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Review

Carbonation of Aggregates from Construction and Demolition Waste Applied to Concrete: A Review

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Abstract: The construction industry is essential to the development and economy, but is also the largest generator of construction and demolition waste (CDW). While efforts are made to minimize such generation, the construction industry has been developing applications for it in the form of aggregates to replace the commonly used natural aggregates. However, in structural applications, it is necessary to ensure that the properties of concrete produced with CDW, as recycled aggregates (CDW-concrete), guarantee adequate performance and do not put the structure at risk. For this, one of the alternatives is improving the properties of CDW aggregates through carbonation, a process called carbonate curing or accelerated carbonation. In this sense, this paper aims to investigate the carbonation of CDW aggregates, clarifying how this process occurs, the existing carbonation methods, the main properties that affect this process, and their influence on the properties of recycled aggregates and the CDW-concrete. To this end, the SREE (systematic review for engineering and experiments) method was used to search and analyze scientific manuscripts published without a time limit. The results revealed that the most widely used method for carbonate curing is recommended by Chinese standard GB50082, and highlighted the need for further research to investigate the CDW-concrete, focusing on its eco-friendly potential to capture CO_2 from the atmosphere.

Keywords: bibliographic analysis; carbon dioxide sequestration; carbonation; durability; recycled aggregates

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1. Introduction

Planet Earth is surrounded by a layer containing several essential gases for sustaining life [1], such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor, which retain the solar radiation on the Earth's surface, preventing its return to space. This phenomenon is called the greenhouse effect, and is primarily responsible for maintaining the global temperature at levels suitable for life maintenance on Earth [1,2]. However, it can be a negative factor because of increased emission of greenhouse gases into the atmosphere [3]. An estimation points out that 76% of all greenhouse gases are composed of CO_2 [2], and that 3.6 billion tons of CO_2 have been emitted annually [3].

The increase in CO_2 concentration in the atmosphere intensifies the greenhouse effect and leads to global warming, an urgent global issue [1]. It generates climate changes, such as increasing global temperature, polar ice caps melting, increasing average sea level, decreasing agriculture production, increasing air pollution, relative humidity variation, and fauna and flora extinction [2,3].

In this context, the construction industry emits large amounts of CO_2 throughout its chain production, with the cement and concrete sectors standing out in this aspect [2]. Moreover, this industry is one of the greatest nonrenewable natural resources explorers, exploiting a significant portion of mineral resources commonly used as aggregates [4]. It is also responsible for increasing greenhouse gases emission, particle and noise pollution, and construction and demolition waste (CDW) generation [5].

CDW production is estimated to have reached 820 million tons in Europe [6], 548 million tons in the United States [7], and 2.4 billion tons in China [8,9]. Therefore, reducing the volume of CDW is one of the most challenging problems of sustainable development for the coming years.

One of the successful strategies to recycle CDW is to use it as raw material to produce recycled aggregates (RAs), minimizing the volume of waste going to landfills, reducing the demand for natural aggregates (NAs), and decreasing the exploitation of natural resources [10]. Thus, researchers have evaluated the possibility of replacing NAs with RAs from CDW (CDW-RA) in mortars [11] and concretes for structural functions [12], which has been an increasingly investigated alternative [13], even though CDWs are very heterogeneous and show lower values for mechanical properties and durability, which can be a problem [14–16]. Spontaneous carbonation is considered a pathology because it decreases the pH of concrete, generating cracks and increasing pores size, and exposing reinforcement steel in reinforced concrete structures [17].

Considering these problems, an alternative to their mitigation is strengthening RAs with the carbonation process, e.g., using controlled climatic chambers for carbonate curing, with promising results found in the literature [3,9,15,18]. The carbonation process occurs due to the reaction between chemical compounds present in concrete ($Ca(OH)_2$—calcium hydroxide and C–S–H—calcium-silicate-hydrates) with CO_2 in the atmosphere, producing smaller calcium carbonate ($CaCO_3$) crystals that fill the pores in the mortar phase of concrete [18–20]. This process reduces the voids present in concrete and, consequently, porosity and water absorption, which improves its mechanical properties [21–23].

With this perspective, this paper investigates the carbonation of CDW–RA applied to concrete, aiming to evaluate the reduction of CO_2 emission and CDW recycling. Specifically, this study aims to define future research directions by presenting consolidated outcomes and knowledge gaps about (i) the influence of using CDW-RA on the physical and mechanical properties of concrete, (ii) the influence on concrete durability, (iii) the carbonation process of CDW-concrete, (iv) the influence of properties in the carbonation process, and (v) the CO_2 quantification and absorption methods. For this, a systematic literature review was conducted.

2. Materials and Methods

2.1. Systematic Review

To select the bibliography concerning the carbonation of CDW-RA applied to concrete, the SREE (systematic review for engineering and experiments) method [24] was used. This approach is based on the ProKnow-C (knowledge development process-constructivist) method [25], which has been employed in several relevant studies [26–31]. However, the SREE method improves and adapts the ProKnow-C method to the subject of engineering and experiments, increasing detail in its steps to be more flexible and easier, mainly for novice researchers to use. As already presented by other authors [13], the SREE method introduces a methodology quality analysis of scientific papers. Figure 1 illustrates the SREE method's main steps, which are used in the present research.

In this work, four research lenses were defined, and for each one, the research questions (or specific objectives) were developed, as shown in Figure 2.

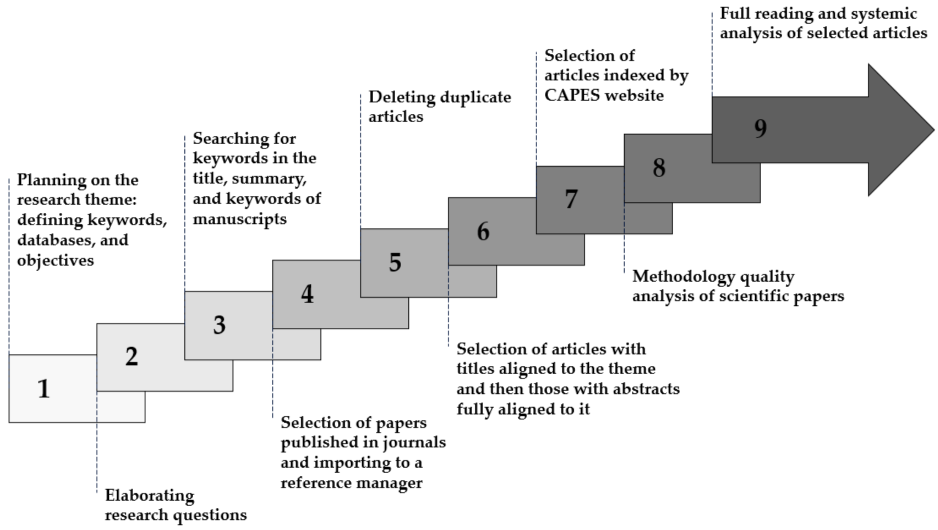

Figure 1. SREE method main stages.

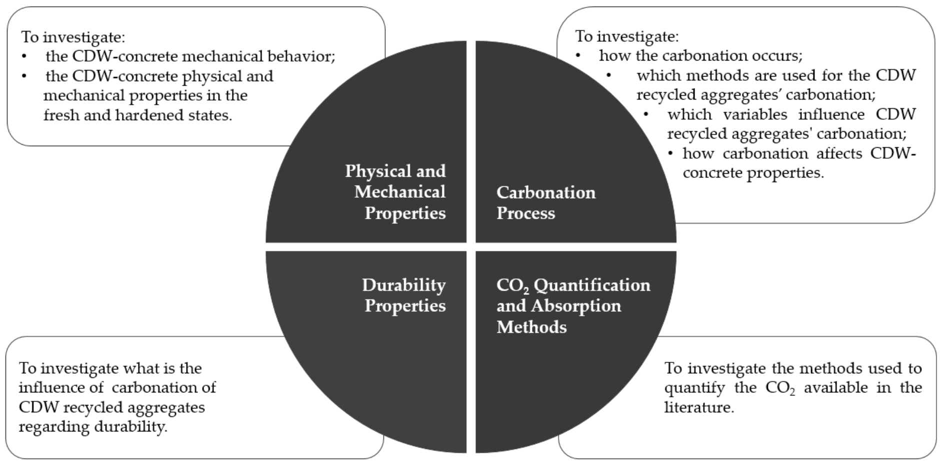

Figure 2. Research lenses and specific objectives.

2.1.1. Bibliography Selection

The research topic—carbonation of CDW-RA applied to concrete—and the objectives (Figure 3) were defined firsthand. The databases chosen for the bibliographic search were Science Direct, Scopus, Compendex, and Web of Science, all indexed by CAPES [32], involving articles published on any date up to 23 June 2021, given the novelty of the topic. Table 1 indicates the keyword combination used and the number of articles found in each database.

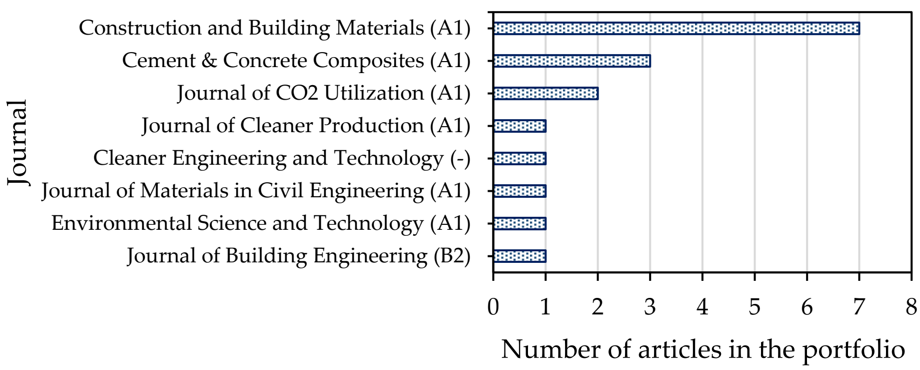

Figure 3. Journal's relevance in the portfolio.

Table 1. Number of articles found in each database using keyword combinations.

Keyword Combination	Database	Number of Articles
"carbon dioxide" AND "accelerated" AND "carbonation" AND "concrete aggregates"	Science Direct Scopus Compendex Web of Science	281 511 36 5

The initial search for the keywords resulted in 753 papers, which were imported into the reference manager—Mendeley software. Duplicate articles were eliminated, and those with titles aligned with the theme were selected, yielding 68 articles. From these, 17 were selected because of their scientific recognition—they presented 85% of the citations in the previously selected portfolio—and 21 were selected because their abstracts were aligned with the theme, yielding 38 articles for a full reading. Considering these, 16 presented total alignment with the theme, and were used to compose the bibliography for the systematic review of this research. Table 2 lists the selected bibliography, detailing their title, journal, publication year, and rating according to CAPES [32].

Table 2. Details of the selected bibliography.

Reference	Title	Journal	Year	Rating
[14]	Performance Enhancement of Recycled Concrete Aggregates through Carbonation	*Journal of Materials in Civil Engineering*	2015	A1
[17]	Carbonation behavior of recycled concrete with CO_2 curing recycled aggregate under various environments	*Journal of CO_2 Utilization*	2020	A1
[18]	CO_2 concrete and its practical value utilizing living lab methodologies	*Cleaner Engineering and Technology*	2021	-
[19]	Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates	*Cement and Concrete Composites*	2016	A1
[21]	An assessment of microcracks in the interfacial transition zone of recycled concrete aggregates cured by CO_2	*Construction and Building Materials*	2020	A1
[22]	Effect of carbonated recycled coarse aggregates on the mechanical and durability properties of concrete	*Journal of Building Engineering*	2022	A1
[23]	Mechanical properties of CO_2 concrete utilizing practical carbonation variables	*Journal of Cleaner Production*	2021	A1
[33]	Microstructure and chemical properties for CO_2 concrete	*Construction and Building Materials*	2020	A1
[34]	Effects of carbonation treatment on the crushing characteristics of recycled coarse aggregates	*Construction and Building Materials*	2019	B2
[35]	Accelerated carbonation of fresh cement-based products containing recycled masonry aggregates for CO_2 sequestration	*Journal of CO_2 Utilization*	2021	A1
[36]	Use of a CO_2 curing step to improve the properties of concrete prepared with recycled aggregates	*Cement and Concrete Composites*	2014	A1
[37]	CO_2 treatment of recycled concrete aggregates to improve mechanical and environmental properties for unbound applications	*Construction and Building Materials*	2021	A1
[38]	Durability of recycled aggregate concrete	*Construction and Building Materials*	2013	A1
[39]	Durability performance of concrete made with fine recycled concrete aggregates	*Cement and Concrete Composites*	2010	A1

Table 2. *Cont.*

Reference	Title	Journal	Year	Rating
[40]	Experimental study on CO_2 curing for enhancement of recycled aggregate properties	*Construction and Building Materials*	2014	A1
[41]	Sequestration of CO_2 by concrete carbonation	*Environmental Science and Technology*	2010	A1

2.1.2. Bibliographic Analysis

The bibliographic analysis considered the journal's relevance according to CAPES classification [32], the number of citations from each article, and the author's relevance. The author's relevance in the portfolio was checked through co-occurrence network analyses (clusters) using VOSviewer, a free software [42]. These clusters visually illustrate the correlation between the authors and the keyword selected for the portfolio, indicating which was the most cited researcher.

According to Figure 3, the article portfolio is concentrated in the journals *Construction and Building Materials*, *Cement and Concrete Composites*, and *Journal of CO_2 Utilization*, which together account for 75% of the portfolio. In addition, most of the articles have the best classification (A1) according to CAPES criteria (A1, A2, B1, B2, B3, B4, B5, and C, from the best to the worst classification) [32], indicating that the SREE method was effective in selecting relevant articles for the systematic review.

Figure 4 presents the number of citations per article reported by Google Scholar [43] on 4 July 2022, indicating that the portfolio obtained high-quality manuscripts, and highlighting their relevance.

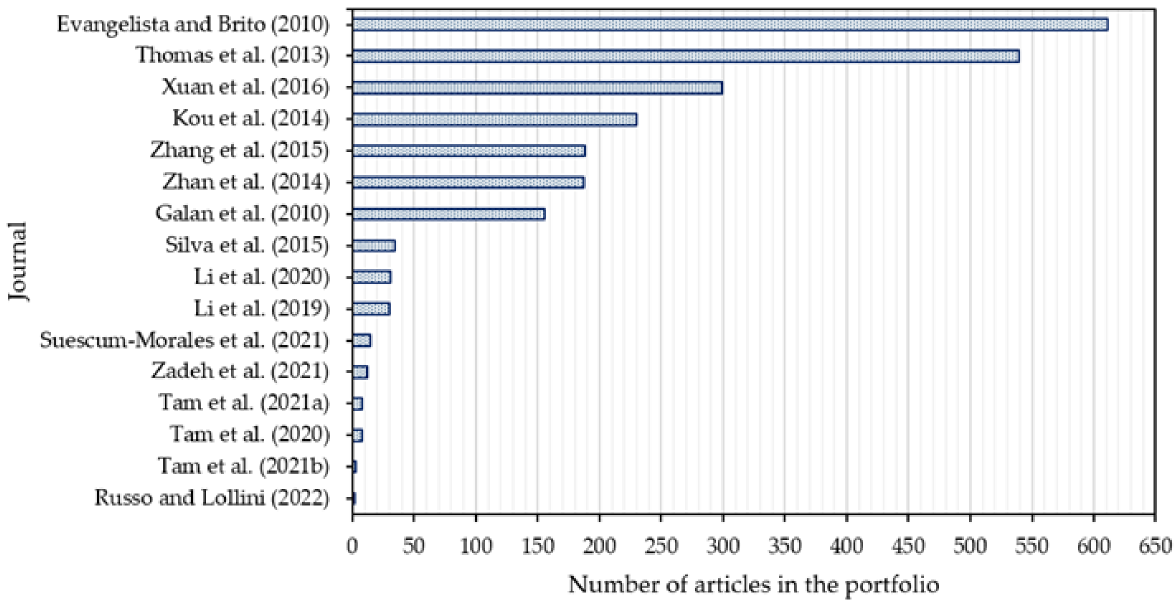

Figure 4. Article's relevance [14,17–19,21–23,33–41].

From the cluster analysis indicated in Figure 5, the division of the authors into groups is observed, with no connections among themselves, indicating the absence of collaboration between each other. This occurs due to CDW particularities in each region, which makes the joint investigation of these materials more difficult.

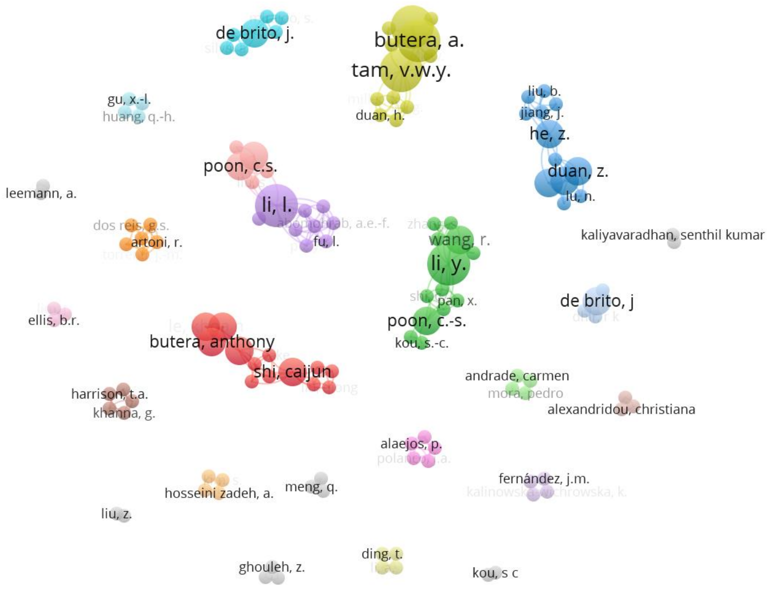

Figure 5. Cluster analysis of the portfolio authors.

2.1.3. Methodology Quality Analysis

The methodological quality analysis was performed through the SREE method [24], which analyzes the paper's results considering three criteria: (I) randomization, (II) analysis, and (III) comparison. Figure 6 presents the classification and description of each criterion.

I	**Randomization**			
	Evidence of randomness in the production and testing of the samples involved			
II	**Analysis**			
	Basic		**Statistic**	
	Use of mean and standard deviation to characterize the sample elements		Use of inferential statistics to characterize the method	
III	**Comparison**			
	Basic	**Median**	**Advanced**	**Statistic**
	Comparison with reference elements (or samples)	Comparison with similar studies without indication of origin	Comparison with similar studies from a systematic review	Use of inferential statistics for comparison with systematic reviews

Figure 6. Criteria for the methodology quality analysis of a manuscript using the SREE method.

Figure 7 presents the results of the methodological quality analysis.

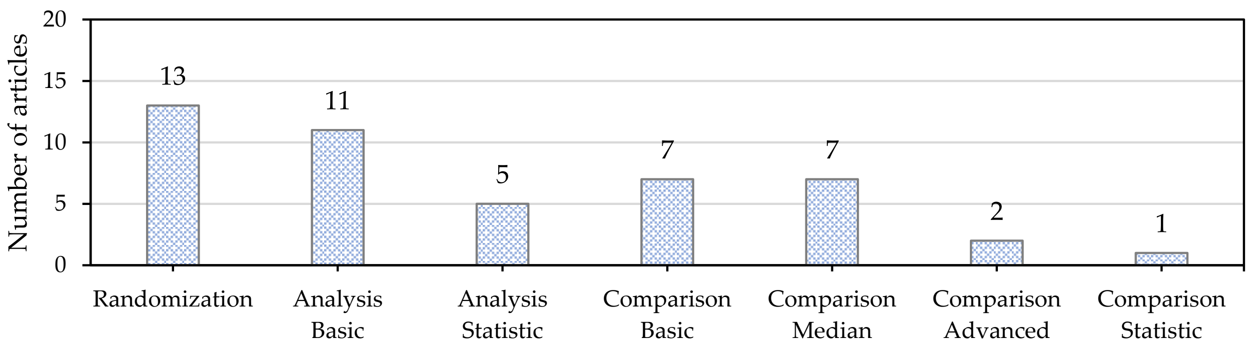

Figure 7. Criteria checked in the methodology quality analysis.

The analysis of Figure 7 indicates that the methodological quality of scientific works regarding the carbonation of CDW-RA, and its influence on the properties of cementitious composites, needs to be improved, even more so because it is a current and relevant theme for the sustainability context within civil engineering. This is demonstrated, for example, by the fact that only 7 articles out of the considered 16 (44%) performed at least a comparison with reference elements (comparison-basic). Therefore, the need for statistical studies that present their results more completely should be highlighted, enabling comparison with similar works, and the convergence of knowledge for the development of new techniques and practical applications.

3. Results and Discussion

3.1. CDW-Concrete Physical and Mechanical Properties

The literature highlights that CDW-RAs present physical and mechanical properties with lower values than NAs [44]. This worse performance is due to several factors, such as the presence of two interfacial transition zones (ITZs) in RAs, CDW's fragility, and divergence between waste types used for aggregate production [18,22,45]. Because of these differences, CDW-RAs can present great variability in their properties when not segregated, leading to a decrease in mechanical strength [4,33]. One of the strategies to minimize this effect is to segregate the waste before disposal, discriminating them according to the material type, and producing RAs that can be organized into three categories, according to the Brazilian standard NBR 15.116 [46]. Table 3 summarizes each aggregate type, and points out which one was used by some references.

Table 3. Classification of CDW-RA according to NBR 15.116 [46].

Classification	Origin	Reference
ARCO *	Concrete waste	[19,39,47]
ARCI *	Cementitious waste (mortars and cement pastes)	[15,45]
ARM *	Cement and ceramic residues	[35]

Note: * In Portuguese, "AR" means "Recycled Aggregates", and there is no translation for the other letters.

As aforementioned, RA presents two ITZs, the first between the original aggregate and the mortar that surrounds it, and the second between this mortar and the new concrete produced, which promotes an increase in the aggregate's void content and worsens its mechanical strength [19]. Furthermore, CDW-RAs are more brittle than NAs, due to the increased volume and depth of microcracks in the recycled material, which are generated during the fragmentation process to produce CDW-RA [18,21,48].

Considering these factors, waste segregation and preferential use of concrete waste (ARCO) are recommended when destined for structural purposes [46]. It is worth mentioning that the increasing interest in using CDW in concrete led to changes in some standards. For instance, the NBR 15.116 [46] allows up to 20% replacement of NAs by artificial ones since its last revision in 2021, provided that the source of the aggregates is only concrete of aggressiveness classes I and II of the NBR 6118 standard [49].

Because of their higher porosity and lower density, CDW-RAs present higher water absorption, and worse mechanical resistance [10,21,35] and durability properties [21,23,47]. Some authors have employed methods to strengthen CDW-concrete, such as varying the replacement ratio of NA for RA, aggregate type, cement, mixing and dosage method, and reinforcing CDW-RA through carbonation. Tam et al. [23], for instance, obtained greater or at least equal tensile, compressive, and flexural strength of CDW-concrete, compared to traditional concrete, by considering replacement ratios of NAs by CDW aggregates equal to 30% and 50%, which indicates it as a feasible and eco-friendly option [23].

3.2. CDW-Concrete Durability Properties

The main durability tests cataloged in the literature, and obtained through the SREE method, were the methods presented by NT BUILT 492 [50], ASTM C1202-97 [51], EN 12390-11 [52], EN 13,295 [53], and RILEM CPC-18 [54] for chloride resistance.

Some authors pointed out changes in the chemical structure of the cementitious paste because of the chemical reactions between CO_2 and $Ca(OH)_2$, which resulted in the material's densification [36,45]. According to these authors, the reactions produced smaller particles of $CaCO_3$ that filled the pores present in the CDW mortars. Due to this process, the average size of the voids was reduced from 50 nm to 10 nm or less, increasing the material's durability against chloride and sulfate penetration, and increasing leaching resistance.

Liang et al. [55] attested that precarbonated CDW-RA decreased the carbonation depth in concrete exposed to freezing cycles, due to the reduced void volume caused by $CaCO_3$ filling, improving the material's durability. According to these authors, there were decreases ranging from 31.9% to 42.5%, varying according to the number of freezing cycles.

Hosseini Zadeh et al. [37], in turn, concluded that carbonation of CDW-RA decreased the concentration of toxic chemical elements (As—arsenic and Cd—cadmium) on the order of 50%. Furthermore, some researchers have verified that prior carbonation decreases the alkalinity of CDW-RA due to the reaction between $Ca(OH)_2$ and CO_2, reducing pathologies such as reinforcement corrosion.

The analysis of the selected articles led to the main conclusions presented in Table 4.

Table 4. Improvements in carbonate CDW-RA.

Reference	Main Conclusions
[3,45,55]	Increased resistance to sulfate attacks. Increased leaching resistance.
[3,37,45,55]	Alkalinity reduction.
[45]	Decreased porosity by densification of the $CaCO_3$ composition. Increased resistance to high temperatures.
[45,55]	Increased resistance to freezing cycles.
[36,45]	Improvement of the penetration resistance against chlorides. Decreased reinforcement corrosion rate.
[55]	Decreased carbonation depth.
[36]	Decreased concentration of chemical and toxic elements in carbonate aggregates.

3.3. Carbonation Process

The carbonation process, also called accelerated carbonation or carbonate curing, occurs from the reaction between CO_2 and $Ca(OH)_2$, as shown in Equation (1), or between CO_2 and calcium-silicate-hydrates (C–S–H), as shown in Equation (2), both present in concrete. The reaction products include $CaCO_3$ and calcium carbonate-silicate-hydrate ($3\,CaCO_3 \cdot 2\,SiO_2 \cdot 3\,H_2O$) [56].

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O, \quad (1)$$

$$C\text{-}S\text{-}H + CO_2 \rightarrow 3\,CaCO_3 \cdot 2\,SiO_2 \cdot 3\,H_2O, \quad (2)$$

In this context, RAs have a greater possibility of reacting with CO_2 compared to natural aggregates due to the $Ca(OH)_2$ present in the mortar coupled to the aggregate surface, which is essential for this process to occur on a large scale [3,19]. The treatment of CDW-RA by carbonation occurs through the strengthening of the mortar coupled to the aggregates due to the porosity reduction, and by mitigating the existing microcracks in the ITZ [10,15,19,21,34,45,48] through the chemical reactions indicated in Equations (1) and (2).

The rate of CO_2 absorption by RA is higher in the first seven days of curing because of the higher concentration of C–S–H and $Ca(OH)_2$ [35,45]. It was observed that longer exposure periods improve concrete properties [57], higher aggregate moisture content improves the reaction conditions [3], and the variability of the waste types alters the reaction capacity with CO_2; therefore, concrete waste is preferable to the others [10,41]. The literature reveals that the application of carbonated CDW-RA in concrete decreases porosity and increases the water absorption rate and density compared to concretes produced with noncarbonated CDW-RA [14,41,58].

With this perspective, the carbonation process has been one of the main strategies used to perform carbon sequestration, and to improve the physical and mechanical properties of RAs [23,47,57]. The methods used to carry out the investigations are the standard carbonation method, recommended by the Chinese standard GB50082 [58], the pressurized carbonation method, the flow-through CO_2 curing method, and the water-CO_2 cooperative curing method. The standard carbonation method, widely used and the most frequent in the selected bibliography, is performed in a carbonation chamber whose variables of temperature, relative humidity, and CO_2 concentration are approximately 20 ± 2 °C, 70 ± 5%, and 20 ± 3%, respectively. It is also common to analyze the content of carbonated material after different exposure periods inside the chamber [10,55].

The literature highlights that variable such as temperature, relative humidity (RH), CO_2 concentration, CO_2 pressure, grain size, and exposition time influence the carbonation rate of recycled aggregates. In order to organize the papers, Table 5 summarizes the main variables of each selected paper.

Table 5. Variables that affect carbonation identified in papers.

Reference	Temperature	RH	CO_2 Concentration	Exposition Time	Grain Size
[14]	20 ± 2 °C	60 ± 5%	20 ± 2%	7 days	Sand
[17]	20 ± 2 °C	70 ± 5%	20 ± 3%	10 days	Sand
[18]	-	-	-	1 h	Gravel
[19]	25 ± 3 °C	50 ± 5%	100%	24 h	Gravel
[21]	20 ± 2 °C	70 ± 5%	20%	0, 7, 14, and 28 days	Gravel
[22]	20 °C	65%	100%	30 days	Gravel
[23]	23 ± 2 °C	-	-	0, 30, 60, and 120 min	Gravel
[33]	-	-	-	120 min	Gravel
[34]	23 ± 2 °C	70 ± 5%	20 ± 3%	12 h	Gravel
[35]	20 ± 2 °C	70 ± 5%	20 ± 3%	-	Sand
[36]	-	-	100%	0, 6, 12, 24, 48, and 72 h	Gravel
[37]	22 ± 1 °C	21 ± 1%	-	48 h	Gravel
[38]	20 ± 5 °C	97 ± 2%	-	-	Gravel
[40]	23 °C	10–90%	-	1–5 h	Gravel

By analyzing the selected papers, it is possible to identify that most of the studies focus on the enhancement of coarse aggregates, due to the fact that it is the main responsible factor for mechanical and durability properties of cementitious composites. An important aspect of carbonation is the solubility of carbon in the cement matrix, which depends on temperature and humidity. Li et al. [57] affirm that temperatures up to 60 °C increase CO_2 solubility [14]; however, higher temperatures compromise carbonation. Moisture content impacts the solubility of carbon due to the fact that water is used to dissolve the calcium present in cement, allowing the formation of calcite when in contact with CO_2 [59].

Jang et al. [60] highlight that RH between 50 and 70% provides optimal carbonation conditions; this was confirmed in the portfolio of Zhan et al. [40], which obtained a higher carbonation rate between 40 and 60% relative humidity. Considering CO_2 concentration, Pu et al. [61] concluded that concentrations between 20 and 40% accelerates carbonation reactions, increasing composites properties [21,22]. Exposition time also affects carbonation. According to Pu et al. [62], carbonation can be divided in three stages: the fast growing stage, which corresponds to the first 30 min and contributes to 62% of the total carbonation; the slow growing stage, a long stage where the carbonation rate decreases and corresponds to 36.5% of the total carbonation; and the stable stage, where the carbonation rate remains stable, which can be observed in [21,36].

The literature also indicates that the granulometry of the aggregates interferes with the capacity for CO_2 reaction. It was verified by Xuan et al. [19], who reported that finer materials presented a higher capacity for CO_2 reaction because of the greater surface area exposed to the environment. Thus, it may be an alternative strategy to implement the carbonate curing method to strengthen the CDW-RA.

Regarding the mechanical properties, some studies reported better performance in terms of compressive, tensile, and flexural strength in concretes with carbonated CDW-RA compared to those produced with noncarbonated aggregates [14,19,40]. For example, according to Li et al. [57], this improvement is up to 20%. These authors also reported that concretes made with aggregates cured with CO_2 had mechanical strength values only 10% lower compared to conventional concretes produced with virgin aggregates. However, there was no improvement in the elastic modulus [19,23,57].

Furthermore, the carbonate curing process of aggregates results in other changes when applied to concrete, such as decreasing electrical conductivity [22], making it possible to use them for electrical discharge grounding systems, decreasing alkalinity [55], and shrinkage of the concrete after drying [36]. These positive factors allow improvement of the mechanical properties of the material, since they limit pathologies caused by alkaline pH and shrinkage.

3.4. CO_2 Quantification and Absorption Methods

The simplest methodology identified in the selected bibliography for quantifying and absorbing CO_2 was the mass weighing method, which quantifies the CO_2 content by weighing the dry aggregates before and after the carbonation process [3,19,40,57]. It is simple because it requires only a carbonation chamber, a scale, and an oven to be applied. Considering the selected bibliography, this method was employed in three articles.

Other approaches that help to identify the CO_2 content absorbed by the aggregates involve the application of phenolphthalein, in which the pink color intensity indicates the carbonation degree of the material [3,55]; X-ray diffraction (XRD), which allows a semiquantitative analysis of the chemical composition of the aggregates before and after carbonation [33,35,55]—this method was used in four manuscripts in the selected bibliography; and thermogravimetric and differential thermal analysis (TGA/DTA), which makes it possible to quantify the carbon crystal particles in fine-grained materials [33,35,55]—this method was employed the most (five times) in the selected bibliography.

4. Conclusions

From this review on the carbonation of CDW-RA applied to concrete, performed using the SREE method, the following conclusions can be drawn:

(i) Using CDW-RA in concrete leads to a decrease in the physical and mechanical properties compared to conventional concrete due to the variability of the wastes and a higher void content in the recycled aggregates, which makes them more brittle than NAs. An alternative to this is to segregate CDW, and prioritize the management of concrete waste to produce ARCO (recycled aggregates of concrete).

(ii) The durability decreases when using CDW-RA in concrete because the CDW-RA's void ratio is higher than conventional aggregate, increasing the concrete's porosity and decreasing its permeability against corrosion.
(iii) The carbonation of CDW-RA, especially ARCO and ARCI, occurs at higher rates than in conventional aggregate because of the extra $Ca(OH)_2$ interacting with the aggregate. When it reacts with CO_2, this process produces $CaCO_3$ that fills the CDW-RA voids, enhancing the aggregate's resistance. This method has been a strategy to increase CDW-RA applications in concretes for structural purposes, reaching promising results. The standard carbonation method, recommended by the Chinese standard GB50082 [59], was the most used in the selected portfolio, leading to positive outcomes as well.
(iv) The carbonation effectiveness is affected by environmental and sample conditions, such as temperature, relative humidity, CO_2 concentration, exposition time, and grain size. In the selected portfolio, the majority of experimental investigations were realized in sands in temperatures of 20 ± 2 °C, moisture content between 50 and 70%, CO_2 concentration between 20 and 100%, and exposition time varying from 30 min to 72 h.
(v) The method identified in the portfolio which was most used to quantify the absorbed CO_2 was TGA/DTA, which was used five times, and has been a reliable method to quantify the carbon embodied in the CDW-RA. It is worth mentioning the X-ray diffraction (XRD) and mass gain methods were also present in the portfolio, the latter being the simplest one.

It should be highlighted that these findings are limited to the bibliography selected using the SREE method, and to the four research lenses (or specific objectives) proposed in this research. Based on these conclusions, there is a need for further research to investigate the CDW-concrete, focusing on its eco-friendly potential to capture CO_2 from the atmosphere, and on its behavior when destined for use in structural components.

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References

1. Kweku, D.W.; Bismark, O.; Maxwell, A. Greenhouse Effect: Greenhouse Gases and Their Impact on Global Warming. *J. Sci. Res. Rep.* **2018**, *17*, 1–9. [CrossRef]
2. Kaliyavaradhan, S.K.; Ling, T.-C. Potential of CO_2 sequestration through construction and demolition (C&D) waste-An overview. *J. CO_2 Util.* **2017**, *20*, 234–242. [CrossRef]
3. Liu, Z.; Meng, W. Fundamental understanding of carbonation curing and durability of carbonation-cured cement-based composites: A review. *J. CO_2 Util.* **2021**, *44*, 101428. [CrossRef]
4. Goldemberg, J.; Agopyan, V.; John, V.M. *O Desafio da Sustentabilidade na Construção Civil*; Editora Blucher: São Paulo, Brazil, 2011.
5. Lu, W.; Webster, C.; Chen, K.; Zhang, X.; Chen, X. Computational Building Information Modelling for construction waste management: Moving from rhetoric to reality. *Renew. Sustain. Energy Rev.* **2017**, *68*, 587–595. [CrossRef]

6. European Commission, Eurostat, European Statistics Code of Practice: For the National Statistical Authorities and Eurostat (EU Statistical Authority). Publications Office (2018). Available online: https://op.europa.eu/en/publication-detail/-/publication/661dd8ef-7439-11e8-9483-01aa75ed71a1/language-en (accessed on 23 June 2022).
7. United States Environmental Protection Agency, Advancing Sustainable Materials Management: 2014 Fact Sheet Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States, United States Environ. Prot. Agency, Off. L. Emerg. Manag. Washington, DC 20460. (2016) 22. Available online: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf. (accessed on 23 June 2022).
8. Wu, H.; Zuo, J.; Yuan, H.; Zillante, G.; Wang, J. A review of performance assessment methods for construction and demolition waste management. *Resour. Conserv. Recycl.* **2019**, *150*, 104407. [CrossRef]
9. Zhang, D.; Ghouleh, Z.; Shao, Y. Review on carbonation curing of cement-based materials. *J. CO_2 Util.* **2017**, *21*, 119–131. [CrossRef]
10. Liang, C.; Pan, B.; Ma, Z.; He, Z.; Duan, Z. Utilization of CO_2 curing to enhance the properties of recycled aggregate and prepared concrete: A review. *Cem. Concr. Compos.* **2020**, *105*, 103446. [CrossRef]
11. Guimarães, M.G.A.; Gomes, H.C.; Urashima, D.d.C.; Oliveira, G.S. Incorporação de resíduos de construção e demolição e pó-de-pedra em dosagens experimentais de argamassa para mitigação de impactos ambientais. *Braz. J. Dev.* **2020**, *6*, 25337–25349. [CrossRef]
12. Gomes, H.C.; Guimarães, M.G.A. Agregados Reciclados em Concretos para a Mitigação de Impactos da Indústria da Construção civil. Final Paper (Bachelor in Civil Engineering)—Federal Center for Technological Education of Minas Gerais. 96. (2021). Available online: https://www.researchgate.net/publication/366055886_APLICABILIDADE_DE_AGREGADOS_RECICLADOS_EM_CONCRETOS_PARA_A_MITIGACAO_DE_IMPACTOS_ADVINDOS_DA_INDUSTRIA_DA_CONSTRUCAO_CIVIL?channel=doi&linkId=638fd66e484e65005be980c1&showFulltext=true (accessed on 23 June 2022).
13. Reis, E.D.; Gomes, H.C.; de Azevedo, R.C.; Poggiali, F.S.J.; Bezerra, A.C.d.S. Bonding of Carbon Steel Bars in Concrete Produced with Recycled Aggregates: A Systematic Review of the Literature. *C-J. Carbon Res.* **2022**, *8*, 76. [CrossRef]
14. Zhang, J.; Shi, C.; Li, Y.; Pan, X.; Poon, C.-S.; Xie, Z. Performance enhancement of recycled concrete aggregates through carbonation. *J. Mater. Civ. Eng.* **2015**, *27*, 04015029. [CrossRef]
15. Shi, C.; Li, Y.; Zhang, J.; Li, W.; Chong, L.; Xie, Z. Performance enhancement of recycled concrete aggregate—A review. *J. Clean. Prod.* **2016**, *112*, 466–472. [CrossRef]
16. Resende, H.F.; Reis, E.D.; Fernandes, F.M.; Rodrigues, L.A.; Ângelo, F.A. Uso de resíduos de construção e demolição como agregado reciclado no concreto: Uma breve revisão de literatura. *Rev. Principia-Divulg. Científica Tecnológica IFPB Early View* **2022**. [CrossRef]
17. Silva, R.V.; Neves, R.; De Brito, J.; Dhir, R.K. Carbonation behaviour of recycled aggregate concrete. *Cem. Concr. Compos.* **2015**, *62*, 22–32. [CrossRef]
18. Tam, V.W.; Butera, A.; Le, K.N.; Li, W. CO_2 concrete and its practical value utilising living lab methodologies. *Clean. Eng. Technol.* **2021**, *3*, 100131. [CrossRef]
19. Xuan, D.; Zhan, B.; Poon, C.S. Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates. *Cem. Concr. Compos.* **2016**, *65*, 67–74. [CrossRef]
20. Zhang, N.; Duan, H.; Miller, T.R.; Tam, V.W.Y.; Liu, G.; Zuo, J. Mitigation of carbon dioxide by accelerated sequestration in concrete debris. *Renew. Sustain. Energy Rev.* **2020**, *117*, 109495. [CrossRef]
21. Li, Y.; Fu, T.; Wang, R.; Li, Y. An assessment of microcracks in the interfacial transition zone of recycled concrete aggregates cured by CO_2. *Constr. Build. Mater.* **2020**, *236*, 117543. [CrossRef]
22. Russo, N.; Lollini, F. Effect of carbonated recycled coarse aggregates on the mechanical and durability properties of concrete. *J. Build. Eng.* **2022**, *51*, 104290. [CrossRef]
23. Tam, V.W.; Butera, A.; Le, K.N. Mechanical properties of CO_2 concrete utilising practical carbonation variables. *J. Clean. Prod.* **2021**, *294*, 126307. [CrossRef]
24. Azevedo, R.C.; de Souza, E.A.; Dias, E.A.P.; Reis, E.D.; Gomes, H.C.; Coelho, I.D. Systematic Review for Engineering and Experiments (SREE). Graduate Program in Civil Engineering at the Federal Center for Technological Education of Minas Gerais. Belo Horizonte. 2022.
25. Ensslin, L.; Ensslin, S.R.; Lacerda, R.T.d.O.; Tasca, J.E. ProKnow-C, knowledge development process-constructivist. *Process. Técnico Com Pat. Regist. Pendente Junto Ao INPI. Bras.* **2010**, *10*, 2015.
26. Campos, T.V.; de Azevedo, R.C. The Lean Methodology and the Civil Construction Industry: A Systematic Review of Literature/a Metodologia Lean E a Industria Da Construcao Civil: Uma Revisao Sistematica Da Literatura. *Prod. Online* **2021**, *21*, 437–456.
27. Vilela Rocha, V.; Cabral De Azevedo, R.; Ludvig, P. Selection Process and Analysis of Bibliographic Set for a Research Involving Carbon Nanotubes Dispersion Using the ProKnow-C. *Int. J. Sci. Eng. Investig.* **2017**, *6*, 23–28.
28. Gomes, C.L.; Poggiali, F.S.J.; de Azevedo, R.C. Concretes with recycled aggregates of construction and demolition waste and mineral additions: A bibliographic analysis. *Rev. Mater.* **2019**, *24*. [CrossRef]
29. França, S.; Schuab, M.R.; Sperandio, K.P.; de Azevedo, R.C.; de Carvalho, M.C.R.; Bezerra, A.C.d.S. Proknow-C: Da Seleção De Um Portfólio De Artigos a Análise Sistêmica Sobre Blocos De Terra Comprimida. *Pensar Acadêmico* **2019**, *17*, 291–308. [CrossRef]
30. Reis, E.D.; Resende, H.F.; Ludvig, P.; De Azevedo, R.C.; Spitale, F.; Poggiali, J.; Cesar, A. Bonding of Steel Bars in Concrete with the Addition of Carbon Nanotubes: A Systematic Review of the Literature. *Buildings* **2022**, *12*, 1626. [CrossRef]

31. Maia, L.; Santos, K.A.; Souza, R. Life Cycle Assessment in Construction and Demolition Waste Management: A Critical Review. *Int. J. Sci. Eng. Investig.* **2022**, *11*, 48–55.
32. CAPES Portal de Periódicos CAPES. 2016. Available online: http://www.periodicos.capes.gov.br/?option=com_phome&Itemid=68& (accessed on 23 June 2022).
33. Tam, V.W.Y.Y.; Butera, A.; Le, K.N. Microstructure and chemical properties for CO_2 concrete. *Constr. Build. Mater.* **2020**, *262*, 120584. [CrossRef]
34. Li, Y.; Zhang, S.; Wang, R.; Zhao, Y.; Men, C. Effects of carbonation treatment on the crushing characteristics of recycled coarse aggregates. *Constr. Build. Mater.* **2019**, *201*, 408–420. [CrossRef]
35. Suescum-Morales, D.; Kalinowska-Wichrowska, K.; Fernández, J.M.; Jiménez, J.R. Accelerated carbonation of fresh cement-based products containing recycled masonry aggregates for CO_2 sequestration. *J. CO_2 Util.* **2021**, *46*, 101461. [CrossRef]
36. Kou, S.C.; Zhan, B.J.; Poon, C.S. Use of a CO_2 curing step to improve the properties of concrete prepared with recycled aggregates. *Cem. Concr. Compos.* **2014**, *45*, 22–28. [CrossRef]
37. Hosseini Zadeh, A.; Mamirov, M.; Kim, S.; Hu, J. CO_2-treatment of recycled concrete aggregates to improve mechanical and environmental properties for unbound applications. *Constr. Build. Mater.* **2021**, *275*, 122180. [CrossRef]
38. 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]
39. Evangelista, L.; de Brito, J. Durability performance of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2010**, *32*, 9–14. [CrossRef]
40. Zhan, B.; Poon, C.S.; Liu, Q.; Kou, S.; Shi, C. Experimental study on CO_2 curing for enhancement of recycled aggregate properties. *Constr. Build. Mater.* **2014**, *67*, 3–7. [CrossRef]
41. Galan, I.; Andrade, C.; Mora, P.; Sanjuan, M.A. Sequestration of CO_2 by concrete carbonation. *Environ. Sci. Technol.* **2010**, *44*, 3181–3186. [CrossRef]
42. van Eck, N.J.; Waltman, L. VOSviewer Manual-Version 1.6.8. 2018. 1–51. Available online: http://www.vosviewer.com/documentation/Manual_VOSviewer_1.5.4.pdf (accessed on 13 July 2022).
43. Google, S. Scholar Google. 2022. Available online: https://scholar.google.com.br/schhp?hl=pt-BR&as_sdt=0,5 (accessed on 4 July 2022).
44. Blengini, G.A.; Garbarino, E. Resources and waste management in Turin (Italy): The role of recycled aggregates in the sustainable supply mix. *J. Clean. Prod.* **2010**, *18*, 1021–1030. [CrossRef]
45. Liu, B.; Qin, J.; Shi, J.; Jiang, J.; Wu, X.; He, Z. New perspectives on utilization of CO_2 sequestration technologies in cement-based materials. *Constr. Build. Mater.* **2021**, *272*, 121660. [CrossRef]
46. *ABNT, NBR 15116*; Agregados Reciclados de Resíduos Sólidos da Construção Civil—Utilização em Pavimentação e Preparo de Concreto Sem Função Estrutural—Requisitos. ABNT: São Paulo, Brazil, 2021.
47. Nedeljković, M.; Visser, J.; Šavija, B.; Valcke, S.; Schlangen, E. Use of fine recycled concrete aggregates in concrete: A critical review. *J. Build. Eng.* **2021**, *38*, 102196. [CrossRef]
48. Tam, V.W.Y.; Butera, A.; Le, K.N.; Li, W. Utilising CO_2 technologies for recycled aggregate concrete: A critical review. *Constr. Build. Mater.* **2020**, *250*, 118903. [CrossRef]
49. *ABNT NBR 6118*; Projeto de Estruturas de Concreto-Procedimento. ABNT: São Paulo, Brazil, 2014.
50. NT Build 492, Concrete, Mortar and Cement-Based Repair Materials: Chloride Migration Coefficient from Non-Steady-State Migration Experiments. *Measurement* **1999**, 1–8. Available online: nordtest.info/images/documents/nt-methods/building/NT%20build%20492_Concrete%20mortar%20and%20cement-based%20repair%20materials_Chloride%20migration%20coefficient%20from%20non-steady-state%20migration%20experiments_Nordtest%20Method.pdf (accessed on 13 July 2022).
51. *ASTM, C1202-97*; Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride ion Penetration. ASTM: São Paulo, Brazil, 1997.
52. *CEN, EN 12390-11*; Testing Hardened Concrete-Part 11: Determination of the Chloride Resistance of Concrete, Unidirectional Diffusion. Brussels, 2015. Available online: https://standards.globalspec.com/std/9952805/EN%2012390-11 (accessed on 13 July 2022).
53. *CEN, EN 13295*; Products and Systems for the Protection and Repair of Concrete Structures-Test Methods-Determination of Resistance to Carbonation. Brussels, 2005. Available online: https://www.en-standard.eu/une-en-13295-2005-products-and-systems-for-the-protection-and-repair-of-concrete-structures-test-methods-determination-of-resistance-to-carbonation/ (accessed on 13 July 2022).
54. RILEM-TC-56-MHM RILEM CPC-18: Measurement of hardened concrete carbonation depth. *Mater. Struct.* **1988**, *21*, 453–455. [CrossRef]
55. Liang, C.; Lu, N.; Ma, H.; Ma, Z.; Duan, Z. Carbonation behavior of recycled concrete with CO_2-curing recycled aggregate under various environments. *J. CO_2 Util.* **2020**, *39*, 101185. [CrossRef]
56. Sulapha, P.; Wong, S.F.; Wee, T.H.; Swaddiwudhipong, S. Carbonation of Concrete Containing Mineral Admixtures. *ASCE J. Mater. Civ. Eng.* **2003**, *15*, 134. [CrossRef]
57. Li, L.; Wu, M. An overview of utilizing CO_2 for accelerated carbonation treatment in the concrete industry. *J. CO_2 Util.* **2022**, *60*, 102000. [CrossRef]

58. *GB50082-2009*; Standard for Test Methods of Long-Term Performance and Durability of Ordinary Concrete (English Version). China Academy of Building Research: 2009. Available online: https://www.chinesestandard.net/PDF/English.aspx/GBT50082-2009 (accessed on 13 July 2022).
59. Ahmad, S. *Accelerated Carbon Dioxide Sequestration*; Elsevier Ltd.: Amsterdam, The Netherlands, 2018. [CrossRef]
60. Jang, J.G.; Kim, G.M.; Kim, H.J.; Lee, H.K. Review on recent advances in CO_2 utilization and sequestration technologies in cement-based materials. *Constr. Build. Mater.* **2016**, *127*, 762–773. [CrossRef]
61. Pu, Y.; Li, L.; Wang, Q.; Shi, X.; Fu, L.; Zhang, G.; Luan, C.; Abomohra, A.E.-F. Accelerated carbonation treatment of recycled concrete aggregates using flue gas: A comparative study towards performance improvement. *J. CO_2 Util.* **2021**, *43*, 101362. [CrossRef]
62. 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]