buildings

MDPI

Review

Enhancing Concrete Sustainability: A Critical Review of the Performance of Recycled Concrete Aggregates (RCAs) in Structural Concrete

Alireza Alibeigibeni [1,*], Flavio Stochino [1], Marco Zucca [1] and Fernando López Gayarre [2]

[1] Department of Civil Environmental Engineering and Architecture, University of Cagliari, 09123 Cagliari, Italy
[2] Department Construction and Manufacturing Engineering, University of Oviedo-Campus Gijón, 33203 Oviedo, Spain
* Correspondence: a.alibeigi.b@gmail.com

Abstract: In the context of sustainable construction, recycled concrete aggregates (RCAs), including both fine and coarse fractions derived from construction and demolition waste (CDW), are gaining traction due to their potential to mitigate environmental impacts by reducing reliance on natural aggregates and minimizing waste. This paper provides a comprehensive review of the effects of RCAs on the mechanical and durability properties of concrete, including compressive and tensile strengths, modulus of elasticity, and resistance to environmental degradation. The review highlights that the presence of adhered mortar and higher porosity in RCAs generally leads to reduced mechanical performance and durability. However, pretreatment methods—mechanical, chemical, and thermal—along with optimized mix designs and the use of supplementary cementitious materials (SCMs) have shown to significantly improve the concrete properties of RCAs. Additionally, recent studies on carbon dioxide (CO_2) capture through the accelerated carbonation of RCAs offer promising environmental benefits. Life cycle assessment (LCA) analyses reveal reductions in energy use, CO_2 emissions, and material costs when RCAs are properly processed and locally sourced. Despite challenges related to RCA quality variability, the review identifies pathways for the effective use of RCAs in structural applications.

Keywords: recycled concrete aggregate (RCA); sustainable concrete; structural concrete; construction and demolition waste (CDW); mechanical properties; durability properties; life cycle assessment (LCA)

check for updates

Academic Editor: Yunchao Tang

Received: 11 March 2025
Revised: 12 April 2025
Accepted: 15 April 2025
Published: 19 April 2025

Citation: Alibeigibeni, A.; Stochino, F.; Zucca, M.; Gayarre, F.L. Enhancing Concrete Sustainability: A Critical Review of the Performance of Recycled Concrete Aggregates (RCAs) in Structural Concrete. *Buildings* **2025**, *15*, 1361. https://doi.org/10.3390/buildings15081361

1. Introduction

Concrete is the most used construction material globally, with its production causing significant environmental impacts, including natural resource depletion and carbon emissions. In response to these challenges, the incorporation of recycled materials, such as RCAs derived from CDW, has emerged as a sustainable solution to reduce the environmental impact of concrete production while enhancing its mechanical and durability properties [1].

The construction industry is one of the largest consumers of natural resources worldwide. Global production of virgin aggregates has increased significantly, from 21 billion tons in 2007 to 50 billion tons in 2017, marking a 58% rise. Projections indicate that this demand will continue to grow, reaching 60 billion tons by 2030 [2,3]. China is the largest consumer, using 40% of these aggregates, followed by India at 10% and other Asian countries, including Indonesia, Malaysia, and Thailand, with a combined total of 16%. Additional major consumers are Turkey (0.96%), Africa (8%), Europe and the European Free Trade

Association (EFTA) (6%), the United States (4.8%), Central and South America (4%), the Middle East (5.6%), and Russia together with the Commonwealth of Independent States (CIS) (5%) [2–4], as illustrated in Figure 1 [5].

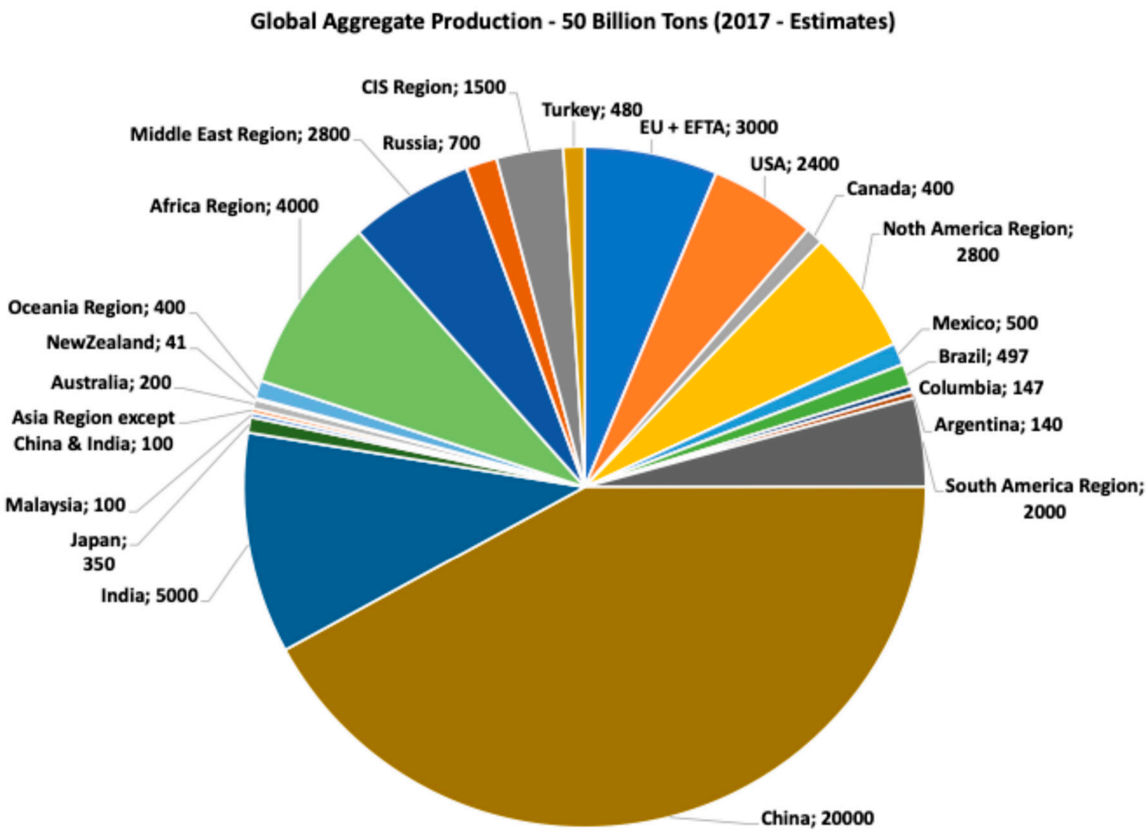

Figure 1. Worldwide production of virgin aggregates (million tons) [5].

RCAs derived from demolished concrete structures offer a sustainable alternative to conventional aggregates. The utilization of RCAs in concrete not only diverts construction waste from landfills, but also conserves natural resources and reduces energy consumption associated with aggregate extraction and processing [6]. Furthermore, incorporating RCAs into concrete mixtures can contribute to mitigating the carbon footprint of the construction industry, aligning with global efforts towards sustainable development and environmental stewardship [7].

Actually, the incorporation of RCAs in concrete raises questions regarding their impact on mechanical and durability properties. The heterogeneous nature of RCAs, varying in size, shape, and quality, presents challenges in predicting their influence on concrete performance [8]. Moreover, factors such as the content of adhered mortar, contaminants, and the presence of residual cementitious materials can influence the properties of RCAs and, consequently, the performance of recycled aggregate concrete [9].

The use of RCAs in structural elements is gaining attention for its environmental and mechanical benefits. Stochino et al. (2024) [10] investigated steel–concrete composite slabs incorporating RCAs and found that, while compressive strength decreased with higher RCA content, structural integrity remained intact. Their study suggests that RCAs can enhance composite action with steel decking, supporting their feasibility for sustainable construction without compromising mechanical performance [10].

Understanding the effects of using RCAs on the mechanical and durability properties of concrete is crucial for optimizing concrete mix designs and ensuring the long-term performance of sustainable construction materials. Previous research has explored various aspects of recycled aggregate concrete, including its compressive strength, tensile strength, modulus of elasticity, durability against freeze–thaw cycles, chloride penetration resistance, and sulfate attack resistance [11,12].

Despite the growing body of research, as illustrated in Figure 2 [13], existing studies often focus on isolated properties of RCA concrete, such as compressive strength or durability against specific environmental factors. To generate this figure, a keyword search was conducted on the Scopus database using the term 'recycled concrete aggregate'. The search was limited to publications from 2000 to 2024 to analyze the trend in research output over time.

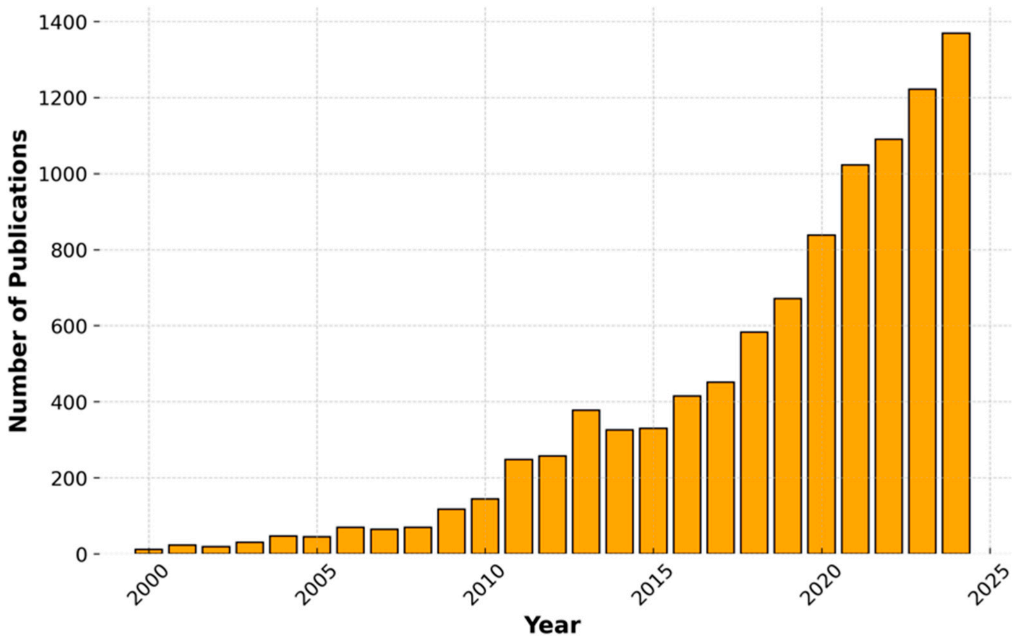

Figure 2. Trend of research publications on RCAs [13].

Few comprehensive reviews systematically synthesize these findings across mechanical and durability dimensions, alongside innovations in pretreatment methods and advanced mix designs. This gap in the literature limits the development of holistic strategies for optimizing RCAs in structural applications.

This paper addresses this gap by presenting an integrated review of the mechanical and durability properties of RCAs, highlighting the interplay between pretreatment techniques, mix designs, and performance outcomes. Additionally, it explores practical applications and future research directions to bridge the knowledge divide.

After this introduction, the paper is structured as follows: Section 2 discusses the recycling of construction and demolition waste for aggregate production. Section 3 focuses on the mechanical properties of concrete with RCAs, while Section 4 explores their durability properties. Section 5 examines carbon dioxide capturing in RCAs, and Section 6 presents an RCA life cycle assessment. Finally, Section 7 concludes the paper with a summary of findings and recommendations.

2. Recycling of Construction of Demolition Waste for Producing the Aggregates

The recycling of CDW for producing aggregates has gained significant attention as a sustainable practice in the construction industry. CDW comprises various materials, including concrete, bricks, tiles, asphalt, wood, and metals, generated from construction, renovation, and demolition activities [14]. Recycling CDW not only reduces the burden on landfills, but also conserves natural resources and reduces energy consumption associated with conventional aggregate production. Moreover, incorporating recycled aggregates from CDW in concrete offers potential economic benefits by lowering material costs and reducing the need for landfill disposal [15].

The quality of recycled aggregates obtained from CDW depends on several factors, including the type and composition of the original materials, the degree of contamination, the efficiency of the recycling process, and the quality control measures implemented [16]. Proper sorting, crushing, and screening techniques are essential to produce recycled aggregates with desirable properties for use in concrete production [17]. However, challenges such as variability in material composition, presence of contaminants, and limitations in processing technology can affect the quality and consistency of recycled aggregates, influencing the performance of concrete mixtures [11].

Despite the challenges, numerous studies have investigated the feasibility and effectiveness of using recycled aggregates from CDW in concrete applications. Research efforts have focused on evaluating the mechanical properties, durability performance, and long-term behavior of concrete incorporating recycled aggregates from CDW [18]. Additionally, advancements in recycling technologies and quality control measures have contributed to improving the quality and reliability of recycled aggregates, further enhancing their suitability for use in concrete production [19].

2.1. Recycled Concrete Aggregates (RCAs)

RCAs obtained from construction and demolition waste are produced by crushing and processing demolished concrete structures, resulting in coarse and fine aggregates that can be used as substitutes for natural aggregates in concrete mixtures [20]. Figure 3 provides an example of RCAs, illustrating their typical particle size and texture.

Figure 3. Recycled concrete aggregates (RCAs).

The properties of RCAs significantly influence the performance of concrete mixtures. The quality of RCAs is affected by factors such as the quality of the original concrete, the degree of contamination, the crushing process, and the particle size distribution [8]. RCAs may contain residual mortar adhered to the aggregate particles, which can affect the workability, strength, and durability of concrete [5]. Therefore, proper characterization and quality control measures are essential to ensure the consistent and reliable performance of concrete containing RCAs.

Regional variations play a crucial role in influencing the performance of RCAs, primarily due to differences in CDW characteristics. Factors such as the age and type of demolished structures, local construction materials, and recycling practices contribute to these differences. For instance, RCAs obtained from regions with older buildings often contain higher proportions of masonry or plaster, which can negatively impact compressive strength and durability compared to RCAs derived from newer, concrete-rich demolitions. Moreover, areas with more regulated and advanced recycling systems, such as parts of Europe, tend to produce more consistent and higher-quality RCAs. These regional disparities underscore the need to consider local CDW characteristics when evaluating the suitability and performance of RCAs in concrete applications [21].

Research on RCAs has focused on evaluating their effects on various properties of concrete, including mechanical strength, durability, shrinkage, and permeability. Numerous studies have investigated the optimal replacement levels of natural aggregates with RCAs to achieve desired concrete performance while minimizing potential drawbacks [22]. Additionally, research efforts have explored different techniques to enhance the properties of recycled aggregate concrete, such as pre-soaking RCAs to reduce their water absorption and improve their compatibility with cement paste [23].

The influence of the quality of parent concrete on RCA properties remains a topic of debate in the literature. While several studies emphasize that the characteristics of the original concrete significantly impact the mechanical performance of recycled aggregate concrete, others suggest that factors such as mix design and curing conditions may play a more dominant role. For instance, Pani et al. (2020) [24] argue that the quality of parent concrete does not substantially affect the compressive strength of recycled concrete, highlighting that mix proportions and other parameters have a greater influence on the final properties of RCA-based concrete. This divergence in findings underscores the complexity of RCA behavior and the need for further research to reconcile these varying perspectives.

RCAs have been extensively studied for their potential to mitigate the environmental impact of concrete production. The use of RCAs reduces the need for landfill space, conserves natural resources, and lowers greenhouse gas emissions associated with traditional aggregate mining and transportation [25]. Furthermore, incorporating RCAs into concrete mixtures aligns with sustainable development goals by promoting resource efficiency and waste reduction [26]. However, challenges such as variability in RCA properties, uncertainty regarding long-term performance, and potential durability issues remain areas of concern [27].

2.2. Pretreatment Methods on RCAs

The quality and performance of RCAs are influenced by factors such as residual mortar content, contaminants, and particle size distribution. Effective pretreatment methods are crucial to enhance the properties of RCAs and optimize their suitability for concrete production.

Mechanical pretreatment methods involve physical processes such as crushing, screening, and sieving to break down demolished concrete structures and segregate RCAs into desired particle sizes [28]. Proper crushing techniques are essential to remove adhered mortar effectively and minimize the generation of fines. Screening and sieving processes further refine RCAs into uniform aggregates suitable for concrete production.

Chemical pretreatment methods utilize solutions to dissolve or weaken the bond between aggregate particles and residual mortar, facilitating separation and improving RCA cleanliness [29]. Acid washing and alkali treatment are common chemical techniques employed. Acid washing removes calcium carbonate in the mortar matrix, while alkali treatment breaks down the bonds between aggregate particles and residual mortar. These methods enhance the quality of RCAs, but require careful handling to mitigate environmental impacts [30].

Thermal pretreatment involves heating and drying RCAs to remove moisture and contaminants, improving their compatibility with cement paste and concrete performance [29,30]. Thermal treatment eliminates organic contaminants and weakens the bond between aggregate particles and residual mortar. However, it may alter the mineralogy and microstructure of RCAs, necessitating careful consideration.

Pretreatment effectiveness depends on factors including the quality of the original concrete, contaminant type and concentration, and desired properties of recycled aggregates [11,31]. High-quality RCAs can be obtained from well-maintained structures, while older or heavily contaminated sources may require more intensive pretreatment. Selection of pretreatment methods should align with concrete mix designs and intended RCA application. Comprehensive testing is crucial to assess pretreated RCA suitability for concrete production. Research aims to optimize recycling processes, improve recycled aggregate quality, and enhance concrete performance [5]. Studies like [29] have shown that chemical pretreatment significantly reduces residual mortar content in RCAs, leading to improved concrete strength and durability. Experimental testing evaluates mechanical strength, durability, shrinkage, and permeability of concrete with pretreated RCAs. Advancements in pretreatment technologies, such as automated sorting and washing systems, streamline recycling processes and increase efficiency [32].

Pretreatment methods are vital for enhancing the quality and performance of RCAs in sustainable concrete production. Mechanical, chemical, and thermal pretreatment techniques effectively address challenges associated with residual mortar, contaminants, and particle size distribution in RCAs. However, their efficacy depends on various factors, necessitating comprehensive characterization and testing. Continued research and development efforts are crucial to optimize pretreatment methods and promote widespread adoption of recycled aggregates in the construction industry.

3. Mechanical Properties of Concrete with RCAs

3.1. Compressive Strength

The compressive strength is the most critical factor in evaluating concrete. Numerous studies have explored how recycled aggregates influence the compressive strength of recycled aggregate concrete (RAC). Silva et al. (2014) [33] reviewed 236 papers on RAC, with 119 focused specifically on compressive strength. However, reaching consistent conclusions has been challenging due to various factors. First, comparisons are often made between RAC and conventional concrete using natural aggregates, but the quality of these natural aggregates greatly influences the outcomes. The impact of recycled aggregates can vary depending on whether they replace natural aggregates with strong or weak mechanical properties. Second, different approaches were used to compare RAC, such as maintaining a consistent total water/cement ratio, an equivalent effective water/cement ratio, or the same workability, each of which can affect the effective water/cement ratio differently. Lastly, the results also depend on the specific properties of the recycled aggregates, such as their shape, size, and mechanical characteristics.

To better illustrate the influence of RCA content on compressive strength, a statistical analysis was conducted based on normalized values from multiple published studies. The results are shown in Figure 4, where the compressive strength of RAC is expressed as a ratio relative to that of conventional concrete and plotted against the percentage of RCAs used as replacements for natural aggregates.

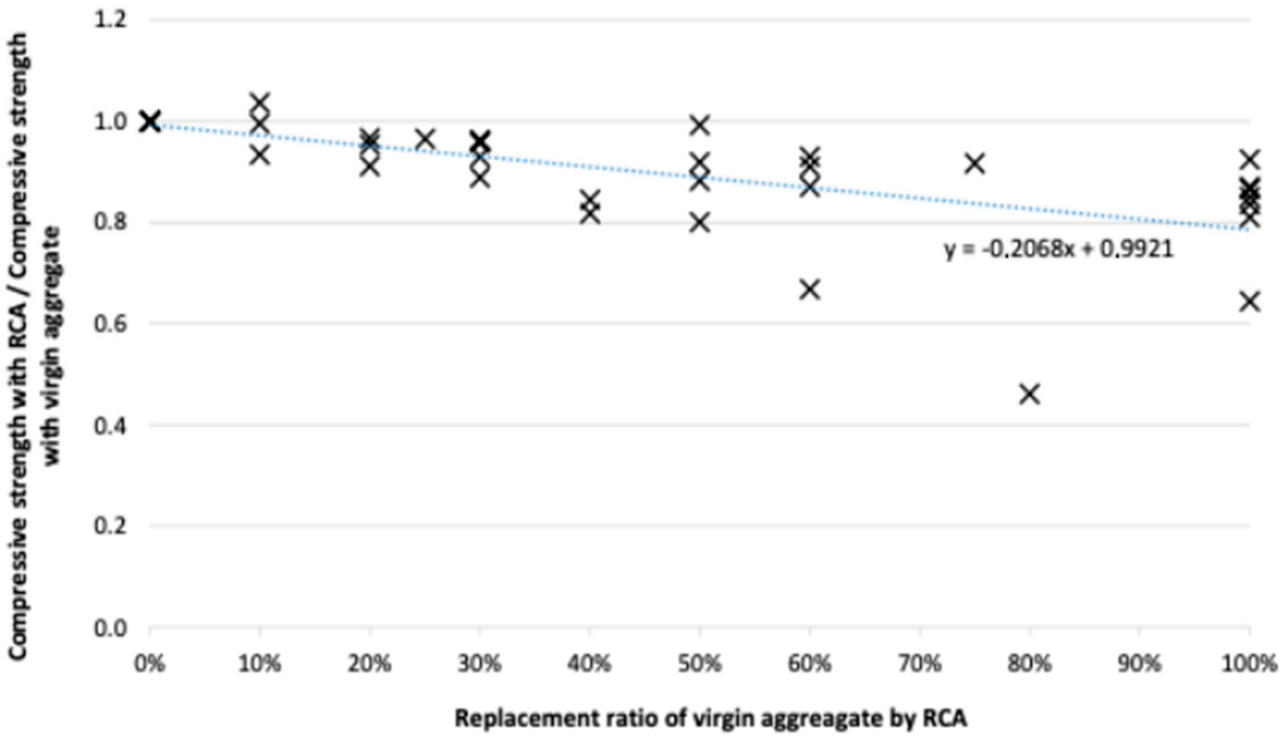

Figure 4. Normalized compressive strength of concrete with RCAs vs. replacements [34–45].

As seen in the figure, there is a clear downward trend: As the replacement level increases, compressive strength generally decreases. The data follow a linear trend, described by the equation $y = -0.2068x + 0.9921$, indicating that a full replacement (100%) could lead to about 79% of the compressive strength compared to concrete made entirely with virgin aggregates. This reduction is largely attributed to the higher porosity and lower mechanical quality of RCAs, which often contain residual mortar and form weaker interfacial transition zones (ITZs). These characteristics compromise the density and overall strength of the concrete matrix.

The compressive strength reduction is primarily due to the weaker adhered mortar present in the RCAs, which compromises the new concrete matrix's overall integrity. For instance, Silva et al. (2016) [46] observed that the compressive strength of RCA concrete could be approximately 10–30% lower than that of conventional concrete, depending on the RCA quality and the original concrete's properties.

The compressive strength of RCA concrete is strongly influenced by the RCA quality, which can be improved through proper pretreatment methods, such as acid washing or mechanical treatment. As mentioned in Section 2.2, these methods help reduce the residual mortar content, which can lead to better interfacial bonding and improved compressive strength.

Another critical factor affecting the compressive strength of RCA concrete is the mix design. Adjustments in the mix proportions, such as increasing the cement content or using supplementary cementitious materials (SCMs) like fly ash or silica fume, can mitigate the strength reduction caused by RCAs. A study by Kurda et al. (2019) [47] demonstrated that incorporating fly ash in RCA concrete mixes could enhance compressive strength by improving the interfacial transition zone between the RCAs and the cement paste. Their findings indicate that with optimal mix design, RCA concrete can achieve compressive strengths comparable to those of traditional concrete.

Curing conditions also play a crucial role in the development of compressive strength in RCA concrete. Proper curing can enhance the long-term strength of RCA concrete, despite initial lower strengths. Zhang et al. (2021) [28] reported that while RCA concrete exhibited lower early-age compressive strength, its long-term strength, particularly after 90 days, was comparable to that of natural aggregate concrete when subjected to appropriate curing practices. Their study emphasizes the importance of extended curing times to allow the RCA concrete to develop its full-strength potential.

With advancements in RCA processing techniques and optimized mix designs, the compressive strength of RCA concrete can be effectively managed to meet structural requirements. For instance, research by Wang et al. (2018) [48] highlights that incorporating RCAs in structural concrete is feasible and practical, provided that the mix design is tailored to account for the specific properties of the RCAs used.

3.2. Tensile Strength

The tensile strength of concrete is a fundamental property that influences its behavior under various loading conditions, especially in scenarios involving flexure or cracking. The introduction of RCAs into concrete mixes has been shown to impact tensile strength differently than compressive strength. Silvia et al. (2015) [49] found that the tensile strength of RAC tends to decrease with an increase in RCA content, primarily due to the weaker interfacial transition zone (ITZ) in RAC compared to natural aggregate concrete. This weaker ITZ is often characterized by micro-cracks and increased porosity, which contribute to the reduced tensile strength.

The source and processing of RCAs play crucial roles in determining the tensile strength of the resulting RAC. Yang et al. (2023) [50] conducted a study comparing the tensile strength of RAC produced with RCAs from different sources. Their research indicated that RCAs from high-strength concrete had a less detrimental effect on tensile strength than RCAs sourced from lower-quality concrete. This finding emphasizes the importance of selecting high-quality RCAs and possibly enhancing them through pretreatment processes, such as washing and mechanical scrubbing, to remove adhered mortar and other contaminants.

Modifications in the mix design can also influence the tensile strength of RAC. Adding supplementary cementitious materials (SCMs) like fly ash or silica fume has been shown to improve tensile strength by refining the microstructure of the ITZ and enhancing the bond between the RCAs and the new cement paste. Incorporating silica fume in RAC mixes improved tensile strength by reducing ITZ porosity and increasing the cohesion between RCA particles and the cement matrix. This modification is particularly effective in mitigating the reduction in tensile strength typically associated with higher RCA content [51,52].

Curing practices significantly affect the tensile strength development of RAC, as they do with compressive strength. Proper curing can enhance the tensile strength, even when using high RCA levels. Dimitriou et al. (2018) [53] demonstrated that RAC subjected to extended curing times showed significant improvements in tensile strength, almost reaching that of natural aggregate concrete. This improvement was more pronounced in mixes where SCMs were used, highlighting the combined effect of optimal curing and mix design on tensile strength.

3.3. Elastic Modulus

Elastic modulus is a critical mechanical property of concrete that defines its stiffness and ability to deform elastically under load. The modulus of elasticity is influenced by the composition of the concrete mix, particularly the quality of aggregates used. When RCAs replace natural aggregates in concrete, the elastic modulus is often observed to decrease due to the inferior quality of RCAs compared to natural aggregates. This reduction is attributed primarily to the quality of the recycled aggregates, which typically have a lower stiffness due to the presence of old adhered mortar and increased porosity. RCA particles contain old mortar and microcracks, which reduce the overall stiffness of the concrete, making it more susceptible to deformation under stress. Various studies have reported a reduction of up to 30% in the elastic modulus of concrete containing 100% RCA compared to natural aggregate concrete (NAC) [54,55]. Understanding how RCAs affect the elastic modulus is essential for ensuring that structural designs maintain adequate stiffness and serviceability.

However, several treatment methods have been investigated to improve the modulus of elasticity in RCA concrete. Based on the study by Silva et al. (2016) [46], pretreatment techniques, such as acid washing, mechanical grinding, and polymer impregnation, have shown significant improvements in the modulus of elasticity. For instance, heating–scrubbing treatment resulted in a 42.92% increase in E-values, while mechanical grinding led to a 31.30% improvement [56]. Furthermore, bio-calcium deposition treatment increased the E-values by 32.8%, from 33.2 GPa for untreated RCAs to 44.1 GPa for treated RCAs [57]. Other methods, such as acetic acid immersion, also demonstrated improvements, with increases ranging from 12% to 29% depending on the treatment method and RCA replacement level [58]. These findings suggest that pretreatment methods can effectively enhance the stiffness and overall mechanical performance of RCA concrete by reducing residual mortar content and improving the bond between RCAs and the cement matrix.

Table 1 presents the modulus of elasticity of RCA concrete at different replacement levels, based on experimental results from a previous study [58]. The results indicate a clear reduction in the elastic modulus as the RCA content increases. The reference mix (M0-0) with natural aggregates exhibited the highest modulus of elasticity (34.7 GPa), whereas the 100% RCA mix (M100-100) recorded the lowest value (16.7 GPa), confirming the negative impact of RCAs on concrete stiffness. In the mix designation "M100-100," the first "100" refers to the percentage of natural fine aggregate replaced with RCAs, and the second "100" refers to the percentage of coarse aggregate replaced with RCAs.

Table 1. Effect of RCA replacement on the modulus of elasticity of concrete.

Mix	Average [GPa]	CoV (%)
M 0-0	34.7	13.43
M 30-30	22.5	0.53
M 50-50	23.7	1.45
M 100-100	16.7	0.03

The reduction in the elastic modulus of RCA concrete can be attributed to the higher porosity and weaker ITZ between the RCAs and the new cement matrix. Studies have shown that the ITZ in RCA concrete tends to be more porous due to the presence of old mortar on the RCA surface, which hinders the bonding between new cement paste and aggregate [59]. As a result, RCA concrete often exhibits lower stiffness, especially at higher replacement ratios of natural aggregates with RCAs. The degradation in elastic modulus becomes more pronounced as the replacement level of RCAs increases, necessitating adjustments in mix designs or additional treatments to the RCAs to mitigate this effect [60].

Several factors influence the elastic modulus of RCA concrete, including the quality of the original concrete from which the RCAs are derived, the RCA treatment methods, and the ratio of RCA replacement. High-quality RCAs derived from strong parent concrete may exhibit a smaller reduction in elastic modulus compared to RCAs from low-strength concrete [61]. Additionally, pretreating RCAs, such as by removing adhered mortar or improving the surface characteristics, has been shown to mitigate the reduction in elastic modulus. Various studies have explored methods such as mechanical rubbing, acid treatment, and thermal treatment to improve RCA properties, ultimately aiming to enhance the elastic modulus of RCA concrete [62].

While the elastic modulus of RCA concrete is generally lower than that of conventional concrete, it is still possible to achieve acceptable stiffness for many structural applications through optimized mix designs and careful selection of RCA quality. The use of supplementary cementitious materials (SCMs) like fly ash, silica fume, or slag in RCA concrete has been shown to enhance the elastic modulus by improving the bond between the RCAs and the cement matrix. These SCMs contribute to a denser microstructure and reduce the porosity of the ITZ, partially compensating for the lower stiffness of RCA concrete [44].

In conclusion, the use of RCAs in concrete has a significant impact on the elastic modulus, primarily due to the porous and weak nature of RCA particles and the associated ITZ. However, by optimizing the quality of RCAs and mix design and incorporating SCMs, the reduction in elastic modulus can be controlled. Further research is needed to develop standard guidelines for improving the elastic modulus of RCA concrete, ensuring its suitability for a wide range of structural applications while promoting sustainability in construction practices.

3.4. Bonding Strength Between Concrete and Steel

The bond strength between concrete and steel reinforcement is a critical factor influencing the mechanical performance of reinforced concrete and composites structures. Several studies have evaluated the bond strength behavior using RCAs, and the findings reveal varied influences based on environmental conditions, mix proportions, and external factors like corrosion and temperature. Ashteyat et al. (2024) [63] examined RCAs and recycled asphalt pavements, reporting a reduction in bond stress with increasing recycled material, especially when smaller diameter bars were used, leading to a bond reduction of 6% to 45% compared to natural aggregates (NAs). Similarly, Abushanab and Alnahhal (2023) [64] investigated the effects of treated wastewater (TWW) and fly ash (FA) in RCA concretes subjected to corrosion. RCAs reduced bond strength by 18%, although the addition of 20% FA improved it by 10%, indicating the sensitivity of RCAs to corrosion when combined with other recycled materials.

The performance of RCA concrete under elevated temperatures was explored by Yusuf et al. (2022) [65], who found that RCAs exhibited adequate bond strength compared to NAs, but with greater deformations. Temperature-induced damage was particularly linked to the deterioration of mechanical properties, such as tensile strength, resulting in higher bond slippage. Zou et al. (2020) [66] corroborated these findings, noting that as temperatures increased, the bond strength between RCA concrete and steel bars significantly dropped, particularly in the post-heating phase, with a flattening of bond–slip curves. Their study introduced a modified model to predict bond strength, aligning well with experimental data.

Alhawat and Ashour (2019) [67] observed that corrosion greatly influences bond strength in RCA concrete, where the bond initially improved with minimal corrosion before degrading as corrosion intensified. Notably, the higher porosity of the RCAs led to faster degradation compared to conventional concrete. Namarak et al. (2018) [68] studied the use of a calcium carbide residue and fly ash binder with RCAs, finding that while RCAs reduced bond strength compared to natural aggregates, they still performed better than ordinary Portland cement concrete with RCAs. The type of steel reinforcement also influenced bond strength, with deformed bars outperforming smooth bars.

Prince and Singh (2015) [69] evaluated high-strength RCA concretes, discovering that the normalized bond strength of RCA concretes exceeded that of normal-strength RCAs and even natural aggregate concretes. Their proposed bond stress–slip relationship model accurately predicted bond behavior for various RCA replacement levels.

Figure 5 shows the relationship between RCA replacement levels and normalized bond strength for different concrete mixes and studies. Specifically, it compares the results for 8 mm and 10 mm deformed steel bars embedded in Mix A and Mix B, with increasing RCA content at 0%, 25%, 50%, 75%, and 100%. The trend lines demonstrate a general increase in normalized bond strength as RCA replacement levels rise. Notably, Mix B (high-strength RCAs) exhibited higher normalized bond strength than Mix A, suggesting that increasing RCA content in high-strength concrete enhances the bond performance more effectively.

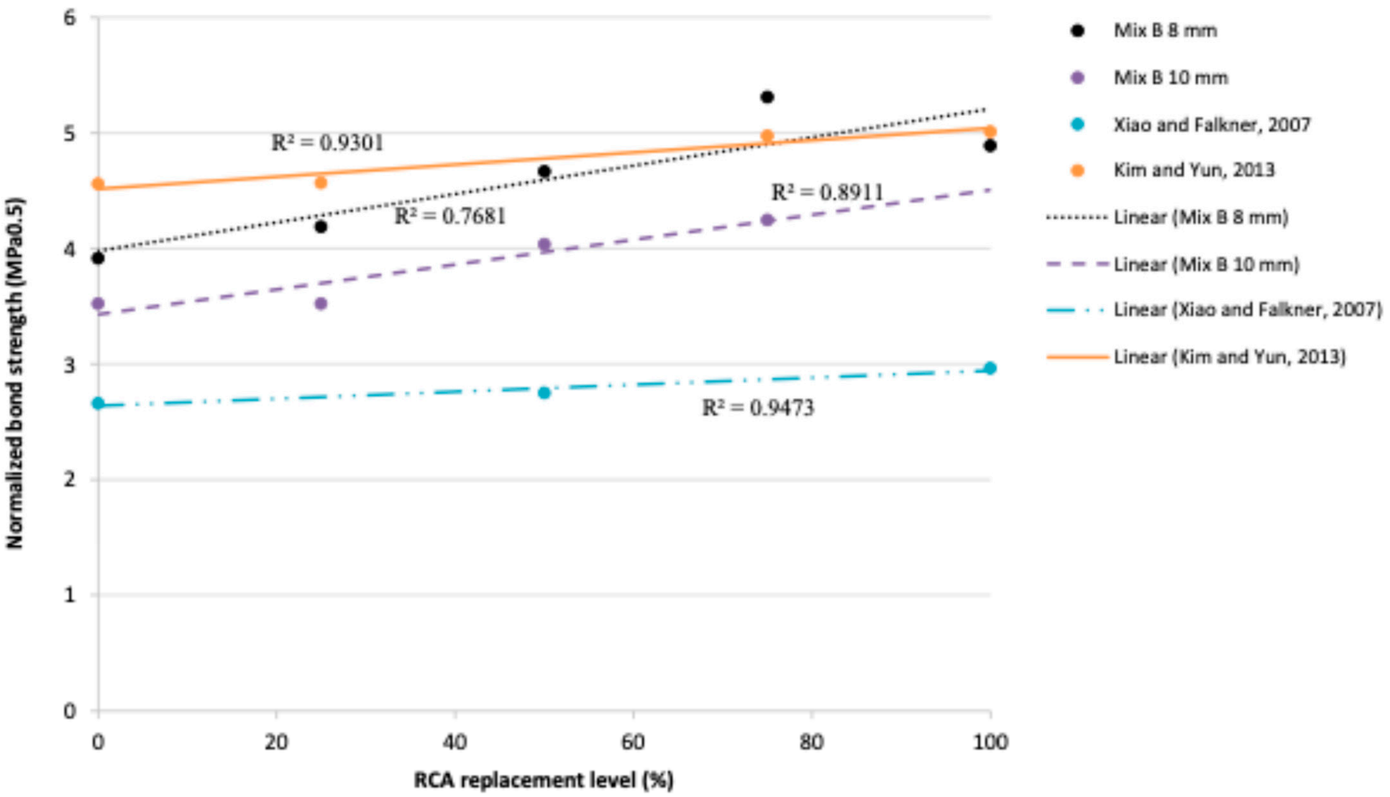

Figure 5. Normalized bond strengths corresponding to varying levels of RCA replacement [69–71].

In addition, the graph includes comparative data from studies by Xiao and Falkner (2007) [70] and Kim and Yun (2013) [71]. These comparisons reveal that the bond strength behavior observed in this experiment aligns closely with established trends in the literature. The R^2 values, which represent the strength of correlation between RCA replacement levels and normalized bond strength, further validate this finding. A higher R^2 value indicates a stronger correlation, with the highest $R^2 = 0.968$ observed for Xiao and Falkner (2007) [70]. Recently, Stochino et al. (2024) [72] investigated the mechanical behavior of composite slabs incorporating RCAs and found a notable enhancement in the bond strength between concrete and metal sheets. Their experimental study demonstrated that the presence of RCAs improves longitudinal shear resistance, suggesting a stronger mechanical interlock at the steel–concrete interface. This improvement is primarily attributed to the rougher surface texture of RCAs, which enhances friction and mechanical interlocking, ultimately leading to better load transfer mechanisms within the composite system. Notably, composite slabs with RCAs exhibited higher debonding resistance and sustained load-bearing capacity post-failure, reinforcing their potential for structural applications where bond performance is critical [72]. This result underscores the significant impact of RCA content on bond strength, reinforcing the notion that increasing RCA content improves the bond performance in reinforced concrete structures.

3.5. Creep

The creep behavior of recycled aggregate concrete (RAC) is one of the least studied aspects of its performance, leaving a critical gap in understanding its long-term deformation characteristics. While the mechanical and durability properties of RAC have been extensively investigated, limited research has addressed the influence of recycled aggregates on creep. This gap hinders the development of predictive models and design standards, particularly for applications requiring stringent long-term performance criteria.

The formulation of creep models has been significantly advanced through large experimental databases, particularly the NU-ITI database, which contains approximately 1400 creep curves for natural aggregate concrete. These curves are evenly divided between basic and drying creep, offering a comprehensive foundation for model development. When reporting experimental results on concrete creep, several metrics are used, including creep strain, ε_{cc}, experimental creep coefficient $\varphi_{exp} = \frac{\varepsilon_{cc}}{\varepsilon_{ci}}$ (where ε_{ci} represents the initial strain at loading), specific creep $\frac{\varepsilon_{cc}}{\sigma_c}$, (i.e., creep strain per unit stress), and creep compliance J_c. Of these, creep compliance is the most general and optimal method of reporting, particularly for linear creep behavior (i.e., exposure to stresses below approximately 40–50% of compressive strength). The relation is defined as:

$$\varepsilon_{c\sigma}(t, t_0) = J_c(t, t_0) \cdot \sigma_c(t_0) \quad (1)$$

where $\varepsilon_{c\sigma}$ is the stress-dependent strain, and t_0 is the age of concrete at loading. This formulation enables the derivation of various creep coefficients, such as the one proposed in the *fib* Model Code 2010:

$$\varepsilon_{c\sigma}(t, t_0) = \left(\frac{1}{E_c(t_0)} + \frac{\varphi(t, t_0)}{E_{ci}} \right) \cdot \sigma_c(t_0) \quad (2)$$

where $E_c(t_0)$ and E_{ci} represent the modulus of elasticity at the age of loading and at 28 days, respectively. However, it is crucial to note that the creep coefficient derived from the *fib* Model Code 2010 does not directly match the experimental creep coefficient $\varphi_{exp} = \frac{\varepsilon_{cc}}{\varepsilon_{ci}}$. This distinction is important when comparing experimental results with code-based predictions [73].

Despite the extensive data available, including nearly 800 creep curves for concretes with various admixtures or additives, the NU-ITI database lacks specific information on the creep behavior of recycled aggregate concrete (RAC). The adhered mortar on recycled aggregate (RA) particles influences creep in several ways, from an internal curing effect to less restraint against creep, and even creep of the adhered mortar itself. In subsequent sections, experimental results on RAC creep are reviewed, and both new and modified models for predicting RAC creep are discussed [73].

A comprehensive literature review by Lye et al. (2014) [74] identified 100 publications on RAC creep from 27 countries, spanning 30 years. The experimental data covered a wide range of recycled materials, including RCAs, recycled masonry aggregates (RMAs), mixed recycled aggregates (MRAs), and fine and coarse RA.

The results consistently showed that creep increases with higher coarse RCA content, mirroring trends. For example, the average increase in creep for RAC with 20% and 100% coarse RCA content was 12% and 32%, respectively. These findings align with other studies, which report increases in the range of 10–50%. Additionally, compressive strength plays a key role in the relative increase in creep. For RAC with 100% coarse RCA, the increase in creep was found to be 35%, 30%, and 25% for f_{cm} in the ranges of 15–40 MPa, 41–50 MPa, and 51–70 MPa, respectively.

Gomez-Soberon (2002) [75] found that, as shown in Figure 6, under permanent stress at 40% of the compressive strength, the creep of RAC with replacement ratios of recycled aggregate (where factor r represents the replacement ratio) between 20% and 100% was higher by 35% to 51%, compared to that of NAC. While basic creep is not significantly affected by recycled aggregate replacement, drying creep is clearly impacted, particularly when the replacement ratio exceeds 30%. Fan et al. (2014) [76] attributed this increase in creep to the characteristics of the old mortar adhered to recycled aggregates, which contributes to the overall creep behavior of RAC.

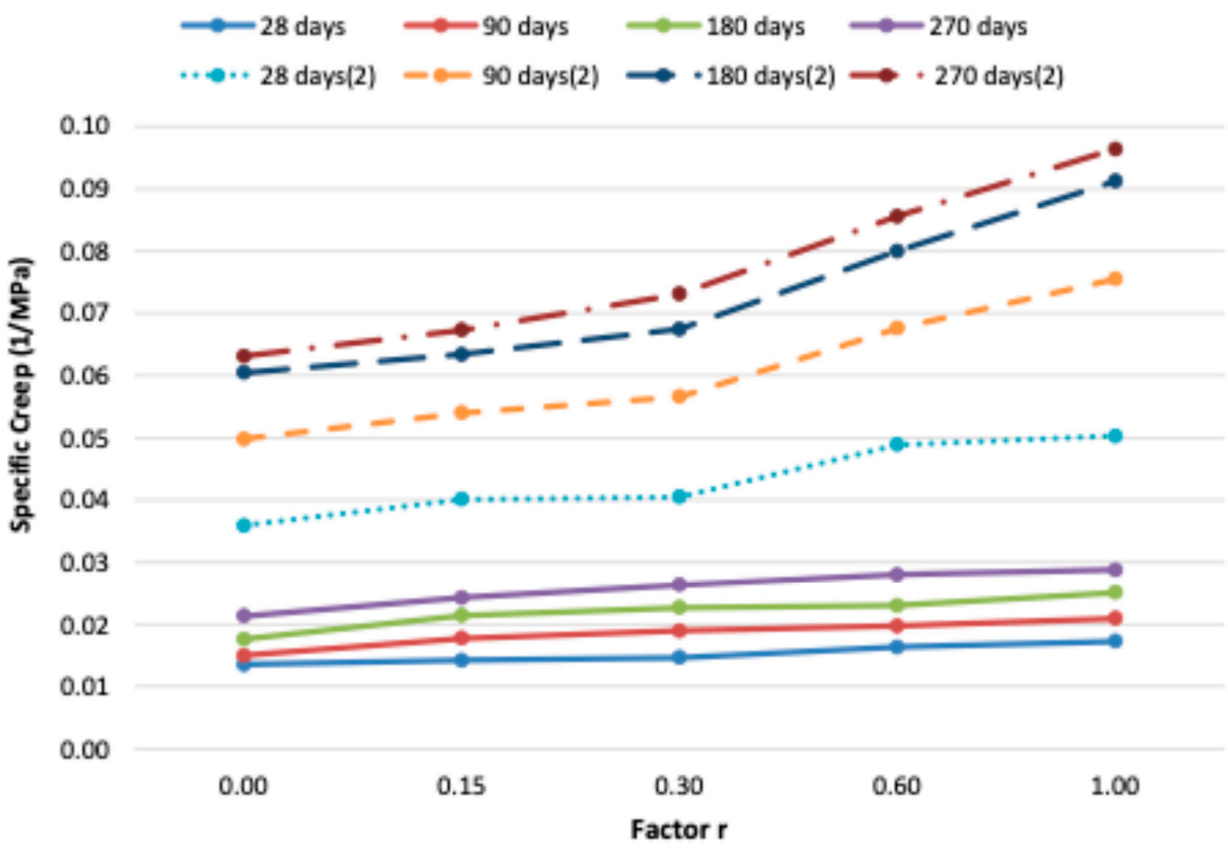

Figure 6. Specific creep for various recycled concretes at different replacement ratios of RCAs [75].

Overall, the mechanical performance of RCA concrete, while influenced by replacement ratios and material quality, can be effectively optimized through mix design and treatment strategies. However, ensuring the long-term serviceability of such concrete requires equal attention to its durability characteristics. In this context, the following section explores key durability concerns, starting with carbonation, which plays a significant role in the long-term performance and sustainability of RCA-based concrete.

4. Durability Properties of Concrete with RCAs

4.1. Carbonation

The carbonation of concrete made with RCAs is an important concern for long-term durability, as the material's porosity tends to increase carbonation depth. Studies show that untreated RCAs, when incorporated into concrete, can lead to an increase in carbonation depth due to the higher water absorption and porosity of RCAs compared to natural aggregates [77,78]. For instance, untreated RCAs increase the porosity of the concrete matrix, facilitating the ingress of carbon dioxide (CO_2) and leading to a faster rate of carbonation, which can impact the pH of concrete and promote the risk of steel reinforcement corrosion. Carbonation depth can increase by up to 20–30% in untreated RCA concrete compared to natural aggregate concrete.

Conversely, carbonation treatment of RCAs has been shown to improve durability properties. The accelerated carbonation of RCAs effectively reduces their porosity, leading to increased carbonation resistance in the resulting concrete [79]. For example, carbonated RCAs (cRCAs) have demonstrated reduced carbonation depth compared to untreated RCAs due to the clogging of micro-pores by calcium carbonate deposits formed during carbonation [80].

The variability of RCA characteristics presents challenges for maintaining consistent carbonation resistance. In repeated recycling cycles, RCAs demonstrate progressively poorer resistance to carbonation, as shown in studies on second- and third-generation RCAs [78,81]. The loss of quality in RCAs with each recycling cycle leads to increased porosity, and under freeze–thaw conditions, carbonation depth can increase further, making the concrete more vulnerable to environmental degradation.

In addition to mechanical improvements, accelerated carbonation can offer environmental benefits by sequestering CO_2 within the concrete matrix. The FastCarb project [82] has demonstrated the feasibility of storing significant amounts of CO_2 within RCAs through accelerated carbonation processes. This approach not only improves the quality of RCAs, but also contributes to CO_2 mitigation, a crucial factor in reducing the carbon footprint of concrete production. Results from large-scale industrial trials show that up to 50 kg of CO_2 per ton of RCAs can be captured through carbonation, significantly enhancing the sustainability of RCA-based concrete.

Finally, the impact of environmental conditions on carbonation treatment must be considered. Gholizadeh-Vayghan et al. (2020) [83] found that optimal carbonation conditions, such as controlled moisture levels and relative humidity, are crucial to achieving significant reductions in porosity and enhancing the mechanical and durability properties of RCAs. However, suboptimal carbonation conditions can lead to limited improvements in durability, indicating the importance of precise control over the carbonation process to maximize the benefits for RCA concrete.

4.2. Chloride Attack

Chloride ion attack is a critical durability concern for concrete, particularly in marine environments and regions exposed to de-icing salts. Wang et al. (2024) [84] found a relationship between the chloride diffusion coefficient (a measure of how easily chloride ions penetrate concrete) and the recycled aggregate (RA) replacement ratio. The trend shows a generally linear increase in the chloride diffusion coefficient as the RA content increases, indicating that a higher proportion of recycled aggregates tends to facilitate chloride ion penetration into the concrete. This is primarily because recycled aggregates contain adhered mortar and ITZs that have higher porosity compared to natural aggregates, making the concrete more permeable. The slope of the increase is steeper in cases where the RA replacement ratio is closer to 100%, showing a more significant impact on chloride penetration at higher RA contents. This linear relationship is essential for understanding the durability concerns in recycled aggregate concrete (RAC), as higher chloride ion penetration could accelerate the corrosion of steel reinforcement in such structures, especially in aggressive environments like coastal areas or where de-icing salts are used. This research underscores the importance of treatments and modifications to recycled aggregates to mitigate this increased permeability [84].

The use of RCAs in concrete has been increasingly promoted for sustainability; however, their vulnerability to chloride penetration due to higher porosity compared to natural aggregates poses challenges for long-term durability. Research shows that chloride ions penetrate more easily into RCA concrete, leading to reinforcement corrosion and a decrease in structural integrity [78,85].

To mitigate chloride ion penetration, carbonation treatments have emerged as an effective solution. Jiang et al. (2024) [86] showed that carbonated recycled coarse aggregate concrete (CRCAC) exhibited significantly reduced chloride penetration depths compared to untreated RCA concrete. The carbonated aggregates help to clog micro-pores, slowing chloride ingress and providing better protection for reinforcement in chloride-rich environments. In marine infrastructure, this treatment has been shown to extend the structure's durability life by up to 28%.

Adding supplementary cementitious materials such as fly ash, silica powder, and ground granulated blast furnace slag (GGBS) also enhances the chloride resistance of RCA-based concrete. Studies like the one by Pandey and Rajhans (2023) [85] demonstrate that incorporating these materials in quaternary blends significantly reduces chloride permeability. Rapid Chloride Permeability Test (RCPT) results showed that quaternary blends containing RCAs exhibited lower chloride ion ingress, improving the durability of the concrete in aggressive environments.

Other innovative methods for chloride resistance include RCA surface treatments. Sasanipour and Aslani (2020) [32] investigated silica fume slurry coatings on RCAs and observed enhanced resistance to chloride ion penetration. The treated RCA mixes showed reduced charge passed during RCPT, indicating less chloride migration through the concrete matrix. Such treatments also improved the concrete's overall strength and electrical resistivity, further contributing to better durability.

Incorporating fibers into RCA-based concrete offers another avenue for improving chloride resistance. Research by Lu et al. (2020) [87] demonstrated that adding basalt fibers and polypropylene fibers enhances the dynamic properties and chloride resistance of RCA concrete. The fibers contribute to a more compact microstructure, reducing chloride penetration and improving durability under cyclic loading and environmental exposure.

Chloride transport models play a key role in predicting the long-term durability of RCA concrete in chloride environments. Chen et al. (2020) [78] developed models based on chloride ion diffusion through RCA concrete, highlighting the importance of assessing the long-term chloride ingress behavior. These models aid in designing mixes with optimal resistance to chloride attack, especially in infrastructure exposed to aggressive environments.

The use of calcined layered double hydroxides (LDOs) to capture chloride ions is another promising technique. Gao et al. (2024) [88] found that LDOs could significantly reduce chloride ion diffusion in RCA concrete. The LDOs function by adsorbing chloride ions, preventing them from migrating through the concrete matrix. This innovative approach enhances both mechanical performance and durability, offering a sustainable solution to chloride-induced degradation.

While these advancements improve chloride resistance in RCA concrete, the quality of RCAs remains a challenge. The porosity of RCAs, which arises from the attached mortar, is a primary pathway for chloride ions to penetrate. Strategies such as carbonation treatment, surface coatings, and the incorporation of supplementary materials offer substantial improvements, but further research is required to optimize these methods for widespread use.

4.3. Oxygen Permeability

Oxygen permeability is a crucial parameter in assessing the durability of RCAs, as it significantly impacts the long-term performance of structures by allowing the ingress of harmful agents. Various studies have evaluated the effects of RCAs on oxygen permeability, highlighting that due to the presence of old adhered mortar, RCA-based concrete tends to have higher porosity and permeability compared to natural aggregate (NA) concrete. This increased porosity can reduce the resistance to oxygen ingress, leading to accelerated carbonation and reinforcement corrosion [89,90]. However, methods such as partial RCA replacement and the addition of supplementary cementitious materials can mitigate this issue by refining the microstructure and reducing pore connectivity [91].

The porosity of RCAs is a significant contributing factor to their higher oxygen permeability. As RCAs are composed of both old mortar and aggregate, the attached mortar increases the interconnected pore structure, facilitating the movement of oxygen and other gases [92]. Kapoor et al. (2018) [93] reported that concrete containing RCAs had higher oxygen permeability coefficients than concrete with natural aggregates, correlating this with the higher porosity of RCAs. The residual mortar in RCAs can create weak zones in the concrete, which act as pathways for oxygen diffusion.

A comparison of the oxygen permeability between RCAs and natural aggregate concretes conducted by Mahmood et al. (2022) [94] revealed that the permeability of RCA concrete is typically higher, especially at higher levels of RCA replacement. At 50% RCA replacement, oxygen permeability increases by nearly 30%, indicating a strong dependence on the quantity of RCAs used. Similar findings were observed by Ismail et al. (2017) [91], who noted that higher RCA content correlates with greater oxygen permeability due to the increased volume of permeable voids within the RCA concrete matrix.

Thomas et al. (2013) illustrated the relationship between compressive strength and oxygen permeability of concrete with varying percentages of recycled aggregate replacement (0%, 20%, 50%, and 100%), as shown in Figure 7 [95]. As the compressive strength increases, oxygen permeability decreases exponentially across all replacement levels, indicating that denser concrete resists gas penetration more effectively. The exponential models fit the data well, as indicated by high R^2 values (ranging from 0.89 to 0.99), suggesting strong predictive accuracy. The slope of the curves shows that higher recycled aggregate content slightly reduces the rate of permeability decrease.

Various techniques have been proposed to mitigate the high permeability of RCA concrete. Studies by Safiuddin et al. (2013) [96] and Zhan et al. (2019) [97] suggest that the use of supplementary cementitious materials (SCMs) such as fly ash and silica fume can significantly reduce the oxygen permeability of RCA concrete. SCMs work by refining the pore structure and reducing the permeability of the cement matrix. For instance, Paul et al. (2013) [90] found that the use of 30% fly ash in RCA concrete reduced the oxygen permeability by up to 40%.

In addition to SCMs, pretreatment of RCAs has also shown promise in improving their performance with respect to oxygen permeability. Cantero et al. (2021) [92] investigated the use of recycled cement fines to coat RCA particles, thereby reducing their porosity and enhancing the overall durability of the concrete. Their results demonstrated a marked reduction in oxygen permeability, suggesting that surface treatment of RCAs could be an effective strategy for reducing permeability in concrete applications.

The influence of oxygen permeability is further emphasized in RCA concrete under different curing conditions. Studies show that untreated RCA concrete exhibits higher oxygen permeability when exposed to open-air curing, compared to water curing. This permeability difference is due to the higher pore volume and the weaker ITZ in RCA concrete. However, treating RCAs with carbonation or surface pretreatment methods like silica fume slurry can significantly reduce oxygen permeability, improving durability [98].

Research by Xuan et al. (2017) [99] found that carbonated RCAs substantially reduce oxygen and gas permeability, enhancing the overall impermeability of the concrete matrix. These findings suggest that carbonation curing of RCAs enhances the durability of concrete by filling micro-cracks and reducing pore volume, thereby impeding the transport of oxygen and other aggressive agents into the concrete.

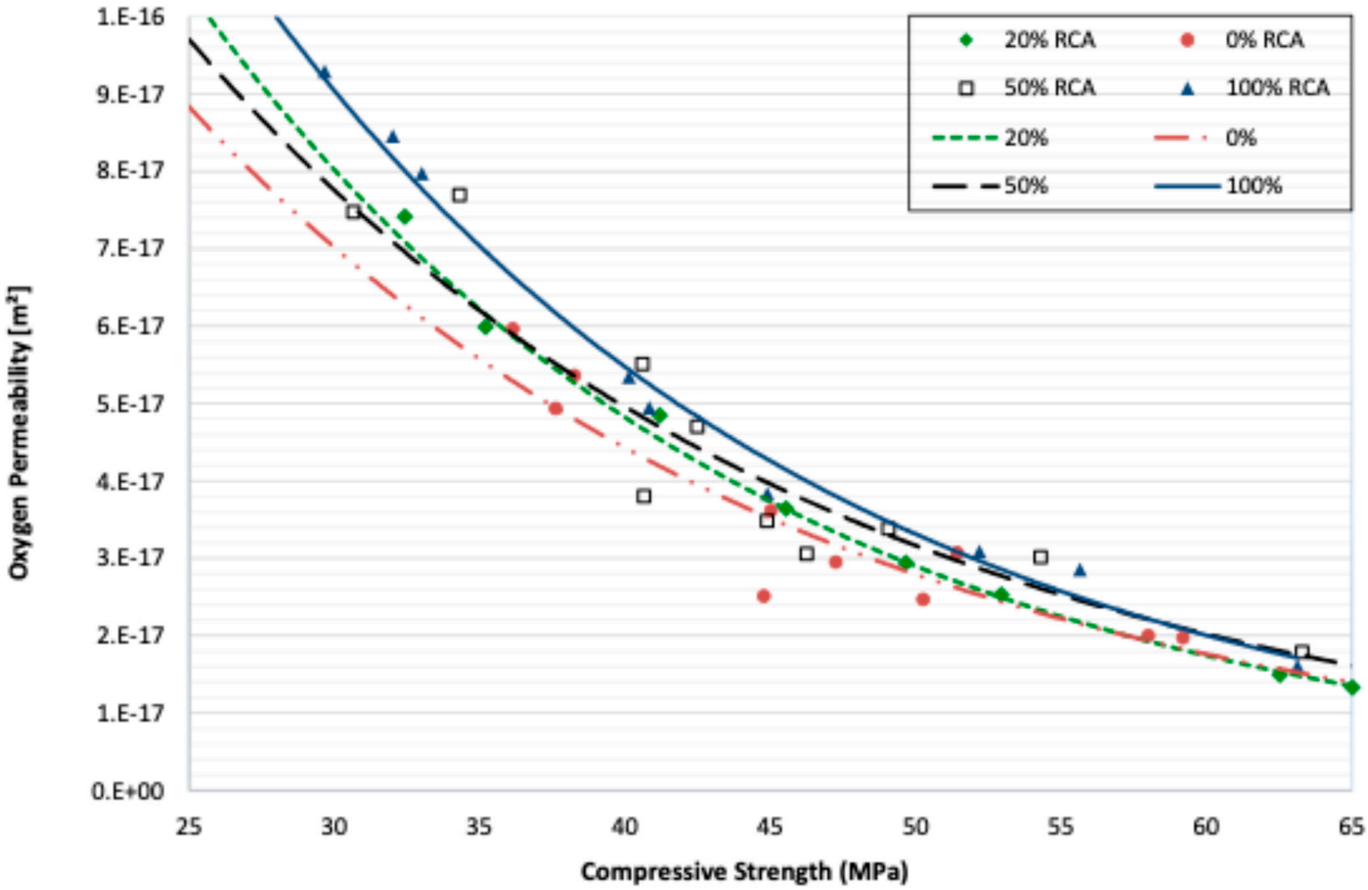

Figure 7. Relationship between oxygen permeability and compressive strength of recycled aggregate concrete (RAC) [95].

Finally, the type and size of RCA particles used in concrete also influence oxygen permeability. Fine RCAs tend to contribute more significantly to permeability than coarse RCAs due to the higher specific surface area and greater volume of attached mortar [100]. Moreover, selective crushing methods that reduce the amount of adhered mortar on RCAs have been shown to lower permeability, as demonstrated in a study by Kubissa et al. (2016) [101].

5. CO_2 Capturing in RCAs

The integration of RCAs in construction is gaining attention for its sustainability and potential for CO_2 capture through carbonation. This section explores recent scientific insights on CO_2 capture mechanisms in RCAs, their efficiency, and their impact on the environment and material properties.

RCAs capture CO_2 through a process called carbonation, where CO_2 reacts with calcium compounds in the concrete to form stable calcium carbonates. This reaction primarily occurs in porous areas of RCAs, which increases their potential for carbon sequestration [102]. Additionally, accelerated carbonation processes enhance the CO_2 uptake capacity by increasing reaction rates [103].

RCAs can store significant amounts of CO_2, particularly when subjected to accelerated carbonation methods. Braymand et al. (2024) [104] employed a calcimetric method to measure CO_2 capture rates, highlighting that RCAs sequestered 15–20% more CO_2 compared to natural aggregates under similar conditions. Additionally, Jiang et al. (2025) [105] showed that optimized aggregate grading and particle size distribution further enhanced CO_2 capture efficiency.

A life cycle assessment conducted by Ang et al. (2024) [106] demonstrated that using RCAs with CO_2 capture reduced the carbon footprint of concrete production by 25–30% over the entire cradle-to-gate cycle. Similarly, Goh et al. (2025) [107] highlighted the techno-economic feasibility of mineralizing CO_2 within RCAs, achieving both carbon capture and material performance enhancement. Over a 100-year life cycle, RCAs can absorb 20–25% of the CO_2 emitted during their production phase. This long-term sequestration potential is critical in reducing the environmental impact of concrete, as the cumulative CO_2 uptake throughout the life cycle can significantly offset the emissions associated with its production. Pade and Guimaraes (2007) further illustrated that the carbonation process in concrete can contribute to a reduction in net CO_2 emissions over time, with environmental benefits intensifying in regions where CO_2 is directly captured from industrial sources and mineralized into construction materials [108].

Carbonation not only captures CO_2, but also strengthens the RCAs by densifying their microstructure. Zhu et al. (2024) [109] analyzed the structural properties and found a 17.6% reduction in porosity, which improved compressive strength and reduced water absorption. However, carbonation reduces the alkalinity of concrete (see [103]), posing a risk for steel reinforcement corrosion by lowering the pH and diminishing the passive protection provided to rebars.

Several innovative carbonation techniques have been proposed to enhance CO_2 capture efficiency. Tham et al. (2024) [110] developed an integrated CO_2 capture and mineralization process with lower energy consumption, which reduced operational costs while maintaining high capture efficiency. Additionally, Chong et al. (2024) [111] introduced an aqueous CO_2 sequestration method suitable for ready-mix concrete containing RCAs, demonstrating its industrial scalability. Despite promising results, some challenges remain. Jiang et al. (2025) [105] pointed out that the efficiency of CO_2 capture in RCAs decreases over time as the surface becomes saturated with carbonates.

Future research should focus on optimizing carbonation conditions, such as temperature, pressure, and humidity, to maximize CO_2 uptake. Additionally, combining RCA carbonation with other sustainable construction practices, such as using cement substitutes, can further reduce the carbon footprint [112]. Life cycle assessments should continue to guide the development of eco-friendly construction practices [106].

6. Life Cycle Assessment (LCA) in RCAs

The application of life cycle assessment (LCA) in RCAs has become critical in evaluating their environmental, economic, and sustainability aspects. With increasing efforts to adopt sustainable construction materials, understanding the full life cycle impact of RCAs is essential for optimizing their use while minimizing their carbon footprint. Recent studies have provided valuable insights into the benefits, challenges, and comparative assessments of RCAs versus natural aggregates, emphasizing the importance of a holistic LCA approach in construction.

One of the fundamental advantages of RCAs, as highlighted by Ang et al. (2024) [106], is their reduction in carbon footprint compared to natural aggregates. Their study demonstrated that incorporating RCAs in concrete mixtures can reduce CO_2 emissions by 30–40%, depending on factors such as processing techniques and transportation distances. Similarly, Huang and Wang (2024) [113] assessed geopolymer concrete incorporating RCAs and found a 25% lower global warming potential (GWP) compared to conventional concrete, further validating their sustainability potential.

Another key component in the RCA life cycle is RCA energy and water consumption. The crushing and processing of RCAs require less energy compared to virgin aggregates, making RCAs a more energy-efficient option. A study conducted by Huang et al. (2025) [114] on LC3 concrete (limestone calcined clay cement) with RCAs found that its embodied energy was 18% lower than traditional concrete, primarily due to lower heat requirements in processing.

The economic viability of RCAs is also an important aspect of LCA studies. While RCAs offer significant environmental advantages, their cost-effectiveness depends on transportation distances, processing costs, and mix design optimizations. Research by Manan et al. (2025) [115] found that transportation distance was the most significant cost factor in RCA utilization. However, when sourced locally, RCAs could be 15–20% more cost-effective than virgin aggregates, making them a viable solution for sustainable construction projects. On the other hand, Ma et al. (2025) [116] conducted an LCA comparing RCAs blended with Supplementary Cementitious Materials (SCMs) and found that CO_2 emissions were reduced by 40–50%, further strengthening the case for RCAs in sustainable concrete production.

Future RCA life cycle assessments and other research should focus on digital modeling and optimization tools that allow for more accurate impact predictions. Pradhan et al. (2024) [117] proposed the use of digital twin models and machine learning algorithms to simulate long-term environmental benefits of RCA-based structures, providing better data-driven decisions for sustainability. With continued advancements in carbon capture, material optimization, and LCA standardization, RCAs are set to play an even more critical role in reducing the construction sector's environmental impact.

In conclusion, LCA studies confirm that RCAs present a viable, sustainable alternative to natural aggregates, offering substantial reductions in carbon emissions, energy use, and environmental degradation. Although economic and regional barriers still exist, ongoing research and policy support can further improve their adoption. As industries continue to seek greener alternatives, RCAs, when optimized through LCA frameworks, offer a promising path toward truly sustainable construction.

7. Conclusions

The use of RCAs derived from CDW represents a significant step toward sustainable concrete production. This review highlights the positive environmental impacts of using RCAs, including the reduction of landfill waste, conservation of natural resources, and lowering of energy consumption. However, the mechanical and durability properties of concrete made with RCAs differ from those made with natural aggregates, primarily due to the variability and quality of RCAs, particularly the presence of adhered mortar, contaminants, and higher porosity. These factors lead to lower compressive and tensile strengths, increased water absorption, and reduced durability against aggressive environments such as chloride ion exposure and carbonation. Nevertheless, numerous studies have shown that with the implementation of appropriate pretreatment methods, including mechanical, chemical, and thermal techniques, the performance of RCAs can be significantly improved. These treatments help reduce the residual mortar content and enhance the bonding between the RCAs and cement paste, thereby improving the strength, modulus of elasticity, and overall durability of RCA concrete.

Additionally, advancements in mix design, such as the inclusion of supplementary cementitious materials (SCMs) like fly ash and silica fume, have proven effective in mitigating the limitations of RCAs. These materials not only enhance the mechanical properties of RCA concrete, but also improve its resistance to environmental degradation by refining the concrete's microstructure. Extended curing times have further been identified as crucial in allowing RCA concrete to develop its full strength potential. Despite the initial reduction in strength and durability, with proper treatments and optimization, RCAs can be a viable alternative to natural aggregates in structural applications, aligning with global goals of sustainability in construction.

Furthermore, the integration of RCAs in construction offers substantial benefits through carbon dioxide (CO_2) capture, providing significant environmental advantages by sequestering carbon within the concrete matrix. Recent research demonstrates that accelerated carbonation processes can significantly increase the CO_2 capture capacity of RCAs, thus reducing the carbon footprint of concrete production. Innovative carbonation techniques, such as optimized aggregate grading and integrated carbonation processes, enhance RCA quality while simultaneously contributing to environmental sustainability goals. However, careful control and optimization of carbonation processes are crucial for balancing improved material properties against potential durability risks, particularly reinforcement corrosion.

Life cycle assessment (LCA) studies underscore the substantial environmental and economic advantages of utilizing RCAs. Incorporating RCAs into concrete significantly reduces CO_2 emissions, energy use, and material costs compared to natural aggregates, particularly when transportation distances are minimized and processing technologies are optimized. Advanced LCA methodologies and digital modeling can further refine these benefits by accurately predicting the long-term environmental impacts of RCA use, thus facilitating informed decision-making in sustainable construction projects. Continued development in digital modeling, predictive analytics, and economic evaluations through comprehensive LCA frameworks will further reinforce the role of RCAs as a mainstream, sustainable construction material.

While the current findings demonstrate significant promise, the widespread adoption of RCAs in construction requires overcoming several challenges. Future research should focus on developing standardized treatment protocols and optimizing recycling processes to ensure consistent quality in RCAs. Additionally, more long-term performance studies under various environmental conditions are needed to improve confidence in the reliability of RCAs. Integrating RCAs with advanced technologies, such as digital modeling for predictive performance analysis and automated quality control systems, could further enhance their applicability.

Future research should focus on exploring the behavior of RCA concrete under cyclic loading conditions, as this is crucial for assessing the material's performance in dynamic and seismic applications. Researchers should investigate the fatigue, deformation, and long-term durability of RCA concrete under repeated stress to better understand its suitability for structural applications subject to cyclic loading. These efforts will provide valuable insights into optimizing RCA concrete for a broader range of real-world engineering challenges.

By addressing these research gaps, RCAs can transition from being a sustainable alternative to becoming a mainstream solution for the construction industry. This transformation will not only support the reduction of the sector's environmental footprint, but also advance global efforts toward a circular economy in construction.

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

Funding: The authors gratefully acknowledge the financial support provided by the PRIN 2022 project—SARCOS: Steel and Recycled Concrete Slab (Prot. 2022WWN3TC).

Data Availability Statement: Data are available upon request.

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

References

1. Barbhuiya, S.; Bhusan Das, B.; Kanavaris, F. Biochar-Concrete: A Comprehensive Review of Properties, Production and Sustainability. *Case Stud. Constr. Mater.* **2024**, *20*, e02859. [CrossRef]
2. Shaban, W.M.; Yang, J.; Su, H.; Mo, K.H.; Li, L.; Xie, J. Quality Improvement Techniques for Recycled Concrete Aggregate: A Review. *J. Adv. Concr. Technol.* **2019**, *17*, 151–167. [CrossRef]
3. Global Aggregates Growth Examined by GAIN Convenor Jim O'Brien. Available online: https://www.aggbusiness.com/feature/global-aggregates-growth-examined-gain-convenor-jim-obrien (accessed on 12 November 2024).
4. Tam, V.W.Y.; Soomro, M.; Evangelista, A.C.J. A Review of Recycled Aggregate in Concrete Applications (2000–2017). *Constr. Build. Mater.* **2018**, *172*, 272–292. [CrossRef]
5. Tam, V.W.Y.; Soomro, M.; Evangelista, A.C.J. Quality Improvement of Recycled Concrete Aggregate by Removal of Residual Mortar: A Comprehensive Review of Approaches Adopted. *Constr. Build. Mater.* **2021**, *288*, 123066. [CrossRef]
6. Marie, I.; Quiasrawi, H. Closed-Loop Recycling of Recycled Concrete Aggregates. *J. Clean. Prod.* **2012**, *37*, 243–248. [CrossRef]
7. Barbhuiya, S.; Kanavaris, F.; Das, B.B.; Idrees, M. Decarbonising Cement and Concrete Production: Strategies, Challenges and Pathways for Sustainable Development. *J. Build. Eng.* **2024**, *86*, 108861. [CrossRef]
8. Gebremariam, H.G.; Taye, S.; Tarekegn, A.G. Parent Concrete Strength Effects on the Quality of Recycled Aggregate Concrete: A Review. *Heliyon* **2024**, *10*, e26212. [CrossRef]
9. Muhammad, F.; Harun, M.; Ahmed, A.; Kabir, N.; Khalid, H.R.; Hanif, A. Influence of Bonded Mortar on Recycled Aggregate Concrete Properties: A Review. *Constr. Build. Mater.* **2024**, *432*, 136564. [CrossRef]
10. Stochino, F.; Zucca, M.; Simoncelli, M.; Alibeigibeni, A.; Concu, G.; Valdes, M.; Pisani, M.A.; Bernuzzi, C.; Saccone, M.; Pani, L. Experimental Investigation on the Structural Performance of Steel-Concrete Composite Slabs Incorporating Recycled Aggregates from Construction and Demolition Waste. In *Proceedings of the 11th International Conference on Behaviour of Steel Structures in Seismic Areas, Salerno, Italy, 8–10 July 2024*; Mazzolani, F.M., Piluso, V., Nastri, E., Formisano, A., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 108–117.
11. Fanijo, E.O.; Kolawole, J.T.; Babafemi, A.J.; Liu, J. A Comprehensive Review on the Use of Recycled Concrete Aggregate for Pavement Construction: Properties, Performance, and Sustainability. *Clean. Mater.* **2023**, *9*, 100199. [CrossRef]
12. Mazhoud, B.; Sedran, T.; Cazacliu, B.; Cothenet, A.; Torrenti, J.-M. Influence of Residual Mortar Volume on the Properties of Recycled Concrete Aggregates. *J. Build. Eng.* **2022**, *57*, 104945. [CrossRef]
13. Scopus—Document Search Results | Signed In. Available online: https://www.scopus.com/ (accessed on 5 February 2025).
14. Ossa, A.; García, J.L.; Botero, E. Use of Recycled Construction and Demolition Waste (CDW) Aggregates: A Sustainable Alternative for the Pavement Construction Industry. *J. Clean. Prod.* **2016**, *135*, 379–386. [CrossRef]
15. Papamichael, I.; Voukkali, I.; Loizia, P.; Zorpas, A.A. Construction and Demolition Waste Framework of Circular Economy: A Mini Review. *Waste Manag. Res.* **2023**, *41*, 1728–1740. [CrossRef] [PubMed]
16. Kim, J. Influence of Quality of Recycled Aggregates on the Mechanical Properties of Recycled Aggregate Concretes: An Overview. *Constr. Build. Mater.* **2022**, *328*, 127071. [CrossRef]
17. Paranhos, R.S.; Cazacliu, B.G.; Sampaio, C.H.; Petter, C.O.; Neto, R.O.; Huchet, F. A Sorting Method to Value Recycled Concrete. *J. Clean. Prod.* **2016**, *112*, 2249–2258. [CrossRef]
18. Kou, S.-C.; Poon, C.-S. Long-Term Mechanical and Durability Properties of Recycled Aggregate Concrete Prepared with the Incorporation of Fly Ash. *Cem. Concr. Compos.* **2013**, *37*, 12–19. [CrossRef]
19. Ferrández, D.; Saiz, P.; Zaragoza-Benzal, A.; Zúñiga-Vicente, J.A. Towards a More Sustainable Environmentally Production System for the Treatment of Recycled Aggregates in the Construction Industry: An Experimental Study. *Heliyon* **2023**, *9*, e16641. [CrossRef]
20. Wagih, A.M.; El-Karmoty, H.Z.; Ebid, M.; Okba, S.H. Recycled Construction and Demolition Concrete Waste as Aggregate for Structural Concrete. *HBRC J.* **2013**, *9*, 193–200. [CrossRef]
21. Wang, Z.; Xie, W.; Liu, J. Regional Differences and Driving Factors of Construction and Demolition Waste Generation in China. *Eng. Constr. Archit. Manag.* **2021**, *29*, 2300–2327. [CrossRef]
22. Ismail, S.; Ramli, M. Engineering Properties of Treated Recycled Concrete Aggregate (RCA) for Structural Applications. *Constr. Build. Mater.* **2013**, *44*, 464–476. [CrossRef]
23. Feng, C.; Cui, B.; Wang, J.; Guo, H.; Zhang, W.; Zhu, J. Changing the Soaking Method of Microbially Induced Calcium Carbonate Precipitation Technology to Improve the Reinforcement Effect of Recycled Concrete Aggregates. *J. Build. Eng.* **2023**, *68*, 106128. [CrossRef]

24. Pani, L.; Francesconi, L.; Rombi, J.; Mistretta, F.; Sassu, M.; Stochino, F. Effect of Parent Concrete on the Performance of Recycled Aggregate Concrete. *Sustainability* **2020**, *12*, 9399. [CrossRef]
25. Zhang, L.W.; Sojobi, A.O.; Kodur, V.K.R.; Liew, K.M. Effective Utilization and Recycling of Mixed Recycled Aggregates for a Greener Environment. *J. Clean. Prod.* **2019**, *236*, 117600. [CrossRef]
26. Makul, N.; Fediuk, R.; Amran, M.; Zeyad, A.M.; de Azevedo, A.R.G.; Klyuev, S.; Vatin, N.; Karelina, M. Capacity to Develop Recycled Aggregate Concrete in South East Asia. *Buildings* **2021**, *11*, 234. [CrossRef]
27. Xu, X.; Luo, Y.; Sreeram, A.; Wu, Q.; Chen, G.; Cheng, S.; Chen, Z.; Chen, X. Potential Use of Recycled Concrete Aggregate (RCA) for Sustainable Asphalt Pavements of the Future: A State-of-the-Art Review. *J. Clean. Prod.* **2022**, *344*, 130893. [CrossRef]
28. Zheng, Y.; Zhang, Y.; Zhang, P. Methods for Improving the Durability of Recycled Aggregate Concrete: A Review. *J. Mater. Res. Technol.* **2021**, *15*, 6367–6386. [CrossRef]
29. Ouyang, K.; Shi, C.; Chu, H.; Guo, H.; Song, B.; Ding, Y.; Guan, X.; Zhu, J.; Zhang, H.; Wang, Y.; et al. An Overview on the Efficiency of Different Pretreatment Techniques for Recycled Concrete Aggregate. *J. Clean. Prod.* **2020**, *263*, 121264. [CrossRef]
30. Forero, J.A.; Brito, J.d.; Evangelista, L.; Pereira, C. Improvement of the Quality of Recycled Concrete Aggregate Subjected to Chemical Treatments: A Review. *Materials* **2022**, *15*, 2740. [CrossRef] [PubMed]
31. Mistri, A.; Bhattacharyya, S.K.; Dhami, N.; Mukherjee, A.; Barai, S.V. A Review on Different Treatment Methods for Enhancing the Properties of Recycled Aggregates for Sustainable Construction Materials. *Constr. Build. Mater.* **2020**, *233*, 117894. [CrossRef]
32. Sasanipour, H.; Aslani, F. Durability Assessment of Concrete Containing Surface Pretreated Coarse Recycled Concrete Aggregates. *Constr. Build. Mater.* **2020**, *264*, 120203. [CrossRef]
33. Silva, R.V.; de Brito, J.; Dhir, R.K. The Influence of the Use of Recycled Aggregates on the Compressive Strength of Concrete: A Review. *Eur. J. Environ. Civ. Eng.* **2015**, *19*, 825–849. [CrossRef]
34. Evangelista, L.; de Brito, J. Mechanical Behaviour of Concrete Made with Fine Recycled Concrete Aggregates. *Cem. Concr. Compos.* **2007**, *29*, 397–401. [CrossRef]
35. Fan, C.-C.; Huang, R.; Hwang, H.; Chao, S.-J. Properties of Concrete Incorporating Fine Recycled Aggregates from Crushed Concrete Wastes. *Constr. Build. Mater.* **2016**, *112*, 708–715. [CrossRef]
36. Evangelista, L.; de Brito, J. Durability Performance of Concrete Made with Fine Recycled Concrete Aggregates. *Cem. Concr. Compos.* **2010**, *32*, 9–14. [CrossRef]
37. Yaprak, H.; Aruntaş, H.; Demir, I.; Şimşek, O.; Durmuş, G. Effects of the Fine Recycled Concrete Aggregates on the Concrete Properties. *Int. J. Phys. Sci.* **2011**, 2455–2461.
38. Geng, J.; Sun, J. Characteristics of the Carbonation Resistance of Recycled Fine Aggregate Concrete. *Constr. Build. Mater.* **2013**, *49*, 814–820. [CrossRef]
39. Cartuxo, F.; de Brito, J.; Evangelista, L.; Jiménez, J.R.; Ledesma, E.F. Rheological Behaviour of Concrete Made with Fine Recycled Concrete Aggregates—Influence of the Superplasticizer. *Constr. Build. Mater.* **2015**, *89*, 36–47. [CrossRef]
40. Cartuxo, F.; De Brito, J.; Evangelista, L.; Jiménez, J.R.; Ledesma, E.F. Increased Durability of Concrete Made with Fine Recycled Concrete Aggregates Using Superplasticizers. *Materials* **2016**, *9*, 98. [CrossRef]
41. Kumar, R.; Gurram, S.C.B.; Minocha, A.K. Influence of Recycled Fine Aggregate on Microstructure and Hardened Properties of Concrete. *Mag. Concr. Res.* **2017**, *69*, 1288–1295. [CrossRef]
42. Khatib, J.M. Properties of Concrete Incorporating Fine Recycled Aggregate. *Cem. Concr. Res.* **2005**, *35*, 763–769. [CrossRef]
43. Pedro, D.; de Brito, J.; Evangelista, L. Structural Concrete with Simultaneous Incorporation of Fine and Coarse Recycled Concrete Aggregates: Mechanical, Durability and Long-Term Properties. *Constr. Build. Mater.* **2017**, *154*, 294–309. [CrossRef]
44. Guo, Z.; Chen, C.; Lehman, D.E.; Xiao, W.; Zheng, S.; Fan, B. Mechanical and Durability Behaviours of Concrete Made with Recycled Coarse and Fine Aggregates. *Eur. J. Environ. Civ. Eng.* **2020**, *24*, 171–189. [CrossRef]
45. Cabral, A.E.B.; Schalch, V.; Molin, D.C.C.D.; Ribeiro, J.L.D. Mechanical Properties Modeling of Recycled Aggregate Concrete. *Constr. Build. Mater.* **2010**, *24*, 421–430. [CrossRef]
46. Silva, R.V.; de Brito, J.; Dhir, R.K. Establishing a Relationship between Modulus of Elasticity and Compressive Strength of Recycled Aggregate Concrete. *J. Clean. Prod.* **2016**, *112*, 2171–2186. [CrossRef]
47. Kurad, R.; Silvestre, J.D.; De Brito, J.; Ahmed, H. Effect of Incorporation of High Volume of Recycled Concrete Aggregates and Fly Ash on the Strength and Global Warming Potential of Concrete. *J. Clean. Prod.* **2017**, *166*, 485–502. [CrossRef]
48. Wang, C.; Xiao, J. Evaluation of the Stress-Strain Behavior of Confined Recycled Aggregate Concrete under Monotonic Dynamic Loadings. *Cem. Concr. Compos.* **2018**, *87*, 149–163. [CrossRef]
49. Silva, R.V.; de Brito, J.; Dhir, R.K. Tensile Strength Behaviour of Recycled Aggregate Concrete. *Constr. Build. Mater.* **2015**, *83*, 108–118. [CrossRef]
50. Yang, X.; Liu, Y.; Liang, J.; Meng, Y.; Rong, H.; Li, D.; Chen, Y.; Lv, J.; Jiang, Y.; Liu, Y. Straightening Methods for RCA and RAC—A Review. *Cem. Concr. Compos.* **2023**, *141*, 105145. [CrossRef]
51. Wang, R.; Yu, N.; Li, Y. Methods for Improving the Microstructure of Recycled Concrete Aggregate: A Review. *Constr. Build. Mater.* **2020**, *242*, 118164. [CrossRef]

52. Wang, J.; Che, Z.; Zhang, K.; Fan, Y.; Niu, D.; Guan, X. Performance of Recycled Aggregate Concrete with Supplementary Cementitious Materials (Fly Ash, GBFS, Silica Fume, and Metakaolin): Mechanical Properties, Pore Structure, and Water Absorption. *Constr. Build. Mater.* **2023**, *368*, 130455. [CrossRef]
53. Dimitriou, G.; Savva, P.; Petrou, M.F. Enhancing Mechanical and Durability Properties of Recycled Aggregate Concrete. *Constr. Build. Mater.* **2018**, *158*, 228–235. [CrossRef]
54. Poon, C.S.; Shui, Z.H.; Lam, L. Effect of Microstructure of ITZ on Compressive Strength of Concrete Prepared with Recycled Aggregates. *Constr. Build. Mater.* **2004**, *18*, 461–468. [CrossRef]
55. Silva, R.V.; de Brito, J.; Dhir, R.K. Properties and Composition of Recycled Aggregates from Construction and Demolition Waste Suitable for Concrete Production. *Constr. Build. Mater.* **2014**, *65*, 201–217. [CrossRef]
56. Purushothaman, R.; Amirthavalli, R.R.; Karan, L. Influence of Treatment Methods on the Strength and Performance Characteristics of Recycled Aggregate Concrete. *J. Mater. Civ. Eng.* **2015**, *27*, 04014168. [CrossRef]
57. Wang, J.; Vandevyvere, B.; Vanhessche, S.; Schoon, J.; Boon, N.; De Belie, N. Microbial Carbonate Precipitation for the Improvement of Quality of Recycled Aggregates. *J. Clean. Prod.* **2017**, *156*, 355–366. [CrossRef]
58. Kazmi, S.M.S.; Munir, M.J.; Wu, Y.-F.; Patnaikuni, I.; Zhou, Y.; Xing, F. Influence of Different Treatment Methods on the Mechanical Behavior of Recycled Aggregate Concrete: A Comparative Study. *Cem. Concr. Compos.* **2019**, *104*, 103398. [CrossRef]
59. Etxeberria, M.; Vázquez, E.; Marí, A.; Barra, M. Influence of Amount of Recycled Coarse Aggregates and Production Process on Properties of Recycled Aggregate Concrete. *Cem. Concr. Res.* **2007**, *37*, 735–742. [CrossRef]
60. Tam, V.W.Y.; Gao, X.F.; Tam, C.M. Microstructural Analysis of Recycled Aggregate Concrete Produced from Two-Stage Mixing Approach. *Cem. Concr. Res.* **2005**, *35*, 1195–1203. [CrossRef]
61. Gómez-Soberón, J.M.V. Porosity of Recycled Concrete with Substitution of Recycled Concrete Aggregate: An Experimental Study. *Cem. Concr. Res.* **2002**, *32*, 1301–1311. [CrossRef]
62. Zaharieva, R.; Buyle-Bodin, F.; Skoczylas, F.; Wirquin, E. Assessment of the Surface Permeation Properties of Recycled Aggregate Concrete. *Cem. Concr. Compos.* **2003**, *25*, 223–232. [CrossRef]
63. Ashteyat, A.M.; Al-Tarawneh, R.; Shatarat, N. Bond Strength between Steel and Recycled Asphalt Pavement Aggregate and Recycled Concrete Aggregate. *Civ. Eng. Archit.* **2024**, *12*, 1190–1203. [CrossRef]
64. Abushanab, A.; Alnahhal, W. Bond Strength of Corroded Reinforced Recycled Aggregate Concrete with Treated Wastewater and Fly Ash. *J. Build. Eng.* **2023**, *79*, 107778. [CrossRef]
65. Yusuf, M.; Sarhat, S.; Hajiloo, H.; Green, M.F. Bond Strength between Steel Reinforcement and RCA Concrete during and after Exposure to Elevated Temperatures. *Constr. Build. Mater.* **2022**, *345*, 128362. [CrossRef]
66. Zou, W.; Liang, J.; Liu, D.; Zhang, G. Bond Behavior between Steel Rebar and RCA Concrete after Exposure to Elevated Temperatures. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 5230295. [CrossRef]
67. Alhawat, M.; Ashour, A. Bond Strength between Corroded Steel Reinforcement and Recycled Aggregate Concrete. *Structures* **2019**, *19*, 369–385. [CrossRef]
68. Namarak, C.; Tangchirapat, W.; Jaturapitakkul, C. Bar-Concrete Bond in Mixes Containing Calcium Carbide Residue, Fly Ash and Recycled Concrete Aggregate. *Cem. Concr. Compos.* **2018**, *89*, 31–40. [CrossRef]
69. Prince, M.J.R.; Singh, B. Bond Strength of Deformed Steel Bars in High-Strength Recycled Aggregate Concrete. *Mater. Struct.* **2015**, *48*, 3913–3928. [CrossRef]
70. Xiao, J.; Falkner, H. Bond Behaviour between Recycled Aggregate Concrete and Steel Rebars. *Constr. Build. Mater.* **2007**, *21*, 395–401. [CrossRef]
71. Kim, S.-W.; Yun, H.-D. Influence of Recycled Coarse Aggregates on the Bond Behavior of Deformed Bars in Concrete. *Eng. Struct.* **2013**, *48*, 133–143. [CrossRef]
72. Stochino, F.; Alibeigibeni, A.; Zucca, M.; Valdes, M.; Concu, G.; Simoncelli, M.; Pisani, M.A.; Bernuzzi, C. Mechanical Behavior of Composite Slabs with Recycled Concrete Aggregates: A Preliminary Study. *Structures* **2024**, *70*, 107838. [CrossRef]
73. de Brito, J.; Silva, R.V. *Sustainability in Structural Concrete Design*; International Association for Bridge and Structural Engineering: Zurich, Switzerland, 2024; ISBN 978-3-85748-201-4.
74. Lye, C.-Q.; Dhir, R.K.; Ghataora, G.S.; Li, H. Creep Strain of Recycled Aggregate Concrete. *Constr. Build. Mater.* **2016**, *102*, 244–259. [CrossRef]
75. Soberón, G.; Vicente, J.M. *Creep of Concrete with Substitution of Normal Aggregate by Recycled Concrete Aggregate*; Malhotra, V.M., Ed.; Polytechnic University of Catalonia: Barcelona, Spain, 2002; ISBN 978-0-87031-089-8.
76. Fan, Y.; Xiao, J.; Tam, V.W.Y. Effect of Old Attached Mortar on the Creep of Recycled Aggregate Concrete. *Struct. Concr.* **2014**, *15*, 169–178. [CrossRef]
77. Gómez-Cano, D.; Arias-Jaramillo, Y.P.; Bernal-Correa, R.; Tobón, J.I. Effect of Enhancement Treatments Applied to Recycled Concrete Aggregates on Concrete Durability: A Review. *Mater. Constr.* **2023**, *73*, e308. [CrossRef]
78. Chen, C.; Liu, R.; Zhu, P.; Liu, H.; Wang, X. Carbonization Durability of Two Generations of Recycled Coarse Aggregate Concrete with Effect of Chloride Ion Corrosion. *Sustainability* **2020**, *12*, 10544. [CrossRef]

79. Etxeberria, M.; Castillo, S. How the Carbonation Treatment of Different Types of Recycled Aggregates Affects the Properties of Concrete. *Sustainability* **2023**, *15*, 3169. [CrossRef]
80. Pu, Y.; Li, L.; Wang, Q.; Shi, X.; Luan, C.; Zhang, G.; Fu, L.; El-Fatah Abomohra, A. Accelerated Carbonation Technology for Enhanced Treatment of Recycled Concrete Aggregates: A State-of-the-Art Review. *Constr. Build. Mater.* **2021**, *282*, 122671. [CrossRef]
81. Liu, H.; Hua, M.; Zhu, P.; Chen, C.; Wang, X.; Qian, Z.; Dong, Y. Effect of Freeze–Thaw Cycles on Carbonation Behavior of Three Generations of Repeatedly Recycled Aggregate Concrete. *Appl. Sci.* **2021**, *11*, 2643. [CrossRef]
82. Torrenti, J.M.; Amiri, O.; Barnes-Davin, L.; Bougrain, F.; Braymand, S.; Cazacliu, B.; Colin, J.; Cudeville, A.; Dangla, P.; Djerbi, A.; et al. The FastCarb Project: Taking Advantage of the Accelerated Carbonation of Recycled Concrete Aggregates. *Case Stud. Constr. Mater.* **2022**, *17*, e01349. [CrossRef]
83. Gholizadeh-Vayghan, A.; Bellinkx, A.; Snellings, R.; Vandoren, B.; Quaghebeur, M. The Effects of Carbonation Conditions on the Physical and Microstructural Properties of Recycled Concrete Coarse Aggregates. *Constr. Build. Mater.* **2020**, *257*, 119486. [CrossRef]
84. Wang, Y.; Liao, J.; Zhang, B. A Review of Chloride Penetration of Recycled Concrete with Enhancement Treatment and Service Life Prediction. *Materials* **2024**, *17*, 1349. [CrossRef]
85. Pandey, S.; Rajhans, P. Durability Assessment of Quaternary Blended Recycled Aggregate Concrete under Chloride Environment. *Mater. Today Proc.* **2023**, *84*, 364–371. [CrossRef]
86. Jiang, H.; Wu, L.; Guan, L.; Liu, M.; Ju, X.; Xiang, Z.; Jiang, X.; Li, Y.; Long, J. Durability Life Evaluation of Marine Infrastructures Built by Using Carbonated Recycled Coarse Aggregate Concrete Due to the Chloride Corrosive Environment. *Front. Mar. Sci.* **2024**, *11*, 1357186. [CrossRef]
87. Lu, D.; Cao, H.; Shen, Q.; Gong, Y.; Zhao, C.; Yan, X. Dynamic Characteristics and Chloride Resistance of Basalt and Polypropylene Fibers Reinforced Recycled Aggregate Concrete. *Adv. Polym. Technol.* **2020**, *2020*, 6029047. [CrossRef]
88. Gao, S.; Ji, Y.; Liu, A.; Zhang, H.; Qin, Z.; Long, W. The Adsorption and Diffusion Behavior of Chloride in Recycled Aggregate Concrete Incorporated with Calcined LDHs. *Cem. Concr. Compos.* **2024**, *148*, 105452. [CrossRef]
89. Ekolu, S.O. Permeation Properties of Recycled Concretes Containing Various Types of Recovered Aggregates. Available online: https://hdl.handle.net/10210/279850 (accessed on 19 September 2024).
90. Paul, S.C.; Van Zijl, G.P.A.G. Durability Index Test Performance of Recycled Concrete Aggregate Mixed with Natural Aggregate. *Int. J. Adv. Civil. Eng. Arch. Res.* **2013**, *2*, 53–64.
91. Ismail, S.; Kwan, W.H.; Ramli, M. Mechanical Strength and Durability Properties of Concrete Containing Treated Recycled Concrete Aggregates under Different Curing Conditions. *Constr. Build. Mater.* **2017**, *155*, 296–306. [CrossRef]
92. Cantero, B.; Bravo, M.; de Brito, J.; Sáez del Bosque, I.F.; Medina, C. Assessment of the Permeability to Aggressive Agents of Concrete with Recycled Cement and Mixed Recycled Aggregate. *Appl. Sci.* **2021**, *11*, 3856. [CrossRef]
93. Kapoor, K.; Singh, S.P.; Singh, B. Water Permeation Properties of Self Compacting Concrete Made with Coarse and Fine Recycled Concrete Aggregates. *Int. J. Civ. Eng.* **2018**, *16*, 47–56. [CrossRef]
94. Mahmood, W.; Khan, A.-R.; Ayub, T. Mechanical and Durability Properties of Concrete Containing Recycled Concrete Aggregates. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2022**, *46*, 2111–2130. [CrossRef]
95. Thomas, C.; Setién, J.; Polanco, J.A.; Alaejos, P.; Sánchez de Juan, M. Durability of Recycled Aggregate Concrete. *Constr. Build. Mater.* **2013**, *40*, 1054–1065. [CrossRef]
96. Safiuddin, M.; Alengaram, U.J.; Rahman, M.M.; Salam, M.A.; Jumaat, M.Z. Use of Recycled Concrete Aggregate in Concrete: A Review. *J. Civ. Eng. Manag.* **2013**, *19*, 796–810. [CrossRef]
97. Zhan, B.J.; Xuan, D.X.; Zeng, W.; Poon, C.S. Carbonation Treatment of Recycled Concrete Aggregate: Effect on Transport Properties and Steel Corrosion of Recycled Aggregate Concrete. *Cem. Concr. Compos.* **2019**, *104*, 103360. [CrossRef]
98. Sasanipour, H.; Aslani, F.; Taherinezhad, J. Chloride Ion Permeability Improvement of Recycled Aggregate Concrete Using Pretreated Recycled Aggregates by Silica Fume Slurry. *Constr. Build. Mater.* **2021**, *270*, 121498. [CrossRef]
99. Xuan, D.; Zhan, B.; Poon, C.S. Durability of Recycled Aggregate Concrete Prepared with Carbonated Recycled Concrete Aggregates. *Cem. Concr. Compos.* **2017**, *84*, 214–221. [CrossRef]
100. Velardo, P.; Sáez del Bosque, I.F.; Sánchez de Rojas, M.I.; De Belie, N.; Medina, C. Durability of Concrete Bearing Polymer-Treated Mixed Recycled Aggregate. *Constr. Build. Mater.* **2022**, *315*, 125781. [CrossRef]
101. Kubissa, W.; Jaskulski, R.; Brodnan, M. Influence of SCM on the Permeability of Concrete with Recycled Aggregate. *Period. Polytech. Civ. Eng.* **2016**, *60*, 583–590. [CrossRef]
102. Gao, Y.; Jiang, Y.; Tao, Y.; Shen, P.; Poon, C.S. Accelerated Carbonation of Recycled Concrete Aggregate in Semi-Wet Environments: A Promising Technique for CO_2 Utilization. *Cem. Concr. Res.* **2024**, *180*, 107486. [CrossRef]

103. Pernin, T.; Torrenti, J.-M.; Potier, J.-M.; Izoret, L.; Mai-Nhu, J. Accelerated Carbonation of Recycled Concrete Aggregates: Impact on Durability of Concrete. In *Proceedings of the 4th FIB International Conference on Concrete Sustainability (ICCS2024), Guimarães, Portugal, 10–12 September 2024*; Barros, J.A.O., Cunha, V.M.C.F., Sousa, H.S., Matos, J.C., Sena-Cruz, J.M., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 36–43.
104. Braymand, S.; Roux, S.; Vial, V.; Bertola, J.; Cazacliu, B. Collaborative Laboratory Experiments to Measure the Rate of CO_2 Captured after Accelerated Carbonation by a Calcimetric Method. In Proceedings of the 1st RILEM International Conference on Mineral Carbonation for Cement and Concrete, Aachen, Germany, 16–17 April 2024.
105. Jiang, T.; Cao, X.; Duan, H.; Shu, K. Recycling Efficiency Mechanism of Recycled Concrete Aggregate to Improve the CO_2 Uptake and Anti-Leakage Properties of CO_2 Sequestration Functional Backfills. *Constr. Build. Mater.* **2025**, *458*, 139663. [CrossRef]
106. Ang, P.; Goh, W.; Bu, J.; Cheng, S. Assessing Carbon Capture and Carbonation in Recycled Concrete Aggregates: A Holistic Life Cycle Assessment Perspective with Simulation at Industrial Scale. *J. Clean. Prod.* **2024**, *474*, 143553. [CrossRef]
107. Goh, W.; Ye, S.; Ou Yong, R.; Tham, K.H.; Wang, C.; Tao, L.; Cheng, S. Techno-Economic Analysis of Mineralization and Utilization of CO_2 in Recycled Concrete Aggregates. *Processes* **2025**, *13*, 410. [CrossRef]
108. Pade, C.; Guimaraes, M. The CO_2 Uptake of Concrete in a 100 Year Perspective. *Cem. Concr. Res.* **2007**, *37*, 1348–1356. [CrossRef]
109. Zhu, X.; Wang, T.; Yi, Z.; Zhu, Z. Kinetics and Structure Analysis of CO_2 Mineralization for Recycled Concrete Aggregate (RCA). *J. Clean. Prod.* **2024**, *448*, 141571. [CrossRef]
110. Tham, K.H.; Seah, T.; Kouk, Q.Y.; Goh, W.; Cheng, S.; Wang, C.; Bu, J.; Tao, L. Developing an Integrated CO_2 Capture and Mineralization Process with Lower Energy Consumption. *Int. J. Energy Water Res.* **2024**. [CrossRef]
111. Chong, Y.; Chua, G.F.; Zhao, M.; Yip, C.; Daneti, S.B.; Jin, F. *Aqueous CO_2 Sequestration for Low-Carbon Ready-Mix Concrete*; Vysoké učení technické v Brně, Fakulta stavební: Brno, Czech Republic, 2024; ISBN 978-80-86433-83-7.
112. Bergmans, J.; Kazemi Kamyab, H.; Ghosh, D.; Van Mierloo, P.; Carens, H.; Nielsen, P. Carbonation of Recycled Concrete Aggregates for New Concrete and Concrete Fines to Make Cement-Free Hollow Blocks. *Sustainability* **2024**, *16*, 3494. [CrossRef]
113. Huang, W.; Wang, H. Comprehensive Assessment of Engineering and Environmental Attributes of Geopolymer Pervious Concrete with Natural and Recycled Aggregate. *J. Clean. Prod.* **2024**, *468*, 143138. [CrossRef]
114. Huang, X.; Huang, Z.; Zhou, Y.; Hu, R.; Hu, B. Life Cycle Assessment and Cost Analysis of LC3 Concrete Considering Sustainability and Uncertainty. *J. Build. Eng.* **2025**, *102*, 111960. [CrossRef]
115. Manan, A.; Zhang, P.; Majdi, A.; Alattyih, W.; Ahmad, J. Utilizing Waste Materials in Concrete: A Review on Mechanical and Sustainable Performance. *Green Mater.* **2025**, 1–18. [CrossRef]
116. Ma, X.; Hu, H.; Luo, Y.; Yao, W.; Wei, Y.; She, A. A Carbon Footprint Assessment for Usage of Recycled Aggregate and Supplementary Cementitious Materials for Sustainable Concrete: A Life-Cycle Perspective in China. *J. Clean. Prod.* **2025**, *490*, 144772. [CrossRef]
117. Pradhan, S.; Kumar, S.; Barai, S.V. *Particle Packing Method for Recycled Aggregate Concrete*; Springer Nature: Singapore, 2024; ISBN 978-981-9975-15-0.