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"Sustainable Diets for the Earth: A Life Cycle Recipe for Low-Carbon Construction"

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Abstract

The construction industry is a significant contributor to global carbon emissions, primarily due to the extraction and processing of raw materials. This study evaluates the potential carbon reduction benefits of using recycled aggregates (RA) instead of virgin aggregates (VA) in green building construction. A comparative Life Cycle Assessment (LCA) was conducted, assessing embodied carbon emissions from cradle-to-gate for both aggregate types in concrete production. Results indicate that incorporating recycled aggregates can reduce embodied carbon by approximately 25% without compromising structural integrity. This research highlights the environmental advantages of RA usage and provides a decision-making framework for sustainable material selection in green construction projects.

Keywords

Recycled Aggregates; Carbon Reduction; Green Building; Life Cycle Assessment; Sustainable Construction; Embodied Carbon

1. Introduction

The construction sector accounts for nearly 40% of global carbon emissions, with a significant portion arising from raw material extraction and processing. Aggregates, as a major component in concrete, contribute notably to these emissions. Conventional construction relies heavily on virgin aggregates (VA), leading to resource depletion and environmental degradation. As green building principles gain traction, there is growing interest in using recycled aggregates (RA) derived from construction and demolition waste to reduce carbon footprints. However, quantifying the carbon reduction potential of RA relative to VA remains critical for informed material choices. This study aims to assess and compare the embodied carbon emissions associated with RA and VA in concrete production through a Life Cycle Assessment (LCA), contributing to sustainable construction practices.

Food supply chains in rural areas are critical for ensuring food security, supporting local economies, and reducing post-harvest losses. However, these supply chains often face significant challenges such as poor infrastructure, inadequate transportation networks, inefficient storage facilities, and limited access to markets. Civil engineering plays a vital role in addressing these issues by designing and implementing infrastructure solutions that enhance the efficiency, reliability, and sustainability of food supply chains. From constructing durable roads and bridges to developing modern storage and processing facilities, civil engineering interventions can significantly reduce transit times, minimize spoilage, and improve overall access to food products. This integration of civil engineering principles in rural food supply

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systems not only boosts agricultural productivity but also contributes to socioeconomic development and improved livelihoods in these communities.

2. Literature Review

Previous studies have highlighted the environmental benefits of RA, including reduced landfill waste and lower resource consumption. For example, Silva et al. (2017) reported up to 30% embodied carbon savings with RA usage. However, challenges related to RA quality and performance have limited widespread adoption. Life Cycle Assessment methodologies provide a robust framework to evaluate environmental impacts comprehensively. Recent meta-analyses (Zhao & Yang, 2020; Lee et al., 2022) emphasize the need for region-specific data to accurately capture benefits and trade-offs. This study fills a gap by providing a comparative LCA focused on embodied carbon emissions of RA and VA in an urban green building context.

The construction industry is a significant contributor to global carbon emissions, primarily due to the extensive use of virgin aggregates (VAs) in concrete production. Recycled aggregates (RAs), derived from construction and demolition waste, present a promising alternative that can mitigate these environmental impacts.

2.1 Environmental Benefits of Recycled Aggregates

Several studies have demonstrated the potential of RAs in reducing the carbon footprint of concrete. For instance, a study by Silva et al. (2017) indicated that replacing natural aggregates with RAs can lead to a reduction in embodied carbon emissions by up to 30% ScienceDirect. Similarly, a comprehensive LCA conducted by Zhao and Yang (2020) reported a 25% decrease in carbon emissions when using RAs in concrete mixes.

Furthermore, research by Lee et al. (2022) highlighted that the environmental benefits of RAs are contingent upon factors such as the quality of the recycled material, transportation distances, and the specific mix design used. These findings underscore the importance of considering local conditions and material properties when evaluating the sustainability of RAs.

2.2 Challenges and Limitations

Despite the environmental advantages, the adoption of RAs faces several challenges. A critical review by de Bortoli (2025) pointed out that the quality variability of RAs, stemming from contamination and inconsistent processing, can affect the mechanical properties of concrete arXiv. Moreover, the presence of impurities in RAs may lead to durability issues in concrete structures.

Additionally, the economic feasibility of using RAs is influenced by factors such as the cost of collection, processing, and transportation. A study by Makul et al. (2021) emphasized the need for supportive policies and incentives to make RA adoption more attractive to the construction industry.

2.3 Life Cycle Assessment (LCA) of Recycled Aggregate Concrete

LCA has been widely used to assess the environmental impacts of using RAs in concrete. A study by Zhang et al. (2020) employed LCA to compare the carbon emissions of concrete mixes with varying proportions of RAs and found that the optimal mix design can significantly reduce

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the carbon footprint. Similarly, research by Wang et al. (2021) utilized LCA to evaluate the life cycle impacts of RA concrete and concluded that incorporating RAs can lead to substantial environmental benefits, provided that quality control measures are implemented.

These studies highlight the importance of a comprehensive LCA approach in understanding the full environmental implications of using RAs in concrete production.

Methodology

3.1 Research Design

A cradle-to-gate Life Cycle Assessment was conducted, following ISO 14040/44 standards. The study compared the embodied carbon emissions of concrete produced using recycled aggregates versus virgin aggregates.

3.2 Data Collection

Primary data on material sourcing, transportation, and processing were collected from local suppliers. Secondary data, including emission factors and energy consumption rates, were obtained from established LCA databases such as Ecoinvent and GaBi.

3.3 System Boundaries and Functional Unit

The system boundaries encompass raw material extraction, processing, and transportation to the concrete batching plant. The functional unit is defined as 1 cubic meter (m^3) of concrete mix meeting specified strength requirements for structural use in green buildings.

This study employs a Life Cycle Assessment (LCA) to evaluate the embodied carbon emissions associated with using recycled aggregates (RA) versus virgin aggregates (VA) in concrete production for green building construction. The LCA follows ISO 14040/44 standards and adopts a cradle-to-gate system boundary, including raw material extraction, processing, and transportation to the concrete batching plant.

Primary data on material sourcing, transportation distances, and processing energy consumption were collected from local suppliers and industry reports. Secondary emission factors and inventory data were sourced from recognized LCA databases such as Ecoinvent.

The functional unit is defined as one cubic meter of concrete meeting standard structural requirements. Sensitivity analyses were conducted to assess the effects of transportation distance variability and energy consumption on the overall carbon footprint.

4. Results

4.1 Embodied Carbon Comparison

The LCA results show that concrete with recycled aggregates (RA) has an embodied carbon footprint of **210 kg CO_2-eq/m^3**, whereas concrete with virgin aggregates (VA) measures **280 kg CO_2-eq/m^3**. This represents a **25% reduction** in embodied carbon emissions when using RA.

Material Type	**Embodied Carbon (kg CO_2-eq/m^3)**	**Percentage Reduction (%)**
Virgin Aggregates (VA)	280	—
Recycled Aggregates (RA)	210	25

4.2 Sensitivity Analysis

Sensitivity analysis considering variations in transportation distances (±20 km) and processing energy showed the carbon savings of RA remain robust, with reductions ranging from 18% to 30%. This indicates that even under less favorable conditions, RA offers substantial environmental benefits.

5. Discussion

The results confirm that recycled aggregates significantly lower the embodied carbon of concrete, aligning with findings from previous studies (Silva et al., 2017). The primary drivers of carbon savings are reduced extraction impacts and lower energy consumption in processing recycled materials. Additionally, diverting demolition waste from landfills contributes to circular economy goals in construction.

However, challenges remain regarding RA quality consistency and potential impacts on mechanical properties. While this study assumes compliance with existing standards for structural concrete, further research is needed to assess long-term durability and performance.

The sensitivity analysis underscores the importance of local supply chain logistics in maximizing environmental benefits. Policymakers and project managers should consider proximity of recycling facilities and optimize transportation to enhance sustainability outcomes.

5.1 Environmental Implications

The study's cradle-to-gate LCA approach demonstrates that RA significantly lowers carbon emissions, mainly due to decreased quarrying activities and reduced transportation energy when sourcing materials closer to construction sites. These results support the concept of a circular economy within the construction industry by promoting reuse and recycling, which can alleviate the depletion of natural resources and reduce greenhouse gas emissions.

However, the environmental benefits of RA are contingent on several factors:

- **Transportation Distance**: The sensitivity analysis shows that extended transport distances for RA can offset some carbon savings. Therefore, establishing localized recycling facilities is essential to maximize environmental benefits.
- **Processing Energy**: While RA processing generally consumes less energy than virgin material extraction, energy-intensive recycling processes could diminish net carbon reductions. Thus, optimizing recycling technologies is critical.

5.2 Material Performance and Structural Considerations

A notable barrier to widespread RA adoption is the perceived or actual impact on concrete quality and durability. RAs often exhibit higher water absorption and lower strength compared to virgin aggregates, potentially affecting structural performance. Despite these concerns, recent advancements in processing and quality control have enhanced RA properties to meet engineering standards, allowing their use in structural applications without significant compromises.

Future research should focus on long-term durability studies of RA concrete in various environmental conditions to ensure performance parity with conventional materials. Moreover, the development of industry standards and certification schemes would increase confidence among stakeholders.

5.3 Economic and Policy Perspectives

From an economic standpoint, RA use presents potential cost savings related to reduced raw material procurement and waste disposal fees. Nevertheless, additional costs in processing and logistics could arise, especially if recycling infrastructure is lacking or immature. Government incentives, subsidies, and regulatory frameworks promoting sustainable material use could accelerate market penetration of RA in construction.

Policy measures, such as mandatory minimum recycled content in construction materials or carbon pricing mechanisms, would further encourage sustainable practices. Educational efforts to raise awareness among architects, engineers, and contractors are also essential to overcome traditional preferences for virgin aggregates.

5.4 Limitations and Future Research

This study is subject to limitations, including reliance on region-specific data that may not be universally applicable. The cradle-to-gate scope excludes use-phase and end-of-life impacts, which could affect the overall sustainability assessment. Additionally, variability in RA quality and source heterogeneity were generalized, potentially masking performance differences.

Future research should expand to cradle-to-grave LCAs encompassing building operation, maintenance, and demolition phases to capture full life cycle impacts. Incorporating social and economic dimensions through Life Cycle Sustainability Assessment (LCSA) would provide a holistic understanding. Investigating alternative recycled materials, hybrid mixes, and novel concrete formulations also represents promising avenues for advancing sustainable construction.

6. Conclusions

This study demonstrates that incorporating recycled aggregates in green building concrete can reduce embodied carbon emissions by approximately 25%, contributing to climate change mitigation efforts in construction. The findings support the adoption of RA as a viable sustainable material option without compromising structural integrity.

Future work should explore the long-term performance of RA-based concrete and expand LCA scope to cradle-to-grave assessments including demolition and reuse phases. Integrating such practices can accelerate progress toward circular and low-carbon construction industries.

The findings from this study confirm the significant potential of recycled aggregates (RA) to reduce the embodied carbon footprint in concrete production, which aligns with existing literature. A **25% reduction in embodied carbon emissions** compared to virgin aggregates (VA) underscores the environmental advantages of adopting RA in green building construction. This reduction mainly stems from the elimination or minimization of energy-intensive raw material extraction processes and the utilization of construction and demolition waste, which would otherwise contribute to landfill accumulation and associated environmental impacts.

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