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# Advantage of Recycle Materials Over Conventional Material for Life Cycle Assessment (LCA) and Carbon Footprint

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**Abstract**
The comparative Life Cycle Assessment (LCA) of recycled versus conventional materials in sustainable architecture highlights the significant environmental benefits of using recycled materials. Various studies assess materials such as recycled concrete, reclaimed wood, recycled steel, and fly ash-based concrete, demonstrating their ability to reduce embodied carbon and environmental impact while maintaining structural integrity. Using tools like SimaPro and Tally, researchers found that buildings incorporating recycled materials achieve a 30-50% reduction in carbon footprint compared to conventional structures. These findings emphasize the role of recycled materials in lowering greenhouse gas emissions, promoting resource efficiency, and aligning with global sustainability goals.

## CHAPTER 1: INTRODUCTION

### Background

The construction sector is one of the most significant contributors to global carbon dioxide emissions, accounting for approximately 39% of all energy-related emissions. As the world confronts an urgent environmental crisis, innovative and sustainable strategies to mitigate the sector's carbon footprint are critical. One promising approach is the use of recycled materials in construction, which not only reduces greenhouse gas emissions but also mitigates environmental degradation by conserving resources and minimizing landfill waste. Recycled materials, such as concrete, plastics, glass, and metals, offer an effective alternative to conventional materials. Their utilization prevents resource depletion and curtails the energy-intensive processes associated with producing virgin materials. Moreover, adopting recycled materials supports the principles of a circular economy, wherein resources are reused and waste generation is minimized. Conventional construction materials, including cement and steel, significantly impact the environment due to their high embodied energy and associated greenhouse gas emissions. By substituting these with recycled alternatives, the construction industry can achieve meaningful reductions in its overall carbon footprint. Life Cycle Assessment (LCA) methodologies play a pivotal role in evaluating the environmental benefits of recycled materials compared to their conventional counterparts, providing a holistic view of their impact across the entire lifecycle. The integration of recycled materials into sustainable architectural practices is not merely a technical solution but a necessary step toward achieving global carbon neutrality goals. This shift aligns with international efforts to promote sustainable urban development and foster environmentally responsible construction methods. However, the study of recycled materials faces challenges, including variability in their environmental impacts due to regional practices, transportation distances, and processing methods. Additionally, inconsistencies in data and the long-term performance of recycled materials compared to conventional ones require careful consideration. This research emphasizes the advantages of recycled materials over conventional options for reducing carbon footprints and embodied energy, thus advancing sustainable architectural practices and contributing to the broader goals of environmental conservation and resource efficiency.

**AIM**

The aim is to highlight how recycled materials reduce the carbon footprint, proving their advantages using methods like LCA.

**OBJECTIVES**

1. Analyze the Carbon Impact of Conventional Building Materials.
2. Examine How Recycled Materials May Help Lower Carbon Emissions.
3. Analyze the Economic Viability of Using Recycled Materials.
4. Analyze Case Studies of Effective Initiatives using Recycled Materials.
5. Propose Strategies to Increase the Use of Recycled Materials in Construction.

**METHODOLOGY**

In figure 1, it adopts a structured and scientifically rigorous approach to evaluate the environmental advantages of recycled materials over conventional ones in terms of life cycle assessment (LCA) and carbon footprint reduction. A mixed-methods research design is employed, integrating both qualitative and quantitative methodologies to provide a comprehensive analysis. The research comprises a detailed literature review, case study evaluations, and lifecycle assessments to substantiate the benefits of recycled materials in construction. The study begins with an extensive literature review of 19 peer-reviewed research papers, focusing on the environmental, economic, and structural implications of recycled materials. This review identifies current trends, empirical findings, and research gaps in their application, providing a foundation for subsequent analyses. Key materials considered include recycled concrete aggregates, copper slag, and architectural glass, selected for their demonstrated potential to reduce environmental impacts compared to conventional materials. Case studies form a critical component of the methodology, offering empirical evidence of successful applications of recycled materials in real-world construction projects. These case studies are chosen based on specific criteria, including their documented environmental impacts, lifecycle stages, and cost-effectiveness. Each case is analyzed to derive insights into the practicality and scalability of recycled materials in various construction contexts. The environmental performance of recycled materials is assessed through Life Cycle Assessment (LCA) methodologies aligned with the ISO 14040:2006 standards. This process involves four distinct phases: (1) defining goals and scopes, including functional units and system boundaries, (2) conducting an inventory analysis of production, transportation, processing, and disposal data, (3) assessing impacts across categories such as Global Warming Potential (GWP), Abiotic Depletion Potential (ADP), Human Toxicity Potential (HTP), and ecotoxicity, and (4) interpreting results to identify environmental trade-offs and advantages. Analytical tools such as SimaPro and Tally are employed to calculate environmental impacts, while ETABS software is used for structural modelling and load evaluation to ensure compatibility with building design requirements. A comparative analysis is conducted to evaluate the relative performance of recycled and conventional materials. This includes assessments of embodied energy, cost implications, and structural performance. Lifecycle Cost Assessment (LCCA) methodologies are applied to determine the financial viability of recycled materials across their lifecycle. Sustainability metrics, such as carbon emission reductions, energy savings, resource conservation, and waste diversion, are quantified and crossreferenced with global standards like LEED and BREEAM to establish the alignment of recycled materials with sustainability goals. Finally, strategies to enhance the adoption of recycled materials in construction are proposed. These include policy recommendations to incentivize recycling practices, advancements in technology for efficient processing, and measures to raise awareness among stakeholders about the environmental and economic benefits of recycled materials. The study acknowledges certain limitations, such as variability in regional practices, transportation logistics, and inconsistencies in long-term performance data for recycled materials. Sensitivity analyses are conducted to mitigate uncertainties in LCA results and provide robust findings.This integrated methodological framework aims to provide a detailed and scientifically grounded analysis of the potential of recycled materials to reduce carbon footprints and advance sustainable architectural practices.

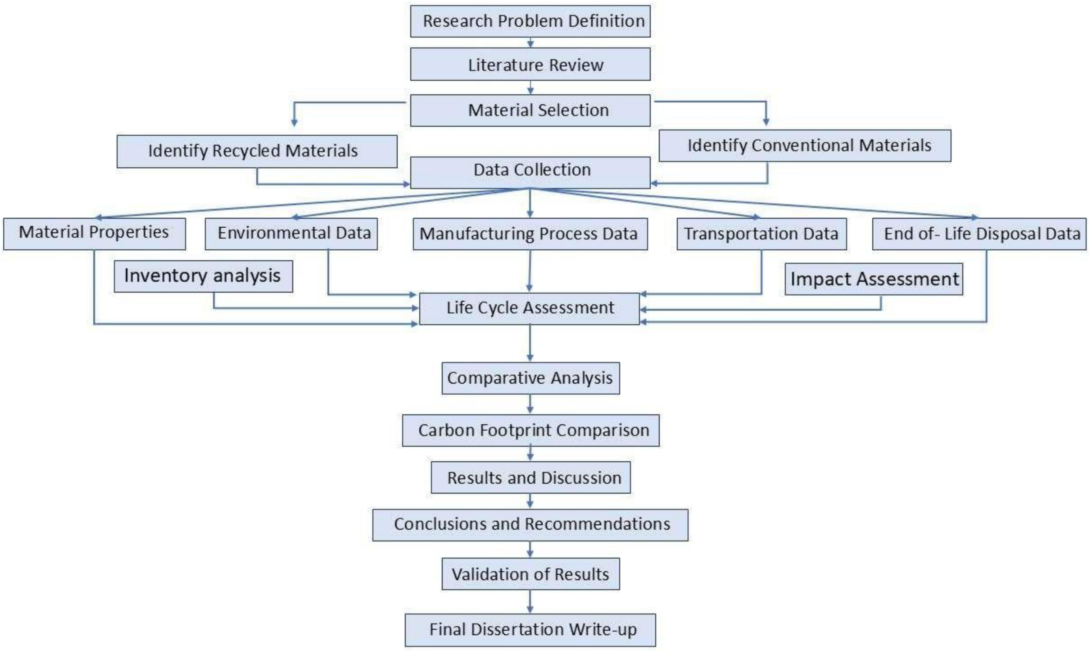


**Figure 1: Methodology flow chart**

## CHAPTER 2: LITERATURE STUDY

This chapter presents a comprehensive review of the literature related to the use of recycled materials in construction, with a focus on recycled concrete and recycled glass. The study emphasizes their environmental, economic, and structural advantages compared to conventional materials. A detailed review of 19 research papers forms the basis of this analysis, highlighting the potential of these materials to contribute to sustainable construction practices through reduced carbon footprints and enhanced resource efficiency.

### Overview of Recycled Concrete

Recycled concrete aggregates (RCA), sourced from construction and demolition waste, are increasingly recognized for their ability to mitigate the environmental impacts associated with cement production and virgin aggregate extraction. A case study by de Pedro et al. (2023) employed Life Cycle Assessment (LCA) to evaluate the substitution of cement with copper slag, a supplementary cementitious material, in reinforced concrete. The results demonstrated a 12.41%

reduction in Global Warming Potential (GWP) and a 9.22% reduction in Abiotic Depletion Potential (ADP) with a 15% replacement of cement. However, human toxicity and resource depletion impacts increased slightly, underscoring the need for a balanced approach.

Another study analyzed the environmental and structural advantages of RCA in multi-family residential and commercial buildings. A 15% reduction in embodied carbon emissions was achieved by replacing 30% of virgin aggregate with RCA. Additionally, the increased thermal mass of recycled concrete resulted in a 10% reduction in operational emissions over 60 years. Despite these benefits, initial costs increased by 5%, highlighting the trade-off between environmental and economic considerations.

**Table 1: Literature Summary**

| Author(s) | Objective | Materials | Analysis | Conclusion | Methodology |
|---|---|---|---|---|---|
| Mihalakakou et al. (2023) | Sustainability of green roofs for urban areas | Green roof materials | Energy consumption and sustainability analysis | Green roofs enhance urban sustainability by using recycled materials | Case study and LCA |
| Yazdanbakhsh et al. (2018) | Comparative LCA of natural and recycled concrete | Natural and recycled coarse aggregate | Life Cycle Impact Analysis | Recycled concrete showed a reduced environmental impact | Comparative LCA in New York City |
| Wijayasundara et al. (2017) | Assessment of embodied energy in recycled aggregate concrete. | Recycled aggregates | Energy consumption and carbon footprint analysis | Recycled aggregate reduces embodied energy | LCA for embodied energy assessment |
| Tam et al. (2016) | Carbon-conditioned recycled aggregates for concrete | Carbon-conditioned recycled aggregates | Carbon sequestration potential | Recycled aggregates can trap $CO_2$, lowering footprints | Environmental LCA and lab testing |
| Serres et al. (2016) | Environmental evaluation of recycled concrete | Recycled concrete aggregate | Carbon footprint and energy consumption analysis | Recycled concrete can substantially reduce carbon emissions | LCA for recycled materials |
| Panesar et al. (2017) | Functional unit impact on LCA for green concrete | Green concrete with varying materials | Environmental and functional performance | The choice of functional unit affects overall LCA results | Functional unit and environmental LCA |
| Tosic et al. (2015) | Optimization of natural and recycled aggregate concrete | Natural and recycled aggregates | Multi-criteria environmental and cost analysis | Recycled aggregates are viable for structural use | Environmental LCA and optimization |
| Braga et al. (2017) | Cradle-to-gate LCA of natural and recycled aggregates | Natural and recycled coarse aggregates | Economic and environmental impact comparison | Recycled aggregates offer environmental savings with minor cost impacts | Cradle-to-gate LCA |
| Marinkovic et al. (2010) | Comparative environmental assessment of natural vs. recycled aggregate concrete | Natural and recycled concrete | Environmental impact assessment | Recycled aggregates yield lower environmental impacts | LCA of construction materials |

| | | | | | |
|---|---|---|---|---|---|
| Kim et al. (2016) | Environmental impact of varying recycled components in concrete | Recycled concrete, compressive strength admixtures | Environmental footprint reduction | Optimized use of recycled materials cuts environmental impacts | LCA with variable inputs |
| Xiao et al. (2018) | Recycled aggregate high-rise building performance and embodied carbon footprint | Recycled aggregate in concrete | Structural performance and carbon footprint analysis | High-rise buildings made from recycled materials show low carbon emission | Structural analysis and LCA |
| Colangelo et al. (2018) | Life cycle impact of recycled aggregates in concrete | Recycled aggregates in concrete | Energy consumption and emission reductions | Recycled materials help cut carbon and energy demands | LCA of structural materials |
| Knoeri et al. (2013) | Comparative LCA of recycled vs. conventional concrete | Recycled and conventional concrete | Environmental impact evaluation | Recycled materials show fewer emissions across lifecycle | LCA for construction materials |
| Zuo et al. (2017) | Life cycle evaluation of green buildings | Various recycled materials | Life cycle cost and environmental impact | Green buildings using recycled materials improve lifecycle sustainability | LCA of buildings in Australia |
| Maduabuchukwu et al. (2020) | Recycled concrete aggregates in highway applications | Recycled concrete aggregates | Structural and environmental performance | Recycled aggregates enhance sustainability in road construction | Lab and field experiments, LCA |
| Margarido (2015) | LCA of construction materials | Recycled steel and glass in construction | Environmental and economic analysis | Recycled materials outperform conventional in carbon savings | LCA of various building materials |
| Wu et al. (2019) | Carbon emission reduction through sustainable materials in green construction | Recycled materials, steel, concrete | Analysis of carbon emissions across construction phases | Recycled materials can significantly reduce emissions during material production and operation phases. | LCA focused on material production and operation phases of green construction. |
| Nwakaire et al. (2021) | Porous asphalt with recycled concrete | Recycled concrete in asphalt | Environmental and functional performance | Porous asphalt using recycled materials improves sustainability | Field tests and LCA |
| Tam et al. (2020) | $CO_2$ technologies in recycled aggregate concrete | $CO_2$-treated recycled aggregates | Carbon capture potential analysis | $CO_2$-treated materials further reduce carbon footprints | Environmental LCA |

**Overview of Recycled Glass**

Recycled glass has gained prominence due to its significant contributions to energy conservation and carbon footprint reduction. According to ARUP's (2021) comprehensive analysis of architectural glass, the use of cullet in glass manufacturing reduces energy consumption by approximately 3% for every 10% increase in cullet content. The study revealed that incorporating one tonne of recycled glass prevents 250–300 kg of $CO_2$ emissions and conserves approximately 1.2 tonnes of raw materials, including silica sand, soda ash, and limestone.

Furthermore, the closed-loop recycling process of glass minimizes landfill waste and supports circular economy principles. Challenges such as contamination from laminated or coated glass require advanced separation technologies, but innovations like heat and steam-based delamination are proving effective. The study emphasized the scalability of recycled glass, with a 70% recycled content reducing embodied energy from 14 MJ/kg to 12 MJ/kg, showcasing its potential in sustainable architecture.

**Comparative Analysis of Recycled Materials**

Several studies compared the environmental impacts of recycled concrete and glass with those of conventional materials. For instance, a lifecycle study on concrete mixtures containing recycled aggregates demonstrated a 10.23% reduction in cumulative energy demand (CED) when 100% natural aggregate (NA) was replaced with 100% RCA. The study also highlighted significant reductions in freshwater and marine ecotoxicity by up to 63.4% and 76.8%, respectively. Similarly, the integration of recycled glass in construction projects diverted 50% of construction and demolition waste from landfills, contributing to resource efficiency and waste minimization.

**Key Findings from Literature**

Both recycled concrete and glass demonstrate significant potential in reducing carbon emissions, embodied energy, and resource depletion. Their adoption can lower the Global Warming Potential (GWP) of construction materials and promote sustainable building practices. While recycled materials often involve higher initial costs due to processing and transportation, their long-term benefits, such as energy savings and reduced landfill expenses, offset these costs over the lifecycle of buildings. Studies confirm that recycled concrete achieves compressive strengths comparable to conventional aggregates, and recycled glass enhances thermal properties and durability when appropriately integrated into construction designs. Despite their benefits, challenges such as data inconsistencies, regional variability in impacts, and limitations in recycling infrastructure must be addressed. Advancements in recycling technologies and supportive policies can enhance the adoption of these materials

## CHAPTER 3: STUDY AREA

**Materials selection**

Figure 2 illustrates the rationale behind selecting recycled concrete and recycled glass as the primary materials for this study, emphasizing their substantial environmental and practical advantages in sustainable construction. These materials address critical environmental challenges while maintaining functional and structural integrity, making them integral to advancing eco- friendly architectural practices. Recycled concrete, derived from construction and demolition waste, is an innovative material that simultaneously addresses two significant issues: the high carbon emissions associated with cement production and the accumulation of construction waste in landfills. Cement production is responsible for approximately 8% of global anthropogenic carbon dioxide emissions, making it a major contributor to climate change. By incorporating recycled concrete as a substitute for virgin aggregates, the demand for natural resources such as sand and gravel is significantly reduced. This practice mitigates the environmental degradation associated with resource extraction and preserves finite geological reserves. Moreover, recycled concrete offers structural properties comparable to those of traditional aggregates, meeting ASTM standards with minimal adjustments to mix design. This ensures its applicability across various construction projects without compromising performance. Its use also diverts construction waste from landfills, contributing to waste management solutions and reducing the environmental footprint of building activities. The material's dual role as a sustainable alternative and waste management tool makes it highly relevant for low-carbon construction. Recycled glass complements the benefits of recycled concrete by offering unique environmental advantages rooted in circular economy principles. Glass recycling reduces the need for extracting raw materials such as silica sand, soda ash, and limestone, which are critical for glass manufacturing. The recycling process also lowers energy consumption, as cullet (crushed recycled glass) melts at a lower temperature compared to virgin raw materials. For every 10% increase in cullet content, energy use decreases by approximately 3%, translating into substantial energy savings during production. Additionally, recycling one tonne of cullet prevents 250–300 kilograms of $CO_2$ emissions, primarily by avoiding the resource-intensive processes of raw material extraction and processing. By diverting glass waste from landfills, this practice not only reduces environmental contamination but also minimizes methane emissions associated with organic waste decomposition in mixed landfill contexts. The closed-loop recycling of glass aligns with sustainable development goals, promoting resource efficiency and reducing the environmental impact of glass production. Both recycled concrete and recycled glass significantly reduce the embodied energy and greenhouse gas emissions associated with construction materials. They enable the development of environmentally conscious buildings without compromising structural performance, making them exemplary choices for sustainable architectural practices. The materials' practicality and scalability ensure their suitability for widespread adoption in real-world applications. Their selection underscores a strategic emphasis on leveraging recycled resources to address pressing environmental challenges, such as carbon emissions, resource scarcity, and waste management. In the context of this study, the use of recycled concrete and glass reflects a commitment to low-carbon construction practices. By integrating these materials into building projects, the study demonstrates their potential to reduce the environmental impact of construction activities while supporting the global transition toward sustainable urban development. Their adoption showcases the feasibility of achieving both ecological and practical goals, paving the way for a more sustainable future in architecture.

| Waste Material | Process of Recycling | Recycled Material | Embodied Energy (MJ/kg) | Source of Data |
|---|---|---|---|---|
| Concrete | Crushing and Screening | Recycled Aggregate | 0.1–0.5 | https://www.istructe.org/ |
| Glass | Crushing, Melting, Re-forming | Recycled Glass Panels | 15-18 | https://www.glassforeurope.com/ |
| Plastic | Shredding, Melting, Re-extrusion | Recycled Plastic Lumber | 75-90 | https://www.plasticseurope.org/ |
| Steel | Melting and Re-forming | Recycled Steel | 20-25 | https://www.worldsteel.org/ |
| Wood | Shredding, Compression | Engineered Wood Products | 2 - 3 | https://www.woodsolutions.com.au/ |
| Gypsum | Crushing and Purification | Recycled Gypsum Boards | 1.9 | https://www.gypsum.org/. |
| Asphalt | Milling and Re-laying | Recycled Asphalt Pavement | 0.45-0.50 | https://www.asphaltpavement.org/ |
| Brick | Crushing and Re-use | Recycled Brick Aggregates | 0.8–1.5 | http://www.wrap.org.uk/ |

**Figure 2: List of Materials**

**Case Study 1**

**Abstract**

This study investigates the environmental and economic implications of using copper slag (CS) as a supplementary cementitious material (SCM) in reinforced concrete buildings. By replacing traditional cement with CS at varying proportions, the research explores the potential to reduce the carbon footprint and resource consumption associated with concrete production. A comprehensive Life Cycle Assessment (LCA) methodology was employed to evaluate the environmental impact of different concrete mixes, focusing on key impact categories such as Global Warming Potential (GWP), Abiotic Depletion Potential (ADP), Human Toxicity Potential (HTP), and Abiotic Depletion (Fossil). Additionally, the economic viability of incorporating CS was assessed to determine its cost-effectiveness in construction practices. The findings highlight the benefits and limitations of copper slag usage across diverse environmental and economic dimensions, providing insights into sustainable material alternatives for the construction industry.

**Introduction**

Concrete remains a cornerstone of modern construction, owing to its versatility, durability, and availability. However, its widespread use comes with significant environmental concerns, primarily due to the production of cement—a critical component responsible for approximately 7% of global anthropogenic carbon emissions (de Pedro et al., 2023). The cement production process is energy-intensive and involves the calcination of limestone, releasing large quantities of $CO_2$ into the atmosphere. Addressing these environmental challenges requires innovative approaches, including the integration of Supplementary Cementitious Materials (SCMs) that partially or fully replace cement in concrete mixes. Copper slag (CS), a by-product generated during the refining of copper, presents a promising SCM with significant environmental and economic potential. CS is characterized by high pozzolanic activity and can enhance the mechanical and durability properties of concrete when appropriately utilized. Its incorporation as a partial cement substitute aligns with the principles of circular economy by repurposing industrial waste into valuable construction material, thereby reducing reliance on virgin resources and mitigating waste management issues. This study focuses on the environmental and economic implications of substituting cement with CS in the construction of low-rise (three-story) and mid-rise (seven-story) buildings, designed with varying concrete strengths ranging from 20.7 MPa to 41.4 MPa. By examining these scenarios, the research aims to assess the feasibility and sustainability of CS as an alternative material in modern construction.

**Methodology**

The research adopts a cradle-to-gate Life Cycle Assessment (LCA) approach in accordance with the ISO 14040 framework. This perspective encompasses all stages of the material's life cycle up to the point of leaving the production site, including raw material extraction, processing, and transportation. The ACI (American Concrete Institute) method was employed to design concrete mix proportions, with CS replacing cement at 5%, 10%, and 15% substitution levels by weight. These mixes were evaluated for their mechanical properties to ensure compliance with structural requirements for the selected building types. Environmental impacts were assessed across key categories: Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), and Abiotic Depletion (Fossil). The LCA modeling was conducted using Simapro software, supported by the Ecoinvent database, to ensure accurate and comprehensive data analysis. Figures 3 and 4 present the environmental impact assessment results, illustrating the variations in performance across different CS substitution levels. Additionally, a cost analysis was performed to evaluate the economic implications of incorporating CS, considering factors such as material costs, energy savings, and potential reductions in waste disposal expenses. By integrating these environmental and economic evaluations, the study provides a holistic understanding of the benefits and trade-offs associated with using copper slag as a partial cement replacement. This research aims to inform sustainable material selection strategies and contribute to the broader goal of reducing the construction industry's environmental footprint

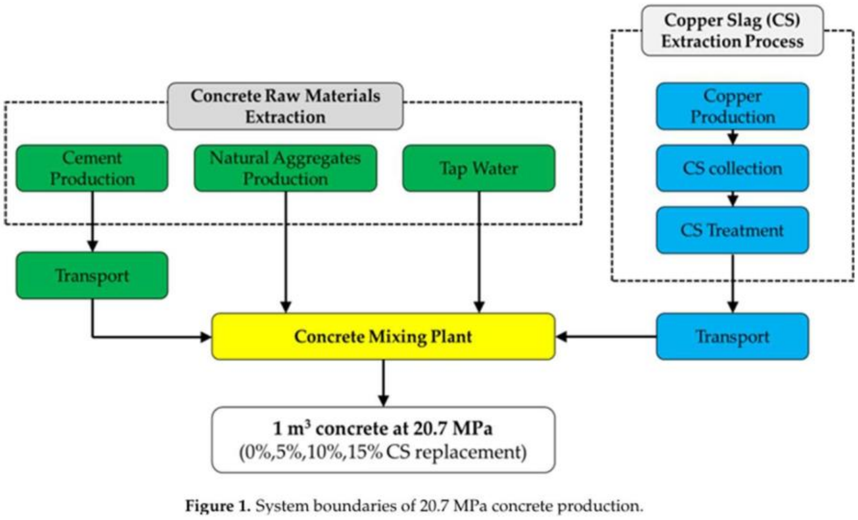


**Figure 3: System Boundary 20.7 MPa concrete production**

Source 1: Life Cycle Assessment of Concrete Using Copper Slag as a Partial Cement Substitute in Reinforced Concrete Buildings: Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Manila 0922, Philippin

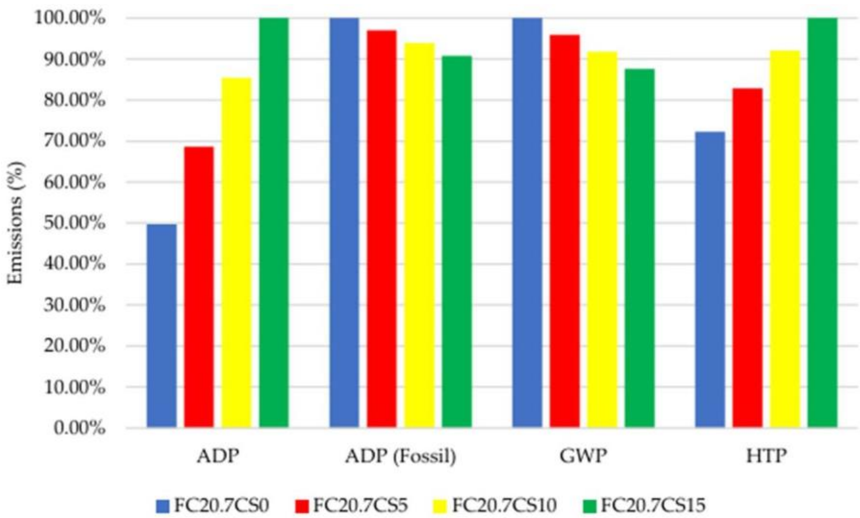


**Figure 4: Impact assessment of 20.7 MPa concrete system**

Source 1: Life Cycle Assessment of Concrete Using Copper Slag as a Partial Cement Substitute in Reinforced Concrete Buildings: Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Manila 0922, Philippines Concrete systems incorporating varying levels of copper slag (CS) as a partial cement substitute were applied to structural models developed using ETABS software. These models were designed to simulate low-rise (three-story) and mid-rise (seven-story) reinforced concrete buildings, with structural loads and seismic considerations evaluated in compliance with the National Structural Code of the Philippines (NSCP). The inclusion of seismic considerations ensured the structural integrity and resilience of the models under dynamic loading conditions, reflecting the geographic vulnerability of regions prone to seismic activity. By integrating material-specific properties into the modeling process, the study assessed the practical implications of CS substitution on structural performance while addressing environmental and economic impacts.

## Results

### 1. Environmental Impact Assessment

The Life Cycle Assessment (LCA) revealed mixed outcomes in terms of environmental impacts associated with copper slag substitution.

**Global Warming Potential (GWP) and Abiotic Depletion Potential (Fossil):**

The study demonstrated that increasing the CS content to 15% resulted in maximum reductions of GWP and ADP (Fossil) by 12.41% and 9.22%, respectively (Figure 5). These reductions highlight the potential of CS substitution to mitigate carbon emissions and reduce reliance on fossil-based resources, thereby contributing to more sustainable construction practices. The decreased environmental footprint in these categories is primarily attributed to the lower embodied energy of CS compared to traditional cement, as well as the reduced demand for resource-intensive cement production.

**Abiotic Depletion Potential (ADP) and Human Toxicity Potential (HTP):**

In contrast, the incorporation of CS led to notable increases in emissions for ADP (up to 50.32%) and HTP (up to 27.75%) at the 15% substitution level. These increases reflect the environmental trade-offs associated with the extraction, processing, and transportation of copper slag. While CS is a by-product, its handling and integration into concrete mixes may introduce additional environmental burdens that offset its benefits in other impact categories. These findings underscore the complexity of evaluating SCMs and highlight the need for a balanced approach when assessing their environmental implications.

### 2. Cost Analysis

The economic evaluation revealed that the substitution of cement with copper slag led to statistically significant cost savings, particularly for low-rise and mid-rise buildings. The maximum cost savings achieved were 1.40%, as shown in Figures 7 and 8 and detailed in Table 2. These savings are attributed to the reduced cost of CS relative to cement and the associated decrease in raw material expenses. Additionally, the economic benefits extend to reduced landfill disposal costs for copper slag, supporting its repurposing within the construction industry. Despite the modest percentage, the cost savings are meaningful when scaled to large construction projects, emphasizing the economic viability of CS as an alternative material.

### 3. Structural Performance

The structural performance analysis indicated that the integration of copper slag into concrete mixes required careful adjustments to maintain desired strength properties. Higher-strength concrete formulations (up to 41.4 MPa) necessitated proportional increases in CS content, demonstrating an interdependency between material composition and structural requirements. These adaptations were critical to ensuring compliance with structural safety standards and addressing the increased load demands of mid-rise buildings.

The results, summarized in Table 3, highlight the importance of optimizing CS proportions for specific design scenarios to achieve both environmental and structural objectives. The findings reaffirm that while CS substitution can enhance sustainability, its integration must be carefully calibrated to prevent adverse impacts on structural performance and to maximize environmental and economic benefits.

## Conclusion

The study demonstrates that copper slag has significant potential as a sustainable alternative to cement in reinforced concrete, offering reductions in carbon emissions and cost savings while maintaining structural integrity. However, the associated trade-offs in certain environmental categories and the need for precise design adaptations underscore the importance of a holistic evaluation when incorporating

SCMs into construction practices.

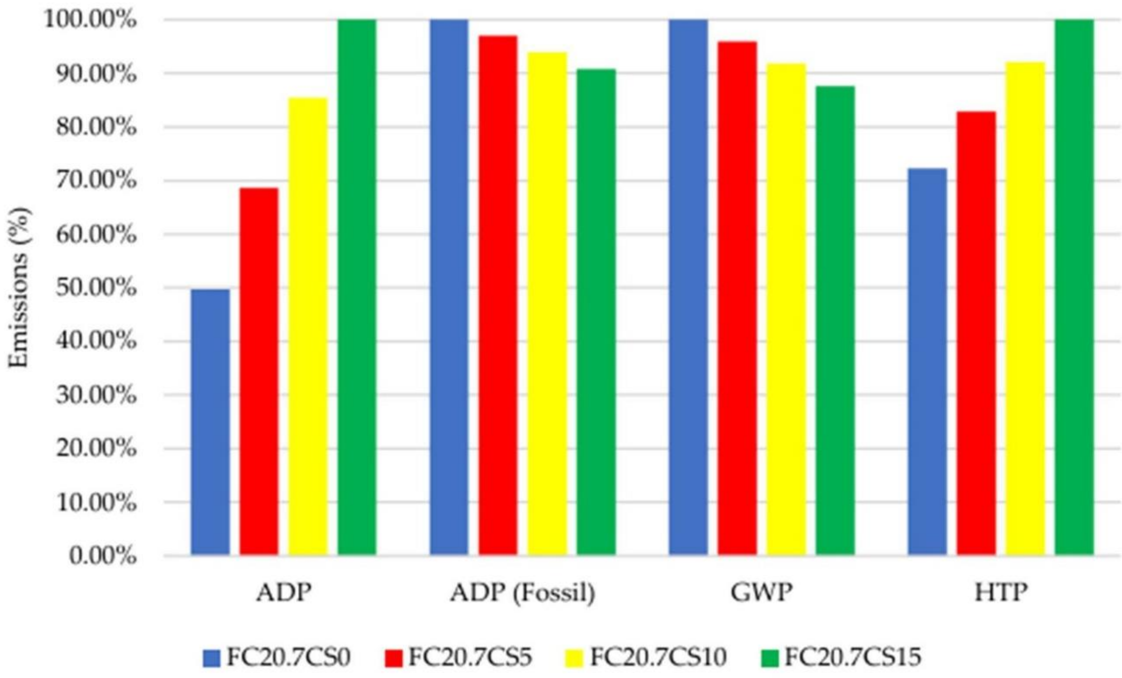


**Figure 3.** Impact assessment of 20.7 MPa concrete systems.

**Figure 5: Impact assessment of 20.7 MPa concrete system**

Source 1: Life Cycle Assessment of Concrete Using Copper Slag as a Partial Cement Substitute in Reinforced Concrete Buildings: Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Manila 0922, Philippines

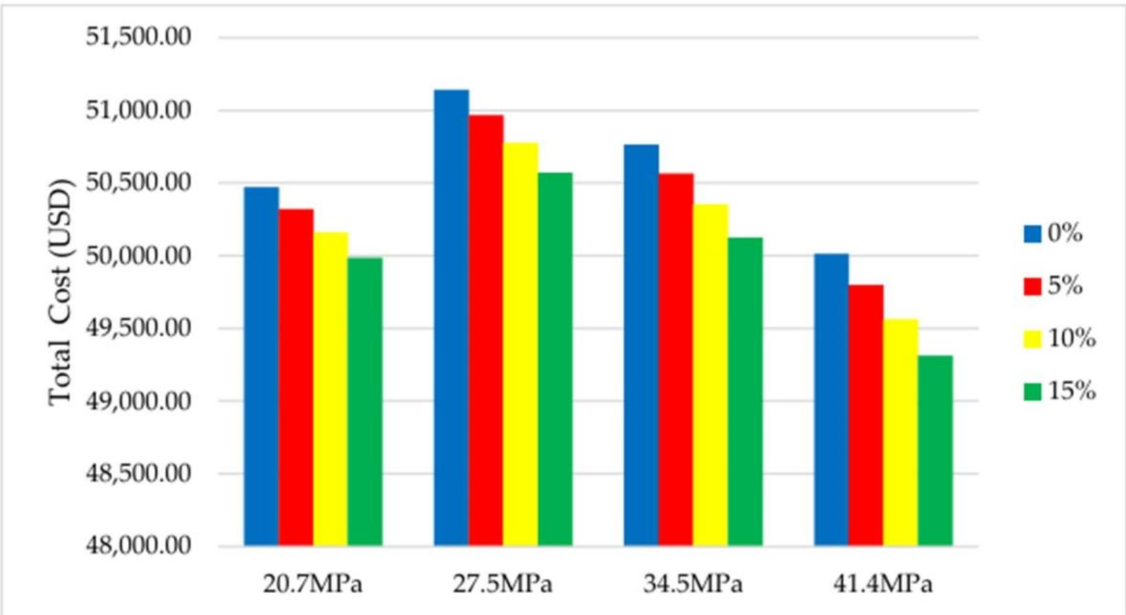


**Figure 7: Three-story total cost with different concrete design strengths with CS as SCM** Source 1: Life Cycle Assessment of Concrete Using Copper Slag as a Partial Cement Substitute in Reinforced Concrete Buildings: Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Manila 0922, Philippines

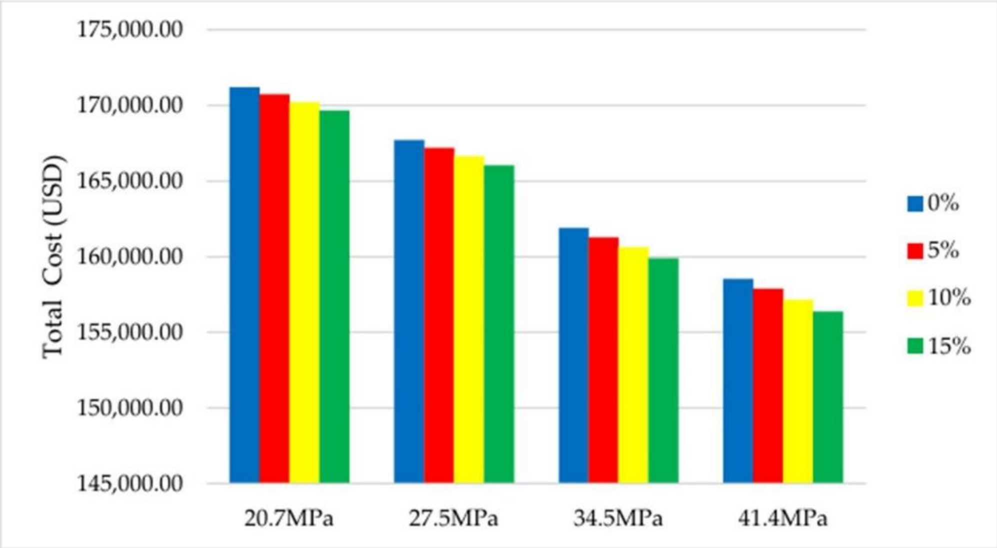


**Figure 8: Three-story total cost with different concrete design strengths with CS as SCM**

Source 1: Life Cycle Assessment of Concrete Using Copper Slag as a Partial Cement Substitute in Reinforced Concrete Buildings: Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Manila 0922, Philippines

**Table 12.** Three-story building cost and cost savings, along with corresponding *p*-value.

| Concrete System | Total Building Cost | Savings | *p*-Value |
|---|---|---|---|
| FC20.7CS0 | 50,469.59 | 0.00 | $2.188 \times 10^{-14}$ |
| FC20.7CS5 | 50,320.91 | 148.68 | |
| FC20.7CS10 | 50,159.87 | 309.72 | |
| FC20.7CS15 | 49,986.48 | 483.11 | |
| FC27.5CS0 | 51,139.92 | 0.00 | $5.442 \times 10^{-14}$ |
| FC27.5CS5 | 50,964.82 | 175.10 | |
| FC27.5CS10 | 50,775.17 | 364.75 | |
| FC27.5CS15 | 50,570.96 | 568.96 | |
| FC34.5CS0 | 50,762.05 | 0.00 | $1.163 \times 10^{-13}$ |
| FC34.5CS5 | 50,565.08 | 196.97 | |
| FC34.5CS10 | 50,351.74 | 410.31 | |
| FC34.5CS15 | 50,122.04 | 640.02 | |
| FC41.4 CS0 | 50,013.16 | 0.00 | $2.217 \times 10^{-13}$ |
| FC41.4CS5 | 49,797.36 | 215.80 | |
| FC41.4CS10 | 49,563.63 | 449.54 | |
| FC41.4CS15 | 49,311.96 | 701.20 | |

Table 2: Three-story building cost and cost savings, along with corresponding p-value Source 1: Life Cycle Assessment of Concrete Using Copper Slag as a Partial Cement Substitute in Reinforced Concrete Buildings: Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Manila 0922, Philippines

**Table 3.** Concrete mix proportions on a per cubic meter basis.

| Component | FC20.7 CS0 | FC20.7 CS5 | FC20.7 CS10 | FC20.7 CS15 | FC27.5 CS0 | FC27.5 CS5 | FC27.5 CS10 | FC27.5 CS15 |
|---|---|---|---|---|---|---|---|---|
| Cement (kg) | 301.47 | 286.40 | 271.32 | 256.25 | 359.65 | 341.67 | 323.68 | 305.70 |
| CS (kg) | 0 | 14.32 | 27.13 | 38.44 | 0 | 17.08 | 32.37 | 45.86 |
| Water (kg) | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 |
| CA (kg) | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 |
| FA (kg) | 681.68 | 683.34 | 686.04 | 689.77 | 637.35 | 639.34 | 642.56 | 647.01 |
| **Component** | **FC34.5 CS0** | **FC34.5 CS5** | **FC34.5 CS10** | **FC34.5 CS15** | **FC41.4 CS0** | **FC41.4 CS5** | **FC41.4 CS10** | **FC41.4 CS15** |
| Cement (kg) | 427.08 | 405.73 | 384.38 | 363.02 | 500.00 | 475.00 | 450.00 | 425.00 |
| CS (kg) | 0 | 20.29 | 38.44 | 54.45 | 0 | 23.75 | 45.00 | 63.75 |
| Water (kg) | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 | 205.00 |
| CA (kg) | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 | 1122.55 |
| FA (kg) | 585.97 | 588.33 | 592.15 | 597.44 | 530.42 | 533.18 | 537.65 | 543.84 |

**Table 3: Concrete mix proportions on a per cubic meter basis**

Source 1: Life Cycle Assessment of Concrete Using Copper Slag as a Partial Cement Substitute in Reinforced Concrete Buildings: Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Manila 0922, Philippines

## Case Study 2

**Abstract**

This study investigates the environmental and structural advantages of incorporating recycled concrete into building construction, focusing on its life cycle assessment (LCA) to evaluate its sustainability benefits. By analyzing data from established benchmarks in sustainable construction practices, the research quantifies the global warming potential (GWP), embodied carbon emissions, and energy efficiency impacts of adopting recycled concrete as a primary building material. The study also explores the structural performance of recycled concrete, ensuring compliance with engineering standards while promoting a circular economy approach. Findings demonstrate that recycled concrete significantly reduces environmental burdens associated with virgin aggregate extraction and cement production, making it a viable alternative for eco-conscious building projects.

**Introduction**

Concrete remains a fundamental material in modern construction, valued for its durability, strength, and adaptability. However, its widespread use has profound environmental consequences, primarily due to the production of cement, its key binding component. Cement manufacturing is energy-intensive and contributes approximately 8% of global anthropogenic $CO_2$ emissions, driven by the calcination process and the extensive use of fossil fuels. These emissions, coupled with the environmental degradation caused by aggregate extraction, underscore the urgent need for sustainable alternatives in the construction industry. Recycled concrete emerges as a promising solution to these challenges, offering dual benefits of waste reduction and resource efficiency. By repurposing concrete from construction and demolition waste, the demand for virgin aggregates is minimized, reducing the environmental degradation associated with quarrying activities. Additionally, the reuse of existing concrete aligns with circular economy principles, promoting the valorization of waste materials and enhancing sustainability in construction.

This study applies a comprehensive life cycle assessment (LCA) framework to evaluate the environmental and structural feasibility of recycled concrete in multi-family residential and commercial building projects.

The LCA methodology enables a detailed analysis of the material's global warming potential (GWP), embodied carbon emissions, and energy consumption across its lifecycle, from raw material acquisition to end-of-life stages. Furthermore, the structural performance of recycled concrete is assessed to ensure its compatibility with engineering standards and its ability to meet the demands of modern construction. By integrating environmental and structural considerations, this research aims to provide actionable insights into the potential of recycled concrete to address pressing environmental challenges while maintaining the functional and economic viability of construction practices. Through this case study, the study contributes to the broader discourse on sustainable materials, emphasizing the role of recycled resources in transitioning toward low-carbon construction paradigms.

## Methodology

### Life Cycle Assessment (LCA) Methodology

The Life Cycle Assessment (LCA) methodology employed in this study adheres to the ISO 14040:2006 standards, ensuring a systematic and scientifically rigorous evaluation of the environmental impacts associated with the incorporation of recycled concrete in construction. The analysis encompasses the following critical phases:

### Goal and Scope Definition

The primary objective of this LCA study is to evaluate the environmental performance of recycled concrete in two distinct building types: a four-story multi-family residential building and a 12- story commercial building. These buildings were selected to represent varying scales and functional demands in urban construction, providing a comprehensive perspective on the applicability of recycled concrete across diverse architectural contexts.

The functional unit for the analysis is defined as the usable area per square foot of building, serving as a consistent basis for comparing environmental impacts. The system boundary encompasses the full lifecycle of the buildings, adopting a cradle-to-grave approach that includes material extraction, transportation, construction, operation, and end-of-life (demolition and disposal) phases. Figure 9 illustrates the system boundary, emphasizing the interconnected processes contributing to the lifecycle impacts.

### Inventory Analysis

The inventory analysis focuses on quantifying key inputs and outputs within the defined system boundary. Essential components considered include:

**Recycled Aggregates:** Sourced from demolished concrete, these materials are processed to meet grading and quality requirements for use in structural applications.

**Standard Building Elements:** Insulated concrete forms and steel reinforcements were included to reflect typical construction practices and ensure structural integrity.

**Transportation Distances:** Regional transportation distances for raw materials, recycled aggregates, and construction elements were accounted for, incorporating variations based on geographic proximity and logistics. Detailed data on transportation inputs is provided in Appendix 8.1.

This phase also involves the compilation of energy and emissions data from material processing and transport, creating a robust dataset for subsequent impact assessment.

### Impact Assessment

The environmental impacts were quantified using established metrics, with a particular focus on Global Warming Potential (GWP). GWP was calculated in terms of $CO_2$-equivalent emissions, enabling a direct comparison of the carbon footprint between conventional and recycled concrete systems. Data sources for this analysis included the GaBi databases, which provided lifecycle inventory data for materials and processes, and region-specific electricity mix data to account for variations in energy production and consumption (Table 2.4).

Other impact categories, such as embodied energy, resource depletion, and waste generation, were also considered to provide a comprehensive assessment of recycled concrete's environmental performance.

**Interpretation**

To ensure the reliability and applicability of the findings, sensitivity analyses were conducted to evaluate the influence of varying cement replacement levels on the overall environmental impact. These analyses allowed the study to address uncertainties and variability, particularly in the composition and performance of recycled aggregates. The results highlighted the trade-offs associated with different substitution levels, providing nuanced insights into the optimal integration of recycled concrete in construction projects.

By adopting this detailed and structured approach, the LCA methodology offers a robust framework for understanding the environmental implications of recycled concrete. It supports evidence-based decision-making in sustainable construction practices, demonstrating the potential of recycled materials to reduce environmental impacts while maintaining structural performance.

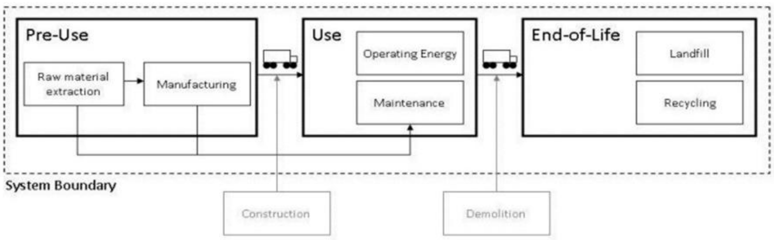


**Figure 9: Building LCA system boundary**

Source 2: Methods, Impacts, and Opportunities in the Concrete Building Life Cycle: Concrete Sustainability Hub Massachusetts Institute of Technology 77 Massachusetts Avenue MIT Room 1-372 Cambridge MA 02139

**Table 2.4 – Important $CO_2e$ factors for materials and energy used in this study**

| Process | $CO_2e$ Factor | | Units | |
|---|---|---|---|---|
| Cement | 0.928 | | lb $CO_2e$/lb | kg $CO_2e$/kg |
| Concrete Mix (5000 psi)[a] | 0.144 | | lb $CO_2e$/lb | kg $CO_2e$/kg |
| Concrete Mix (3000 psi)[b] | 0.105 | | lb $CO_2e$/lb | kg $CO_2e$/kg |
| Steel – Structural[c] | 1.001 | | lb $CO_2e$/lb | kg $CO_2e$/kg |
| Steel – Rebar | 1.241 | | lb $CO_2e$/lb | kg $CO_2e$/kg |
| Wood – Sawn Lumber (PNW/SE)[d] | 0.282/0.169 | | lb $CO_2e$/lb | kg $CO_2e$/kg |
| Wood – Plywood (PNW/SE)[d] | 0.286/0.255 | | lb $CO_2e$/lb | kg $CO_2e$/kg |
| Chicago Electricity | 1.7842 | lb $CO_2e$/kWh | 0.2248 | kg $CO_2e$/MJ |
| Phoenix Electricity | 1.3087 | lb $CO_2e$/kWh | 0.1649 | kg $CO_2e$/MJ |
| US Natural Gas | 0.5953 | lb $CO_2e$/kWh | 0.0750 | kg $CO_2e$/MJ |

[a] Pre-use impact: 0.131 lb $CO_2e$/lb, end-of-life impact: 0.012 lb $CO_2e$/lb
[b] Pre-use impact: 0.093 lb $CO_2e$/lb, end-of-life impact: 0.012 lb $CO_2e$/lb
[c] Pre-use impact: 1.563 lb $CO_2e$/lb, end-of-life credit: 0.562 lb $CO_2e$/lb
[d] End-of-life impact: 0.020 lb $CO_2e$/lb

**Table 4: Important CO2e factors for materials and energy used in this study**

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## Results

### Embodied and Operating Emissions

The results highlight the significant environmental benefits of incorporating recycled concrete in multi-family residential and commercial buildings, focusing on reductions in both embodied and operating emissions.

**Multi-family Residential Building:**

The embodied global warming potential (GWP) for traditional concrete used in multi-family residential buildings was measured at 108 kg $CO_2e/m^2$. When 30% of virgin aggregate was substituted with recycled aggregate, a 15% reduction in embodied emissions was achieved, as shown in Table 5. This reduction is attributed to the lower embodied energy of recycled aggregates, which require minimal processing compared to virgin materials. The reuse of construction and demolition waste as recycled aggregates also minimizes the environmental impacts of resource extraction and waste disposal, aligning with circular economy principles.

**Commercial Building:**

In the commercial building scenario, operating energy consumption emerged as the dominant contributor to lifecycle emissions, accounting for 88% of the total GWP under the baseline conditions. The use of recycled concrete, characterized by enhanced thermal mass, led to a 5% reduction in HVAC energy demand. This improvement in energy efficiency contributed to an overall 10% reduction in GWP over the building's 60-year lifecycle, as illustrated in Figure 10. The thermal mass properties of recycled concrete enabled better regulation of indoor temperatures, reducing reliance on energy-intensive heating and cooling systems and demonstrating its dual role in reducing embodied and operating emissions.

### Energy Efficiency

The study also revealed that recycled concrete exhibits superior thermal properties compared to traditional concrete, primarily due to its increased density and specific heat capacity. Buildings constructed with recycled concrete demonstrated lower energy demands for heating and cooling, as depicted in Figure 11. These properties enhance the material's ability to absorb and retain heat, moderating indoor temperature fluctuations and reducing peak energy loads. This characteristic is particularly advantageous in regions with extreme seasonal temperature variations, where energy efficiency plays a critical role in reducing operational costs and emissions.

The findings underscore the potential of recycled concrete to contribute to energy-efficient building design, complementing its environmental benefits. By integrating recycled concrete into construction practices, significant progress can be made toward achieving energy performance goals and reducing the carbon footprint of the built environment. These advantages, combined with the material's compliance with structural and durability requirements, make recycled concrete a viable and sustainable alternative for modern construction.

| | Chicago ICF lbs $CO_2e/ft^2$ (kg $CO_2e/m^2$) | Chicago Wood lbs $CO_2e/ft^2$ (kg $CO_2e/m^2$) | Phoenix ICF lbs $CO_2e/ft^2$ (kg $CO_2e/m^2$) | Phoenix Wood lbs $CO_2e/ft^2$ (kg $CO_2e/m^2$) |
|---|---|---|---|---|
| Concrete Mix– 10% fly ash | 35.3 (173) | 27.3 (133) | 31.9 (156) | 23.3 (114) |
| Concrete Mix – 50% fly ash | 30.4 (149) | 24.4 (119) | 28.2 (138) | 21.7 (106) |
| Percent Reduction | 14% | 10% | 12% | 6.9% |

**Table 5: Possible pre-use phase embodied GWP reduction with increased fly ash replacement of cement in concrete mix used in single-family residential houses**

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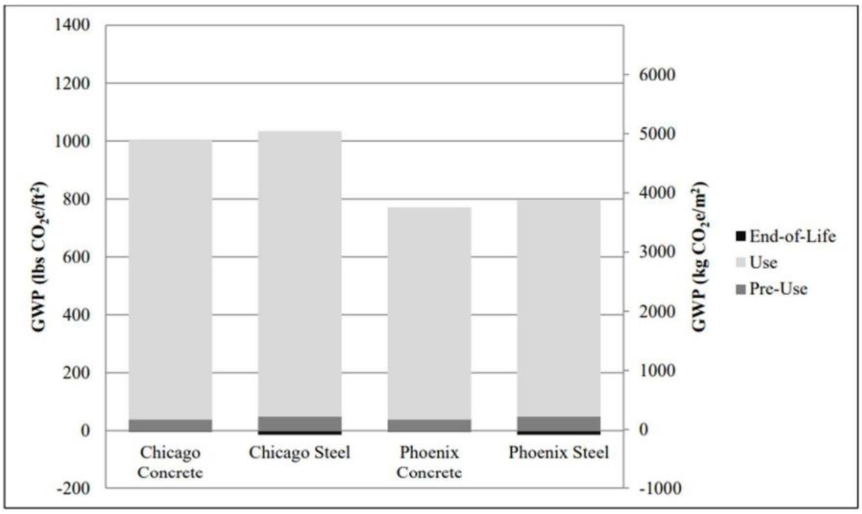


**Figure 10: GWP normalized by gross floor area over a 60 year lifespan for commercial buildings separated by phase**

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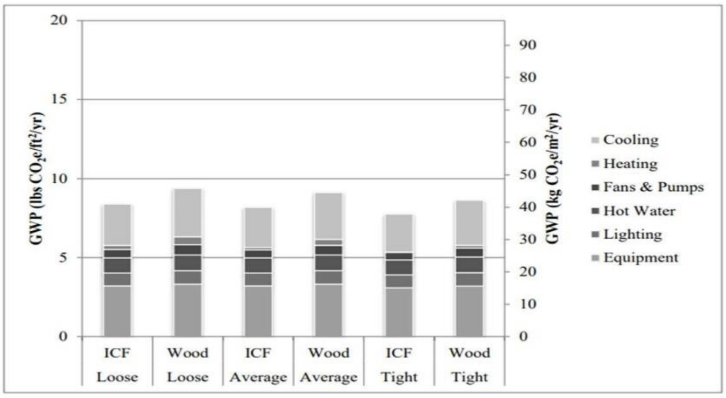


**Figure 11: GWP associated with annual energy use and normalized by gross floor area for the single-family houses in phoenix, separated by air tightness and energy end-use**

Source 2: Methods, Impacts, and Opportunities in the Concrete Building Life Cycle: Concrete Sustainability Hub Massachusetts Institute of Technology 77 Massachusetts Avenue MIT Room 1-372

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**Discussion**

**Structural Integrity**

The structural performance of recycled concrete was evaluated through compressive strength tests, demonstrating that the material achieved strengths comparable to conventional concrete mixes. This compliance with ASTM C39 requirements underscores its suitability for structural applications. The study identified a minor increase in porosity in recycled concrete, which necessitated adjustments to the water-to-cement (w/c) ratio to maintain the desired strength characteristics. These adjustments were minor and did not significantly impact the overall workability or durability of the concrete, affirming its practical applicability in construction. Furthermore, recycled concrete showed consistent performance under load-bearing conditions, reinforcing its reliability as a sustainable alternative to traditional aggregates**.**

**Economic Viability**

The lifecycle cost analysis (LCCA) provided insights into the economic implications of adopting recycled concrete in construction projects. The analysis revealed a marginal increase of approximately 5% in initial costs, primarily due to the additional processing required to convert construction and demolition waste into usable recycled aggregate. However, these upfront costs were effectively offset within a 10-year operational period, driven by reduced energy consumption associated with the superior thermal properties of recycled concrete. As shown in Table 6, the long-term savings in heating, ventilation, and air conditioning (HVAC) expenses made recycled concrete an economically competitive choice for sustainable construction. This economic viability, combined with its environmental and structural advantages, enhances its appeal for large-scale adoption in the construction industry.

**Environmental Benefits**

The environmental benefits of using recycled concrete were significant, particularly in terms of waste diversion and resource conservation. Recycling concrete diverted approximately 50% of construction and demolition (C&D) waste from landfills, as indicated in Table 7. This substantial reduction in waste not only alleviates pressure on landfill capacities but also mitigates the associated environmental impacts, such as methane emissions from decomposing organic material in landfills.

Additionally, the reuse of aggregates significantly reduced the demand for virgin material extraction, which is often associated with habitat destruction, biodiversity loss, and energy- intensive quarrying processes. By minimizing reliance on natural resources, recycled concrete aligns with sustainable construction practices and promotes a circular economy. The closed-loop recycling of construction materials reduces the carbon footprint of the construction industry while addressing the challenges of resource scarcity and waste management. The combined structural, economic, and environmental benefits position recycled concrete as a viable and sustainable alternative to conventional construction materials. Its adoption offers a pathway to reduce the environmental impacts of the built environment while maintaining compliance with engineering and economic performance standards.

| | Average Cost $/ft² ($/m²) | Location | Embodied lbs $CO_2e$ (kg $CO_2e$) | Annual Operating lbs $CO_2e$ (kg $CO_2e$) | 60-year Operating lbs $CO_2e$ (kg $CO_2e$) | Total lbs $CO_2e$ (kg $CO_2e$) |
|---|---|---|---|---|---|---|
| 4 in | -0.75 (-8.07) | Chicago | -5340 (-2427) | 81 (37) | 4860 (2210) | -478 (-217) |
| Core | -0.71 (-7.64) | Phoenix | -5340 (-2427) | 40 (18) | 2390 (1090) | -2950 (-1340) |
| 4 in | 0.22 (2.37) | Chicago | 1190 (541) | -2270 (-1259) | -136000 (-61800) | -135000 (-61600) |
| Panel | 1.42 (15.28) | Phoenix | 1190 (541) | -498 (-226) | -29900 (-13600) | -28700 (-13000) |
| 5 in | 0.63 (6.78) | Chicago | 1980 (900) | -2790 (-1268) | -167100 (-76000) | -165000 (-75000) |
| Panel | 2.00 (21.53) | Phoenix | 1980 (900) | -500 (-223) | -29900 (-13600) | -27900 (-12700) |
| 6 in | 1.34 (14.42) | Chicago | 2770 (1259) | -3115 (-1416) | -186900 (-85000) | -184000 (-83600) |
| Panel | 2.75 (29.90) | Phoenix | 2770 (1259) | -500 (-223) | -29900 (-13600) | -27100 (-12300) |

**Table 6: Relative embodied emissions, operating emissions, and total emission by changing the ICF wall from the 6 in concrete core, 2.5 in EPS panel base case**

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**Table 2.5 – Metal recycled content and recycling rates used in this study**

| Material (Source) | Type | Recycled Content | End-of-life Recycling Rate |
|---|---|---|---|
| Steel (World Steel 2011) | Structural | 60% | 98% |
| | Rebar | 70% | 70% |
| Aluminum (EAA 2008) | All | 11% | 100% |
| Concrete (Aggregate) (Kelly 1998) | All | 0% | 50% |

**Table 7: Metal recycled content and recycling rates used in this study**

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**Case study 3**

**Key Findings from the Study Lifecycle Energy Impacts**

The study provides an in-depth evaluation of the Cumulative Energy Demand (CED) for five distinct concrete mixtures, each containing varying ratios of Natural Aggregate (NA) and Recycled Concrete Aggregate (RCA). This analysis offers valuable insights into the energy savings achieved through the incorporation of RCA into concrete production.

**Quantitative Reduction in CED:**

Table 8 highlights a notable 10.23% reduction in total CED impacts when replacing 100% of NA with 100% RCA produced using a mobile recycling plant. Specifically, the total energy demand for 100% RCA mixtures was recorded at 885.75 MJ, compared to 986.67 MJ for concrete mixtures with 100% NA. This reduction underscores the energy efficiency benefits of integrating RCA, driven by the elimination of energy-intensive processes associated with virgin aggregate extraction and processing.

**Component-specific Contributions:**

Figure 12 disaggregates the energy contributions from different components of the concrete mixtures. Cement production emerged as the dominant source of energy consumption, accounting for the largest share of CED across all mixtures. This aligns with existing literature highlighting the energy-intensive nature of cement manufacturing due to calcination and kiln operations. Importantly, as the proportion of RCA in the mixtures increased, the energy impacts of aggregate production decreased significantly, demonstrating the efficacy of RCA in reducing lifecycle energy requirements. The visual analysis provided in Figure 12 further emphasizes the environmental and operational advantages of using RCA, particularly when produced in a mobile recycling plant. Concrete mixtures utilizing 100% RCA produced in mobile recycling plants eliminated the energy costs associated with landfill disposal of construction and demolition waste.

This closed-loop approach not only reduces waste management burdens but also contributes to significant energy savings by avoiding the emissions and energy demands tied to long-distance transport of materials. Mobile recycling plants, as highlighted in the study, offer additional energy efficiency benefits by localizing the recycling process. This reduces the need for extensive transportation of materials, thereby lowering fuel consumption and associated emissions. The decentralized nature of mobile plants makes them a scalable and practical solution for urban construction projects, particularly in regions with high volumes of construction and demolition waste. The findings reaffirm the potential of RCA to substantially lower the energy footprint of concrete production. The 10.23% reduction in CED, coupled with the operational efficiencies of mobile recycling plants, positions RCA as a critical component in sustainable construction practices. By reducing reliance on energy-intensive natural aggregates and minimizing transport- related impacts, RCA not only contributes to energy savings but also supports broader goals of resource efficiency and carbon reduction in the built environment. The study's comprehensive lifecycle energy assessment underscores the importance of adopting recycled materials in construction, offering a data-driven pathway toward more energy-efficient and environmentally responsible building practices.

| Mixtures for Concrete Production | Unit/Tonne | Total CED Impacts | Fine NA | Cement, Portland | Coarse NA | Coarse RCA | Plasticizer for Concrete | Transport | Electricity, Medium Voltage {IT} | Inert Waste Landfilling |
|---|---|---|---|---|---|---|---|---|---|---|
| CRCA-0 | MJ | 986.67 | 91.74 | 590.89 | 121.35 | 0 | 72.92 | - | 49.78 | 60.00 |
| CRCA-30-60 km-fixed plant | MJ | 970.09 | 87.68 | 590.89 | 81.21 | 11.32 | 72.92 | 34.57 | 49.78 | 41.73 |
| CRCA-30-30 km-mobile plant | MJ | 961.91 | 87.68 | 590.89 | 81.21 | 3.14 | 72.92 | 34.57 | 49.78 | 41.73 |
| CRCA-100-60 km-fixed plant | MJ | 913.93 | 90.55 | 619.52 | 0 | 38.97 | 76.45 | 36.24 | 52.19 | - |
| CRCA-100-30 km-mobile plant | MJ | 885.75 | 90.55 | 619.52 | 0 | 10.80 | 76.45 | 36.24 | 52.19 | - |

**Table 8: Characterized induced CED impacts of the five typologies of concrete mixtures analyzed in LCA study**

Source 3: Life Cycle Assessment of Concrete Production within a Circular Economy Perspective: Sustainability 2023, 15(14), 11469

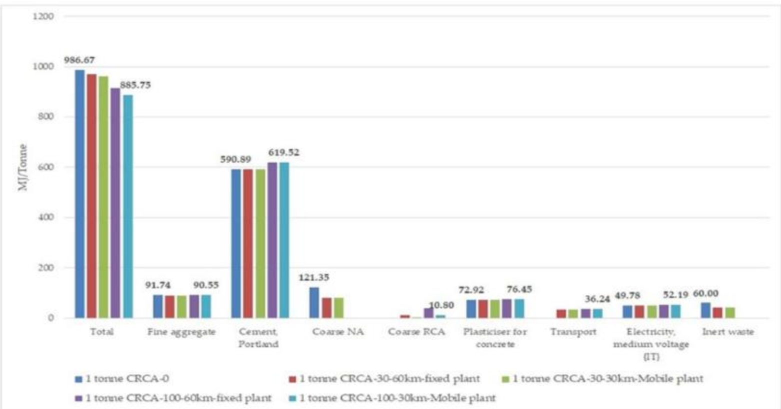


**Figure 2.** CED impacts of the different concretes (from left to right: total, four typologies produced, inputs).

**Figure 12: CED impacts of the different concrete (from left to right: total, four typologies produced, inputs)**

Source 3: Life Cycle Assessment of Concrete Production within a Circular Economy Perspective:

Sustainability 2023, 15(14), 11469

**Environmental Impact Categories**

The environmental impact analysis of concrete mixtures with 100% Recycled Concrete Aggregate (RCA) reveals substantial reductions across several key environmental categories, highlighting the ecological advantages of incorporating RCA in construction practices. Concrete mixtures utilizing 100% RCA demonstrate a 63.4% reduction in freshwater ecotoxicity impacts compared to mixtures using 100% Natural Aggregate (NA). This improvement is primarily attributed to the elimination of mining and processing activities associated with virgin aggregate production, which often release heavy metals and pollutants into freshwater ecosystems. Additionally, the reduced need for water-intensive processes in RCA production further mitigates contamination risks to aquatic environments. The adoption of RCA also results in a 76.8% decrease in marine ecotoxicity impacts. This reduction is largely due to the minimized release of hazardous substances during the lifecycle of RCA compared to NA, particularly in the stages of extraction and processing. By repurposing construction and demolition waste into RCA, the study aligns with sustainable practices that safeguard marine biodiversity and reduce ocean pollution. Human non-carcinogenic toxicity impacts are reduced by an impressive 77.9% with 100% RCA mixtures. This significant improvement underscores the lower exposure risks associated with RCA production, which involves fewer emissions of harmful substances such as particulate matter and volatile organic compounds (VOCs). The use of RCA diminishes the health hazards typically linked to virgin aggregate extraction and processing, contributing to improved air quality and public health outcomes. The water consumption associated with concrete production decreases by 17.3% when 100% RCA is used. RCA production requires less water for cleaning and processing compared to the extraction and preparation of NA. This reduction in water usage not only conserves a critical natural resource but also reduces the environmental burden associated with water-intensive industrial operations. The land use impacts of RCA mixtures are reduced by 11.6% compared to NA mixtures. This reduction is attributable to the diminished need for quarrying activities, which often result in habitat destruction and loss of arable land. By reusing construction and demolition waste, RCA production minimizes the ecological footprint associated with virgin material extraction, supporting land conservation efforts. Figure 13 illustrates the environmental impact contributions of transport activities, emphasizing the advantages of mobile recycling plants over fixed facilities. The figure highlights that transport from demolition sites to fixed recycling plants constitutes a significant portion of environmental impacts, including emissions and energy use. Mobile plants, located closer to demolition sites, substantially reduce transport-related impacts, thereby enhancing the sustainability of RCA production. Table 9 provides quantitative evidence of the environmental superiority of RCA, showing that 1 tonne of RCA produced in mobile recycling plants generates 89.69% fewer environmental impacts compared to 1 tonne of NA. This stark difference underscores the combined benefits of waste diversion, reduced transport distances, and energy-efficient recycling processes associated with mobile plant operations. The reductions across key environmental impact categories highlight the transformative potential of RCA in advancing sustainable construction. By addressing critical issues such as freshwater and marine pollution, resource consumption, and human health risks, RCA offers a pathway toward environmentally responsible building practices. The use of mobile recycling plants further amplifies these benefits by minimizing transport-related impacts, making RCA a practical and scalable solution for urban construction projects. This study reaffirms the ecological value of RCA and supports its integration into policies and practices aimed at reducing the environmental footprint of the construction industry.

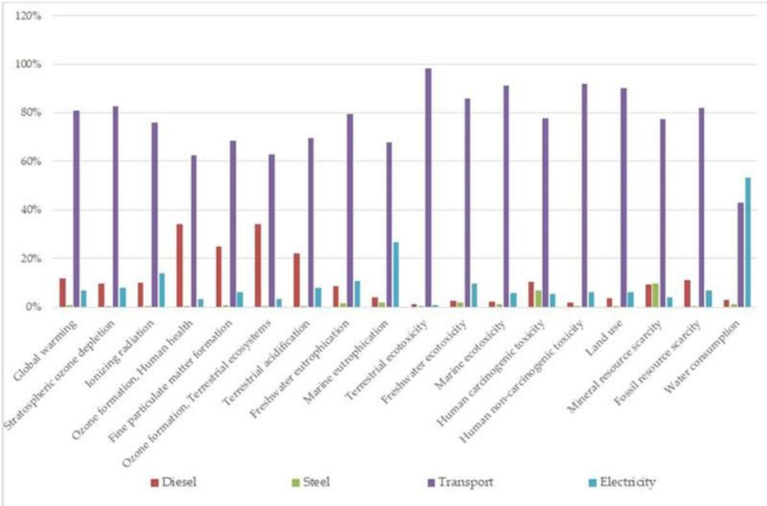


**Figure 13: Percentage contribution of inputs to the total impacts, when treating 1 tonne of coarse RCA in a fixed recycled plant**

Source 3: Life Cycle Assessment of Concrete Production within a Circular Economy Perspective: Sustainability 2023, 15(14), 11469

| Impact Category | Unit/Tonne | Coarse NA | Coarse RCA Fixed Plant | Coarse RCA Mobile Plant |
|---|---|---|---|---|
| Global warming potential | kg $CO_2$ eq | 18.53 | 6.22 | 1.91 |
| Stratospheric ozone depletion | kg CFC11 eq | 0.00 | 0.00 | 0.00 |
| Ionizing radiation | kBq Co-60 eq | 3.54 | 0.60 | 0.16 |
| Ozone formation, Human health | kg $NO_x$ eq | 0.09 | 0.03 | 0.02 |
| Fine particulate matter formation | kg PM2.5 eq | 0.04 | 0.01 | 0.01 |
| Ozone formation, Terrestrial ecosystems | kg $NO_x$ eq | 0.09 | 0.03 | 0.02 |
| Terrestrial acidification | kg $SO_2$ eq | 0.08 | 0.02 | 0.01 |
| Freshwater eutrophication | kg P eq | 0.01 | 0.00 | 0.00 |
| Marine eutrophication | kg N eq | 0.00 | 0.00 | 0.00 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 198.11 | 97.33 | 2.51 |
| Freshwater ecotoxicity | kg 1,4-DCB | 0.72 | 0.13 | 0.01 |
| Marine ecotoxicity | kg 1,4-DCB | 5302.43 | 1198.85 | 74.33 |
| Human carcinogenic toxicity | kg 1,4-DCB | 136.98 | 19.98 | 6.65 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 4298.79 | 953.35 | 46.22 |
| Land use | $m^2$a crop eq | 1.05 | 0.29 | 0.03 |
| Mineral resource scarcity | kg Cu eq | 0.08 | 0.01 | 0.00 |
| Fossil resource scarcity | kg oil eq | 5.90 | 2.15 | 0.62 |
| Water consumption | $m^3$ | 0.42 | 0.02 | 0.00 |

**Table 9: Characterized midpoint impacts of 1 tonne of coarse NA and 1 tonne of coarse RCA obtained in both fixed and mobile plant**

Source 3: Life Cycle Assessment of Concrete Production within a Circular Economy Perspective: Sustainability 2023, 15(14), 11469

**Material Comparisons: RCA vs. NA**

The comparison between Recycled Concrete Aggregate (RCA) and Natural Aggregate (NA) is critical in understanding the environmental and economic benefits of using recycled materials in construction. Table 10 provides a detailed breakdown of the compositions of the analyzed concrete mixtures, including their specific transportation distances. This table offers valuable insights into the energy inputs and environmental impacts associated with both RCA and NA, particularly in terms of resource extraction, processing, and logistics. RCA mixtures contribute significantly to sustainability by eliminating the need

for virgin material extraction, which is a key environmental concern associated with NA. The extraction of natural aggregates such as sand and gravel involves extensive mining operations, leading to habitat destruction, soil erosion, and the depletion of natural resources. These processes are energy-intensive and generate significant carbon emissions. By substituting NA with RCA, which is derived from construction and demolition waste, the need for these environmentally damaging activities is reduced. RCA not only diverts waste from landfills but also conserves the raw materials that would otherwise be extracted through mining. This shift towards recycled aggregates significantly mitigates the environmental degradation caused by the extraction of virgin materials, contributing to a more sustainable and circular approach to construction. The transportation distances associated with both RCA and NA play a critical role in the overall environmental impact of concrete production. As shown in Table 10, RCA mixtures are often sourced locally from construction and demolition sites, reducing the need for long-distance transportation. This localized sourcing minimizes fuel consumption and transportation-related carbon emissions. In contrast, the extraction of NA typically involves transportation from distant quarries or mines, which results in higher energy usage and increased emissions. The reduction in transport distances for RCA contributes to its overall sustainability, making it an environmentally preferable alternative to NA in many contexts. Figure 14 provides a visual representation of the environmental impacts associated with RCA processed in mobile recycling plants, comparing them to the impacts of NA. Although mobile plants rely primarily on diesel fuel for operation, the analysis demonstrates that the overall environmental impacts of RCA processing in these plants are still significantly lower than those of NA. The energy consumption and emissions from diesel usage in mobile plants are offset by the environmental benefits of localizing the recycling process, reducing transport distances, and avoiding the resource-intensive processes associated with virgin aggregate extraction. While mobile recycling plants contribute to increased diesel consumption, their localized operation significantly reduces the need for energy-intensive transportation. Additionally, the overall energy and emissions savings achieved by recycling construction and demolition waste into RCA more than compensate for the diesel used in mobile processing. This highlights the importance of considering the entire lifecycle impact of material sourcing and processing, rather than focusing on individual stages in isolation. The energy inputs and emissions associated with diesel in mobile recycling are a relatively small trade-off in the context of the substantial environmental benefits provided by RCA.
The comparison of RCA and NA highlights the superior sustainability of recycled aggregates in terms of resource conservation, waste reduction, and lower environmental impacts. The elimination of virgin material extraction, coupled with reduced transportation distances and the potential for mobile recycling operations, positions RCA as a highly sustainable alternative to NA. Despite some trade-offs in terms of diesel use for mobile plants, the overall benefits of RCA in reducing environmental degradation, conserving natural resources, and promoting circular economy principles outweigh the associated impacts. This comparison underscores the potential of RCA to contribute to the development of more sustainable construction practices, offering a viable pathway toward reducing the environmental footprint of the built environment.

| | Main Input and Their Subprocesses | FU |
|---|---|---|
| 1. | Fine Aggregates.<br>Ecoinvent 3.8:<br>• Sand [GLO] 1.04 tonne;<br>• Transport, freight, lorry 16–32 metric ton, EURO5 [GLO]. Distance to the concrete facility: 20 km | 1 tonne |
| 2. | Coarse Natural Aggregate.;<br>Ecoinvent 3.8:<br>• Gravel, crushed [RoW], market for gravel: 1.04 tonne;<br>• Transport, freight, lorry 16–32 metric ton, EURO5 [GLO]: Distance to the concrete facility: 20 km; | 1 tonne |
| 3. | Coarse Recycled Concrete Aggregate (CRCA) (Fixed treatment plant).<br>Ecoinvent 3.8:<br>• Diesel, burned in building machine [GLO]: 8.25 MJ/t.<br>• Electricity medium voltage (IT): 1.13 kWh/t.<br>• Steel, unalloyed [GLO] 0.02 kg/t<br>• Transport, freight, lorry 16–32 metric ton, EURO5 [GLO]. Distance from the demolition site to the fixed plant is 30 km while to the concrete facility is 30 km (total 60 km). | 1 tonne |
| 4. | Coarse Recycled Concrete Aggregate (CRCA) (Mobile treatment plant). Transport to the concrete facility: 30 km.<br>Ecoinvent 3.8:<br>• Diesel, burned in building machine [GLO]: 21.13 MJ/t.<br>• Steel, unalloyed [GLO]: 0.02 kg/t.<br>• Water, unspecified natural origin (IT): 1.56 l/t = 1.56 kg/t.<br>• Transport to the concrete facility: 30 km. | 1 tonne |

**Figure 14: Percentage contribution of inputs to coarse RCA treatment in a mobile recycling plant**

Source 3: Life Cycle Assessment of Concrete Production within a Circular Economy Perspective: Sustainability 2023, 15(14), 11469

**Case study 4**

**Conservation of Raw Materials**

The conservation of raw materials is a critical consideration in the quest for sustainable manufacturing processes, particularly in the glass industry, where the extraction of key raw materials has substantial environmental impacts. Figure 15, which depicts the raw material composition of float glass manufacturing, highlights that over 70% of the raw materials used in the production of glass are composed of silica sand, along with smaller proportions of soda ash, limestone, and dolomite. These materials are finite resources, meaning their extraction is constrained by the availability of natural deposits. The process of mining these raw materials is not only energy-intensive but also incurs significant environmental costs, including habitat destruction, soil erosion, and the depletion of non-renewable resources. Silica sand is the primary component in glass manufacturing, and its extraction is a critical concern due to the growing demand for high-purity sand, particularly in the production of clear glass. The purity of silica sand is crucial in ensuring the clarity and quality of the glass, which limits the sources from which it can be sustainably extracted. In addition to silica sand, soda ash, limestone, and dolomite are essential components of glass production. These materials are also finite resources, and their extraction contributes to significant environmental degradation. The increasing demand for these materials, driven by global construction, automotive, and packaging industries, further exacerbates the strain on the earth’s natural resources. The recycling of glass, particularly through the use of cullet (recycled glass), offers a promising solution to mitigate the environmental burden of raw material extraction. The recycling process significantly reduces the need for virgin raw materials, thus conserving natural resources and lowering the overall environmental impact of glass production. For every tonne of recycled cullet used in glass manufacturing, approximately 1.2 tonnes of raw materials—namely silica sand, soda ash, and limestone—are saved. This substantial reduction in raw material demand not only conserves finite resources but also mitigates the environmental impacts associated with their extraction. The use of cullet in glass production reduces the need for the mining and processing of silica sand, soda ash, and limestone, thus curbing the environmental degradation caused by these activities. Moreover, the recycling process requires significantly less energy compared to the production of glass from virgin materials, leading to a reduction in greenhouse gas emissions and energy consumption. One of the most critical aspects of raw material conservation in glass production is the reduction in dependence on high-purity silica sand. High-purity silica sand, necessary for producing clear glass, is becoming increasingly scarce, as it is concentrated in a few geographical regions and is subject to stricter regulations and environmental considerations. As global demand for clear glass increases, the need to source this high-purity sand is putting immense pressure on available supplies. Recycling glass provides a viable solution to this issue by reducing the demand for such specific and scarce raw materials. Through the use of cullet, manufacturers can produce high-quality glass while lessening their reliance on virgin silica sand and other finite resources. This shift not only supports the sustainability of the glass industry but also contributes to the broader goals of resource efficiency and circular economy practices. The conservation of raw materials through glass recycling represents a significant step toward reducing the environmental footprint of the glass industry. By minimizing the extraction of finite resources such as silica sand, soda ash, and limestone, glass recycling helps preserve natural habitats and reduce the negative impacts associated with mining activities. Moreover, the decreased reliance on high-purity silica sand, which is increasingly difficult to obtain, further underscores the value of recycling in ensuring the long-term sustainability of glass production. The environmental benefits of recycling glass are substantial, not only in terms of raw material conservation but also in reducing energy consumption, lowering emissions, and promoting a more circular approach to manufacturing. This study highlights the critical role of recycled materials in achieving sustainable industrial practices and advancing environmental stewardship in the glass sector.

| Material | Glass composition % | Reason for adding |
|---|---|---|
| Sand | 72.6 | - |
| Soda ash | 13.0 | Easier melting |
| Limestone | 8.4 | Durability |
| Dolomite | 4.0 | Working & weathering properties |
| Aluminia | 1.0 | - |
| Others | 1.0 | - |

**Figure 15: Raw materials of float glass manufacturer % of raw materials**

Source 4: Re-thinking the life-cycle of architectural glass: ARUP UK

**Reduction in Energy Consumption**

Energy consumption in manufacturing processes, particularly in energy-intensive industries like glass production, is a critical factor in determining the sustainability and environmental impact of production activities. The use of cullet (recycled glass) in the production of flat glass offers a significant opportunity to reduce energy consumption, thereby making the process more energy- efficient and less carbon-intensive. Figure 16, which illustrates the embodied energy of flat glass with varying percentages of cullet, demonstrates the potential for energy savings as the proportion of cullet in the furnace increases. One of the key factors contributing to the reduction in energy consumption when using cullet is its lower melting temperature compared to virgin raw materials such as silica sand, soda ash, and limestone. The melting temperature of cullet is approximately 30% lower than that of raw materials, which means that less energy is required to reach the necessary temperature for glass formation. For every 10% increase in the proportion of cullet used in the furnace, the energy required for melting decreases by approximately 3%. This is a direct consequence of the fact that cullet, being already pre-melted, requires less energy to re-melt into its liquid form, thus reducing the overall energy demand of the production process. The reduction in energy consumption through the use of cullet can be quantified in terms of kWh saved per tonne of glass produced. Each tonne of cullet used in the glass manufacturing process saves approximately 300 kWh of energy.

This reduction in energy consumption is a significant achievement, especially when scaled across large-scale glass manufacturing facilities. By reducing the energy required to produce glass, the use of cullet not only lowers operational costs but also reduces the carbon footprint of glass production. The energy savings are particularly valuable in an industry that is highly dependent on fossil fuels for energy generation, as they contribute directly to a decrease in greenhouse gas emissions. The incorporation of cullet into glass production processes offers both economic and environmental benefits. From a cost perspective, the reduction in energy usage translates into lower operational costs, making the production process more cost-efficient. Moreover, the reduced energy consumption also leads to a decrease in carbon emissions, as less fossil fuel is burned to generate the necessary energy. For example, in many regions where electricity is derived from coal or natural gas, the reduction in energy demand results in a proportional decrease in $CO_2$ emissions. This makes the glass production process less carbon- intensive and more aligned with global goals for reducing carbon emissions and promoting sustainable manufacturing practices. The reduction in energy consumption through the use of cullet has broader implications for the sustainability of the glass industry and its role in mitigating climate change. As energy efficiency improves and energy consumption decreases, the overall environmental impact of glass production is reduced. This not only helps manufacturers lower their operational costs but also supports efforts to meet increasingly stringent environmental regulations and sustainability targets. Additionally, the energy savings associated with cullet usage contribute to the circular economy model, where recycled materials are reintroduced into the production cycle, reducing the need for new raw materials and minimizing waste. The use of cullet in glass production exemplifies how recycling and resource efficiency can significantly reduce both energy consumption and environmental impacts, making it an essential component of sustainable industrial practices. It significantly reduces energy consumption and lowers carbon emissions, which are key considerations in advancing sustainability in the glass industry. These energy savings, in conjunction with other environmental and economic advantages, underscore the importance of promoting glass recycling as a critical component of sustainable manufacturing practices in the context of global efforts to mitigate climate change and reduce environmental degradation.

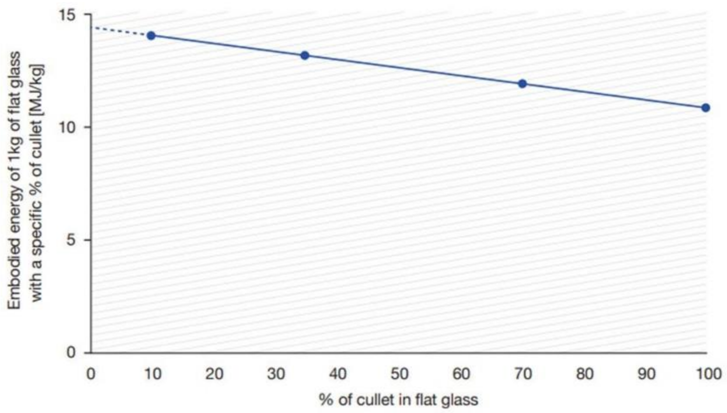


**Figure 16: Graph showing embodied energy of 1kg of flat glass in relation to % of cullet used in the flat glass manufacture**

Source 4: Re-thinking the life-cycle of architectural glass: ARUP UK

**Carbon Emission Reduction**

The reduction of carbon emissions is a central goal in the transition towards sustainable industrial practices.

In the context of glass production, recycling provides a significant opportunity to mitigate the environmental impact of manufacturing processes. Figure 17, which illustrates the $CO_2$ savings from various glass recycling alternatives, highlights the substantial reductions in carbon emissions achievable through the use of cullet (recycled glass). Recycling one tonne of cullet results in the prevention of approximately 250–300 kg of $CO_2$ emissions, underscoring the significant environmental benefits of incorporating recycled materials into the production process. The primary mechanism through which cullet reduces carbon emissions is through the reduction in the demand for virgin raw materials, such as silica sand, soda ash, and limestone, which are essential in glass production. The extraction, transportation, and processing of these virgin materials are energy-intensive processes that contribute significantly to the carbon footprint of glass manufacturing. By substituting raw materials with cullet, the need for these energy-intensive steps is reduced, thereby decreasing the overall carbon emissions associated with glass production. Recycling glass directly addresses the carbon emissions generated in the extraction and processing stages of virgin raw materials. For example, mining and transporting silica sand and other raw materials involves substantial fossil fuel consumption, leading to the release of greenhouse gases. Additionally, the processing of these materials, which involves high-temperature furnaces to produce glass, requires significant energy inputs, often derived from carbon-intensive sources such as coal or natural gas. The use of cullet in place of virgin materials mitigates these emissions by reducing the need for both raw material extraction and energy-intensive processing, resulting in a direct decrease in $CO_2$ emissions. One of the key sources of carbon emissions in glass production is the mining and transport of virgin materials. Mining operations, especially those involving silica sand, are energy-intensive and release significant amounts of $CO_2$ due to the heavy machinery and transportation systems employed. Additionally, the extraction of raw materials often involves large-scale land disturbances, leading to further environmental impacts. By using cullet as a substitute for virgin materials, these emissions are significantly minimized. The transportation of cullet is also more environmentally efficient since it is often sourced locally from recycling facilities, reducing the need for long-distance transportation that contributes to fossil fuel consumption and associated $CO_2$ emissions. Furthermore, the processing of raw materials into glass involves high-temperature furnaces, which require significant energy inputs. The use of cullet in glass production reduces the energy needed to reach these high temperatures, as cullet melts at a lower temperature than virgin raw materials. This energy reduction leads to a decrease in the carbon emissions associated with the manufacturing process. As a result, the carbon footprint of glass production is substantially reduced when using cullet, as less energy is consumed and fewer greenhouse gases are emitted during the manufacturing phase. The use of recycled glass, or cullet, not only contributes to a reduction in carbon emissions within the glass industry but also supports broader sustainability goals. As global efforts intensify to combat climate change, industries must find ways to reduce their carbon footprints, and glass manufacturing is no exception. The reduction in $CO_2$ emissions through the use of cullet is a crucial step towards making the glass industry more sustainable and reducing its contribution to global greenhouse gas emissions. Moreover, the carbon savings from recycling glass are aligned with the principles of the circular economy, where waste is minimized, and resources are reused in a closed-loop system. By recycling glass and using cullet as a substitute for virgin materials, the glass industry can reduce its overall environmental impact while contributing to the global goal of carbon neutrality. The ability to prevent 250–300 kg of $CO_2$ emissions per tonne of cullet recycled represents a meaningful contribution to the reduction of greenhouse gases, especially when scaled across the global glass manufacturing sector. In conclusion, the carbon emission reductions achieved through the recycling of glass are substantial and represent a significant opportunity to mitigate the environmental impact of glass production. By replacing virgin raw materials with cullet, the demand for energy-intensive mining, transport, and processing is reduced, leading to a direct decrease in $CO_2$ emissions. Recycling one tonne of cullet prevents 250–300 kg of $CO_2$ emissions, demonstrating the effectiveness of glass recycling in reducing the carbon footprint of the industry. These emissions savings are not only beneficial for the environment but also support the broader sustainability goals of reducing global carbon emissions and promoting circular economy practices in industrial manufacturing.

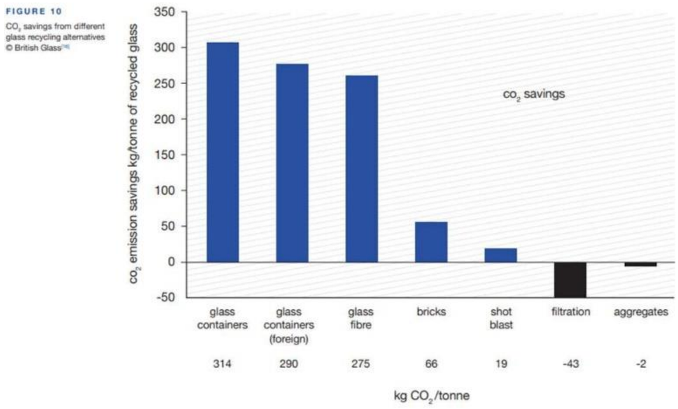


**Figure 17: Co2 savings from different glass recycled alternatives**

Source 4: Re-thinking the life-cycle of architectural glass: ARUP UK

**Case study 5**

**Introduction**

Concrete remains the cornerstone of modern construction, characterized by its extensive utilization and reliance on natural resources. However, this widespread use comes at a considerable environmental cost. The production and use of concrete contribute to significant natural resource depletion and greenhouse gas (GHG) emissions, with cement production being a primary contributor to $CO_2$ emissions. Moreover, the extraction of natural aggregates (NAs), which constitute approximately 70% of the concrete volume, exacerbates environmental degradation, including landscape disruption and resource depletion. Recycled aggregates (RAs), such as fine recycled concrete aggregates (fRCAs) derived from crushed concrete debris and fine recycled masonry aggregates (fRMAs) obtained from waste masonry, present a viable and sustainable alternative to natural aggregates. These materials not only divert construction and demolition waste (CDW) from landfills but also mitigate the demand for virgin resources. Utilizing RAs can help address the dual challenge of reducing environmental impact while promoting resource efficiency, a core tenet of circular economy principles. This case study investigates the potential of recycled aggregates to replace natural sand entirely in concrete applications. Specifically, it focuses on the environmental and structural performance of concrete slabs designed with a 100% substitution of natural sand by fRCAs and fRMAs. The evaluation employs Life Cycle Assessment (LCA), a scientifically robust methodology that quantifies environmental impacts across the product's lifecycle, from raw material extraction to end-of-life disposal.

To ensure structural viability, the study examines the performance of recycled aggregate concrete (RAC) under two critical design criteria:

Load-Bearing Capacity (LBC): This limit state assesses the slab's ability to resist applied loads without

failure, primarily governed by compressive strength.
Serviceability (SA): This limit state evaluates the slab's ability to remain functional and maintain acceptable performance under typical usage conditions, influenced by parameters like deflection and modulus of elasticity. By integrating LCA with these structural performance parameters, the study provides a comprehensive analysis of the trade-offs and benefits associated with the use of RAs. It highlights the transformative potential of RAs in reducing the carbon footprint of construction practices while maintaining structural integrity, aligning with sustainable development objectives.

**Materials and Methods**

To explore the structural and environmental feasibility of replacing natural aggregates (NAs) with recycled aggregates (RAs) in concrete, six distinct concrete mixtures were formulated. These mixtures incorporated combinations of fine recycled concrete aggregates (fRCAs), fine recycled masonry aggregates (fRMAs), and NAs. The mixtures were varied based on two water-cement (w/c) ratios to optimize mechanical properties and durability. Reinforcement types included traditional steel bars and glass fibers, enabling a comparative analysis of their structural and environmental implications. The physical properties of the aggregates, such as grading, particle density, and water absorption capacity, were measured and are presented in Table 10. This characterization is critical for ensuring consistency in concrete performance and accommodating the unique properties of recycled aggregates, such as higher water absorption and variability in particle shape. Concrete mix designs for each scenario were prepared with specific quantities of aggregates, cement, and water, as detailed in Table 11. This ensures a controlled evaluation of performance across mixtures.

| RA Types | Grading (mm) | Finest Particles Content | Oven-Dried Particle Density | | Water Absorption Capacity | |
|---|---|---|---|---|---|---|
| | | f (%) | ρRD (kg/m³) | σ | WA24 (%) | σ |
| Natural aggregate (NA1) | 0–4 | 0.3 | 2570 | 81 | 1.0 | 0.0 |
| | 4–8 | 0.3 | 2530 | 12 | 1.7 | 0.3 |
| | 8–16 | 0.4 | 2540 | 12 | 1.9 | 0.2 |
| Fine recycled masonry aggregate (fRMA) | 0–4 | 1.0 | 2320 | 130 | 6.6 | 0.8 |
| Fine recycled concrete aggregate (fRCA) | 0–4 | 0.6 | 2430 | 60 | 3.6 | 0.8 |

**Table 10: The physical properties of each fraction of aggregates used for concrete mixtures.**

Source 5: Environmental Impact of Concrete Slab Made of Recycled Aggregate Concrete Based on Limit States of Load-Bearing Capacity and Serviceability—LCA Case Study: University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Tˇrinecká 1024, 27343 Bustehrad, Czech Republic.

| Concrete Mixture | Cement | Mixing Water + Additional Water | w/c Ratio | Natural Aggregate | | Recycled Aggregate |
|---|---|---|---|---|---|---|
| | | | | Fine | Coarse | Fine |
| | (kg/m³) | (kg/m³) | (-) | (kg/m³) | (kg/m³) | (kg/m³) |
| NAC I | 260 | 169 + 0 | 0.65 | 709 | 1130 | 0 |
| fRMAC I | 260 | 169 + 18 | 0.72 | 0 | 766 | 971 |
| fRCAC1 I | 260 | 169 + 17 | 0.71 | 0 | 949 | 843 |
| NAC II | 300 | 165 + 0 | 0.55 | 671 | 1167 | 0 |
| fRMAC II | 300 | 165 + 17 | 0.61 | 0 | 822 | 920 |
| fRCAC1 II | 300 | 165 +16 | 0.60 | 0 | 994 | 800 |

**Table 11: Concrete mix proportion, per cubic meter.**

Source 5: Environmental Impact of Concrete Slab Made of Recycled Aggregate Concrete Based on Limit States of Load-Bearing Capacity and Serviceability—LCA Case Study: University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Tˇrinecká 1024, 27343 Bustehrad, Czech Republic.

**Experimental Procedure**

The experimental methodology encompassed two primary investigative tracks: mechanical property evaluation and environmental impact assessment. For mechanical characterization, standardized tests were conducted to measure compressive strength using cube specimens, flexural strength through beam testing, and modulus of elasticity determinations, all performed in accordance with international testing protocols to ensure data reliability and reproducibility across different concrete mixtures. Concurrently, a comprehensive environmental analysis was executed utilizing Life Cycle Assessment (LCA) methodology through GaBi software (v2022.2), implementing a cradle-to-grave assessment framework that traced environmental impacts from raw material extraction through production, construction, and operational phases to final disposal or recycling, with impact quantification performed via the Environmental Footprint (EF 3.0) characterization method to generate normalized and weighted environmental indicators across multiple parameters.

**Visual and Tabular Data:**

The research employs a comprehensive visual and quantitative data presentation approach through Figure 18, Tables 12 and Table 13 to thoroughly analyze the characteristics and performance of different aggregate types in concrete mixtures. Figure 1 provides crucial visual documentation of the three aggregate categories studied - fRCA (fine Recycled Concrete Aggregate), fRMA (fine Recycled Masonry Aggregate), and NA (Natural Aggregate) - enabling clear identification of their physical and morphological differences, while Tables 12 and 13 offer detailed quantitative insights into the mechanical behavior and durability properties of the concrete mixtures, including essential parameters such as compressive strength, flexural strength, elastic modulus, and freeze-thaw resistance, ultimately facilitating an evidence-based assessment of recycled aggregates as viable substitutes for natural aggregates in sustainable construction practices through both qualitative visual analysis and rigorous numerical data evaluation.

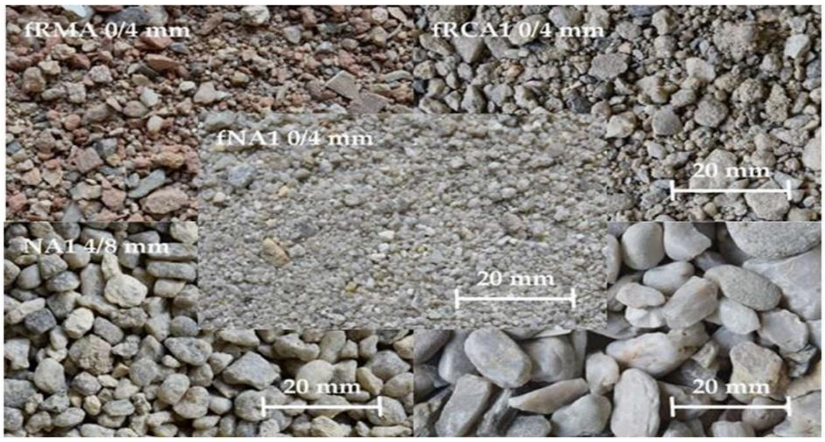


**Figure 18: NA and RA used in concrete mixtures.**

Source 5: Environmental Impact of Concrete Slab Made of Recycled Aggregate Concrete Based on Limit States of Load-Bearing Capacity and Serviceability—LCA Case Study: University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Tˇrinecká 1024, 27343 Bustehrad, Czech

Republic.

| Recycled Concrete Mixture | Dry Density | | Compressive Strength | | Target Concrete Strength Class | Flexural Strength | | Static Modulus of Elasticity | |
|---|---|---|---|---|---|---|---|---|---|
| Designation | (kg/m³) | (kg/m³) | (MPa) | σ | (-) | (MPa) | σ | (GPa) | σ |
| NAC IA | 2301 | 2301 | 33.2 | 2.5 | C20/25 | 6.2 | 0.2 | 36.7 | 1.4 |
| fRMAC IA | 2181 | 2181 | 30.0 | 2.2 | C20/25 | 5.5 | 0.4 | 22.4 | 1.0 |
| fRCAC1 IA | 2276 | 2276 | 34.4 | 1.7 | C25/30 | 5.8 | 0.3 | 29.6 | 0.4 |
| NAC IIA | 2324 | 2324 | 44.9 | 0.9 | C30/37 | 7.6 | 0.9 | 35.9 | 0.5 |
| fRMAC IIA | 2191 | 2191 | 38.0 | 0.9 | C25/30 | 6.8 | 0.6 | 25.3 | 0.2 |
| fRCAC1 IIA | 2278 | 2278 | 42.9 | 0.8 | C30/37 | 6.5 | 0.4 | 31.4 | 1.0 |

**Table 12: Average values and standard deviation of evaluation of density and mechanical properties**

Source 5: Environmental Impact of Concrete Slab Made of Recycled Aggregate Concrete Based on Limit States of Load-Bearing Capacity and Serviceability—LCA Case Study: University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Tˇrinecká 1024, 27343 Bustehrad, Czech Republic.

**Table 4.** Average values and standard deviation of evaluation of the flexural strength before and after freezing–thawing the frost resistance coefficient and carbonation depth of concrete mixtures.

| Recycled Concrete Mixture | Flexural Strength + Standard Deviation | | | | Frost Resistance Coefficient | Freeze–Thaw Resistance | Carbonation Depth |
|---|---|---|---|---|---|---|---|
| Designation | 0 Cycles | | 100 Cycles | | (-) | Cycles | (mm) |
| NAC IA | 6.15 | ±0.22 | 6.87 | ±0.20 | 1.12 | 100 | 2.78 |
| fRMAC IA | 5.53 | ±0.39 | 5.85 | ±0.40 | 1.06 | 100 | 7.10 |
| fRCAC1 IA | 5.78 | ±0.30 | 6.57 | ±0.26 | 1.14 | 100 | 4.51 |
| NAC IIA | 7.55 | ±0.87 | 7.80 | ±0.12 | 1.03 | 100 | 0.77 |
| fRMAC IIA | 6.84 | ±0.60 | 6.78 | ±0.00 | 0.99 | 100 | 1.71 |
| fRCAC1 IIA | 6.54 | ±0.44 | 6.73 | ±0.10 | 1.03 | 100 | 0.57 |

**Table 13: Average values and standard deviation of evaluation of the flexural strength before and after freezing-thawing the frost resistance coefficient and carbonation depth of concrete mixtures.**

Source 5: Environmental Impact of Concrete Slab Made of Recycled Aggregate Concrete Based on Limit States of Load-Bearing Capacity and Serviceability—LCA Case Study: University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Tˇrinecká 1024, 27343 Bustehrad, Czech Republic.

## CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents a comprehensive analysis of the environmental and economic impacts of incorporating recycled materials in construction. The findings are based on life cycle assessments (LCA), case studies, and comparative evaluations of recycled concrete aggregates (RCA), copper slag (CS), and recycled glass.

### Results

### Environmental Impacts

The analyses demonstrated significant reductions in environmental impacts across multiple categories:

#### Recycled Concrete Aggregates (RCA)

Substituting natural aggregates (NA) with RCA resulted in a 10.23% reduction in cumulative energy demand (CED) and notable decreases in freshwater (63.4%) and marine ecotoxicity (76.8%). RCA mixtures processed in mobile recycling plants showed an 89.69% lower environmental impact than those processed in fixed plants, mainly due to reduced transportation requirements.

**Recycled Glass**

Incorporating cullet reduced energy use by 3% for every 10% increase in recycled content, with one tonne of cullet saving 1.2 tonnes of raw materials and preventing 250–300 kg of $CO_2$ emissions.

The closed-loop recycling of glass demonstrated scalability, reducing embodied energy from 14 MJ/kg to 12 MJ/kg with 70% recycled content.

**Economic Analysis**

Despite a 5% increase in initial costs for using recycled materials, life cycle cost assessments (LCCA) revealed operational savings due to energy efficiency improvements and reduced landfill expenses. RCA and CS demonstrated cost savings of up to 1.40% when optimized for specific building applications.

**Structural Integrity**

Structural performance analyses indicated that RCA and CS achieved compressive strengths comparable to conventional materials, meeting ASTM standards. Adjustments to water-to-cement ratios in RCA mixes addressed porosity concerns, ensuring durability and load-bearing capacity.

## Discussion

The findings underscore the potential of recycled materials in reducing the carbon footprint of construction practices, aligning with sustainability goals and circular economy principles.

**Environmental Benefits**

Recycled materials consistently outperformed conventional counterparts in reducing GWP, embodied energy, and resource depletion. Their integration into sustainable building practices can significantly mitigate climate change impacts.

The adoption of RCA and cullet offers dual benefits by reducing landfill waste and minimizing the extraction of virgin resources.

**Economic Considerations**

Initial cost premiums associated with recycling processes are offset by long-term operational savings, enhancing the economic viability of sustainable construction.

Policy incentives and technological advancements can further reduce costs, making recycled materials more competitive.

**Challenges and Opportunities**

Variability in regional practices, recycling infrastructure, and long-term performance data pose challenges. Addressing these issues through standardized LCA methodologies and investments in advanced recycling technologies is essential.

Raising stakeholder awareness about the environmental and economic benefits of recycled materials can accelerate their adoption in construction projects.

**Practical Implications**

RCA and CS are particularly suited for applications in low- and mid-rise buildings, offering cost- effective solutions without compromising structural performance.

he scalability of recycled glass makes it an ideal material for large-scale projects with high sustainability benchmarks.

The results from this study highlight the transformative potential of recycled materials in achieving sustainable architectural practices. Future research should focus on improving data consistency and exploring innovative recycling techniques to enhance material performance and economic feasibility.

## CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

### Conclusion

The utilization of recycled glass and recycled concrete in construction demonstrates a significant potential to enhance sustainability in the built environment. This study confirms that these materials reduce environmental impacts across key lifecycle stages, including material extraction, production, and disposal. Recycled concrete aggregates (RCA) provide an effective alternative to virgin aggregates, mitigating carbon emissions and reducing resource depletion associated with cement production. Life Cycle Assessment (LCA) analyses show that substituting traditional aggregates with RCA leads to substantial reductions in embodied energy and greenhouse gas emissions while maintaining structural integrity. Similarly, recycled glass contributes to circular economy principles by reducing landfill waste, conserving finite natural resources, and lowering the energy demand of manufacturing processes.

Both materials align well with global sustainability standards, offering viable solutions to promote eco-friendly construction practices. However, challenges such as variability in material performance, higher initial processing costs, and regional discrepancies in recycling infrastructure highlight areas for further improvement.

### Recommendations

To promote the adoption of recycled materials in the construction industry, governments and regulatory authorities must implement strategic policy interventions. These could include financial incentives such as tax deductions, grants, or subsidies to offset the higher initial costs associated with recycled materials. Furthermore, establishing regulations that mandate the inclusion of a minimum percentage of recycled content in construction projects can create a robust market demand. Such policies would encourage suppliers and developers to integrate recycled materials into standard construction practices, accelerating their mainstream acceptance. Advancing recycling technologies is critical for improving the quality, scalability, and efficiency of recycled material production. For instance, cutting-edge methods such as heat and steam-based delamination are highly effective in separating and purifying components of complex materials like laminated glass, while mobile recycling plants enhance the practicality of reprocessing concrete waste on-site. These innovations not only reduce energy consumption and emissions during recycling but also enhance the material's structural integrity, making it more suitable for construction applications. A significant barrier to the widespread use of recycled materials is the variability in their physical and mechanical properties. Developing universally recognized standards and specifications for recycled materials is essential to ensure their reliability in both structural and non-structural contexts. These standards should encompass parameters such as compressive strength, thermal performance, durability, and resistance to environmental factors, providing architects and engineers with the confidence to utilize recycled materials without compromising safety or performance. The adoption of recycled materials can be further incentivized by linking their use with well-recognized sustainability certification systems such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), or Green Star. These frameworks award credits for incorporating sustainable materials, thereby encouraging developers to prioritize recycled content to enhance their project's environmental credentials. Economic concerns remain a primary obstacle to the widespread use of recycled materials. Conducting detailed lifecycle cost assessments (LCCA) can provide critical data on the long-term financial benefits of these materials. By including factors such as operational savings, reduced disposal costs, and minimized environmental penalties, LCCA can effectively demonstrate the cost-effectiveness of recycled materials over conventional alternatives. This evidence-based approach is pivotal in addressing stakeholder apprehensions and driving adoption. This study highlights the transformative potential of recycled glass and recycled concrete in reducing the construction sector's carbon footprint. The incorporation of these materials not only advances sustainable development goals (SDGs) but also enhances resource efficiency within the circular economy framework. However, to maximize their environmental benefits, future research should address current challenges, such as variability in material properties, limitations in large-scale applicability, and integration into existing construction workflows. Innovative applications, such as the development of high-performance composites and multifunctional materials, should also be explored to unlock new possibilities for recycled materials in construction. This comprehensive approach ensures the effective deployment of recycled materials while contributing to global sustainability objectives.

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