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Construction and Demolition Waste as Coarse Aggregate in Structural Beam: An Analysis of Physical, Mechanical, and Environmental Impacts

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Abstract: The substitution of natural coarse aggregate with recycled coarse aggregate from construction and demolition (RCD) waste has been demonstrated as feasible for structural concrete applications. This research is crucial because it addresses both performance and sustainability aspects, ensuring that concrete with recycled aggregates meets strength and durability requirements while supporting quality assurance and regulatory compliance. By showcasing that up to 100% substitution is viable, the study highlights a significant reduction in environmental impacts, such as reduced aggregate extraction and minimized RCD waste disposal issues. The Life Cycle Assessment (LCA) further emphasizes the environmental benefits, showing that using 100% recycled aggregates generates fewer emissions, consumes less energy, and utilizes fewer non-renewable resources. This underscores the potential of recycled materials to lower the environmental footprint of construction practices. However, the research also identifies the importance of considering transportation distances, which affect environmental impact categories, suggesting that future studies should address this variable to optimize the benefits of using recycled aggregates.

***Keywords*: ** Construction and Demolition waste, LCA, recycled coarse aggregate, sustainability, sustainable concrete

1. Introduction

Construction and Demolition (C&D) waste is among the largest global waste streams. In the European Union, C&D waste constitutes over 30% of total waste generation, exceeding 450 million tons [1]. The United States produces an estimated 600 million tons of C&D waste annually, more than double the volume of municipal solid waste [2-3]. In Brazil, C&D waste makes up 40% to 70% of urban solid waste in medium and large cities, totaling over 80 million tons each year [4], though official figures reported 45 million tons in 2017 [5]. Notably, 61% of Brazil's C&D waste is masonry and concrete, classified as "type A" waste, which offers potential for recycling and diverse applications [6, 7].

Addressing this issue is crucial, as highlighted by [8], which underscores the need for innovative technologies and production processes to minimize waste generation and promote recycling, thereby reducing reliance on landfills. This focus is a significant research trend [9], aligning with the UN's Sustainable Development Goals for 2030 [10] and ESG

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(environmental, social, and governance) factors for stakeholders [11].

Given the substantial volumes of C&D waste in Brazil and the widespread use of concrete, replacing natural coarse aggregates with recycled aggregates from C&D waste presents a promising solution. This approach is already utilized in pavements and non-structural concrete elements, though its application in structural elements remains largely experimental. For example, [12] conducted tests on precast slabs and T-beams, replacing 50% and 100% of natural coarse and fine aggregates with recycled C&D aggregates. These experiments demonstrated satisfactory physical and mechanical properties, with moment-displacement curves showing similar behavior in both experimental and theoretical analyses. Studies [13-15] reveal that replacing 50% of natural aggregates (NA) in recycled aggregate concrete (RAC) with recycled concrete aggregate (RCA) can reduce compressive strength by up to 25% and tensile splitting strength by 39%. The modulus of elasticity of RAC may drop to 60% compared to natural aggregate concrete (NAC). However, replacing up to 30% of NA with RCA does not significantly impact mechanical performance [16]. Zhang et al. [17] emphasized that factors such as RCA properties and mix design workability are crucial for optimal RCA replacement. Additionally, while reducing the water-to-cement ratio improves strength, it also reduces workability [18].

Recent studies have also employed Life Cycle Analysis (LCA) to assess the environmental viability of using waste in structural elements. LCA quantifies emissions from waste generation and resource consumption in the production of products and services. It connects these emissions with their respective environmental impacts and resource depletion, providing valuable insights for sustainable product development and informing decision-makers about environmental performance. [19] and [20] emphasize the importance of conducting LCA studies for the use of RCD waste in new processes and products to assess their primary environmental and economic impacts.

In this context, our article evaluates the substitution of natural coarse aggregate with recycled RCD waste aggregate in structural beams, building upon previous research that explored various levels of natural coarse aggregate replacement [21]. For each replacement level, we assessed the primary physical and mechanical properties of concrete that determine its suitability for structural applications, with the most promising combinations involving 50% and 100% substitution of natural coarse aggregate with recycled RCD aggregate.

Consequently, our study performs a Life Cycle Assessment (LCA) for three structural beams with different percentages of recycled RCD coarse aggregate: one with 0%, another with 50%, and a third with 100%. These beams share dimensions of 2.5 meters in length with a cross-section measuring 12 cm in width and 25 cm in height, serving as the functional unit for our analysis. This assessment reinforces the use of recycled materials in structural concrete, provides insights into environmental impacts, and aligns with the goals of the National Policy on Solid Waste regarding waste valorization.

2. Materials and methods

2.1 *Materials*

To produce the concrete beams, we utilized conventional materials procured from stores in the city of Bauru and stored in the laboratories of the Faculty of Engineering at UNESP, located on the Bauru campus. These materials are described as follows.

2.1.1 *Cement*

The cement chosen for the analysis is ordinary Portland cement (CPII F-32). This selection was made due to its widespread use in various construction projects, including floors, concrete structures, coatings, and precast elements.

2.1.2 *Fine aggregate*

The sand used in this study was sourced from the Tietê River in the municipality of Iacanga, São Paulo (SP). It is classified as coarse sand, falling within zone 2 according to the [22] specification. The sand used in this study has a fineness modulus (MF) of 3.0, which indicates its particle size distribution. Figure 1 displays the granulometric curve of this sand. This curve clearly shows that the sand's particle size (blue dot line) falls within the specified boundaries for zone 2, thereby confirming its compliance with the standard's classification criteria.

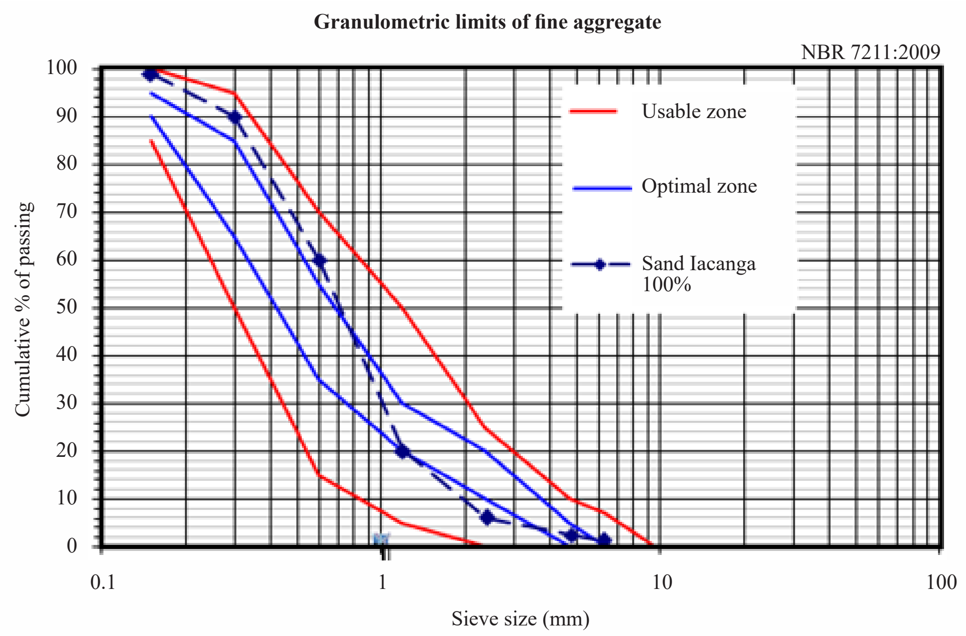

Figure 1. Fine Agregate Granulometric Curve

2.1.3 *Natural coarse aggregate-gravel type 1*

The coarse aggregate used in the study was extracted from basaltic rocks near the municipality of Pederneiras, São Paulo (SP). This coarse aggregate is classified as gravel type 1 and possesses a specific mass of 2.65 kg/m^3 with a water absorption rate of 0.5%.

2.1.4 *Recycled coarse aggregate from RCD waste*

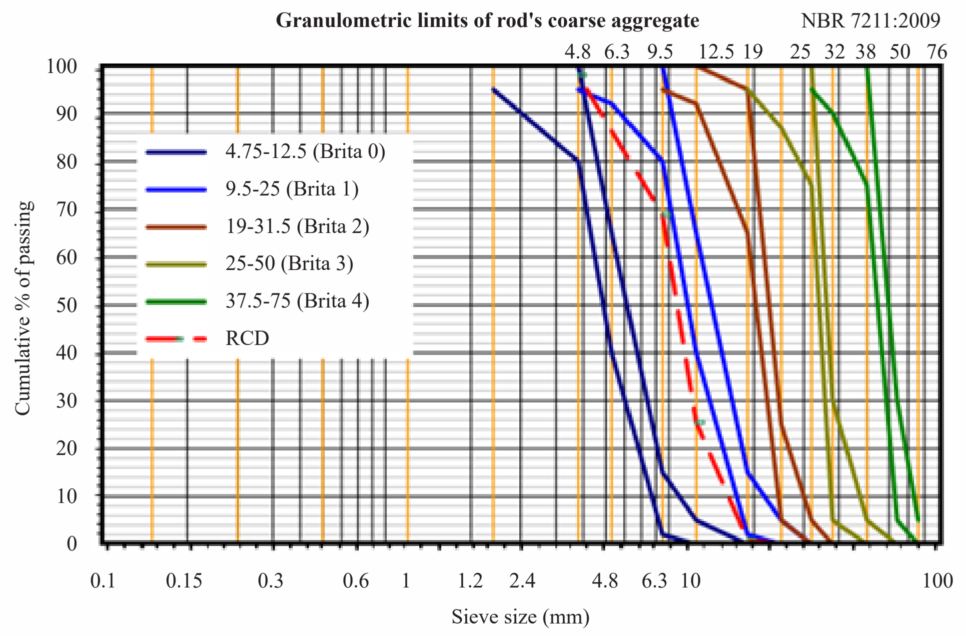

Figure 2. Coarse Recycle Aggregate Granulometric Curve

The recycled coarse aggregate used to replace natural aggregate was obtained as a donation from Portal Rays, located at 4-65 Ronize Motta Pegoraro de Souza Street, Industrial District III, São Paulo-Bauru. Once acquired, the aggregate was tested following Brazilian standards, and its properties were found to closely match those of natural aggregate type 1 used in concrete.

The recycled aggregate, derived from construction waste including masonry, mortar, concrete, and ceramics, was carefully processed. Contaminants such as glass, paper, plastics, and organic matter were manually removed to ensure the quality of the concrete. After sieving to separate fines, a particle size test was performed, and the results are illustrated in Figure 2. This figure shows that the recycled coarse aggregate is classified as gravel type 1 (Brita 1), as indicated by the red dot line marking its limits (RCD). The aggregate has a specific mass of 2.23 kg/m^3 and a water absorption rate of 5.57%.

2.1.5 *Reinforcement*

For reinforcement, CA-50 steel bars were employed, with stirrups and stirrup-holder bars having a diameter of 5 mm, while the two main bars (positive reinforcement) had a diameter of 12.5 mm. These dimensions were selected to ensure that the beam's failure mode occurs due to bending moment, falling within domain 2, where steel yields.

2.1.6 *Water*

The water used in the production of concrete is sourced from an artesian well located on the UNESP campus in Bauru.

2.2 *Production of concrete samples*

The concrete mixtures in this study were determined based on volumetric compositions associated with the specific mass of both natural and recycled aggregates. The nomenclature of the mixtures denotes the concrete proportions and is explained as follows:

- TR_50: Recycled concrete mixture with a 50% replacement of natural coarse aggregate.
- TR_100: Recycled concrete mixture with a 100% replacement of natural coarse aggregate.

Water was added to compensate for the varying water absorptions between natural and recycled aggregates. The concrete mix design in this research was initially based on mixtures suitable for small-scale projects as presented by [23]. Using the dosage diagrams provided by these authors, a correlation of mass proportions was developed, defining a reference mixture for conventional concrete aiming to achieve an average compressive strength ranging from 25 MPa to 30 MPa. The mass proportions for this standard mix are 1:2.625:2.75:0.55.

Subsequently, substitutions of the natural coarse aggregate with the recycled aggregate were made in proportions of 25%, 50%, 75%, and 100%. The other components of the concrete remained consistent across all mixtures.

Pilot mixes were initially conducted, serving as references to exclude the mixtures with 25% and 75% replacements, ultimately focusing on the substitutions with 50% and 100%. These two replacement levels were evaluated with two different water-to-cement ratios (w/c), as indicated in Table 1. The notation used in Table 1 is as follows:

- TR1_50: 50% of coarse aggregate from RCD waste with a w/c of 0.55.
- TR2_50: 50% of coarse aggregate from RCD waste with a w/c of 0.67.
- TR1_100: 100% of coarse aggregate from RCD waste with a w/c of 0.55.
- TR2_100: 100% of coarse aggregate from RCD waste with a w/c of 0.67.

Table 1 presents the dosages for different levels of coarse aggregate replacement in terms of mass (kg) for each material, as well as the two types of water-to-cement ratios with a volume corresponding to 2.625 liters.

In accordance with [24], the number of samples to be molded and tested was determined through statistical analysis based on pilot tests.

For each mixture, a minimum of 31 cylindrical samples (10 cm × 20 cm) were molded following the guidelines of [25]. These samples were then cured in a humid chamber, and at 28 days of age, they underwent axial compression testing using a universal EMIC machine, as specified in [25].

Table 1. Dosages for different coarse aggregate replacements and w/c variation

Material	Beam type				
	Standard	TR1_50*	TR2_50*	TR1_100*	TR2_100*
Cement	1	1	1	1	1
Fine Aggregate	2.63	2.63	2.63	2.63	2.63
Coarse Aggregate	2.75	1.38	1.38	0	0
W/C	0.55	0.55	0. 67	0.55	0. 67
RCD	0	1.17	1.17	2.34	2.34
Volume (l)	2.625	2.625	2.625	2.625	2.625

*TR1: 0.55 w/c and TR2: 0.67 w/c;
TR1_50 or TR2_50: 50% of recycled coarse aggregate form RCD waste;
TR1_100 or TR2_100: 100% of recycled coarse aggregate form RCD waste.

The results from the axial compressive strength tests indicated that the most suitable mixture for structural concrete had a water/cement ratio (w/c) of 0.55, aligning with the strength classes defined in [26]. You can find these results in [21] and a summary is presented in Table 2. Notably, the coefficient of variation (Cv) is calculated as the ratio between the fck value of the recycled mixture and the standard mixture. For instance, for TR2_50: 21.91/29.44 = 0.7442, which equals 74.42%.

Table 2. Comparison between compressive strengths for each mixture

Mixture*	w/c	f_{c28} (MPa)	Cv** (%)	ABNT (NBR 8953:2015) Standard [26]
Standard	0.55	29.44	100	Fck > 20 Mpa
TR1_50	0.55	27.58	93.68	
TR2_50	0.667	21.91	74.42	
TR1_100	0.55	23.30	79.14	
TR2_100	0.667	21.65	73.54	

*TR1: 0.55 w/c and TR2: 0.67 w/c;
TR1_50 or TR2_50: 50% of recycled coarse aggregate form RCD waste;
TR1_100 or TR2_100: 100% of recycled coarse aggregate form RCD waste;
**Cv: coefficient of variation among fck of Standard mixture and RCD recycled coarse aggregate.

2.3 *Beam production*

To conduct the Life Cycle Assessment (LCA), three reinforced concrete beams were fabricated. Each beam measured 2.5 meters in length, 12 cm in width, and 25 cm in height. The first beam, labeled VP, was constructed using the standard mixture. The second beam, corresponding to the TR1_50 mixture, was designated as VR_50. The third beam, produced with the TR2_100 mixture, was identified as VR_100.

The Life Cycle Inventory (LCI), which includes the quantification of materials used in the production of each beam, is presented in Table 3. The dosages, molds, filling, and curing procedures for beam production were consistent across all three beams. It is noteworthy that as the percentage of RCD aggregate increases, the total mass of the beam decreases, as reported by [27].

Table 3. LCI: Amounts of materials required for each beam (kg)

Beam	Cement	Fine Aggregate	Natural Coarse Aggregate	RCD Coarse Aggregate	Water	Steel	Diesel fuel	Enerrgy (kWh)	Total Mass kg
VP	28.57	75.14	78.57	-	15.71	13.38	53	178	211.37
VR_ 50	28.57	75.14	39.43	33.43	15.71	13.38	61	176	205.66
VR_100	28.57	75.14	-	66.86	19.14	13.38	44	167	203.09

VP: Standard concrete beams, having only the natural coarse aggregate, being used as a reference for comparison of the others;
VR_50: Recycled concrete beam with 50% replacement;
VR_100: Recycled concrete beams with total replacement of coarse natural aggregate by recycled RCD aggregate.

2.4 *Life Cycle Assessment (LCA)*

Life Cycle Assessment (LCA) is a comprehensive method for evaluating the environmental impacts associated with all stages of a product's life, from raw material extraction through processing, manufacturing, distribution, use, and disposal or recycling. When applying LCA to alternative types of materials, such as recycled aggregates or alternative binders in the construction sector, it provides a detailed understanding of their environmental performance compared to conventional materials. An overview of LCA in the context of alternative construction materials and a step-by-step guide on how to conduct it:

Purpose and Scope Definition

- Goal: To evaluate and compare the environmental impacts of alternative materials (e.g., recycled coarse aggregates, fly ash, slag) versus conventional materials.
- Scope: Define system boundaries, functional unit (e.g., 1 cubic meter of concrete), and impact categories (e.g., global warming potential, energy consumption, resource depletion).

Inventory Analysis

- Data Collection: Gather data on raw material extraction, manufacturing processes, transportation, and end-of-life scenarios.
- Material Inputs: Quantify inputs such as raw materials, energy, and water.
- Emission Outputs: Measure outputs like greenhouse gases, waste, and other pollutants.

Impact Assessment

- Impact Categories: Analyze impacts in categories such as:
  - ○ Global Warming Potential (GWP)
  - ○ Acidification Potential
  - ○ Eutrophication Potential
  - ○ Ozone Depletion Potential
  - ○ Resource Depletion
- Characterization Models: Use models to translate inventory data into potential environmental impacts.

Interpretation

- Results Analysis: Interpret the results to identify which materials have the lowest environmental impacts.
- Sensitivity Analysis: Conduct sensitivity analysis to understand the influence of key parameters on the results.
- Recommendations: Provide recommendations based on the findings.

The Life Cycle Assessment (LCA) was conducted following the standards [28] and [29], as well as the procedures outlined in [1]. The product system includes the following production chains: materials (sand, gravel, steel, cement), equipment used, electricity consumption (based on the Brazilian energy matrix), and the transport and distribution of the materials used. Transport distances covered for collecting and delivering materials are converted into kilograms of diesel fuel. Figure 3 illustrates the system of the product under consideration.

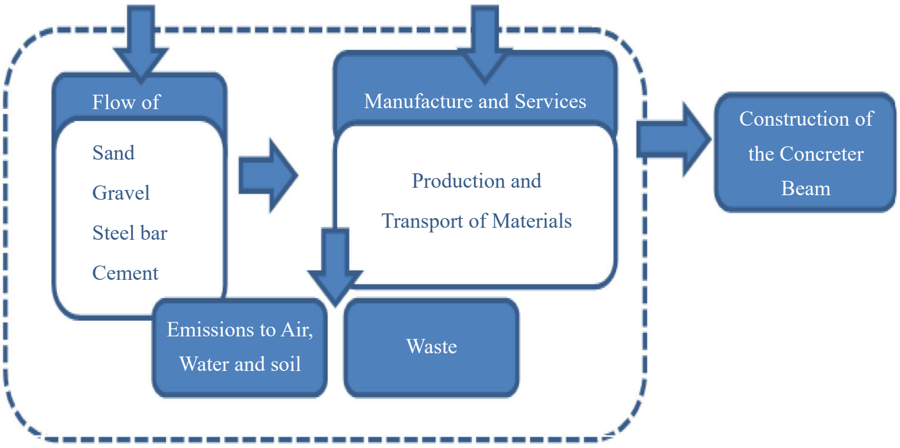

Figure 3. Production System boundaries for the concrete beam

The function of the product system is to produce a single concrete beam. Therefore, the functional unit should encompass both qualitative and quantitative aspects of the beam's useful life. The estimated functional life of the beam is 20 years, considering usage specifications and, notably, the average interval for maintenance. The Functional Unit for this product system is expressed as kilograms per constructed beam (cradle-to-gate method). This study was conducted in the year 2021, involving inventories of primary sources, and all emission and depletion calculations were performed using an electronic spreadsheet.

The study encompassed the calculation of potential environmental impacts associated with the collected flows. This required an understanding of how emitted substances contribute to each type of impact. The process involved two steps:

- Classification: Categorizing flows based on their contribution to specific environmental impact categories.
- Characterization: Following flow classification, applying equivalence factors based on the unit of measurement for each impact category. After this conversion, the data is consolidated by impact category.

2.5 *Methods, impact categories and study limitations*

Consequential impacts were not considered in this study, as attributional modeling was used. This approach was chosen because consequential modeling is more subjective. The Life Cycle Impact Assessment (LCIA) methodology employed in this study followed the Environment Design of Industrial Product (EDIP) criteria. Interpretation should align with the study's objective, which is to analyze the life cycle of the respective process and identify potential environmental impacts. The impact categories considered in this study are as follows:

- Human toxicity: This category encompasses impacts related to human toxicity, measured concerning body mass per 1 kg of toxic substance.
- Acidification: Impacts linked to acid rain formation, measured in terms of 1 kg of SO_4.
- Global warming: This category comprises greenhouse gas emissions, measured in terms of 1 kg of CO_2.
- Ozone layer depletion: Measured in terms of 1 kg of C_2H_4.
- Formation of photochemical oxidants: Measured in terms of 1 kg of ethylene.
- Eutrophication: This category includes impacts related to the eutrophication of water resources resulting from organic matter disposal or diffuse releases, measured in terms of 1 kg of PO_4 equivalent.
- Ecotoxicity: Impacts related to aquatic and soil ecotoxicity, measured in terms of 1 m^3 of water and 1 m^3 of soil per mass of substance.

- Energy depletion: Impacts linked to energy consumption throughout the life cycle.
- Depletion of natural resources: Impacts related to the consumption of renewable and non-renewable natural resources.
- Depletion of residues: Impacts associated with the production of residues.

Table 4 provides details of the flows included in the product system, along with their references. The LCI data is presented in Table 3. It's worth noting that only the production chain of the considered relevant flows is included. The electricity consumption for this product system was deemed insignificant, representing less than 0.001% of resource consumption. Consequently, it was excluded from the calculation following [1], as it would have negligible impact on this analysis.

Table 4. Product flows applied in primary inventories

Flows	References
Diesel fuel-Transport (kg of material)	[30]
Cement (kg of material)	[31]
Gravel (kg of material)	[32]
Steel bars (kg of material)	[30]
Sand (kg of material)	[33]
Energy (kWh)	[30]

3. Results

3.1 *Physical properties of fresh and hardened concretes*

To validate the potential for substituting natural coarse aggregate with recycled RCD coarse aggregate, various tests were conducted on the concrete in both its fresh and hardened states. The results of the slump tests are depicted in Figure 4.

Standard mixture-90.0 mm TR1_50 mixture-40.0 mm TR2_100 mixture-25.0 mm

Figure 4. Concrete slump tests and concrete slump variation

In the fresh state, a slump test was conducted. It was generally observed that concretes containing recycled aggregates exhibited reduced workability compared to those with natural aggregates. This reduced workability can be attributed to the higher water absorption of recycled aggregates.

For the hardened state, several properties were evaluated, including specific mass, void ratio, and water absorption by immersion. These assessments were conducted following the procedures outlined in standard [34]. The progress of the tests is illustrated in Figure 5, and the obtained results are presented in Table 5. It is noteworthy that the use of recycled RCD aggregates increases the porosity of concrete, leading to a decrease in its specific mass. However, these values remain within the range suitable for structural concrete.

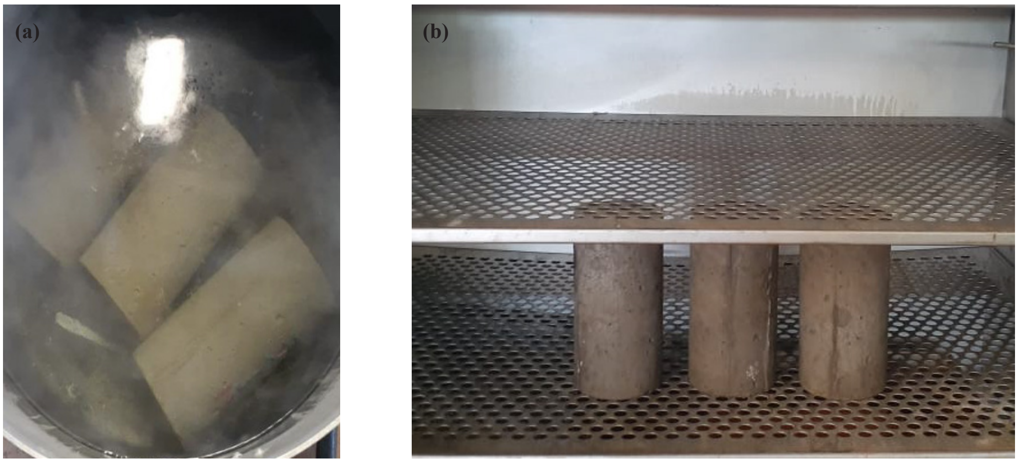

Figure 5. (a) Boiling test; (b) Samples placed in a greenhouse

Table 5. Water absorption, void ratio and specific mass

Mixtures	Water absorption (%)	Void Ratio (%)	Dry specific mass (g/cm^3)
VCP	2.48	5.92	2.39
VCR_ 50	2.75	6.44	2.34
VCR_100	2.83	6.23	2.35

3.2 *Axial compressive strength and modulus of elasticity*

The axial compression strength test was conducted following the guidelines provided in [34], and the results are presented in Table 6. Additionally, the static modulus of elasticity was determined in accordance with the requirements specified in standard [35], and the average results are also presented in Table 6.

Table 6. Modulus of elasticity values (GPa)

Beam	f_{c28} (MPa)	Comparison with the literature (f_{c28})		E (GPa)	Comparison with the literature E (GPa)	
		[36]	[37]		[36]	[37]
VCP	41.18	40.2	45.0	25.68	32.2	30.4
VCR_50	34.69	33.6	35.0	24.81	28.1	29.8
VCR_100	34.78	23.6	28.9	24.40	25.7	24.9

3.3 *Life cycle analysis of the beam element*

The results of the LCA for the selected impact categories are presented in Table 7. Interestingly, the beam produced with 100% recycled coarse aggregate exhibited the lowest emissions. According to the data in Table 7, it emitted 4% fewer greenhouse gases compared to the standard beam. Conversely, the beam with 50% recycled coarse aggregate generated more emissions due to its hybrid nature, which involved the additional process of gravel production (accounting for 50% of the gravel in its construction).

Across all three beam production scenarios (standard, 50% recycled coarse aggregate, and 100% recycled coarse aggregate), greenhouse gas emissions (CO_2) were the predominant emissions, accounting for more than 98% of emissions in each product system process. These emissions primarily stemmed from the production of cement and steel, as illustrated in Figure 6.

Table 7. Impact Category Emissions for the three beams

Impact Category	Beam Type		
	VCP	VCR_50	VCR_100
Human toxicity-kg of toxic substance	0.01	0.01	0.01
Acidification-kg de SO_4 equivalente	0.13	0.13	0.11
Global warming-kg of CO_2 equivalent	38.60	38.89	32.25
Ozone layer depletion-kg of CFC-11 equivalent	0.000	0.000	0.000
Formation of photochemical oxidants-kg of ethylene equivalent	0.010×10^{-4}	0.010×10^{-4}	0.010×10^{-4}
Eutrophication-kg of PO_4 equivalent	0.000	0.001	0.001
Ecotoxicity-m^3 of water and m^3 of soil per substance mass	42.00×10^{-3}	47.00×10^{-3}	35.00×10^{-3}
Energy Depletion-kWh	178.750	176.540	167.990
Depletion of renewable natural resources-kg	5,488.54	5,464.26	5,439.52
Depletion of non-renewable natural resources-kg	515.21	296.71	76.53
Residues Depletion-kg	223.02	192.46	161.62

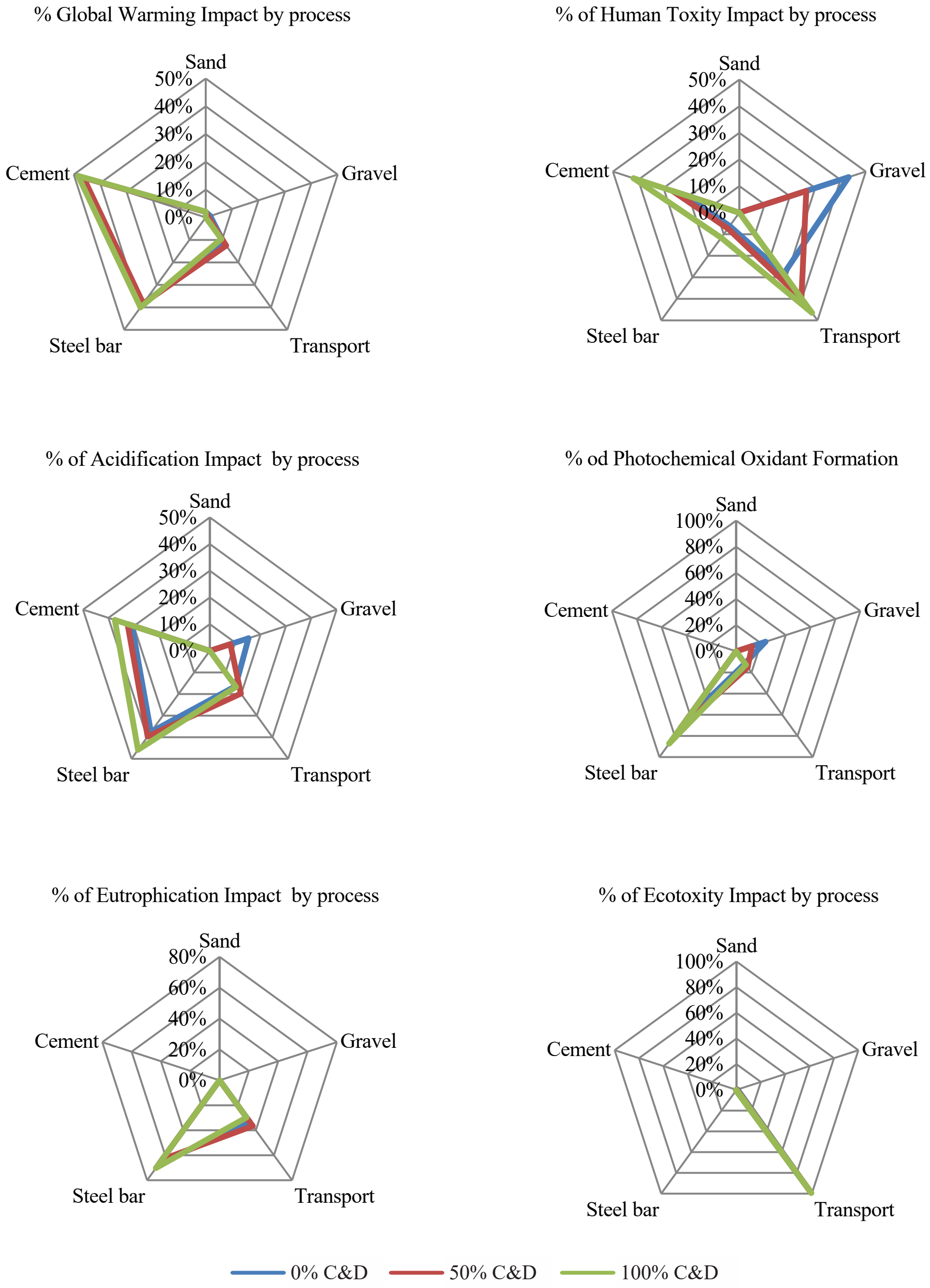

Figure 6. Percentage of Environmental Impact category by production process

In this study, we conducted Life Cycle Assessments (LCAs) to evaluate the environmental impact indicators for three types of beams: standard, 50% recycled RCD coarse aggregate, and 100% recycled RCD coarse aggregate. Our assessment utilized primary inventory data, summarized in an electronic spreadsheet, and revealed notable differences in impact values due to variations in material composition.

For instance, in terms of energy depletion, the beam made with 100% recycled coarse aggregate consumed approximately 9% less kWh compared to the standard beam. This reduction was primarily due to the absence of the gravel production process.

Regarding the extraction of natural resources, the rates of renewable resource extraction were similar across all three processes, with only a 0.9% variation observed between the standard beam and the 100% recycled coarse aggregate beam. For non-renewable resources, the beam made with 100% recycled coarse aggregate had the lowest impact, as it did not require natural gravel.

In terms of waste generation, the beam made with 100% recycled coarse aggregate produced the least waste within the product system (supply chain), generating 27% less waste compared to the others. This reduction can be attributed to the absence of gravel, which is known for generating significant waste. These findings are consistent with the study by [27], which highlighted the environmental benefits of using higher proportions of recycled coarse aggregate in concrete mixtures. However, it is important to note that transport distance also influences the environmental impact.

Considering the impact categories, a key recommendation is to optimize transport systems to enhance efficiency and reduce mileage in the distribution and handling of materials, especially in the construction sector. To align with circular economy principles, this involves strategies that prioritize the reuse, recycling, and recovery of construction materials. Implementing advanced logistics technologies that support circular practices, such as efficient material sorting, recycling facilities, and reverse logistics, can significantly minimize waste and extend the lifecycle of building materials. Additionally, integrating real-time tracking and data analytics can improve the flow of materials, reduce inefficiencies, and support sustainable construction practices. By focusing on these circular economy strategies, the construction industry can lower its carbon footprint, decrease waste, and build a more sustainable and resource-efficient future.

This study emphasizes the importance of ongoing research into new additives for reinforced concrete, particularly when using recycled aggregates. For instance, the use of contemporary insulation plaster (CIP) has shown promise in enhancing fire resistance and durability, demonstrating the potential of innovative materials to improve concrete performance under extreme conditions [38]. As the construction industry increasingly prioritizes sustainability, the development of advanced additives for recycled aggregate concrete becomes even more critical. Future research should focus on refining these additives to optimize the mechanical properties and resilience of concrete, enabling its use in more challenging environments. By advancing these materials, we can develop more sustainable, durable, and safer construction solutions for the future.

4. Conclusions

The substitution of natural coarse aggregate with recycled RCD (Recycled Construction and Demolition) waste coarse aggregate has proven its suitability for structural concrete applications. The key physical and mechanical properties in both the fresh and hardened states support complete replacement, significantly mitigating environmental impacts related to both aggregate extraction and irregular RCD waste disposal.

Furthermore, the Life Cycle Assessment (LCA) results indicate that the production process of beams using 100% recycled coarse aggregate results in the lowest emissions, reduced energy consumption, and minimized use of non-renewable resources. This underscores the substantial environmental benefits of such substitutions.

For future research, it is advisable to incorporate a sensitivity analysis, including Life Cycle Costing (LCC) and the effects of transportation distances on environmental considerations. This would provide a more comprehensive understanding of the economic and environmental impacts of using recycled aggregates.

In summary, this study adds to the growing body of evidence supporting the use of recycled coarse aggregate from RCD waste in structural concrete elements. However, further investigations are needed to potentially standardize its usage. It is crucial that the utilization of RCD waste aligns with national solid waste policies, necessitating the establishment of recycling and crushing facilities for RCD waste to promote its reuse in civil construction.

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Conflict of interest

The authors declare no competing financial interest.

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