

Review

A Review: Construction and Demolition Waste as a Novel Source for CO₂ Reduction in Portland Cement Production for Concrete

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Abstract: There is an increasing global recognition of the need for environmental sustainability in mitigating the adverse impacts of cement production. Despite the implementation of various carbon dioxide (CO₂) mitigation strategies in the cement industry, such as waste heat recovery, the use of alternative raw materials and alternative fuels, energy efficiency improvements, and carbon capture and storage, overall emissions have still increased due to the higher production levels. The resolution of this matter can be efficiently achieved by the substitution of traditional materials with an alternative material, such as calcined clay (CC), construction and demolition waste (CDW), which have a significant impact on various areas of sustainable development, including environmental, economic, and social considerations. The primary objectives of employing CDW in the Portland cement production are twofold: firstly, to mitigate the release of CO₂ into the atmosphere, as it is a significant contributor to environmental pollution and climate change; and secondly, to optimize the utilization of waste materials, thereby addressing the challenges associated with their disposal. The purpose of this work is to present a thorough examination of the existing body of literature pertaining to the partial replacement of traditional raw materials by CDW and the partial replacement of Portland cement by CDW and to analyze the resulting impact on CO₂ emissions.

Keywords: construction and demolition waste; carbon dioxide reduction; cement production



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1. Introduction

Cement, being one of the most widely utilized materials for construction, plays a crucial role as the primary binder in concrete, leading to the formation of a durable, stone-like, hard material capable of withstanding various loads [1–4].

The conventional kind of cement, known as ordinary Portland cement (OPC), primarily comprises over 90% Portland cement clinker. This particular type of cement is derived from readily accessible raw materials that are widely abundant and cost-effective, making it easily obtainable in nearly all regions [5].

This inexpensive mineral binder has rapid hardening properties in nearly all livable environments, enabling the creation of diverse structures [6]. Moreover, its user-friendly nature allows untrained individuals, including those lacking literacy skills, to utilize it effectively for self-construction purposes [5].

Cement constitutes approximately 10% of the total volume of concrete on a global scale, and approximately 50% of cement is allocated to produce concrete, while the remaining portion is designated for applications such as mortars, pastes, and pre-manufactured products [7].

1.1. Cement Production

1.1.1. Global Cement Production

The global output of cement has witnessed a significant rise over the years. Specifically, it has escalated from 0.94 billion tons in 1970 to 2.284 billion tons in 2005, further increasing to 4.05 billion tons in 2017 and reaching 4.1 billion tons in 2018 [8].

In the year 2017, the countries of China and India, which are recognized as the largest global manufacturers, collectively accounted for 64% of the global cement production. This equated to a total output of 2.61 billion tons of cement out of the whole global production of 4.05 billion tons [6]. In the year 2019, the primary producers of cement were China, India, the European Union, and the United States [9,10]. These four entities collectively accounted for 56.1%, 7.8%, 4.4%, and 2.2% of the total cement production, respectively [11].

Current cement consumption is about 4.2 billion tons per year [12], which is enough to produce almost 1.6 m³ of concrete per person. This amount, which is approximately half of the volume of food produced worldwide, is expected to reach approximately 6 billion tons by the end of 2050 [7,13].

1.1.2. Cement Production Stages

Cement is derived from a combination of limestone, clay, and sand, which serve as the primary sources of lime, silica, alumina, and iron [14]. Cement production by the dry manufacturing process consists of six stages [6,15–18].

During the initial phase, the raw materials necessary for the process are extracted through mining operations, such as limestone, clay, laterite, bauxite, iron ore, kaolinite, sandstone, and other similar inorganic materials. All of them, properly dosed, constitute the “Portland clinker crude” (PCC), the last six being in addition the fluxes or mineralizers of the first two (those with the highest dosage), to which, despite their very considerable lower dosage, they reduce their melting point so that they can chemically react more and better and thus form Portland clinker permanently. The second stage of the process entails the characterization of diverse raw materials and their proper dosage to create PCC. During the third stage, the PCC is introduced into a preheating chamber. During the fourth stage, the pre-heated decarbonized PCC is introduced into the rotary kiln to undergo the process of clinkerization at a temperature ≥ 1450 °C. During the fifth stage, the clinker that emerges from the kiln undergoes a quick cooling process facilitated using pressurized air. During the concluding phase, the cooled clinker is recovered from the cooling vessels and then transferred to the mills. The clinker is ground together with the optimum amount of setting regulator [19] (natural gypsum stone) into powder using a ball mill or roller mill, or a vertical mill, and the pulverized cement is transported to storage silos using a transportation system suitable for shipping (Figure 1). Nevertheless, if the composition of the ground material consists of a combination of natural and/or artificial pozzolans and/or GGBFS along with Portland clinker, the ideal quantity of setting regulator needs to be determined utilizing the R. Talero method [20].

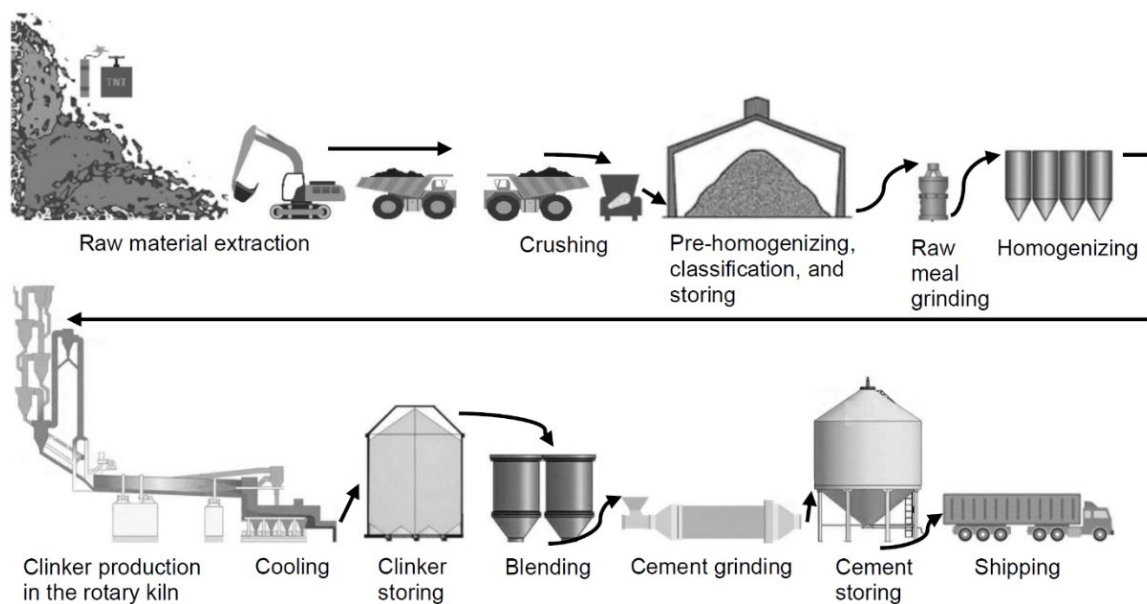


Figure 1. Cement production.

The six phases can be condensed into three primary stages: raw meal preparation, clinker production, and finish grinding [21,22].

1.2. Environmental Impacts of Cement Production

In comparison to the year 1750, it has been observed that concentrations of CO₂ in the Earth's atmosphere have risen from 280 to 410 parts per million by volume (ppmV) [23–29]. This upward trajectory is projected to persist in the coming decades, potentially leading to a temperature rise of up to 5.8 °C during the present century [29,30].

Approximately 40% of worldwide CO₂ emissions can be attributed to four key industries: power plants, iron and steel manufacturing, cement manufacturing, and chemicals and petrochemicals [29]. The cement sector is identified as the primary contributor of process emissions [16,31].

Based on the available worldwide CO₂ emission data, cement plants made a substantial contribution of 2.9 billion tons of CO₂ in the year 2021 [7]. This figure represents an almost fivefold increase when compared to the emission level of 0.57 billion tons recorded in 1990 [29,32].

CO₂ Emissions from the Cement Industry

Cement production is a highly resource-intensive process that consumes significant amounts of energy and raw materials [16]. This process leads to the emission of CO₂ through two primary pathways: direct emissions from the combustion of fossil fuels in the kiln and indirect emissions from the calcination process of the primary raw material, predominantly limestone [33]. Additionally, the consumption of electricity in cement production, particularly when generated from fossil fuel combustion, contributes to overall CO₂ emissions [34].

The emission of CO₂ during the manufacturing of one metric ton of Portland cement is predicted to range from 0.73 to 0.99 metric tons throughout various geographical regions [34]. It can be asserted that the manufacturing of one kilogram of Portland cement results in the emission of about one kilogram of CO₂ into the atmosphere [35,36].

The global production of this product is responsible for approximately 5–9% of CO₂ emissions [13,16,29,37–41]. Furthermore, it accounts for significant emissions of carbon monoxide (CO) and heavy metals [14]. In addition to CO₂, CO, and heavy metals, the use of a substantial quantity of material has led to the excessive burden on deposits of these materials and the alteration of the environment. The production of Portland cement alone

entails the consumption of approximately double the quantity of raw materials required to manufacture one metric ton of Portland cement [35].

As previously stated, the process of manufacturing Portland cement results in the emission of carbon dioxide through both direct and indirect means [39]. Indirect emissions are generated because of the calcination process, wherein limestone, the principal constituent of cement, undergoes heating [39,42,43]. The process of thermal decomposition causes the calcium carbonate present in limestone to undergo a chemical transformation, resulting in the formation of calcium oxide and the liberation of CO₂ gas [39]. This procedure is responsible for approximately 50% of the total emissions generated during the manufacture of cement [32,41]. The production of cement involves subjecting limestone and other clay-like materials to high temperatures of approximately 1450 °C within a kiln [39,44]. Direct emissions arise because of the combustion of fossil fuels utilized for the purpose of heating the kiln, constituting approximately 40% of the total emissions associated with cement manufacturing [5,16,45]. The emissions associated with the quarrying of raw materials, their transportation, grinding processes [46], the electricity consumption for operating additional plant machinery, as well as the packaging and final delivery of cement, all contribute to the remaining 10% of the overall emissions [43,47].

Furthermore, a range of technological and managerial inefficiencies within the typical cement production process might result in additional CO₂ emissions. Geographical location, technological factors, plant and manufacturing efficiency, the energy mix utilized for electricity generation, and the choice of kiln fuels all contribute to additional carbon dioxide CO₂ emissions [29,38,39].

1.3. Construction and Demolition Waste

Construction waste results from building constructions and building renovations and consists of surplus material, unusable impaired or fractured material, cut-off pieces, processing waste, worn-out tools and accessories, dismantled shuttering, packaging, and waste produced by construction workers [48–50]. On the other hand, after the end of a structure's life cycle, its demolition is crucial for the growth of cities where inadequate space is the major obstruction. CDW can also be generated in the aftermath of a natural disaster, which presents several significant challenges, such as transportation, storage in an appropriate location prior to processing, and disposal at landfill sites [51].

Overall, it can be stated that CDW is a type of solid waste generated on construction sites and during the entire or partial demolition of buildings and infrastructures [52–58].

1.3.1. CDW Composition and Generation

CDW consists primarily of inert and non-inert materials, such as gravel, concrete, sand, ceramic, tile, metal, plastic, glass, roofing materials, paper, cardboard, etc. The inert waste materials consist of soft and hard inert materials, whereas the noninert waste consists of residual waste and other materials such as metals, wood, plastic, and glass [53,59,60]. Inert fraction waste accounts for between 40 and 85 percent of total waste volume, excluding excavation soils [50,58,61].

It is estimated that the construction industry annually generates more than 3 billion tons of CDW worldwide [62–64]. This indicates that CDW accounts for approximately 36% of the world's total waste production [65]. CDW in the United States rose from 50 million tons in 1980 to 600 million tons in 2018 [61]. More than 1.5 billion tons of CDW are produced annually in China [66,67], while in the European Union (EU), countries produce about 850 million tons/year, or 31% of the total waste generation in the EU [68].

1.3.2. Environmental Impacts of CDW

The generation of waste results in adverse externalities on the environment, even while a significant portion of CDW consists of inert materials that may not provide as significant a risk as hazardous waste [69,70]. The disposal of CDW in landfills causes landslides [71], depletes limited landfill resources, exacerbates energy consumption, amplifies

greenhouse gas (GHG) emissions, poses public health concerns, and contaminates the environment [44,72–75].

In recent years, governmental bodies have enacted new regulations pertaining to the management of waste, encompassing responsibilities, disposal practices, and recycling efforts on a broader scale [76]. Consequently, the urban landscape is undergoing transformation through the establishment of recycling facilities, yet the current recovery rate for CDW remains very low [49,77]. The expansion of the worldwide population and the concurrent rise in sea levels have resulted in a reduction in the accessible land for dump sites, hence leading to an indirect escalation in the expenses associated with landfills [78].

1.4. Scope of the Study

The current solutions for cement manufacturing have issues in meeting the increasing market demand, hindering the transition towards a sustainable and low-carbon footprint material. Hence, it is imperative to explore various approaches that might effectively address the dual objectives of promoting sustainability and minimizing the carbon emissions associated with cement production. Parallely, due to the rapid process of urbanization and the increasing global population, it is projected that the annual production of waste worldwide will experience a significant increase, reaching 3.4 billion tons within the next three decades. This anticipated figure represents a notable rise from the 2.01 billion tons recorded in 2016 [79].

The decrease in CO₂ emissions resulting from the cement production process and waste management has consistently been a topic of great interest for researchers in both academic institutions and industry. Numerous endeavors have been undertaken to address the substantial volume of CO₂ emissions stemming from the cement sector, as well as the incorporation of waste materials within the framework of the circular economy. Despite the technological viability of the bulk of these techniques, the level of CO₂ mitigation in the cement industry and waste reuse remains unsatisfactory due to different impediments [80].

Furthermore, the utilization of non-renewable materials in the process of cement manufacture has given rise to a novel environmental apprehension. Consequently, professionals in the industry and scholars have developed novel approaches to tackle these increasingly complex issues [16].

In contrast with its detrimental effects on the environment and on human life, the utilization of CDW may contribute to a more sustainable and greener society. Since some of its components have a high resource value, the majority of CDW is recoverable. CDW might be recycled and utilized for both economic and environmental gain. The technologies for the separation and recovery of CDW are well-established, widely available, and generally affordable [48].

This paper first presents an overview of recent advancements in CO₂ mitigation technologies within the cement industry. This study, then, gives a brief analysis of alternative fuels (AFs), substitution of alternative raw materials (ARMs) in the raw meal, and substitution of waste/by-product/recycled materials in Portland cement production. Furthermore, this study presents comprehensive analysis of the utilization of CDW in the cement industry, emphasizing the beneficial effects of CDW when it is utilized in partial raw material substitution and in partial Portland cement replacement to reduce CO₂ emissions.

1.4.1. Methodology of the Review Paper

The methodology followed in the creation of this review was based on the premise of giving priority to papers published in the last 10 years with the objective of keeping the review up to date. The search for scientific papers and books was carried out using internationally recognized databases, such as SCOPUS, Web of Science, and open-access databases. The papers were selected by taking into account their contribution to the topic and scientific relevance.

1.4.2. Limitation of the Study

The limitations of the study are listed below:

- Non-material related mitigation measures (energy efficiency, waste heat recovery (WHR), technological upgrading, etc.) are not reviewed.
- The present study does not consider the studies related to alternative binders, alternative clinkers, and total replacement of Portland cement.
- For the CO₂ reduction studies, the present study only considers the research conducted on concrete mixes.
- The primary focus of the study on reducing CO₂ emissions lies in the utilization of CDW-derived products as a partial replacement in Portland cement to produce concrete.

2. Mitigation and Improvement Measures to Reduce CO₂ in Portland Cement Production

Clinker is a transitional product in the production of cement, occurring before the mineral additions (MAs) to create the final cement product. As the temperature rises, the pre-calcined materials undergo physical and chemical transformations, causing them to liquefy and combine, resulting in the formation of lumps [39]. Thus, the manufacturing of cement emits greenhouse gases through both chemical and physical processes.

The thermal decomposition of limestone releases CO₂ by an endothermic chemical reaction, and the combustion of coal, fuel, or AF releases it as well (but exothermically), only that the transmission to the limestone of the heat generated at the same time, to decompose it and decarbonate it, is not carried out chemically but physically by the following ways: conduction, convection, and radiation.

Although it is not possible to completely eliminate these emissions, the use of energy-saving technologies can help reduce physical emissions. Therefore, the cement industry had been actively engaged in the pursuit of techniques aimed at reducing CO₂ emissions far in advance of the emergence of global warming as a prominent concern. To address this predicament, an increasing body of research has delved into the process of decarbonization within the cement sector, as outlined in Table 1.

Table 1. Relevant studies on CO₂ reduction methods for the cement industry.

Reference	Region	Reviewed Methods
[81]	Global	Utilization of Afs/ARMs, supplementary cementitious materials (SCMs), and alternative low-carbon binders.
[5]	Global	Improving energy efficiency; use of Afs; clinker substitution by MAs/SCMs; utilization of carbon capture and storage (CCS), alternative clinkers, and alkali-activated materials; and improving the efficiency of cement use.
[82]	Global	Increased use of calcined clay and engineered filler with dispersants, introduction of new Portland clinker-based cement alternatives, use of alkali-activated materials, and improvement of the efficiency of cement use.
[16]	Global	Energy savings and the use of CCS and alternative materials (AFs, ARMs, and clinker substitute).
[14]	Global	Improving energy efficiency, material substitution, and the use of AFs and CCS.
[83]	Global	The use of CCS technologies, reduction of clinker/cement ratio, use of AFs, and pyro-processing improvements.
[84]	Global	Improving energy efficiency, changing fuel type, the use of CCS, substituting clinker, and improving cement use efficiency.
[22]	Global	Reduction of the clinker/cement ratio and the use of ARMs/AFs, energy efficiency improvements, the use of WHR and CCS, and the replacement of cement in concrete or mortar with alternative materials.
[85]	Global	Utilization of energy conservation approaches.
[86]	Global	Utilization of CCS, SCMs, and nanotechnology.
[87]	Global	Utilization of WHR, blended cements, efficiency improvements, and CCS.
[88]	Global	Utilization of CCS.
[10]	Global	Use of low-carbon cement technologies.

Table 1. Cont.

Reference	Region	Reviewed Methods
[89]	Asia	Improving energy efficiency, the use of AFs, reduction of the clinker-to-cement ratio, and utilization of emerging and innovative technologies (excess heat recovery, CCS, energy management systems, etc.)
[21]	China	The use of energy efficiency improvement technology, WHR, CCS, AFs, and clinker substitution.
[90]	China	The use of energy efficiency improvements, AFs, clinker substitution, and CCS.
[91]	China	Utilization of advanced efficiency technologies, ARMs, AFs, renewable electricity, CCS, and cement carbonation effects.
[92]	China	Use of energy efficiency, AFs, ARMs, and CCS.
[93]	Indonesia	The use of clinker substitutes, AFs, and WHR and upgrading kilns.
[94]	Indonesia	Improving energy efficiency and the use of clinker substitution, AFs, and CCS.
[95]	Japan	The use of energy and material efficiency strategies, AFs, reducing clinker-to-cement ratios, lowering transportation emissions, and decarbonizing electricity supply.
[96]	Japan	Reuse of building material waste.
[39]	Malaysia	The use of energy-efficient technologies, WHR, AFs (fuel switching/co-processing), alternative binders, and CCS.
[97]	Thailand	The use of WHR.
[38]	Hong Kong	The use of AFs and ARMs and the application of combined strategies.
[98]	USA	Improving energy efficiency.
[2]	Portugal	Use of alternative clinker technologies.
[99]	Poland	Improving energy efficiency and the use of waste as raw materials and MAs in cement production.
[100]	Italy and Germany	The use of AFs and ARMs.
[101]	Sweden	The use of CCS.

As depicted in Table 1, the cement industry globally implements a range of mitigation techniques, with variable degrees of adoption. Some of these mitigation techniques are reviewed in the following sections.

2.1. Substitution of Alternative Fuels (AFs)

While AF substitution in the cement production process is not a novel concept [16,102], its prominence has grown considerably, and the utilization of AFs in cement manufacturing has received significant attention in recent years due to its efficacy in replacing the thermal energy derived from fossil fuels and mitigating pollutant emissions. The contemporary cement kiln exhibits a high degree of adaptability, enabling the cement industry to seamlessly transition between different fuel sources with moderate ease [5,16]. The cement rotary kiln possesses the capability to incinerate a diverse array of materials because of the extended durations spent at elevated temperatures, the inherent capacity of clinker to assimilate and confine impurities such as heavy metals within itself, and the alkaline conditions prevailing within the kiln [103].

The cement industry utilizes conventional fossil fuels, including coal, fuel oil, petroleum coke (petcoke), natural gas, and diesel, in its kilns and pre-heater systems to generate the elevated temperatures required for clinker production [46]. The aforementioned fuels account for over 94% of the thermal energy need in the worldwide cement industry [104].

The suitability of AFs is contingent upon various properties, including their physical state (solid, liquid, or gaseous), lower heating value, ash composition and content, toxicity (organic compounds, heavy metals), volatile content [105], humidity content, physical properties (scrap size, density, and homogeneity), content of circulating elements, grinding properties, storage/feeding capabilities, and calorific value [15,16,43,105–107].

The utilization of AFs offers several key benefits, namely enhanced energy recovery and the preservation of finite fossil fuel resources. These advantages result in the reduction of pollutant emissions, particularly CO₂, and a projected decrease in the expenses associated with cement production [16,102,103,108,109]. Nevertheless, the adoption of AFs presents numerous problems as a result of the complexities associated with inte-

grating supplementary fuel-saving methodologies. Furthermore, it is important to note that not all AFs guarantee a reduction in CO₂ emissions due to their elevated carbon intensities [45,81,102,110,111].

AFs can be broadly categorized into three primary groups [112]. The first group comprises liquid AFs, encompassing materials such as waste oil, solvents, animal fat, and sewage sludge. The second group consists of solid AFs, which include waste tires (either chipped or whole), animal and bone meal, dried sewage sludge, scrap wood, and waste materials originating from various industries, such as the pulp, paper, cardboard, plastics, packaging, and textile industries. Lastly, the third group encompasses gas AFs, which encompass landfill gases, pyrolytic gases, and biogases.

Typical AFs used by the cement industry include animal meat and bone meat [113–121], municipal solid waste [110,122–128], refuse derived fuel [129–131], waste tires [110,132–134], plastic waste [22,106,135], saw dust or wood [136,137], straw [138,139], agriculture and forest wastes [140–142], almond shells [143,144], olive residues [145], oil palm [146], food residue [147], rice husk ash [148], natural gas [149], biogas [150], sewage sludge [151–153], oil sludge [154], slaughterhouse residues [155], spent solvents [110], and solid recovered fuels [156,157].

It is projected that the global utilization of AFs will increase from 3% in 2006 to around 37% by 2050, resulting in a contribution of approximately 15% towards the intended overall reduction in CO₂ emissions [5,34].

2.2. Substitution of Alternative Raw Materials (ARMs)

The process of the decarbonation of commonly used raw materials, primarily limestone, results in the release of around 0.53 metric tons of CO₂ for each metric ton of clinker produced [153]. Utilizing waste and by-products that include valuable minerals, such as calcium, silica, alumina, and iron, is a viable option to substitute for traditional raw materials, including clay, shale, and limestone [15,158].

The incorporation of alternative materials into the clinker recipe necessitates a prudent methodology, since any modification in the chemical composition of cement will have an impact on the ultimate quality of the product [22,159].

Various industrial by-products and waste-derived materials have been investigated as potential substitutes for limestone and clay in the production of cement. The objective is to minimize the utilization of natural resources, decrease CO₂ emissions, and reduce heat consumption while ensuring that the manufacturing processes remain unaltered [159].

Some of the ARMs utilized in the raw meal for cement production are presented in Table 2.

Table 2. Typical ARMs utilized as a partial replacement in the raw meal.

Sector	Contribution
Construction Industry	CDW [44,160–164], concrete waste [26,165–169], cement waste [170–172], recycled aggregates (RAs) [173,174], marble and brick waste [175], cement kiln dust [176,177], ceramic wastes [178–180], recycled mortar or paste [181], cellular concrete [182], asbestos cement tile waste [183], inorganic construction waste [184], dam fine sediments [185,186], and dredged sediments [187,188].

Table 2. Cont.

Sector	Contribution
Manufacturing Industry	Sewage sludge [189–196], blast furnace slag [197–202], lime sludge [13,203,204], steel slag [201,205,206], stainless steel slag [207], basic oxygen furnace slag [208,209], calcium carbide slag [210], magnesium slag [211], water purification sludge [212], heavy metal-containing sludge [213], electric arc furnace slag [214], fly ash [197,198,200,215–222], red mud [199,223–225], oil-based mud [226,227], iron ore tailings [228,229], copper tailings [230], industrial hazardous waste [231], paper pulp waste [232,233], marine bio-refinery waste [234], glass waste [38,235], plastic waste [236], fiber-cement waste [237], black dross leached residue [238], and titanium dioxide waste [239].
Agricultural and Aquacultural Industries	Wood ash [240,241], biomass ash [110], sugar filter mud [242,243], pulverized eggshell waste [244], bone ash [121], and pulverized oyster and scallop shell waste [245].
Natural sources	Basalt rock [104,108,246], natural fluorapatite [247], meta-schist [248], Callovo-Oxfordian argillite [249], spent volcanic soil [18], calcined clay [250,251], and spent limestone sorbent [252].
Other sources	Municipal solid waste [253–255], contaminated soil [256], and mining waste [257].

2.2.1. Consideration of CC as SCM: Replacement of Portland Cement by CC

The materials evaluated in Table 2 have the potential to partially substitute for Portland clinker by means of novel variations of already utilized SCMs. Among these materials, calcined clay (CC) deserves particular attention.

By subjecting ordinary clay, which typically contains at least 40% kaolinite and is widely available in the earth's crust, to moderate heat treatment (about 700 and 850 °C), it can be transformed into a pozzolanic material called CC [258,259].

CCs, especially when combined with limestone, are being recognized as a highly promising solution due to their excellent performance and the abundance of sufficient reserves of these materials [260]. Limestone calcined clay (LC2) and limestone calcined clay cement (LC3) systems exploit the synergistic effects of calcined clay and limestone, enabling a significant decrease of up to 50% in the utilization of clinker [261]. Nevertheless, the clays typically employed in LC3 systems consist of a minimum of 40% kaolinite [258,262].

Recently, there has been a significant increase in research [263–271] focused on the potential utilization of CC as an SCM in the manufacturing of cement, with a particular emphasis on advancing its economic viability [272].

Zhu et al. [273] conducted a study on the characteristics of LC2 blended cement and compared them with fly ash (FA) and granulated blast-furnace slag (GGBS). They reported that the normal consistency of LC2 blended cement was greatly raised and the substitution of LC2 at a rate of 60% resulted in an almost twofold increase in normal consistency.

Dhandapani et al. [274] reported that concrete produced with LC3 had superior compressive strengths compared to concrete with equal combination proportions at all ages up to 1 year.

The investigation carried out by Vaasudevaa et al. [275] involved the substitution of cement in concrete with a combination of LC2 at a proportion of 45%. They concluded that the compressive strength of steam-cured LC3 concrete after 1 day is comparable to that of OPC concrete, exhibiting a similar strength enhancement resulting from the steam curing conditions.

The study carried out by Aramburo et al. [276] aimed to evaluate the mechanical properties and sulfate resistance of blended cements containing a significant amount of

CC as pozzolanic material. The objective was to demonstrate that these cements can meet the requirements of CEM type IV/A-SR and IV/B-SR cements as defined by the EN 197-1:2011 standard. The results obtained validated the increase in sulfate resistance and the decrease in the mechanical strength of PC when it was replaced by CC (whose matrix clay was kaolin doped with $\approx 50\%$ quartz) in quantities greater than 40%. They also stated that the blended cements with high percentages of CC replacement successfully met the specified requirements regarding compressive and flexural strengths without prejudice to its decrease observed with the increase in its replacement by PC. The reason for both opposing behaviors, sulfatic and mechanical strengths, was the same: the very high, early, and fast pozzolanic activity of its silica and reactive alumina contents especially (38.0% and 15.0%, respectively) [277–279], which excessively decreases the $[Ca(OH)]$ in the liquid phase of its pastes. To verify this, the authors repeated the tests, replacing a small portion of the CC used with slaked lime powder (calcium hydroxide, $Ca(OH)_2$). Both behaviors contrasted again, but in the opposite direction; that is, the sulfate resistance decreased, and the mechanical strengths increased, as when the replacement by PC was $\leq 40\%$. This was similar to how it also increased its resistance to carbonation, which had also been significantly diminished and seriously compromised, with an increase in the replacement of CC by PC. The more impaired the material, the greater the 40% replacement was [280].

A study carried out by Yu et al. [281] investigated the practicality of creating a cost-effective and environmentally friendly cement by combining LC2 at a significant proportion of 50–80% relative to the weight of the cement. They reported that blended cements containing 50–60% LC2 exhibit satisfactory compressive strength, decreased hydration heat, reduced environmental effect, and lower material cost per unit strength but reduced workability in comparison to plain Portland cement. This contrasts quite a bit with the results of flexural and compressive strengths obtained by Arámburo et al. [276].

With regard to CO_2 emissions, a review of the existing literature [82,260,267,281–288] has revealed that CC can serve as a viable substitute due to its lower carbon emissions. Specifically, LC3 technology offers advantages such as resource conservation, global scalability, cost effectiveness, high performance, and ease of implementation on standard construction sites.

A comprehensive life cycle assessment (LCA) study has been conducted by Scrivener et al. [258] for the Cuban cement industry, covering the entire life cycle from production to the factory gate. Remarkably, regardless of the technological level, LC3 cement consistently achieved an approximately 30% reduction in CO_2 emissions. Moreover, it has been observed that the lowest quality LC3 cement produced during the initial industrial trial outperforms the highest quality OPC in terms of CO_2 emissions. The primary factors contributing to the large decrease in emissions were energy savings and the use of clinker substitution. Additionally, it was observed that the grinding process using LC3 resulted in a notable reduction in electricity usage compared to OPC, likely due to the softness of LC3.

Researchers at the Indian Institute of Technology, Madras, have conducted another comprehensive investigation using actual data from several cement factories [289]. This investigation demonstrated a 30% reduction in CO_2 emissions for LC3 compared to OPC at the cement level.

Research conducted by Pillai et al. [283] has shown that structures constructed with concrete containing LC3 have considerably longer service lives compared to those using solely OPC as the binder (which also contrasts quite a bit with the carbonation results obtained by Arámburo et al. [280]). Furthermore, it was discovered that LC3 concrete has much lower CO footprints per year of service life compared to the OPC concrete that was examined.

The work by Zhang et al. [284] highlighted a new application of LC3 in the production of engineered cementitious composites (ECC) that possess exceptional tensile ductility and strain hardening properties. From an environmental perspective, the utilization of LC3 in ECC demonstrated a significant reduction in carbon emissions, with 28% less CO_2 released

compared to the production of conventional concrete. However, there was only a modest decrease in energy usage and manufacturing cost.

Guo et al. [285] examined recycled aggregate concrete (RAC) incorporating LC3. They stated that the utilization of both RCA and LC3 exhibits significant promise in reducing the environmental consequences associated with concrete manufacturing.

In their study, Barbhuiya et al. [288] stated that LC3 exhibits a substantial capacity to diminish CO₂ emissions in comparison to conventional cement. The authors reported that research has demonstrated that LC3 has the capability to decrease CO₂ emissions by as much as 40% because of its reduced clinker concentration and the utilization of calcined clay. Additionally, LC3 exhibited reduced production cost in comparison to conventional cement due to its lower energy requirements during manufacturing and its ability to utilize locally sourced raw materials.

Due to all of the above, CC has been identified as one of the most promising materials that can help the cement industry achieve its emissions objectives, but perhaps not so much in terms of the durability of the works built with its concretes, mortars, pastes, and precast components.

2.2.2. Substitution of CDW as an ARM

The chemical and mineralogical properties of CDW are sufficient to qualify it as a viable substitute raw material in the limestone–clay mixture produced during the manufacturing process of Portland clinker. The composition of CDW typically includes calcium, silicon, aluminum, iron, and several trace elements, including magnesium, potassium, titanium, and sulfur. These minor elements have the potential to contribute to the development of the primary phases of Portland cement [163,169,180,290,291].

Furthermore, the substitution of CDW leads to a decrease in the generation of CO₂. This waste serves as a source of CO₂ that is separated from calcium oxide (CaO), thereby reducing the decarbonation of limestone that occurs during the flaring process in the manufacturing of clinker [163,180].

From the above-mentioned ARMs, CO₂ emission related studies concerning CDW are listed in Table 3.

Table 3. CO₂ emissions for CDW substituted in the raw meal.

Reference	CDW Type	CDW Composition	Raw Mix Designation	Raw Materials (wt %)				CO ₂ Emission by Ton		CO ₂ Emission Reductions by Ton	
				Limestone	Clay	Schist	Waste	of Raw Mix (kg/t)	of Clinker (kg/t)	of Raw Mix (%)	of Clinker (%)
[170]	Hydrated cement waste (HCW)	HCW is obtained as a by-product from the efficient separation of fine recycled concrete aggregates. CWp-A is prepared by replacing 30% weight of ordinary Portland powder by HCW. CWp-B is prepared with a higher amount of HCW, 55% in weight.	OPp	76.00	-	24.00	-	Significant reductions in CO ₂ emissions connected with clinker/cement production are reported in both scenarios (low or high amounts of HCW).			
			CWp-A	53.00	-	17.00	30.00				
			CWp-B	25.00	-	20.00	55.00				
[44]	Civil construction waste (CCW)	Reusable or recyclable aggregate waste materials, such as soil from earthworks, bricks, tiles, cladding plates, mortar, concrete, and curbs, are used for CCW. CCW0–10: concrete (1%), mortar (47%), rock (2%), ceramic (13%), and soil (37%); CCW10–20: concrete (41%), mortar (39%), rock (13%), and ceramic (7%); CCW20–40: concrete (57%), mortar (34%), rock (7%), and ceramic (2%).	C-REF	93.20	6.80	-	-	328.00	500.00	-	-
			C-CCW-1	85.71	-	-	14.29	326.00	488.00	0.60	2.40
			C-CCW-4	89.53	-	-	10.47	318.00	471.80	3.00	5.60
			C-CCW _{0–10}	90.14	-	-	9.86	312.00	459.50	4.90	8.10
			C-CCW _{10–20}	90.90	-	-	9.10	324.00	488.00	1.20	2.40
			C-CCW _{20–40}	90.50	-	-	9.50	325.00	488.00	0.90	2.40
[183]	Asbestos cement tile waste (ACW)	ACW in the form of aged tiles extracted from a roof.	CL-AC0	94.53	5.47	-	-	335.00	503.76	-	-
			CL-AC24	72.05	3.94	-	24.01	-	-	-	-
			CL-AC49	48.82	2.36	-	48.82	319.01	468.45	4.77	7.00
			CL-AC74	24.82	0.72	-	74.46	303.06	434.84	9.53	13.68
			CL-AC86	14.24	-	-	85.76	-	-	-	-

According to Gastaldi et al. [170], the utilization of HCW as a substitute for naturally mined minerals has the potential to decrease the consumption of non-renewable resources. Hydrated cement is composed of amorphous calcium silicate and calcium aluminate hydrates, as well as calcium hydroxide and a small quantity of calcium/magnesium carbonate. It was found that ordinary Portland powder and samples demonstrate weight losses of 29% and 20%, respectively. According to the authors, this implies that when 30% of HCW is utilized, it is possible to make a clinker with an equivalent mineralogical composition that emits approximately one-third less CO₂ during the combustion process. It was also reported that the substitution of regular Portland clinker with recovered samples containing HCW, Portland clinker, and gypsum results in a reduction in the emission of CO₂. Specifically, when the replacement extent reaches 40%, the amount of CO₂ released during cement manufacturing drops by more than one-fourth compared to the scenario without any replacement.

The primary aim of the research conducted by Santos and Cilla [183] was to generate Portland clinker through the utilization of ACW as a mineralizer, thereby substituting a portion of the traditional combination of limestone and clay. Based on the findings derived from the experimental procedures and subsequent analyses conducted throughout the course of this study, it was reported that ACW functions as a mineralizer, expediting the reactions within the clinker formation process and augmenting the proportion of alite (C₃S) present in the resulting clinker. Furthermore, it was observed that the integration of ACW facilitated a reduction in the utilization of approximately 73.70% of limestone and 86.80% of clay in the composition of the raw material blend employed in the manufacturing process of Portland clinker. It was reported that the utilization of up to 74% ACW in the production of eco-efficient cement through experimental means offers a viable solution from both technical and environmental perspectives. This approach not only ensures the safe disposal of hazardous waste, thereby eliminating its potential to cause cancer, but also has the potential to decrease CO₂ emissions by up to 13.68% and reduce energy consumption by 10.13%.

Based on the findings derived from the study conducted by Costa and Ribeiro [44], it can be inferred that the integration of the CCW technology has facilitated a reduction in the utilization of roughly 8% of limestone in the raw mix to produce Portland clinker. Consequently, its implementation has resulted in a decrease in the extraction of this natural resource. It was reported that utilizing CCW offers a potential reduction of up to 8.1% in CO₂ emissions per ton of clinker produced, solely accounting for decarbonation-related emissions. It was also stated that, when considering the entire process, including fuel combustion, the reduction amounts to 4.9% compared to clinker produced using conventional raw materials.

In summary, it is important to acknowledge that the implementation of ARMs in kiln feeds has the potential to decrease specific CO₂ emissions. However, the implementation of partial raw material substitution has been limited due to several limitations. The utilization of alternate materials in partial substitution of traditional clinker leads to a reduction in initial strength and a constrained quantity of limestone [292]. Conversely, coal fire is subject to ongoing regulatory limitations in Europe, hence posing increasing challenges in terms of accessing fly ash [81,110].

2.3. Replacement of MAs in Portland Cement

Due to the production of GHGs, a majority of concrete mixtures use SCMs either through the use of blended cements or by individually adding them to the mixer [217]. The incorporation of low-embodied carbon and low-energy elements in the substitution of Portland cement can significantly diminish the overall environmental consequences of binders and, as a result, of concrete [159,293]. These materials are commonly known as MAs or SCMs. When they are included into concrete and mixed with Portland cement, they create cementitious particles. However, on their own, they do not contain any cementitious compounds [217].

The selection of MAs for substituting Portland cement is contingent upon the geographical area and the specific solid waste or byproducts produced by industries or the presence of naturally occurring minerals in these regions [37]. The utilization of MAs as substitutes for Portland cement in concrete offers various sustainability benefits.

MAs typically consist of industrial waste products, natural pozzolans, and activated minerals that possess either hydraulic or pozzolanic characteristics. When MAs are used alone or in contact with water, they generally do not exhibit substantial hydraulic reactions that contribute to the cementitious properties. Nevertheless, when exposed to alkaline aqueous conditions or in the presence of calcium hydroxide, fine particles undergo a chemical process known as the pozzolanic reaction. This reaction leads to the formation of hydration products that resemble those seen in Portland cement systems [200,294,295].

A wide variety of materials are available for use as MAs, including natural MAs (volcanic materials, including tuffs, ashes, pumicites, perlites, zeolites, etc.), calcined natural MAs (calcined kaolinite clay or metakaolin), LC3 materials (limestone calcined clay cement), by-product materials (agricultural wastes, CDW, ashes, glass, ferrous slags, non-ferrous slags, basic oxygen furnaces, and electric arc furnaces) [200,295–298].

The substitution of Portland cement with solid waste derived from various economic sectors has been extensively investigated in numerous studies as a promising alternative. These studies aim to identify optimal circumstances for such replacements, considering the necessary features for their effective application.

Some of the waste, by-products, recycled materials, and natural resources used as an addition or as a partial replacement of Portland cement to produce concrete are presented in Table 4.

Table 4. Minerals used as an addition or partial replacement for Portland cement to produce concrete.

MA	Mix Type	Optimum Substitution (wt.%)	References
Agricultural Industry			
Sugarcane bagasse ash (SCBA)	Ordinary concrete	<25	[299–308]
	Eco-friendly concrete	<30	[309–311]
	Self-compacting concrete	15	[312]
	Ultra-high-strength concrete	15–30	[313–315]
Rice husk ash (RHA)	Ordinary concrete	10–25	[80,316–319]
	Eco-friendly concrete	5–15	[320–324]
	Self-compacting concrete	5–15	[325–327]
	Ultra-high-performance concrete	20	[328,329]
	Pervious concrete	10–15	[330]
Wood waste ash (WWA)	Recycled aggregate concrete	20	[331,332]
	Ordinary concrete	10	[333–337]
Palm oil fuel ash (POFA)	Self-compacting concrete	10	[338]
	Ordinary concrete	10–20	[339–341]
	Eco-friendly structural foamed concrete	25	[342]
	Lightweight concrete	10–15	[343]
	Sustainable lightweight foamed concrete	20	[344]
	Sustainable foamed concrete	15	[345]
	Self-compacting concrete	<70	[346–349]
	Self-consolidating high-strength concrete	<50	[350,351]
	Structural lightweight aggregate concrete	37.5	[352]
Recycled aggregate concrete	20	[331,332]	
Palm oil clinker powder (POCP)	Environmentally friendly lightweight concrete	15	[353]
	Lightweight concrete	15	[354]
	Recycled aggregate concrete	15	[331,332]
Eggshell powder (ESP)	Ordinary concrete	10–15	[355–359]
	Green concrete	10–15	[16,323]
	Eco-friendly structural foamed concrete	5	[342]
	Sustainable foamed concrete	5	[345]
Olive waste ash (OWA)	Ordinary concrete	5	[360]
	High-strength concrete	5	[333]

Table 4. Cont.

MA	Mix Type	Optimum Substitution (wt.%)	References
Sawdust ash (SDA)	Ordinary concrete	5–20	[361,362]
	Self-compacting concrete	10	[363,364]
Coconut shell ash (CNSA)	Ordinary concrete	10	[365,366]
Wheat straw ash (WSA)	Ordinary concrete	5	[317]
Nano-POFA	Ordinary concrete	10–20	[367]
	Lightweight concrete	15	[354]
Nano-POCP	Semi-lightweight concrete	10	[368]
Nano-ESP	Ordinary concrete	12.5	[367]
	High-strength concrete	5	[369]
Aquacultural Industry			
Seashell powder (SSP)	Ordinary concrete	5–15	[370–373]
	High-strength concrete	5	[374]
Oyster shell powder (OSP)	Ordinary concrete	5–15	[375]
	Green concrete	<20	[376]
Periwinkle shell (PS)	Ordinary concrete	5	[377]
Scallop shell (SLS)	Ordinary concrete	<10	[378]
Manufacturing Industry			
Red ceramic waste (RCW)	Structural concrete	20–40	[379]
Ceramic waste powder (CWP)	Ordinary concrete	10–20	[380]
	Self-consolidating concrete	15	[381]
	High-performance concrete	25–35	[382,383]
Recycled glass powder (RGP)	Ordinary concrete	10–20	[384–391]
	Environmentally friendly concrete	25	[392,393]
	Self-compacting concrete	24	[394]
Fly ash (FA)	Ordinary concrete	30	[395,396]
	Self-compacting concrete	10–55	[325,397]
	Pervious concrete	10–15	[330]
	High-performance concrete	30	[398,399]
Granulated blast-furnace slag (GGBFS)	Ordinary concrete	<50	[400]
	Recycled aggregate concrete	<20	[401]
Steel slag (SS)	Ordinary concrete	20	[402]
	High-early-strength concrete	30	[403]
Silica fume (SF)	Ordinary concrete	10	[358]
	Self-compacting concrete	10	[325]
	Recycled aggregate concrete	10	[401]
Porcelain Tile Polishing Residue (PPR)	Ordinary concrete	10–40	[404]
	Self-compacting concrete	25	[405]
Electric Arc Furnace Dust (EAFD)	Ordinary concrete	10	[406]
Red mud (RM)	Ordinary concrete	12	[407]
	Sustainable concrete	10–15	[408]
Sewage sludge ash (SSA)	Ordinary concrete	10	[409]
Waste marble dust (WMD)	Ordinary concrete	<15	[318,410,411]
	High-strength concrete	15	[412]
Titanium dioxide (TiO ₂) nanoparticles	Blended cement concrete	3	[413]
Coal bottom ash (CBA)	Sustainable concrete	15	[414]
Copper Slag (CS)	Ordinary concrete	10	[396,415]
Foundry sand waste (FSW)	Ordinary concrete	<30	[416,417]
Polyvinyl chloride (PVC) waste powder (WP)	Green concrete	15–20	[296]

Table 4. Cont.

MA	Mix Type	Optimum Substitution (wt.%)	References
Others			
Limestone powder (LP)	Self-consolidating concrete	55	[397]
	Ultra-high-performance concrete	54	[418]
Metakaolin (MK)	High-performance concrete	10	[399]
Volcanic ash (VA)	Ordinary concrete	10–15	[419]
Crushed rock dust (CRD)	Ordinary concrete	20	[294]
Municipal solid waste incineration ash (MSWI)	Ordinary concrete	<12	[297,420]

As presented in Table 4, MAs such as sugarcane bagasse ash, rice husk ash, palm oil fuel ash, seashell powder, recycled glass powder, ceramic waste powder, fly ash, granulated blast-furnace slag and limestone powder can be used in amounts as high as 30%, 25%, 70%, 20%, 25%, 35%, 55%, 50%, and 55% respectively as replacements for Portland cement for various types of concrete production.

Nevertheless, the slow rate at which strength is developed in concrete that incorporates MAs remains a significant obstacle. The utilization of MAs in concrete is accompanied by significant quality control issues, mostly stemming from the diverse chemical and physical properties exhibited by MAs. These properties are influenced by factors such as the source and location of the materials, further complicating the task of ensuring consistent quality in concrete production [37,292].

CO₂ Reduction through the Partial Replacement of Portland Cement with MA

CO₂ reduction by the partial replacement of Portland cement with MAs is reviewed for two cases: first for binary blended cements in Table 5, and second for ternary blended cements in Table 6.

Table 5. CO₂ reduction through the partial replacement of Portland cement with AM (binary blended cements).

Reference	MA	Mix Type	Amounts of Substitution (wt.%)	Optimum Substitution (wt.%)	Results for CO ₂ Emissions
[421]	Biochar rice husk (BRH)	Ordinary concrete	5, 10, 15, 20	Not stated	Global warming values (kg CO ₂ eq) for BRH0%, BRH5%, BRH10%, BRH15% and BRH20% are 2.51×10^{-5} , 2.41×10^{-5} , 2.3×10^{-5} , 2.2×10^{-5} , and 2.1×10^{-5} respectively.
[366]	CNSA	Ordinary concrete	5, 10, 15, 20	10	The embodied carbon of 5%, 10%, 15%, and 20% CSA is 4%, 7%, 11%, and 15% lower than that of the control mix.
[422]	RHA	Calcium aluminate cement concrete	2.5, 5, 7.5, 10	5	5%RHA could reduce CO ₂ emissions by 18.75%.
[307]	SDA	Ordinary concrete	5, 10, 15, 20	<20	Embodied carbon (kg CO ₂ /kg) for SDA is 0.0014. The embodied carbon of concrete mixtures incorporating 20% SDA is approximately 20% lower than that of the concrete mixtures incorporating PC as the only binder.
[307]	SCBA	Portland fly ash cement concrete	50, 60, 70	50	The CO ₂ -eq intensity values of control mix, BA50, BA60 and BA70 concretes were 9.65, 6.17, 6.73, and 7.67 kg CO ₂ M-3/MPa, respectively. The best environmental assessment results occur when the SCBA substitution rate is 80%. The global warming potential data decreased by 17.47%.
[317]		Ultra-high-performance concrete	20, 40, 60, 80	60	

Table 5. Cont.

Reference	MA	Mix Type	Amounts of Substitution (wt.%)	Optimum Substitution (wt.%)	Results for CO ₂ Emmissions
[382]	Ceramic	Ultra-high-performance concrete	15, 25, 35, 45, 55	25–35	Compared to UHPC without CTWP, the energy intensity, and CO ₂ emissions of UHPC with 55% CTWP were reduced by 41.0% and 33.1%, respectively.
[423]	CLBA	Ordinary concrete	10, 20, 30, 40	<40	CO ₂ released from limestone calcination is 0.37 kg for the control sample (CAC0), 0.33 kg for CAC10, 0.29 kg for CAC20, 0.26 kg for CAC30, and 0.22 kg for CAC40.
[396]		Green structural concrete	20, 40, 60, 80, 98	<80	Compared to commercial Grade 45 concrete, the proposed concrete shows a reduction in CO ₂ emission of around 70%.
[398]	FA	High-strength concrete	30, 40	30–40	The replacement of FA0 with FA30 and FA40 could potentially reduce the carbon footprint by 22.1% and 21.9% per m ³ of concrete, respectively.
[424]		Ordinary concrete	25	25	Fly ash was found to be capable of reducing concrete CO ₂ emissions by 13% to 15% in typical concrete mixes.
[424]	GGBFS	Ordinary concrete	40	40	Replacing 40% of GGBS with Portland cement in 25 or 32 MPa concrete outputs results in a 22% reduction in CO ₂ emissions.
[404]		Ordinary concrete	10, 20, 30, 40, 50	10–30	For a compressive strength of 54 MPa at 91 days, the emission was reduced from 564 kg CO ₂ -eq/m ³ of concrete for the reference mixture to 473 kg CO ₂ -eq/m ³ of concrete (i.e., 16%) for 30% replacement and to 349 kg CO ₂ -eq/m ³ of concrete (i.e., 38%) for 50% addition.
[405]	PPR	Self-compacting concrete	10, 20, 30	<20	For a compressive strength of 70 MPa, the incorporation of PPR would reduce the emission of CO ₂ -eq/m ³ of concrete by up to 17% when incorporating 127 kg of the residue per m ³ of concrete.
[425]	SF	High-strength concrete	8, 10, 12	12	The climate change index for reference concrete is 534.26 kg CO ₂ eq. Values for HSC-SF8, HSC-SF10, and HSC-SF12 are 520.75, 495.11 and 453.15, respectively.
[425]	Nano silica (NS)	High-strength concrete	1, 2, 3	2	The climate change index for reference concrete is 534.26 kg CO ₂ eq. The climate change index for HSC-NS1, HSC-NS2, and HSC-NS3 is 438.55, 426.70, and 415.56, respectively.
[348]		Self-compacting concrete	50, 60, 70	50–70	The concrete specimens have up to 32–45% reduced carbon dioxide emissions.
[343]	POFA	Lightweight concrete	5, 10, 15, 20, 25	10–15	Total CO ₂ emission values for mixes M0, M5, M10, M15, M20, and M25 were 0.477, 0.454, 0.430, 0.407, 0.384, and 0.361 CO ₂ -e/m ³ , respectively.
[426]	Limestone	Ordinary concrete	35–65	<50	The production of concretes made of limestone-rich cements exhibited roughly 25% less CO ₂ emissions.
[397]		Self-compacting concrete	15, 25	<25	For control mix, CO ₂ -eq is 5.69 × 10 ² kg/m ³ . For 15% and 25% replacement levels, CO ₂ -eq is 4.87 × 10 ² and 25 4.34 × 10 ² , respectively.

Table 6. CO₂ reduction through partial replacement of Portland cement with AM (ternary blended cements).

Reference	MAs	Mix Type	Amounts of Substitution (wt.%)	Optimum Substitution (wt.%)	Results for CO ₂ Emissions
[427]	Brick dust (BD) and LP	Plain cement concrete	BD/LP: 15/5, 10/10, 7/13, 5/15	15/5	Using PL and BD can save costs of cement in the range of 7–12.5%, which eventually reduces CO ₂ .
[428]	Biomass fly ash (BFA) and coal fly ash (CFA)	Ordinary concrete	BFA/CFA: 10/10, 20/20, 30/30	30/30	GWP impact values (kg CO ₂ eq) are 7.84×10^2 for the control mix, 6.62×10^2 for 10/10, 5.38×10^2 for 20/20, and 4.15×10^2 for 30/30.
[429]	SCBA and CSA	Ultra-high-strength concrete	SBA/CSA: 10/2, 20/2, 30/2, 10/4, 20/4, 30/4, 10/6, 20/6, 30/6, 10/8, 20/8, 30/8	20/4	Considering the cost/MPa, the results show that the use of 20/4 had a higher lower cost per m ³ in comparison with all concrete mixture. The reduction in concrete cost was 18.50% compared to the control mix.
[430]	Corn cob ash (CCA) and glass powder (GP) as binary cementitious material (BCM)	Ordinary concrete	CCA/GP: 2.5/2.5, 5/5, 7.5/7.5, 10/10	5/5	Concrete mixtures incorporating 5%, 10%, 15%, and 20% BCM as partial replacement of Portland cement have 4.3%, 8.3%, 12.7%, and 16.8% lower embodied carbon control than the mixtures without BCM. Similarly, the incorporation of BCM into the mixtures led to a reduction of approximately 21% in the embodied energy of the concrete.
[392]	Mixed cathode ray tubes (CRT) and mixed-container glass (MRF)	Ordinary concrete	MRF/CRT: 17/3	17/3	The GWP value is 1040 kg CO ₂ -eq. for the control mix and 849 kg CO ₂ -eq for 17/3.
[342]	POFA and ESP	Eco-friendly structural foamed concrete	POFA/ESP: 20/5, 20/10, 20/15, 25/5, 25/10, 25/15	25/5	CO ₂ emissions (kg CO ₂ /m ³) are 453.97 for control mix, 358.29 for 20/5, 339.61 for 20/10, 320.93 for 20/15, 339.04 for 25/5, 320.36 for 25/10, and 301.68 for 25/15.
[431]	Cane bagasse ash (CBA) and waste glass (WG)	Green concrete	CBA/WG: 15/5, 10/10, 5/15	15/5	Replacement of 20% of cement with CBA and WG showed reductions in CO ₂ emissions of about 20% compared to control mix.
[311]	SCBA and SF	Ecofriendly ternary concrete	SCBA/SF: 10/10, 20/20, 30/30, 40/40, 50/50	30/30 and 20/20	The use of ETC concretes has a very significant sustainability impact by contributing to the reduction in CO ₂ emissions caused by Portland cement.
[432]	Limestone filler (LSF), calcined orange illitic clay (OIC), natural pozzolan (NP) and GGBS	Ordinary concrete	LSF/OIC: 20/7.5, LF/NP: 12.4/12.6, LF/GGBS: 6/22; 11/11	20% of LF	CO ₂ emissions (kg CO ₂ /m ³) for control mix is 399.8, 378.6 for 20/7.5, 380.6 for 12.4/12.6, 322.6 for 6/22, 341.7 for 11/11.
[397]	FA and LP	Self-consolidating concrete	FA/LP: 30/15, 40/15, 50/15, 60/15, 20/25, 30/25, 40/25, 50/25	<50%	CO ₂ -eq (kg/m ³) for control mix is 5.69×10^2 , 3.33×10^2 for 30/15, 2.82×10^2 for 40/15, 2.32×10^2 for 50/15, 1.83×10^2 for 60/15, 3.32×10^2 for 20/25, 2.81×10^2 for 30/25, 2.31×10^2 for 40/25, 1.82×10^2 for 50/25.

Beside the studies presented in Table 5 and 6, there have been commentary research on CO₂ reduction by partly replacing Portland cement with different supplementary cementing materials.

Soliman and Tagnit-Hamou [433], as well as Rajendran et al. [434], reported that the substitution of 20%w.t. glass powder can significantly reduce the cost of ultra-high-strength concrete and decrease the carbon footprint of a typical ultra-high-strength concrete.

In their study, Soltanzadeh et al. [435] conducted an evaluation of the potential use of waste seashells in the manufacturing of blended cement. The findings suggest that the utilization of seashell powder as a substitute for Portland cement in the production of blended cements has the potential to improve sustainability and reduce production costs.

In a study conducted by Qin et al. [436], pervious concrete samples were examined, wherein a fraction of the Portland cement was substituted with crushed biochar. Based on the results of the study, the researchers hypothesized that it is possible to reduce CO₂ emissions by making pervious concrete by the substitution of powdered biochar for up to 6.5% of the cement's weight.

For the studies presented in this section, it should be noted that a significant reduction in CO₂ emissions can be achieved by utilizing MAs as a substitute for Portland cement, which in turn leads to a decrease in cement consumption and subsequently lower cement output. Furthermore, the decrease in the disposal of non-biodegradable materials in landfills leads to the preservation of limited landfill capacity and mitigates the unsustainable consequences associated with waste disposal in open areas.

2.4. Substitution of CDW as a MA

Concrete, masonry, and brick wastes are prominent among the various waste fractions, exhibiting a significant proportion of approximately 80% in the overall global production of CDW [66,437–439]. Researchers have proposed the recycling of this prominent part to serve as a viable solution to address the sustainability issues encountered by the concrete industry [71,440–446].

The recycling process involves the conversion of CDW into a reduced-sized fraction through the utilization of mobile or fixed recycling plants [447]. The recycling process of CDW primarily results in the production of three distinct fractions [84,448–450]. One of these fractions includes a range of 25.00–5.00 mm, which is classified as recycled coarse aggregate (RCA). Another fraction falls within the range of 5.00–0.15 mm and is referred to as recycled fine aggregates (RFA). Lastly, there is a fraction that measures less than 0.15 mm, known as recycled powder (RP).

It is important to highlight that in addition to the production of recycled coarse and fine aggregates, a significant quantity of fine recycled powder (RP), comprising approximately 15–35% of the total processed CDW mass, is generated [448,449]. This fine powder lacks a suitable destination and is typically disposed of in landfills [441,451]. The particulate matter emanating from cement mortar, concrete, or bricks typically has a fine texture. The observed range of diameters for the hybrid powder obtained from the crushing and sieving location of CDW was found to vary between 45 and 150 µm [441].

Although the application of RCA has gained increasing popularity in the past years, the possible use of RP as a partial replacement for Portland cement in concrete has received significant attention due to its tiny particle size and consequential reactivity [452].

Nevertheless, the efficacy of RPs is contingent upon their primary sources, which are impeded in their practical implementation due to their intricate components. When comparing RPs to Portland cement, it is observed that RPs exhibit a greater degree of irregularity and roughness in their shapes. Additionally, the little particles tend to cluster on the larger ones, resulting in a higher water consumption requirement to obtain a desired standard consistency [439,452].

The primary factor impeding the utilization of untreated RP derived from CDW in cementitious materials is its inherent low activity. The untreated powder is primarily comprised of inert hydrated materials, namely quartz or calcite [439,445].

Several modification approaches have been devised to enhance the characteristics of untreated RP, including mechanical activation [453,454], CO₂ curing treatment [455–458], thermal treatment [445,459–461], tannic acid treatment [462], and chemical activators [463].

CDW-based material additions used as an addition or as a partial replacement of Portland cement to produce concrete are presented in Table 7.

Table 7. Substitution of CDW in Portland cement to produce concrete.

Reference	CDW Type	Mix Type	Materials Used in the Mix	Treatment Method	Particle Size or Median Particle Size of CDW (d50)	Amount of Substitution (wt.%)	Optimum Substitution (wt.%)
[464]	Dehydrated cement paste (DCP)	Green ultra-high-performance concrete	Cement (PO 52.5), DCP, LP, SF, sand, superplasticizer (SP).	Heating	<75 μm	12.5, 25, 37.5, 50	<25
[444]	RP	Ordinary concrete	Cement (OPC), RP, natural coarse aggregate (NCA), natural fine aggregate (NFA).	Repeated recycling	<150 μm	10, 20, 30	10–20
[465]	Ground recycled concrete (GRC)	Structural concrete	Cement (OPC), GRC, mixed recycled CDW aggregate.	NA	Not stated	10, 25	10
[466]	Recycled brick powder (RBP)	Ultra-high-performance concrete	Cement (P.II 52.5R), RBP, SF sand, SP.	NA	d50: 9.8 μm	15, 30, 45	15
[439]	RP	Ordinary concrete	Cement (OPC), RP, FA, sand, NCA, water reducing agent.	NA	d50: 9.06 μm	15, 30, 45	15–30
[467]	Waste brick powder (WBP)	Ordinary concrete	Cement (OPC-Grade C-53), WBP, natural aggregate (NA), sand.	NA	<75 μm	5, 10	10
[468]	Recycled concrete powder (RCP)	Green ultra-high-performance concrete	Cement (P.II 52.5R), RCP, SF, sand, SP.	NA	d50: 12.04 μm	15, 30, 45	30
[469]	RP	Green concrete	Cement (PO 42.5), RP (brick powder and concrete powder), NA, RA, river sand, SP.	NA	d50: 17.15 μm	15, 30, 45	15
[470]	Humid hardened concrete waste (HHCW)	Ordinary concrete	Cement (OPC- PI 52.5), HHCW, FA, GGBFS, machine-made sand, river sand, crushed stone, SP.	Multiple wet grinding	d50: 26.5 μm , 5.71 μm , and 2.52 μm	5, 10, 15	HHCWS of 2.52 μm at the dosage of 10%
[471]	Ground recycled masonry aggregate (GR-RMA)	Ordinary concrete	Cement (CEM I 42.5 R OPC), GR-RMA, NA, MRA, natural sand, SP.	NA	Not stated	25	25% GR and 25–50% MRA
[472]	RCP	Ordinary concrete	Cement (CEM I 42.5), RCP, NA, SP.	NA	d50: 22 μm	10, 20, 30, 40, 50	<10%
[473]	RP	Sustainable concrete	Cement (OPC), RP (RCP, RBP), NCA, NFA, FA, GGBFS, air entrainer admixture, water reducer admixture.	NA	d50: RCP: 11.8 μm , RBP: 13.4 μm	20	RBP can provide equivalent strength and even better durability.
[474]	WP	WP concrete	Cement (OPC), WP (mixture of waste concrete and bricks), NA, sand.	NA	d50: 12.54 μm	15, 30, 45	15
[475]	RP	Reactive powder concrete	Cement (PO 42.5), RP (abandoned clay bricks and cement solids), SF, SP.	NA	d50: 31.4 μm	5, 10, 15, 25	10
[476]	Waste concrete powder (WCP)	Self-consolidating concrete	Cement (OPC), WCP, GGBFS, NCA, NFA, SP.	NA	d50: 90 μm	15, 30, 45	15
[477]	RP	Ordinary concrete	Cement (OPC), RP (80% fired brick and 20% waste concrete), NA, sand, water reducer.	NA	<75 μm	15, 30, 45	<30%
[478]	Waste brick powder (WBP)	Ordinary concrete	Cement (type II OPC), WBP, NCA, sand.	NA	d50: 45 μm	10, 15, 20, 25, 30, 40	<20%
[479]	Cement kiln dust (CKD)	Ordinary concrete	Cement (ASTM C 150 Type I and Type V), CKD, NCA, sand.	NA	not stated	5, 10, 15	5

Table 7. Cont.

Reference	CDW Type	Mix Type	Materials Used in the Mix	Treatment Method	Particle Size or Median Particle Size of CDW (d50)	Amount of Substitution (wt.%)	Optimum Substitution (wt.%)
[480]	CKD	Self-consolidating Concrete	Cement (OPC Type I), CKD, NCA, sand, SP.	NA	not stated	10, 20, 30, 40	20
[449]	RP	Sustainable recycled concrete	Cement (PO42.5), RP, FA, NCA, NFA, river sand, SP.	NA	<45 μm	15, 30	15
[481]	Ceramic (fired clay-based) fraction of CDW	Structural concrete	Cement (CEM I 42.5 R), ceramic (fired clay-based) fraction of CDW, NCA, RA, sand, SP.	NA	not stated	25, 50	25
[482]	CKD	High performance self-compacting concrete	Cement (OPC), CKD, NCA, mineral sand, SP.	NA	<50 μm	10, 20, 30	<10%
[483]	Burnt clay and CKD	Blended concrete	Cement (OPC), burnt clay and CKD, NCA, NFA.	NA	<75 μm	10, 20, 30, 40	<20%CKD
[484]	CKD	Ordinary concrete	Cement (cement of Indian Standards (IS) mark 43 grade), CKD, NCA, NFA.	Bacterial treatment	not stated	5, 10, 15	10%
[485]	Clay brick powder (CBP)	Ordinary concrete	Cement (OPC), CBP (Recycled construction waste), natural sand.	NA	d50: 300 μm , 100 μm , 60 μm and 40 μm	10, 20, 25, 30	10%
[486]	Construction waste composite powder	Small-scale prefabricated concrete	Cement (42.5 OPC), CWBP (building demolition waste), NCA, sand.	NA	d50: 8–16 μm	20, 30, 40	30
[487]	GRC	Ordinary concrete	Cement (CEM I 42.5 R), GRC, NCA, MRA.	NA	<147 μm	10, 25	25
[488]	CKD	Green concrete	Cement (OPC Type II), CKD, FA, river sand, NCA, SP.	NA	<45 μm	10, 15, 20, 30, 40	<20%
[489]	CBP	Ordinary concrete	Cement (OPC), CBP (mainly, bricks and tiles), NA, recycled gravel.	NA	<63 μm	25	25

2.4.1. CO₂ Reduction by the Partial Replacement of Portland Cement with CDW

Studies conducted regarding CO₂ reduction by the partial replacement of Portland cement with CDW and chemical properties of cementitious materials used in these studies are presented in Tables 8 and 9.

Table 8. Chemical properties of cementitious materials used (%).

Reference	Cementitious Material Type	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	Loss-on-Ignition (LOI)
[464]	OPC	19.383	4.581	3.282	63.074	2.786	0.175	1.027	3.498	1.540
	DCP	19.967	4.997	4.125	62.405	1.849	0.137	0.781	2.949	2.261
[465]	OPC	18.700	5.100	2.600	65.100	1.800	0.200	0.500	3.000	2.500
	GRC	46.100	3.800	1.500	40.000	0.500	0.300	1.200	0.400	6.200
[467]	WBP	36.510	23.440	15.140	4.530	-	-	1.510	-	4.520
[468]	OPC	23.770	4.960	4.130	60.320	2.680	0.320	0.620	2.260	2.380
	RCP	39.830	12.500	6.010	18.660	1.970	0.850	2.340	2.040	16.750
[469]	OPC	19.240	4.080	3.250	62.470	4.190	-	-	4.810	-
	Brick powder	65.240	18.080	4.250	1.470	2.190	-	-	0.340	-
	Concrete powder	31.850	7.040	4.840	48.950	1.850	-	-	0.780	-
[470]	OPC	20.040	4.198	3.365	63.058	1.930	0.092	0.748	3.276	2.653
	HHCW	29.689	7.948	2.453	31.713	2.728	0.842	1.078	0.685	21.986
[471]	GR-RMA	60.000	19.000	6.000	-	-	-	-	-	-

Table 8. Cont.

Reference	Cementitious Material Type	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	Loss-on-Ignition (LOI)
[473]	OPC	21.300	3.200	2.900	64.300	2.100	0.260	0.420	3.100	1.350
	RCP	51.000	10.130	5.360	26.310	1.380	1.230	1.780	1.940	9.900
	RBP	69.870	20.980	3.610	0.400	0.390	0.590	2.420	0.330	0.980
[449]	OPC	19.900	4.420	3.560	64.900	0.660	0.080	0.790	2.670	-
	RP	57.010	10.930	3.450	21.300	1.820	1.580	2.220	1.170	-
[488]	OPC	21.700	5.100	3.400	65.000	1.400	0.300	0.550	1.500	1.050
	CKD	11.690	3.250	2.400	44.900	0.800	0.290	0.500	0.000	36.000

Table 9. CO₂ reduction by the partial replacement of Portland cement with CDW.

Reference	Label	Proportions	w/b ^a	SP ^b	28 d Compressive Strength (MPa)	CO ₂ Emission (kg/m ³)	Global Warming Potential (GWP)
[464] ^c	DCP0	Control mix	0.5	33.00	105.00	377.00	1.000
	DCP50	12.5%DCP1	0.5	33.00	102.00	337.00	0.894
	DCP100	25%DCP1	0.5	33.00	100.50	298.00	0.790
	DCP150	37.5%DCP1	0.5	33.00	95.50	258.00	0.684
	DCP200	50%DCP1	0.5	33.00	83.00	219.00	0.581
[444] ^c	NAC	Control mix	0.45	-	36.80	-	1.000
	RP1	10%RP	0.45	-	36.00	-	0.980
	RP1	20%RP	0.45	-	33.50	-	0.950
	RP1	30%RP	0.45	-	27.00	-	0.930
	RP2	10%RP	0.45	-	35.50	-	0.950
	RP2	20%RP	0.45	-	32.00	-	0.900
	RP2	30%RP	0.45	-	27.50	-	0.850
	RP3	10%RP	0.45	-	34.00	-	0.930
	RP3	20%RP	0.45	-	31.50	-	0.850
RP3	30%RP	0.45	-	27.50	-	0.780	
[465]	NAC	Control mix	0.56	1.0–1.5%	46.60	269.83	1.000
	N10/0	10%GRC	0.58	1.0–1.5%	37.80	249.65	0.925
	N25/0	25%GRC	0.60	1.0–1.5%	27.70	218.43	0.810
	R0/50	0%GRC, 50% RA-CDW	0.59	1.0–1.5%	34.80	267.10	0.990
	R10/50	10%GRC, 50% RA-CDW	0.61	1.0–1.5%	32.80	246.94	0.915
	R25/50	25%GRC, 50% RA-CDW	0.63	1.0–1.5%	23.30	216.70	0.803
[468] ^c	RCP0	Control mix	0.16	41.64	100.00	502.63	1.000
	RCP15	15%RCP	0.16	40.06	82.80	501.75	0.998
	RCP30	30%RCP	0.16	39.08	96.10	500.86	0.996
	RCP45	45%RCP	0.16	37.13	88.30	499.27	0.993
[469]	RAPC-0-0	Control mix	0.49	0.14	39.04	-	1.000
	RAPC-0-15	15%RP	0.49	0.16	40.12	-	0.850
	RAPC-0-30	30%RP	0.49	0.17	35.45	-	0.710
	RAPC-0-45	45%RP	0.49	0.16	30.27	-	0.560
	RAPC-30-0	30%RA + 0%RP	0.49	0.14	41.17	-	1.000
	RAPC-30-15	30%RA + 15%RP	0.49	0.16	43.29	-	0.850
	RAPC-30-30	30%RA + 30%RP	0.49	0.17	37.45	-	0.700
	RAPC-30-45	30%RA + 30%RP	0.49	0.16	31.32	-	0.560
	RAPC-50-0	50%RA + 0%RP	0.49	0.14	36.44	-	0.990
	RAPC-50-15	50%RA + 15%RP	0.49	0.16	37.28	-	0.850
	RAPC-50-30	50%RA + 30%RP	0.49	0.17	33.56	-	0.700
	RAPC-50-45	50%RA + 45%RP	0.49	0.16	29.56	-	0.550
	RAPC-100-0	100%RA + 0%RP	0.49	0.14	33.26	-	0.990
	RAPC-100-15	100%RA + 15%RP	0.49	0.16	35.18	-	0.840
	RAPC-100-30	100%RA + 30%RP	0.49	0.17	28.36	-	0.690
RAPC-100-45	100%RA + 30%RP	0.49	0.16	22.79	-	0.550	

Table 9. Cont.

Reference	Label	Proportions	w/b ^a	SP ^b	28 d Compressive Strength (MPa)	CO ₂ Emission (kg/m ³)	Global Warming Potential (GWP)
[471]	CC	Control mix	0.45	6.20	51.2	407.00	1.000
	C25	0%CDW + 25% MRA	0.45	6.20	51.7	399.00	0.980
	C50	0%CDW + 50% MRA	0.45	6.20	51.1	351.00	0.862
	R25/0	25%CDW	0.45	6.20	46.1	335.00	0.823
	R25/25	25%CDW + 25% MRA	0.45	6.20	45.7	327.00	0.803
	R25/R50	50%CDW + 50% MRA	0.45	6.20	41.2	319.00	0.784
[472]	RCP0	Control mix	0.55	3.00	51.60	333.00	1.000
	RCP10	10%RCP	0.55	3.00	41.30	304.00	0.913
	RCP20	20%RCP	0.55	3.00	31.70	275.00	0.826
	RCP30	30%RCP	0.55	3.00	22.80	246.00	0.739
	RCP40	40%RCP	0.55	3.00	13.60	217.00	0.652
	RCP50	50%RCP	0.55	3.00	10.00	188.00	0.565
[449] ^d	Control	Control mix	0.36	2.16%	877.30	367.50	1.000
	RP1	15%RP	0.36	2.84%	613.92	325.00	0.884
	RP2	30%RP	0.36	3.52%	786.23	278.00	0.756
	RP3	15%RP + 15%FA	0.36	2.50%	1298.73	275.60	0.750
[488]	Ctrl-W37	Control mix	0.37	0.33	53.41	510.77	1.000
	C5W37	5%CKD	0.37	0.33	55.47	487.57	0.955
	C10W37	10%CKD	0.37	0.33	52.13	464.36	0.909
	C15W37	15%CKD	0.37	0.45	47.45	441.24	0.864
	C20W37	20%CKD	0.37	0.54	41.42	418.10	0.819
	C30W37	30%CKD	0.37	0.67	34.90	371.79	0.728
	C40W37	40%CKD	0.37	1.63	28.09	326.07	0.638
	Ctrl-W40	Control mix	0.40	0.00	52.23	476.71	1.000
	C5W40	5%CKD	0.40	0.00	49.52	457.94	0.961
	C10W40	10%CKD	0.40	0.00	43.24	433.78	0.910
	C15W40	15%CKD	0.40	0.00	37.97	412.32	0.865
	C20W40	20%CKD	0.40	0.00	36.93	390.85	0.820
	C30W40	30%CKD	0.40	0.33	34.94	348.16	0.730
	C40W40	40%CKD	0.40	0.67	28.79	305.48	0.641
	Ctrl-W45	Control mix	0.45	0.00	50.14	430.36	1.000
	C5W45	5%CKD	0.45	0.00	46.93	411.29	0.956
	C10W45	10%CKD	0.45	0.00	44.76	392.20	0.911
	C15W45	15%CKD	0.45	0.00	40.75	373.13	0.867
	C20W45	20%CKD	0.45	0.00	37.53	354.05	0.823
	C30W45	30%CKD	0.40	0.00	34.79	315.89	0.734
	C40W45	40%CKD	0.40	0.33	28.59	277.96	0.646
	C5F15W37	5%CKD + 15%FA	0.37	0.33	55.93	419.60	0.822
	C10F15W37	10%CKD + 15%FA	0.37	0.33	48.64	396.52	0.776
	C5F15W40	5%CKD + 10%FA	0.40	0.00	45.69	392.52	0.823
C10F15W40	10%CKD + 15%FA	0.40	0.00	46.44	371.28	0.779	
C5F15W45	5%CKD + 10%FA	0.45	0.00	44.19	355.83	0.827	
C10F15W45	10%CKD + 15%FA	0.45	0.00	40.03	336.44	0.782	

^a Water–binder ratio. ^b Superplasticizer; if % is not stated, the values are in kg/m³. ^c 28 day compressive stresses are approximately derived from the figure. ^d Static yield stresses (Pa) are given in the study.

In their study, Qian et al. [464] examined a viable approach to the production of environmentally friendly ultra-high-performance concrete (UHPC) through the integration of recycled concrete waste coarse aggregate material (RCWCM). By subjecting RCWCM to a heating treatment process, they produced DCP. Subsequently, DCP was employed in a progressive manner to substitute the Portland cement content, thereby being incorporated into the formulation of UHPC utilizing the modified Andreasen and Andersen particle packing model. The findings indicate that the substitution of up to 25% Portland cement with DCP does not significantly affect the compressive strength variation of UHPC. Moreover, the researchers utilized the EN ISO 14040 and EN ISO standards to evaluate the environmental impact of UHPC by employing the carbon footprint metric. To establish the sustainability and environmental cleanliness of the UHPC, this study undertook calculations to determine CO₂ emissions per unit of green UHPC with varying DCP levels. Additionally, the ratio of

CO₂ emissions to compressive strength per unit of green UHPC was also evaluated. From the results, it can be noticed that the inclusion of DCP yields advantageous outcomes in enhancing the performance of UHPC from a sustainability perspective.

The objective of the study carried out by Kim and Jang [444] was to examine the feasibility of closed-loop recycling for construction waste. Specifically, the focus was on examining the impact of utilizing concrete powder, which is a byproduct of producing recycled aggregates, on the fresh and hardened mechanical properties of concrete. The authors assert that concretes produced using recycled materials such as RCA, RFA, and RP exhibit a lower cost compared to natural coarse aggregate (NAC). However, it is important to note that these recycled concretes also have reduced compressive strength. Additionally, it was asserted that the utilization of RP as a substitute for Portland cement yields environmental advantages, including reductions in CO₂ emissions, the preservation of natural resources, and the mitigation of landfill usage.

Cantero et al. [465] examined the cumulative impact of using ground recycled concrete (GRC) as a Portland cement replacement along with the use of mixed recycled construction and demolition waste aggregate (RA-CDW) in the context of structural concrete. The mechanical performance of concrete mixes with GRC and recycled aggregate from CDW (RA-CDW) was shown to be inferior compared to mixes made solely with natural aggregate and cement. However, it is worth noting that the difference in performance was relatively smaller when considering the corresponding replacement ratios. The authors did not consider the emissions associated with manufacturing and transportation when assessing the environmental impact of the mixtures in terms of CO₂ emissions from materials. These emissions were considered smaller than those created during material manufacturing. In accordance with the provided statistics, the implementation of GRC resulted in a reduction in CO₂ emissions by 7.5% in N10/0, 18.7% in N25/0, 8.5% in R10/50, and 19.7% in R25/50. The utilization of GRC, in conjunction with RA-CDW, has been found to augment the environmental efficacy of concrete. When the replacement rate was set at 10%, the amount of CO₂ released during the manufacturing process of concrete decreased by 8.5% compared to concrete produced with OPC and 100% natural aggregates (NA). Similarly, when the replacement rate was increased to 25%, the greenhouse gas emissions associated with GRC decreased by 19.7% compared to OPC-based concrete with 100% NA.

The study conducted by He et al. [468] aimed to evaluate the influence mechanism of RCP on the multi-scale properties of UHPC mixtures. The findings of the study revealed that the UHPC combination with 30% RCP exhibited a comparatively reduced strain in early-age autogenous shrinkage, along with the highest mechanical characteristics. The reference parameters used by the authors to assess UHPC's positive environmental impact included the mixture's total carbon emissions and non-renewable energy consumption (NREC). The study demonstrates that there is a decrease in the NREC per cubic meter of UHPC mixture when the RCP substitution ratio increases. In parallel, it can be observed that the augmentation in the substitution proportion of RCP leads to a corresponding reduction in the carbon emissions per unit volume of UHPC mixture.

The objective of the study of Wu et al. [469] was to examine the characteristics of pore structure, carbonation, and chloride ion permeability in recycled aggregate-powder concrete (RAPC). The findings of the study indicate that there is a positive correlation between the replacement rate of recycled aggregate (RA) and both the carbonation depth and chloride ion permeability of RAPC. The research indicates that the inclusion of 15% RP resulted in the enhanced performance of RAC. This addition has effectively addressed the issue of by-products generated during the manufacturing of RA, leading to cost reduction and a reduction in the adverse environmental effects associated with RAC production.

The durability of a concrete mixture containing ground recycled masonry aggregate (GR-RMA) as a partial replacement for cement and coarse mixed recycled aggregate (MRA), both obtained from CDW, was examined by Cantero et al. [471]. The investigation involved the indirect characterization of pore system permeability by utilizing important indicators of water transport. Based on the results obtained from the defined scenario, it was determined

that the optimal combinations of mechanical efficiency and durability were observed in mixes with a 25% GR content as a replacement for Portland cement. Additionally, it was found that the mixes with the highest environmental benefits in terms of reducing CO₂ emissions were those that included both 25% GR and 25% to 50% MRA.

In the study done by Pešta et al. [473], the researchers evaluated the environmental viewpoints pertaining to the utilization of RCP as a substitute for Portland cement. The findings from the assessment of mechanical properties indicate that RCP exhibits favorable characteristics as a substitute for Portland cement, particularly in scenarios with a low degree of replacement. Furthermore, the findings of the environmental assessment provide confirmation that the implementation of RCP resulted in a decrease in the adverse effects of climate change, as well as potential effects in other related domains.

Singh et al. [449] examined the practical application of recycled fines (RFs), namely RFA and RP, in the context of recycled concrete. The investigation focused on evaluating the fresh qualities (empirical and rheological) of the recycled concrete. The findings indicated that the decrease in slump was more pronounced in the series with RFA compared to RP. According to the authors, the inclusion of RF in concrete mixtures not only enhances material performance but also presents notable environmental advantages, specifically in mitigating carbon emissions linked to the production of concrete.

Bagheri et al. [488] utilized varying quantities of CKD, a waste material, and FA, a pozzolanic material, as replacements for Portland cement, both alone and in combination. The comparison between the Taguchi technique and experimental outcomes for the purpose of picking the most advantageous mixture designs revealed that the Taguchi approach demonstrated appropriate selections within the range of optimal experimental results taking into consideration the initial parameters. Furthermore, the values for the cost and CO₂ emission factors of each plan were determined by considering the CO₂ production cost associated with each material and the corresponding size of said material inside the relevant plan. The observed decrease in cost of 23% resulting from the substitution of Portland cement with cement additions, alongside the concurrent reduction in volume within the C40W45 mixture, was found to be statistically significant. Additionally, it is worth noting that the CO₂ emission factor associated with the Ctrl-W37 value (510.8 kg/m³) exhibited a reduction of almost 50% when considering the C40F0W45 mixture (278 kg/m³).

2.4.2. Evaluation of CO₂ Emissions with Respect to Compressive Strength

For the studies presented in Table 9, the global warming potential (GWP) was calculated (Equation (2)) using the environmental parameter presented by Khodabakhshian et al. [490]. The GWP was formulated to quantify the alteration in the greenhouse effect resulting from human-caused emissions and absorptions.

$$GWP = (0.885 \times C) + (0.0032 \times A) + (0.0025 \times W) + (1.11 \times SP) \quad (1)$$

where C is the cement content of concrete (kg/m³), A is the aggregate content (kg/m³), W is the water content (kg/m³), and SP is the superplasticizer content (kg/m³).

Figures 2–10 display the collected data on the GWP of the produced concrete, as well as the ratio of GWP to compressive strength per unit of the concrete, for various levels of CDW content. The second measure indicated above corresponds to the quantity of GWP per unit of strength. A higher GWP/compressive strength ratio in the produced concrete indicates a bigger quantity of carbon dioxide generated during the production of concrete, provided that the compressive strength remains constant. Based on the results depicted in the figures, it is evident that the inclusion of CDW has a positive impact on enhancing the performance of concrete from a sustainability perspective.

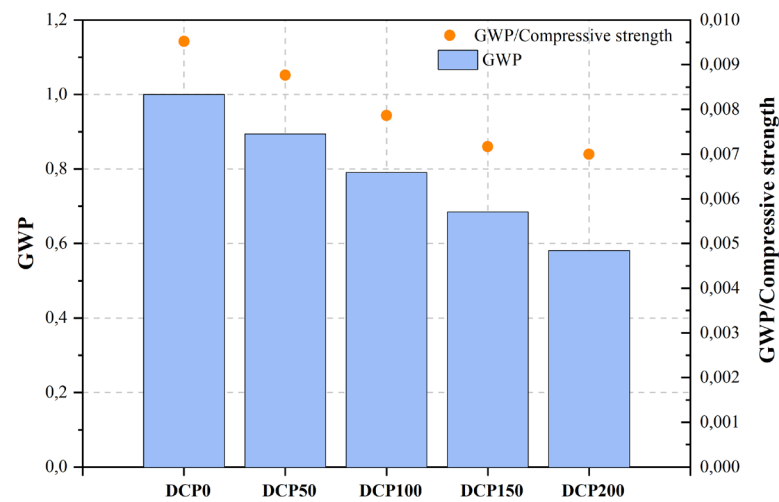


Figure 2. GWP and GWP/compressive strength ratio of the concretes developed by Qian et al. [464], (Data from Qian et al. [464]).

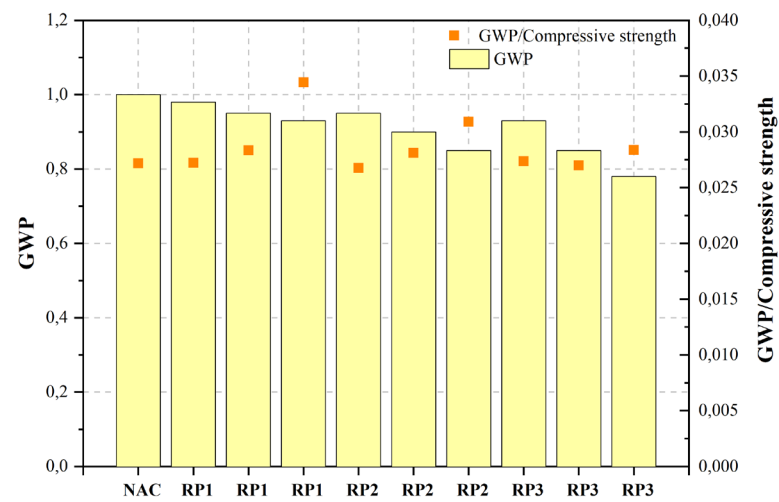


Figure 3. GWP and GWP/compressive strength ratio of the concretes developed by Kim et al. [444], (Data from Kim et al. [444]).

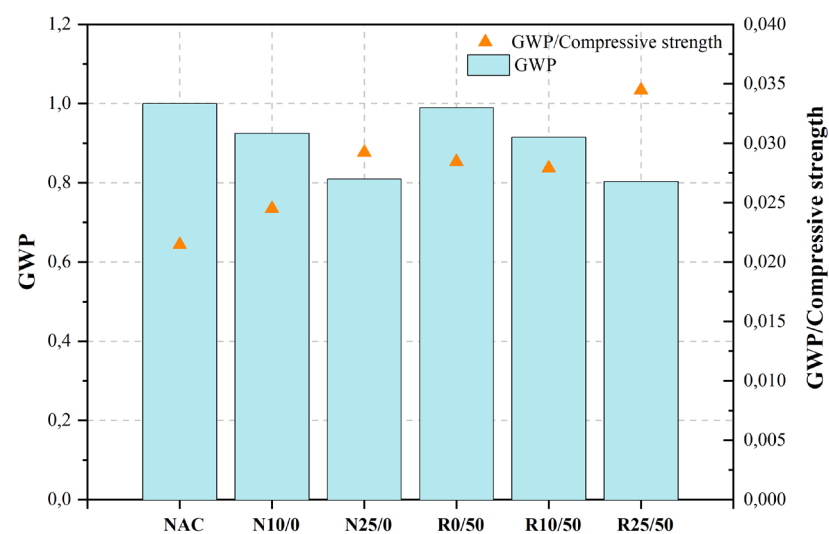


Figure 4. GWP and GWP/compressive strength ratio of the concretes developed by Cantero et al. [465], (Data from Cantero et al. [465]).

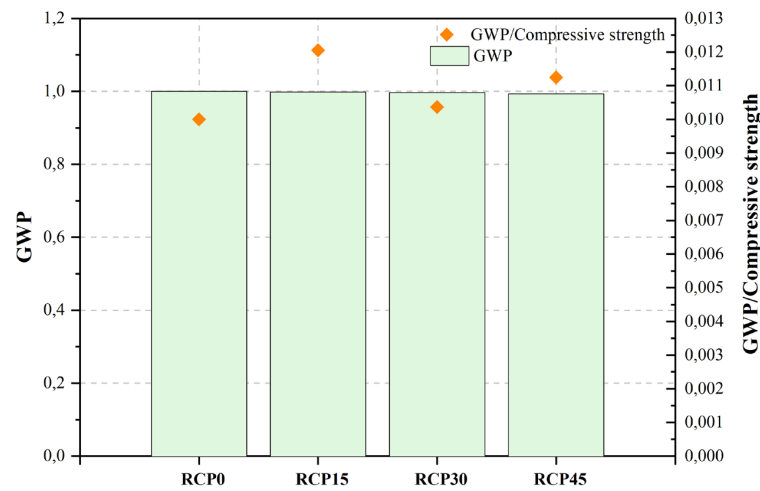


Figure 5. GWP and GWP/compressive strength ratio of the concretes developed by He et al. [468], (Data from He et al. [468]).

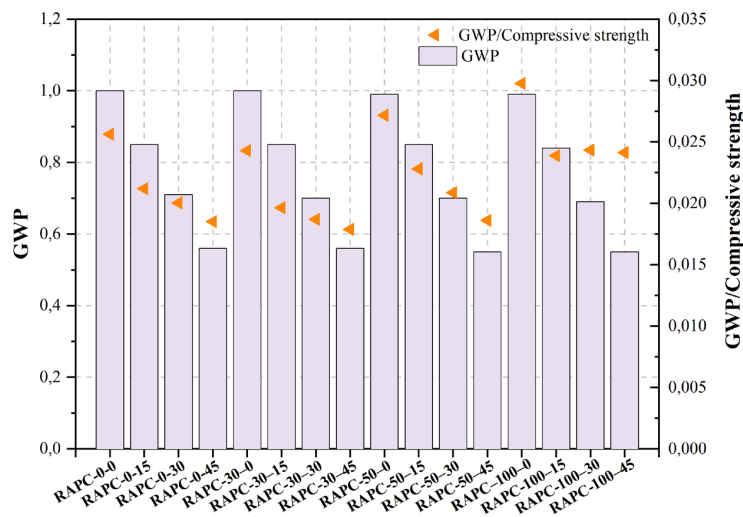


Figure 6. GWP and GWP/compressive strength ratio of the concretes developed by Wu et al. [469], (Data from Wu et al. [469]).

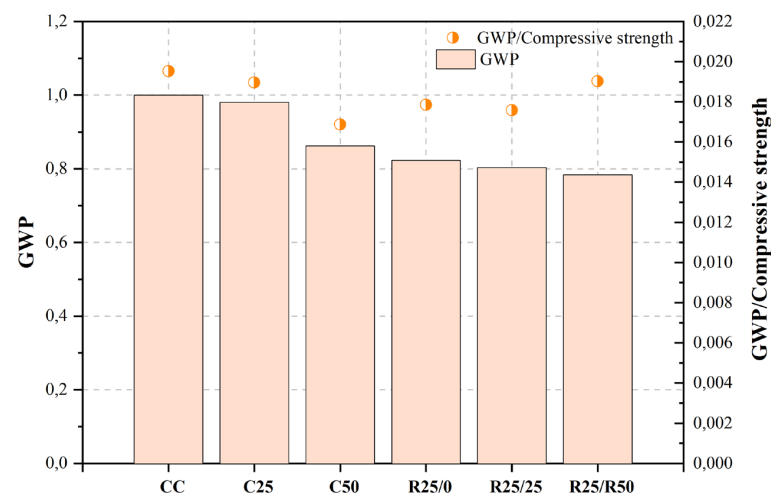


Figure 7. GWP and GWP/compressive strength ratio of the concretes developed by Cantero et al. [471], (Data from Cantero et al. [471]).

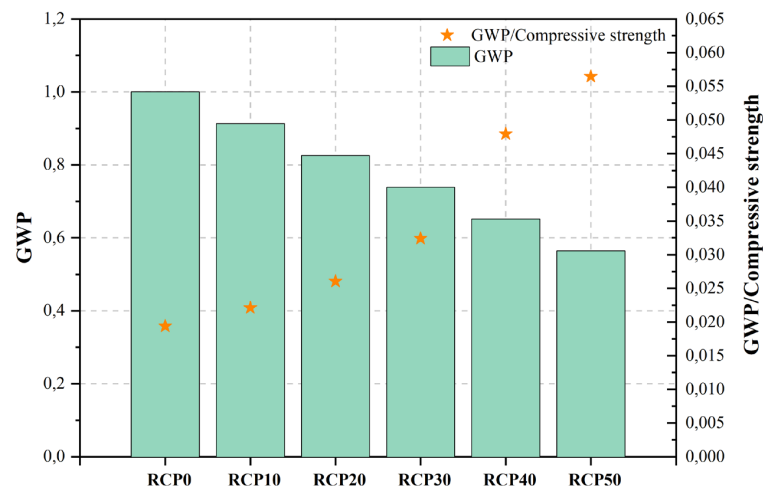


Figure 8. GWP and GWP/compressive strength ratio of the concretes developed by Pešta et al. [472], (Data from Pešta et al. [472]).

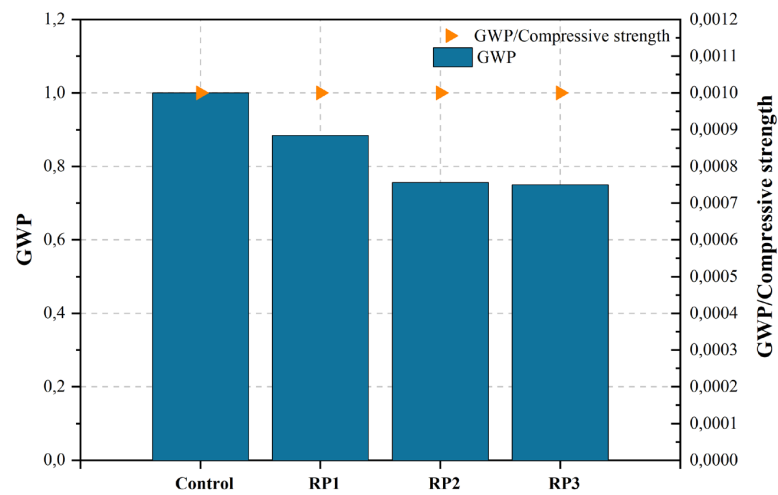


Figure 9. GWP and GWP/compressive strength ratio of the concretes developed by Singh et al. [449], (Data from Singh et al. [449]).

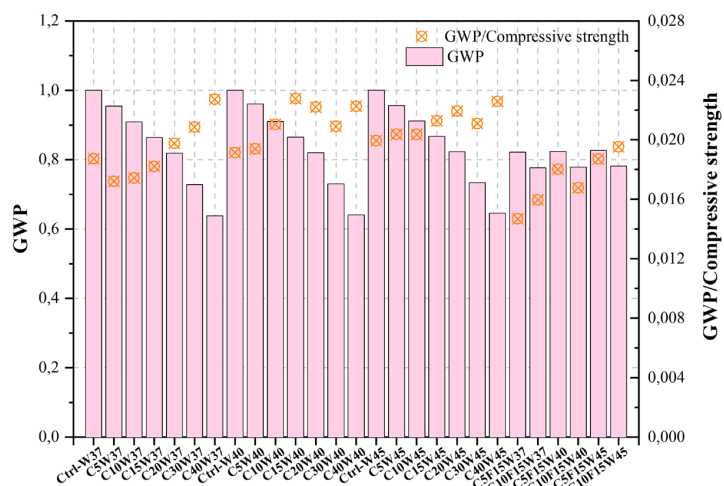


Figure 10. GWP and GWP/compressive strength ratio of the concretes developed by Bagheri et al. [488], (Data from Bagheri et al. [488]).

When comparing the identical strength conditions, the produced concrete including DCP [464], RP [463], GRC [465], RCP [468,472], RAPC [469], GR-RMA [471], RF [449], and CKD [488] exhibits a lower CO₂ emission per unit volume compared to the reference sample. This indicates a higher efficiency in utilizing Portland cement in the produced concrete. In addition, the increase in all types of CDW contents leads to a significant reduction in carbon dioxide emissions during the production of the concrete.

3. Conclusions

This paper presents a review of the utilization of CDW as a partial replacement for Portland cement or as a partial replacement for raw materials in raw meal to produce concrete. Based on the review above, the following conclusions can be drawn:

1. CDW particles, which possess a comparable size range to cement particles, exhibit a satisfactory level of reactivity that renders them suitable for utilization as supplemental cementitious materials in concrete;
2. The effective usage of the finest portion of CDW in the manufacturing of Portland cement is a feasible approach;
3. An observed correlation exists between a rise in fineness and an increase in the reactivity of CDW. It is recommended that the median diameter of CDW particles be maintained below 30 µm during the process of concrete production;
4. Higher water-to-binder ratios have been found to result in a decrease in the compressive strength of concrete made with CDW;
5. In terms of CO₂ reduction, CDW as a partial replacement of Portland cement provides equal or better results compared to various agricultural, industrial and municipal waste materials in concrete production;
6. CDW as a partial replacement for Portland cement provides better CO₂ reduction results compared to CDW as a partial replacement for the natural materials in the raw meal;
7. The application of a treatment on CDW has been shown to significantly enhance the characteristics of the concrete while also facilitating the valorization of waste materials and addressing pressing environmental concerns related to resource depletion, CO₂ emissions, and waste formation;
8. The high fineness and reactivity of CDW (specifically RP, DCP, CKD, GRC, RCP, HHCW, and RBP) have been observed to result in negligible adverse impacts on compressive strength when up to 30% of Portland cement is replaced with CDW;
9. The utilization of CDW concrete results in a reduction in the preparation cost compared to plain concrete while also leading to a drop in energy consumption and CO₂ emissions during the concrete preparation process;
10. Given the extensive scope and widespread nature of concrete manufacturing, even minor enhancements in the resource recovery efficiency of construction and demolition waste (CDW) can yield significant cost reductions and mitigate its detrimental environmental impacts;
11. The use of SCM (CC, fly ash, silica fume, etc.) together with CDW as a replacement for Portland cement provides beneficial ecological results; but if the substitution is CC by PC, the beneficial ecological results are greater, and the greater the higher the reactive alumina content, that is, the quality of its matrix clay, because its replacement amount will be greater;
12. The combined effect of CDW as partial Portland cement replacement and mixed recycled construction and demolition waste aggregate (RACDW) or RA in structural concrete provides promising results;
13. The findings of the ecological assessment indicate that the substitution of Portland cement with CDW can significantly decrease CO₂ emissions per unit volume of concrete while also ensuring the continued high performance of the concrete.

The results mentioned above suggest that incorporating CDW as a partial substitute for Portland cement offers a viable approach to address many issues, including limited

disposal locations, environmental consequences, and cost reductions in the manufacturing of concrete. Based on the available evidence, it can be inferred that the substitution of Portland cement with CDW in the production of environmentally friendly concrete is a justifiable approach. This innovation presents a novel concept for the development of sustainable products in the foreseeable future.

Prospects and Recommendations

In the recent literature, various approaches to addressing sustainable production in the cement industry have been examined, and notable advancements have been achieved in the realm of research. The literature analysis revealed that the utilization of CDW in the cement manufacturing process offers a technically, environmentally, and economically advantageous approach when compared to traditional methods of cement manufacturing. However, it is imperative to conduct a thorough and comprehensive study to validate or make any adjustments to the stated conclusions of this review. More extensive investigation is required for the following aspects:

- Low-emission cement production methods should be developed. Simultaneously, efforts should be directed towards formulating strategies for incorporating CDW into the industrial process;
- The CDW utilized in several investigations was acquired from a singular source of concrete waste, and the experiments were carried out at the laboratory scale. In practical applications, the underlying origin of CDW might exhibit a higher level of complexity. Hence, to achieve generalizability, future research endeavors should duly include the inherent diversity in the characteristics of CDW;
- The investigation of the long-term behavior and alteration of microstructure is crucial;
- Further exploration of treatment strategies for CDW is necessary to identify potential enhancements that do not have a negative impact on the Portland cement and concrete quality. To enhance the performance of CDW, scholarly investigations have emphasized the use of a combination of diverse treatment techniques as a feasible and strategic approach. Hence, enhancing the methodologies employed for the treatment of CDW holds significant importance;
- Additional research is needed to better investigate chemical recycling methods for CDW. There is a need for additional economic, environmental, and feasibility analyses to be conducted, ensuring that all procedures employed adhere to pertinent legal and environmental requirements;
- Previous studies have documented a dearth of sufficient evidence pertaining to the substitution of mixed CDW and recycled aggregate simultaneously, resulting in incongruities among the findings of various researchers. In forthcoming experimental investigations, it is vital to allocate due consideration to these features;
- In contrast, manufacturing calcined clay in cement plants seems to be much more feasible in all senses: the technical aspect of its manufacturing and of its quality control, and the economic aspect. In addition, the amount of replacement by PC for each construction purpose is relatively quick to determine and, consequently, economical as well;
- Further research is needed to conduct further LCA studies to establish a comprehensive and methodical comparison of the carbon footprint associated with CDW in contrast to standard SCMs. It is important to evaluate various landfilling and downcycling scenarios in these studies. The current LCA studies failed to incorporate the technical and economic dimensions of CDW utilization in Portland cement, both as a raw material and as a Portland cement replacement. The primary concern pertains to the establishment of a life cycle costing analysis (LCC) for the purpose of ascertaining the most economically advantageous choice among the available possibilities. The second problem pertains to the examination of the environmental and economic consequences in relation to varying distances, which influence the effects resulting from transportation. Another suggestion is for analysts conducting LCA to undertake

a comparable investigation. Given the potential variability of inventory analysis across different regions, it is imperative to enhance the accuracy of LCA data.

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Abbreviations

ACW	Asbestos cement tile waste
AFs	Alternative fuels
AP	Acidification potential
ARMs	Alternative raw materials
BCM	Binary cementitious material
BD	Brick dust
BFA	Biomass fly ash
BRH	Biochar rice husk
°C	Celsius
CaCO ₃	Calcium carbonate
CaO	Calcium oxide
CBA	Cane bagasse ash
CBP	Clay brick powder
CC	Calcined clay
CCA	Corn cob ash
CCS	Carbon capture and storage
CCW	Civil construction waste
CDW	Construction and demolition waste
CFA	Coal fly ash
CI	Carbon dioxide equivalent emissions
CKD	Cement kiln dust
CLBA	Coal bottom ash
CNSA	Coconut shell ash
CO	Carbon monoxide
CO ₂	Carbon dioxide
CRD	Crushed rock dust
CS	Copper slag
CWP	Ceramic waste powder
d ₅₀	Mean or average particle size of a mineral
DCP	Dehydrated cement paste
EAFD	Electric arc furnace dust
ECC	Engineered cementitious composites
ESP	Eggshell powder
EU	European Union
FA	Fly ash
FP	Fossil fuel depletion potential
FSW	Foundry sand waste
GGBFS	Granulated blast-furnace slag
GHG	Greenhouse gas

GP	Glass powder
GRC	Ground recycled concrete
GR-RMA	Ground recycled masonry aggregate
GWP	Global warming potential
HCW	Hydrated cement waste
HHCW	Humid hardened concrete waste
kg-CO ₂ eq	Kilogram of carbon dioxide equivalent per kilogram
kg-CO ₂ /m ³	Kilogram of carbon dioxide equivalent per cubic meter
LC2	Limestone calcined clay
LC3	Limestone calcined clay cement
LCA	Life cycle assessment
LCC	Life cycle costing analysis
LOI	Loss-on-ignition
LP	Limestone powder
LSF	Limestone filler
MA	Mineral addition
MCRT	Mixed cathode ray tubes
MPa	Megapascal
MRA	Mixed recycled aggregate
MRF	Mixed container glass
MK	Metakaolin
MSWI	Municipal solid waste incineration ash
NA	Natural aggregate
na	Not applicable
μm	Micrometers
NCA	Natural coarse aggregate
NFA	Natural fine aggregate
NP	Natural pozzolan
NREC	Non-renewable energy consumption
NS	Nanosilica
ns	Not stated
OIC	Orange illitic clay
OPC	Ordinary Portland cement
OSP	Oyster shell powder
OWA	Olive waste ash
PCC	Portland clinker crude
POFA	Palm oil fuel ash
POCP	Palm oil clinker powder
ppmV	Parts per million by volume
PPR	Porcelain tile polishing residue
PS	Periwinkle shell
PVC	Polyvinyl chloride
RA	Recycled aggregate
RA-CDW	Recycled construction and demolition waste aggregate
RAPC	Recycled aggregate powder concrete
RBP	Recycled brick powder
RCA	Recycled coarse aggregate
RCP	Recycled concrete powder
RCW	Red ceramic waste
RCWCM	Recycled concrete waste coarse aggregate material
RF	Recycled fine
RFA	Recycled fine aggregate
RGP	Recycled glass powder
RHA	Rice husk ash
RM	Red mud
RP	Recycled powder
SCBA	Sugarcane bagasse ash
SCMs	Supplementary cementitious materials

SDA	Sawdust ash
SF	Silica fume
SLS	Scallop shell
SP	Superplasticizer
SS	Steel slag
SSA	Sewage sludge ash
SSP	Seashell powder
TiO ₂	Titanium dioxide
UHPC	Ultra-high-performance concrete
VA	Volcanic ash
WBP	Waste brick powder
WCP	Waste concrete powder
WG	Waste glass
WHR	Waste heat recovery
WMD	Waste marble dust
WP	Waste powder
WSA	Wheat straw ash
wt.%	Weight percentage
WWA	Wood waste ash

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