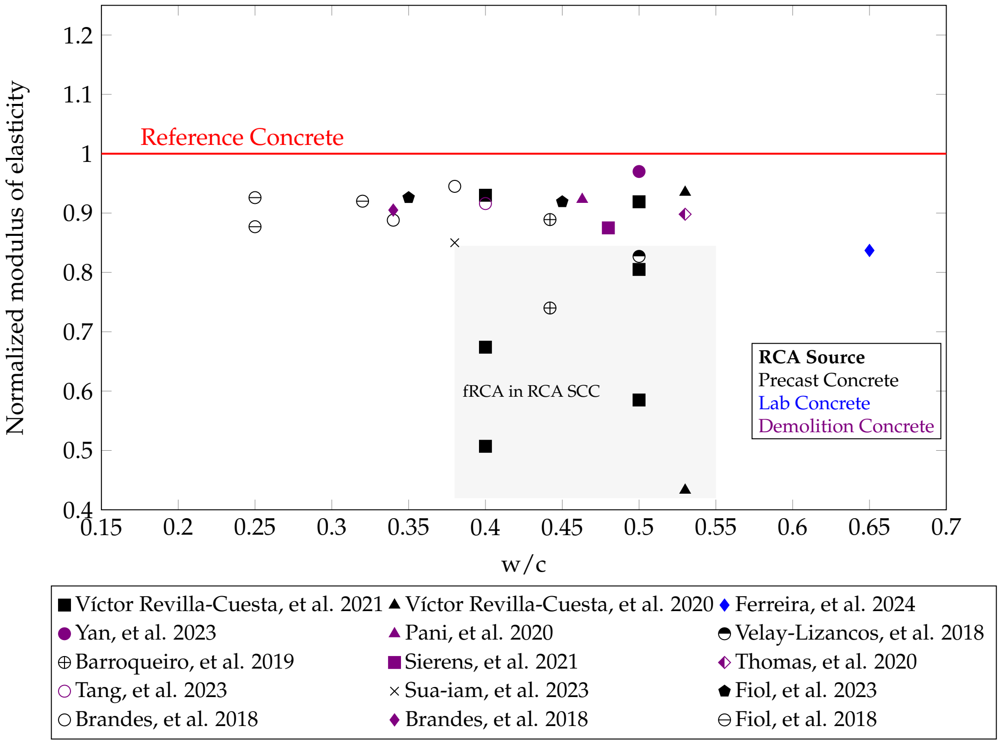

Figure 6. RCA SCC normalised modulus of elasticity. Tang, et al. [22], Víctor Revilla-Cuesta, et al. [28],Víctor Revilla-Cuesta, et al. [29], Fiol, et al. [30], Fiol, et al. [32], Velay-Lizancos, et al. [34], Barroqueiro, et al. [35], Ferreira, et al. [48], Yan, et al. [49], Pani, et al. [50], Sierens, et al. [53], Thomas, et al. [55], Sua-iam, et al. [57], Brandes, et al. [58].

5.3. RCA-SCC Durability

The durability of RCA-SCC is largely governed by the quality of the recycled aggregates, which are typically more porous than natural aggregates. Although many studies have demonstrated the successful incorporation of RCA as a replacement for natural aggregates in concrete [20,30–32,48,50,55,58], its durability performance remains a critical area of investigation. Guessoum et al. [20] reported that RCA-SCC exhibited reduced durability, with higher carbonation depths and decreased performance under freeze–thaw cycles compared to reference concretes. Zhao et al. [60] also reported that after 14 freeze–thaw cycles, RCA-containing specimens did not show visible deterioration; however, residual resonant frequency measurements indicated lower stiffness in RCA blocks compared to control specimens. In contrast, Fiol et al. [31] observed that the resistance to freezing and thawing was strongly dependent on the ratio of water-to-cement (w/c). At higher w/c ratios, compressive strength losses reached a maximum of 30% under full RCA replacement, while at lower w/c ratios the residual strength of RCA-SCC after exposure to freeze thaw was slightly higher than that of control concrete. Similar findings were presented by Juan-Valdés et al. [33], where RCA mixtures demonstrated superior freeze–thaw resistance relative to conventional concrete mixes.

The long-term durability of concrete is often evaluated through electrical resistivity testing, which provides an indication of chloride diffusion within the matrix. Chloride ingress initiates the corrosion of embedded steel reinforcement, leading to volumetric expansion of the corroded steel and subsequent cracking of the surrounding concrete [64]. Studies have reported mixed outcomes: for instance, mixes with 100% RCA replacement showed up to 50% lower resistivity than reference concrete at 28 days [57], whereas Juan-Valdés et al. [33] observed only a 1.4% reduction under similar curing conditions.

Creep and shrinkage are also key indicators of long-term performance. Since these properties are directly related to the stiffness of the concrete, the presence of recycled aggregates tends to increase both creep and shrinkage strains. This is attributed to the weaker adhered mortar and higher porosity of RCA, which reduces the overall stiffness of the concrete [31,35,60].

Other durability assessments studied within the systemic review include abrasion resistance and water penetration tests. Interestingly, RCA concretes have demonstrated superior performance in abrasion resistance compared to reference concretes [33,56]. This improvement in performance is due to the recycled particles' rough, angular surfaces, which are often coated with residual cement and ceramics that promote a denser surface paste and a stronger ITZ, which increases the mechanical interlock and reduces material loss under rubbing [33]. On the other hand, the water penetration test, which evaluates the depth of water ingress after prolonged exposure to pressurized water, has consistently shown that penetration depth increases with higher RCA content. This trend is largely attributed to the typology, distribution, and impurities of recycled aggregates [32,55].

6. Discussion

This section discusses the findings of the systematic literature review on the use of RCA in SCC, with the aim of assessing its feasibility for sustainable structural and non-structural applications. The discussion synthesises results from the reviewed experimental studies, highlighting trends in mechanical and durability performance as a function of aggregate replacement ratio and source. Particular attention is given to the implications for precast concrete production, where a carefully optimised concrete mix design facilitates a higher RCA substitution level. Although each concrete application requires different mix adjustments, some of the publications used admixtures to achieve structural behaviour in fully aggregate replacement mix. Furthermore, a real-scale application and industrial practice case is included as a successful demonstration of the potential of RCA-SCC to meet structural performance requirements while contributing to the circularity goals of the concrete industry.

6.1. RCA-SCC for Structural Use

After analysing the literature, it was found that most studies focusing on the use of RCA in SCC evaluated the compressive strength and the modulus of elasticity of the experimental concrete mixes. In the studies where both coarse and fine aggregates were replaced, compressive strength and stiffness decreased significantly [21,28,29,34,35,56]. Nevertheless, when the replacement ratio was limited to 20–30% of the coarse aggregate, no change in the mechanical performance of the concrete was observed, allowing the RAC to be used for structural applications without changes in the production process. When the replacement ratio increased to 50% of the coarse aggregate, some concrete mixes showed, on average, a 20% decrease in stiffness; however, with small mix design optimisations using superplasticisers and water reducers, the mechanical properties could be recovered [28,35].

Additionally, the literature included studies evaluating not only the material properties but also the structural behaviour using large RCA replacement ratios. It was observed across different research studies that RCA can be successfully used in structural elements and connections. In the study conducted by Ferreira et al., 100% RCA was incorporated in headed bars embedded in slender structural members. As a result, full aggregate replacement did not affect the performance of the connection [48]. When high replacement ratios were used in the production of structural concrete blocks, Pani et al. reported that using 80% coarse aggregate replacement showed no mechanical difference compared to natural aggregates. In fact, it was concluded that RAC blocks can be produced without any modifications to the production process [50].

Similarly, in the research conducted by McGinnis et al., hollow-core slabs with a maximum of 60% coarse aggregate replacement were produced. The compressive strength of concrete, as well as the flexural bending, one-way shear, and punching shear of the slabs, was studied. The study concluded that aggregate replacement has little impact on these mechanical behaviours, and the industrial production of hollow-core slabs with high coarse aggregate replacement ratios is possible while following the producer's standard practices [52].

In a related study, Fantilli et al. found that although full aggregate replacement with RCA resulted in a reduction in the compressive strength of concrete, the use of recycled steel fibres in the production of a one-way slab led to even better structural performance compared to a slab made with natural aggregates [54].

In the study evaluating pre-stressed concrete beams by Velay-Lizancos et al., 50% replacement of coarse aggregate led to a 13% reduction in concrete compressive strength and a 17% reduction in the MOE. However, the experimental structural tests for yielding and failure bending moments at mid-span were not significantly affected by the aggregate replacement [34].

Finally, Zhao et al. reported that the production of concrete blocks with 100% coarse aggregate replacement showed only a 16.5% reduction in compressive strength, which represents a slight decrease overall. It was concluded that with adjustments to the concrete mix, concrete blocks with full RCA replacement can be produced while meeting the requirements set by the standards [60].

6.2. RCA SCC for Non-Structural Use

In the context of non-structural use, the applications of RCA in SCC were included in four studies within the meta-analysis for applications in curbstones [33], paving [56,59], non-structural concrete paver blocks [33], and precast concrete barriers [55]. In the study of RCA in paver concrete blocks, 50% of the coarse aggregate was replaced with RCA, leading to an increase in the water absorption and a reduction in the bulk density and strength; however, the breaking load and durability of the concrete still satisfy the minimum requirements [33,56]. In the study conducted by Contreras-Llanes et al., the evaluation of urban pavements using RCA showed that the breaking load was higher than the minimum required, and in some cases the tensile strength was slightly higher than the reference material, concluding that the use of RCA was suitable in the use of the pavement of high traffic areas [56]. In another study on RCA in pavement, it was found that the 45% aggregate substitution led to a decrease in strength of 17%; however, the workability of the mix increased by 2.6%. It was also found that the blocks built with higher replacement ratios showed higher deterioration than the reference blocks, and it was attributed to the high water absorption of the recycled aggregates [59].

In the study conducted by Thomas et al., the application of different RCA in precast barriers was evaluated. The author used RCA from concretes using different cements and found that RCA obtained from low-clicker concrete showed more porosity and less density and strength than those coming from ordinary Portland cement concrete. However, it was concluded that both RCA, from low-clinker and Portland cement are suitable for the manufacturing of precast barrier elements with medium and coarse recycled aggregates [55].

6.3. Real Case Applications

In June 2021, Betonwerk Büscher GmbH and Co. KG received the first national technical approval to fully substitute natural aggregates with mixed recycled demolition materials, including crushed sand, in precast concrete elements. This approval covers both load-bearing and non-load-bearing interior walls for buildings up to building class IV, which allows a maximum height of 13 m for residential or commercial buildings. The approval is limited to exposure classes XC1 and X0, which correspond to environments with no risk of corrosion or chemical attack.

Büscher developed an innovative precast concrete system for aggregate replacement, branded as the "Büscher Wall". This system was approved by the German Institute of Construction Technology (DIBt) to fully replace natural aggregates with mixed recycled demolition materials [65]. University partners, including TU Kaiserslautern and the University of Duisburg-Essen, verified that the RCA walls are technically and structurally equivalent to standard precast walls [66]. Büscher demonstrated the concept in a pilot project, constructing a three-unit apartment building near its production facility. The reported recycled content in the finished precast elements is approximately 75% by mass, representing the complete substitution of primary aggregates with processed demolition material [67,68].

7. Conclusions

RCA can be effectively used in SCC for structural and non-structural applications, provided that the source quality, replacement level, and mix design are carefully controlled. Evidence shows that high-quality RCA, usually originating from precast rejects or screened demolition waste, offers superior mechanical and durability performance compared to unscreened aggregates. Moderate replacement levels of about 20%–50% often achieve standard-compliant workability and compressive strengths while keeping shrinkage, creep, and serviceability within acceptable limits. Moreover, higher replacement levels or full course aggregate substitution, with no mix design modification, ingredient adjustment and/or aggregate pre-treatment, typically reduce compressive strength and stiffness of the concrete, leading to greater structural deflections and long-term durability problems, making them unsuitable for high-load-bearing elements. In some cases, such as precast or industrial applications, high RCA contents may still be viable if supported by proper mix optimisation and reinforcement detailing. Overall, RCA-SCC offers significant potential for sustainable concrete and material circularity, but structural use requires careful engineering judgement.

7.1. Workability and Mix Design

Due to RCA's higher porosity, the water used in the concrete mix is absorbed rapidly by the recycled aggregate before reacting with the cement. For this reason, the effective w/c ratio must be adjusted based on the water absorption of the aggregate to maintain flowability in the mix, which is a key aspect of SCC. Fine RCA, in particular, reduces concrete workability and slump unless additional water or superplasticiser is added. Mechanical screening or chemical washing of the aggregates to remove fines, combining RCA with supplementary cementitious materials, and slightly increasing cement content can produce workable mixtures that meet standards, although in some cases compromising sustainability.

7.2. Shrinkage, Creep and Prestress Losses

RCA concrete tends to exhibit greater shrinkage and creep than natural aggregate concrete due to the decrease in the concrete stiffness and higher water absorption of the aggregates, especially if fine RCA is used. Long-term prestress losses and deflections in structural members increase with higher RCA content, indicating that serviceability criteria require attention. Shrinkage decreases as compressive strength increases; thus, designing high-strength RCA-SCC mixes and limiting RCA content can mitigate shrinkage.

7.3. Structural Applications

Experiments on hollow-core slabs, headed bar sandwich panels and prestressed elements demonstrate that RCA-SCC can be used structurally if replacement levels are controlled and appropriate reinforcement arrangements are provided. Headed bars and hollow-core slabs, designed per ACI Committee 318, showed that RCA did not adversely affect structural capacity; however, reductions in ultimate load or increased deflections were observed at high replacement ratios. For prestressed beams, designed per ACI Committee 318, an appropriate RCA level must be selected to limit long-term deflections.

8. Future Research

The systematic review highlights the considerable potential of RCA for sustainable SCC but also reveals knowledge gaps and methodological limitations. The available evidence-based research is small and heterogeneous: only 24 unique experimental studies met the inclusion criteria, and they vary in RCA origin, pre-treatment methods, replacement ratios and mix designs. Moreover, most experiments report only compressive strength and modulus of elasticity, leaving other mechanical and durability properties underexplored. Future work must therefore expand and deepen the experimental database while developing standardised methodologies. Key research priorities include the optimisation of an RCA pre-treatment to enhance the material properties, thus the concrete performance. Expand the experimental database to other countries and different RCA origins. Investigate the influence of the RCA source and develop a quality classification based on the concrete's early-age performance. Address the effect of the alkali–silica reaction on SCC using RCA. Last but not least, build a comprehensive durability study and a more in-depth evaluation of RCA in structural precast elements.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling1010000/s1, Table S1: Meta Analysis; Table S2: PRISMA 2020 Checklist Mapping

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