

Original Article

Comparative Study of Global Warming Potential and Production Cost of Concrete Mixes Incorporating Waste and Recycled Material

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Abstract - Concrete is a widely used construction material. The production and use of concrete contribute significantly to greenhouse gas emissions. While most existing studies focus only on the Life Cycle Assessment (LCA) production phase to understand and analyze the greenhouse gas emissions generated due to concrete, this research comprehensively compares three life cycle stages: production, construction, and end-of-life. Eight concrete mixes are analyzed for their Global Warming Potential (GWP) and production cost per cubic meter. These mixes include Supplementary Cementitious Materials (SCMs) such as fly ash, ceramic tile waste powder, and Recycled Concrete Aggregates (RCAs) as sustainable alternatives. The main objective is to assess and compare the Global Warming Potential (GWP) and production cost per cubic meter of each concrete mix against a conventional baseline mix using Portland Pozzolana Cement (PPC). Mixes with partial replacement of cement using fly ash and ceramic tile waste powder demonstrate up to 25% reduction in GWP and 7% lower production cost. The fly ash and RCA combination also shows similar environmental benefits and up to 9% cost savings. In contrast, using RCA alone as a partial substitution of coarse aggregates does not significantly alter the outcomes. A key finding is that adding fly ash directly at the concrete batching plant is more environmentally beneficial than using PPC, even when both contain almost equivalent amounts of fly ash. These insights offer a sustainable and cost-effective solution for all stakeholders associated with concrete production.

Keywords - Concrete, Global Warming Potential (GWP), Supplementary Cementitious Materials (SCMs), Recycled Concrete Aggregates (RCAs), Life Cycle Assessment (LCA).

1. Introduction

Concrete has become the backbone of modern infrastructure mainly due to its durability and affordability [1]. However, this widespread use of concrete comes with significant environmental cost, mainly due to high carbon emissions associated with cement. Cement significantly contributes to global CO₂ emissions, with approximately 1.56 billion metric tons reported in the year 2023, according to the report of the Global Carbon Project, 2024.

In developing countries like India, where the pace of infrastructural expansion demands large volumes of concrete and cement, it is crucial to find ways to reduce CO₂ emissions associated with it. To address these concerns without compromising the structural integrity and economic feasibility, researchers have increasingly focused on innovative technologies and sustainable alternatives. One of the widely adopted strategies includes incorporating

Supplementary Cementitious Materials (SCMs) such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and silica fumes to partially replace the cement [2]. These materials reduce the burden on landfilling sites and significantly reduce CO₂ emissions. For instance, Fly Ash (FA) can partially replace cement in the raw materials for cement clinker production or be blended with the finished cement during concrete production [3]. Studies suggest that replacing 30% of cement with fly ash can reduce CO₂ emissions by 20–25%.

However, K. E Seto et al. (2017) [4] observed that the percentage reduction depends on the LCA allocation method; treating flyash as zero burden waste, as in the case of the present study, yields greater environmental benefits. Additionally, the pozzolanic nature of fly ash contributes to improved long-term durability and strength by lowering the heat of hydration [5].



Another viable approach involves replacing natural aggregates with Recycled Concrete Aggregates (RCAs), sourced from demolished concrete. This substitution cuts down the use of natural aggregates and reduces construction and demolition waste. Depending on transportation distance and processing techniques, the use of RCAs can reduce the carbon footprint of concrete by 20%. L.F. Jiménez et al. (2018) [6] found that mixes with RCAs exhibit a lower carbon footprint compared to conventional mixes, particularly when aggregates are sourced locally and processed with minimum energy input. However, the mechanical properties of RCAs are often inferior due to their lower density, higher water absorption, and presence of adhered mortar, which can affect strength and durability.

K. McNeil et al. (2013) [7] reviewed a wide range of RCA studies and emphasized that variability in quality necessitates cautious mix design and performance validation. Many treatment techniques have been developed to improve the quality of recycled concrete aggregates. H. Nguyen et al. (2020) [8] found that surface treatment of RCAs using cement-silica fume slurry improves their quality and performance in concrete mixes. S. C. Kou et al. (2009) [9] found that use of RCAs in self-compacting concrete maintained desirable workability and compressive strength when combined with proper admixtures and optimized mixed proportions.

Velumani and Venkatraman (2024) [10] presented a study on the combined effect of fly ash and steamed-treated Recycled Concrete Aggregates (RCAs) in fibre-reinforced self-compacting concrete. The study concluded that the inclusion of fly ash significantly reduces the water absorption and enhances the workability. An LCA study of Recycled Aggregate Concrete (RAC) has been presented by A. Petek Gürsel et al. (2014) [11] and identified that crushing energy, transportation distance, and quality of recycled aggregates influence the environmental performance and GWP.

In addition to SCMs and RCAs, ceramic tile waste, due to its pozzolanic properties and ability to enhance the Calcium Silicate Hydrate (C-S-H) gel, improves concrete's mechanical properties and durability [12]. A. Gonzalez-Corominas et al. (2014) [13] explore the use of crushed ceramic tiles as fine or coarse aggregates in high-performance concrete. The research showed that adding up to 25% of ceramic waste in place of natural aggregates improves strength and durability. Amin et al. (2021) [14] looked into the use of porous ceramic waste as coarse aggregates combined with polyethylene glycol to enable self-curing. The result showed that concrete performed well in terms of durability and maintained strength without external curing. Paul et al. (2023) [15] assessed the use of ceramic tile waste as a coarse aggregate replacement and concluded that 30% replacement provides comparable compressive strength and durability to conventional mixes. Better bonding is observed due to the angular texture of ceramic tile waste.

Dhanasekar et al. (2018) [16] found that replacing 20% of fine aggregates with ceramic tile waste improves durability and strength in M50 concrete mixes. However, the variability in the chemical composition of ceramic waste based on its source poses challenges in standardizing LCA results. A more comprehensive LCA database for ceramic waste is required to provide accurate and comparable results.

Despite increasing research on individual alternatives, there is a greater need for comprehensive studies that examine the combined use of SCMs and RCAs. Furthermore, most existing research focuses only on the production stage. Furthermore, incorporating regional variability in material properties, cost of materials, and transportation logistics into LCA studies is still rare.

The present study addresses these gaps by evaluating different life cycle stages of eight concrete mixes incorporating SCMs and RCAs under region-specific conditions. The analysis looks at both the environmental and economic aspects of concrete mixes over 50 years of building lifespan, including End-of-Life (EOL) scenarios. The key focus is on Global Warming Potential (GWP), which measures the amount of heat a Greenhouse Gas (GHG) can trap in atmosphere compared to Carbon Dioxide (CO₂), over a 100 year period relative to a GWP of CO₂ as 1. [17] By evaluating GWP with cost, the study aims to highlight practical ways to use more sustainable materials in concrete, especially in rapidly developing urban areas. The goal is to shift towards more climate-friendly and sustainable construction practices.

2. Methodology

This study uses the Life Cycle Assessment (LCA) approach to evaluate each mix's environmental and economic performance. The assessment is carried out in line with the ISO 14040 and ISO 14044 standards and considers the entire life cycle from cradle to grave. The analysis is supplemented by a cost assessment to evaluate the feasibility of sustainable alternatives. A case study of a Ready-Mix Concrete (RMC) plant and a mid-rise residential building project in Rajkot city, India, serves as a basis for this study. This approach ensures that the research is based on construction practices specific to the region and actual operational data, thereby enhancing its relevance to real-world applications.

2.1. Objective

The main goal of this study is to evaluate the environmental and economic performance of eight different concrete mixes through LCA methodology. The specific objectives of the study are as follows:

- To assess the environmental impacts, specifically Global Warming Potential (GWP), of eight concrete mixes incorporating different combinations of SCMs and RCAs across different life cycle stages.

- To evaluate the potential for reducing carbon footprint using alternative materials such as fly ash, ceramic waste, and recycled concrete aggregates as partial replacements of cement and natural aggregates.
- To perform an economic analysis comparing each mix's cost per cubic meter, accounting for material cost, processing, and transportation.
- To provide recommendations for industry stakeholders and urban planners to promote sustainable concrete practices in developing urban settings.

2.2. Scope and System Boundaries

This study assesses the environmental impacts of eight concrete mixes across their life cycle stages, specifically focusing on greenhouse gas emissions. The assessment is done within the context of a mid-rise building project located in Rajkot City, India.

The primary aim is to quantify and compare each mix's Global Warming Potential (GWP) by analyzing emissions generated during production, transportation, and end-of-life stages.

This study excludes the analysis of building use and maintenance based on the assumption that once the concrete is used in the construction, factors like maintenance, energy consumption, and operational lifespan remain the same, regardless of the specific raw material used. The life cycle stages are defined as follows:

2.2.1. Production Stage

This life cycle stage includes raw material extraction, transportation to the ready-mix concrete plant, processing, and production. Emissions related to fuel use, quarrying, and industrial processing are included.

2.2.2. Construction Stage

This phase includes transportation of ready-mix concrete from the plant to the construction site (here, a mid-rise building is under consideration) and its subsequent handling and installation. Emissions from vehicle fuel consumption due to transportation, on-site equipment usage, and placement activities are accounted for in this stage.

2.2.3. Use Stage

This stage includes building operation, maintenance, repair, and replacement throughout the life of the building. However, this phase is excluded from the GWP calculation, assuming that the operational energy use and maintenance requirements are not significantly influenced by the type of concrete mixes [18].

2.2.4. End of Life Stage

This stage includes processes such as building demolition, waste transportation, and disposal. Emissions associated with these processes are quantified for each mix based on their specific waste material scenarios. The emission during the processing and recycling of waste is not included in the overall calculation of GWP due to the lack of availability of data.

The functional unit for the study is 1 cubic meter (m^3) of M20-grade concrete over 50 years of building service life. The unit of analysis provides a consistent basis for comparing the performance of each mix, reflecting the quantity of concrete typically used in structural elements such as foundations, beams, columns, and slabs in mid-rise building construction. Using the same functional unit allows the study to compare the GWP results for concrete mixes using different materials and waste management methods. Figure 1 represents the overview of the concrete life cycle stages.

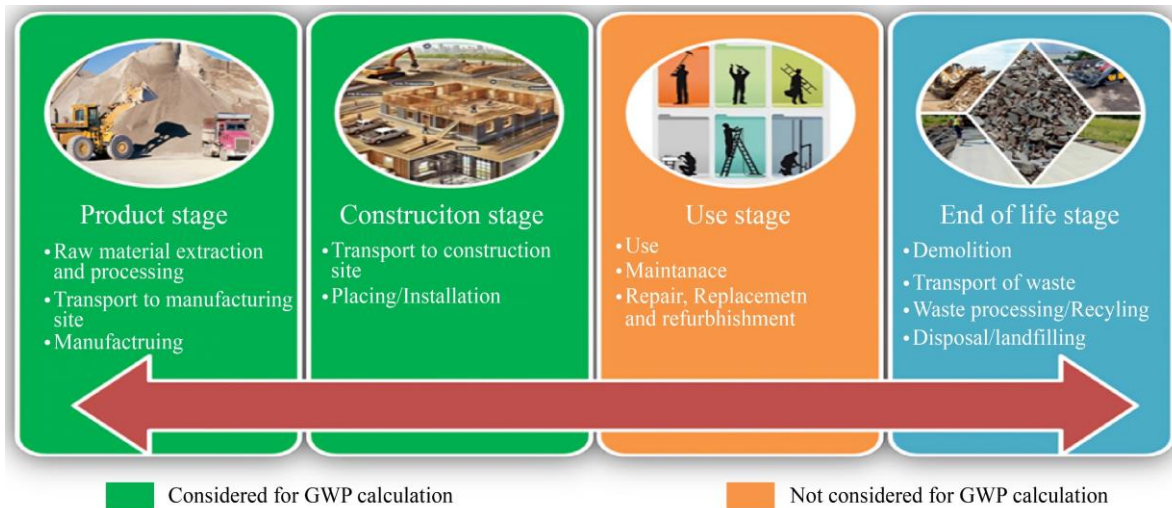


Fig. 1 Overview of concrete life cycle stages

2.3. Inventory Data Collection

This study evaluates eight M20-grade concrete mixes, categorized based on their material composition and End-of-Life (EOL) scenarios. The inventory data are collected from both field and laboratory sources. The mix design details for the first four concrete mixes are collected from a commercial ready-mix concrete plant based in Rajkot. The remaining four concrete mixes were designed and tested in the materials laboratory at Marwadi University, Rajkot. The data collection process encompassed the sourcing, production, transportation, and processing of raw materials used in each concrete mix. Key constituents included Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), Fly Ash (FA), Ceramic Tiles Waste Aggregates (CTWA), Ceramic Tiles Waste Powder (CTWP), and Recycled Concrete Aggregates (RCA). Transportation distances are determined based on the flow of materials from the source locations to the ready-mix concrete plant, then to the mid-rise building construction site, and finally to the landfill or recycling site, as applicable. All eight concrete mixes are designed to meet the requirements for M20-grade concrete, commonly used in structural components such as foundations, beams, columns, and slabs of mid-rise buildings. Table 1 summarized each mix paired with a specific EOL strategy: landfilling or recycling.

The quantity and type of raw materials, especially cement, significantly influence each mix's Global Warming Potential (GWP). Cement production accounts for approximately 80% to 90% of the total embodied carbon in concrete, mostly due to the major carbon dioxide emissions linked with clinker production and fuel consumption. Adding materials like fly ash, slag, or silica fume can reduce the Global Warming Potential (GWP) by thirty percent [19]. Similarly, recycled aggregates also help lower CO₂ emissions. Using recycled or locally produced aggregates instead of natural ones will greatly lower emissions from extraction and transportation, thereby lowering the Global Warming Potential (GWP). Using the old concrete as aggregates further cuts the emissions; however, emissions during processing need to be included [20]. Moreover, an optimum water-to-cement ratio leads to more durable concrete and reduces the need for frequent repairs and maintenance [21]. Table 2 presents the material composition of each concrete mix. This comprehensive data inventory forms the foundation for the subsequent life cycle assessment and cost analysis. The use of recycled materials and SCMs in concrete production aligns with circular economy principles and sustainable urban development objectives.

2.4. Impact Assessment

The environmental impact assessment for the eight concrete mixes was carried out using the cloud-based software, One Click LCA. The software is primarily used in the construction and manufacturing industries. The software complies with internationally recognized standards, including

ISO 14040 and EN 15804, and offers region and country-specific environmental databases, enabling the integration of localized impact factors and transportation data. Additionally, it allows the import of external data sources to enhance the accuracy of inventory. The analysis involved adding the quantities of raw materials of each concrete mix and specifying the transportation mode and distances relevant to the case study of a mid-rise building in Rajkot city, India. Concrete mixes are assumed to be used in the key structural components, including foundations, beams, columns, and slabs. This modeling approach enabled a life cycle analysis of mixes at each stage.

2.4.1. Global Warming Potential (GWP) Calculation

The Global Warming Potential (GWP) was quantified in terms of kilograms of CO₂ equivalent per cubic meter of concrete, computed across life cycle stages using embedded emission factors within the software.

Two End-of-Life (EOL) scenarios were considered:

Cost Analysis

The cost analysis was performed in parallel with the environmental assessment. Costs were calculated by multiplying each material's unit cost by its respective quantity in the mix, including transportation and processing charges. Market rates for materials were sourced from the suppliers operating in and around the city of Rajkot to ensure regional accuracy. This analysis provides the opportunity to compare each mix's economic and environmental performance.

Key Assumption

The following are the assumptions made to maintain consistency in the assessment:

- All concrete mixes are assumed to be made at the same ready-mix concrete plant to ensure uniform transportation distances for input materials.
- Fly ash and ceramic waste were treated as zero-emission inputs as byproducts of existing industrial processes and hence do not contribute to the new emissions.

Landfilling: In this scenario, construction waste is assumed to be disposed of in landfills after demolition, which contributes to emissions from transportation and landfill operations.

Recycling: In this scenario, waste materials are assumed to be recovered and reused in the production of new concrete mixes. This leads to the environmental benefits of avoided extraction and the emissions associated with material processing and transportation. The comparison of these two scenarios helps in the assessment of the long-term environmental implications of different waste management strategies.

Table 1. Key features of eight concrete mixes

Sr. No.	Concrete Mix	Key Features	EOL Scenario
1.	CONPPC-1	PPC based concrete without any SCMs or recycled aggregates.	Land filling
2.	CONPPC-II	PPC based concrete without any SCMs or recycled aggregates.	Recycling
3.	CONOPC FA-I	OPC-based concrete with 26% fly ash as SCM	Land filling
4.	CONOPC FA-II	OPC-based concrete with 26% fly ash as SCM	Recycling
5.	CONOPC FA, RCA	OPC-based concrete with 26% fly ash as SCM and 20% RCA replacing coarse aggregates	Recycling
6.	CONPPC, RCA	PPC with 30% RCA replacing coarse aggregates	Recycling
7.	CONOPC, CTWA	OPC with 30% Ceramic Tiles Waste Aggregates replacing coarse aggregates	Recycling
8.	CONOPC, CTWP	OPC with 30% Ceramic Tiles Waste Powder as SCM.	Recycling

Table 2. Material composition of concrete mixes (kg/m³)

Name of Concrete Mix	Cement (OPC/PPC)	Coarse Aggregates	Fine Aggregates	RCA	Fly ash	CTWA	CTWP	Water	Ad-mix-tures
CONPPC-1	396	1023	803	-	-	-	-	197	-
CONPPC-II	396	1023	803	-	-	-	-	197	-
CONOPC FA-I	260	1077	756		90	-	-	175	2.1
CONOPC FA-II	260	1077	756	-	90	-	-	175	2.1
CONOPC FA, RCA	260	862	756	215	90	-	-	175	-
CONPPC, RCA	396	716	803	307	-	-	-	197	-
CONOPC,CTWA	394	716	805	-	-	307	-	197	-
CONOPC,CTWP	268	1173	730	-	-	-	115	191	-

Table 3. Comparative Global Warming Potential (GWP) of all mixes

Sr. No.	Concrete Mix	GWP KgCO _{2e} /m ³	% reduction compared to CONPPC-I
1.	CONPPC-1	645	Baseline
2.	CONPPC-II	640	-1
3.	CONOPC FA-I	488	-24
4.	CONOPC FA-II	483	-25
5.	CONOPC FA, RCA	484	-25
6.	CONPPC, RCA	645	0
7.	CONOPC,CTWA	612	-5
8.	CONOPC, CTWP	496	-23

2.4.2. Comparative Assessment

CONPPC-I, a conventional PPC based mix without SCMs or RCAs, is taken as a baseline for comparative analysis. The results of GWP and the cost of the remaining mixes were compared with the baseline mix to evaluate the potential benefits of incorporating the SCMs and RCAs in the

concrete production. The percentage decrease or increase in GWP and cost was calculated for each mix relative to CONPPC-I. This comparative assessment enables a more profound understanding of the benefits of waste material substitutions and end-of-life strategies.

3. Results and Discussion

The results of the overall Global Warming Potential (GWP) and production cost of eight concrete mixes are discussed in this section. Additionally, results of three life cycle stages: production, construction, and End of Life (EOL) are presented separately. Percentage reductions in GWP and production cost relative to the CONPPC-I baseline mix indicate the environmental benefits of using SCMs and recycled aggregates. The GWP values are also analyzed material-wise.

3.1. Overall global warming potential (GWP)

Table 3 displays the GWP values, which combine emissions from the production, construction, and EOL stages. The key findings reveal that replacing cement with fly ash and ceramic tile waste powder and incorporating recycled aggregates significantly reduces the GWP. The mix CONOPC FA-II achieved the lowest GWP at 483/m³ with a 25% reduction compared to CONPPC-I. The following are the key observations:

3.1.1. PPC-based Mixes

CONPPC-I is a baseline mix with an overall GWP of 645 kgCO₂e/m³. The GWP of CONPPC-II decreased slightly by 1% due to recycling benefits at the End of Life (EOL).

3.1.2. Concrete with Secondary Cementitious Materials (SCMs)

Mixes incorporating fly ash (CONOPC FA-I & II) showed substantial GWP reduction of 24% and 25%, respectively. Lee et al. (2021) [22] have observed that a 10% increment in fly ash replacement could lower GWP by approximately 1.1 kgCO₂e/m³, implying that a 25-30% replacement similar to that used in CONOPC FA-I and FA-II can yield a GWP reduction of around 22-25%, consistent with the 25% reduction in the present study. CTWP-based concrete mix (CONOPC, CTWP) also performed well with a reduction of 23% in GWP.

3.1.3. Concrete with Secondary Cementitious Materials (SCMs) and Recycled Concrete Aggregates (RCAs)

The combination of SCMs and RCAs in CONOPC FA, RCA achieved a 25% reduction in GWP, which is similar to the reduction observed in CONOPC FA-II, demonstrating that these materials can optimize environmental performance. A similar study by Kudra et al. (2018) [23] demonstrated that incorporating both fly ash and RCA can significantly reduce GWP.

3.1.4. Concrete with Recycled Aggregates

CONPPC, RCA showed no reduction in GWP, indicating that RCA alone is insufficient to reduce overall emissions unless paired with SCMs or if EOL recycling benefits are included in the present case scenario. CONOPC, CTWA achieve a modest 5% reduction, likely due to lower

transportation distance-related emissions from locally available ceramic waste aggregates. A similar study by Adriana B. et al. (2021) [24] concluded that recycled aggregates offer better sustainability based on the transport logistics and local availability.

3.2. Life Cycle Stage-Wise GWP

To provide a detailed understanding, GWP contributions from each life cycle stage - production, construction, and End of life were analyzed and presented in Table 4. Most studies on the life cycle of concrete, particularly in India, follow a “cradle-to-gate” approach, which focuses only on the production stage. This study extends the analysis to include the construction and end-of-life stages, which provides a more comprehensive assessment. This broader perspective provides valuable insights to concrete manufacturers and users.

3.2.1. Production Stage

The Global Warming Potential (GWP) for different concrete mixes during the production stage reveals significant variations based on the materials used in the mix, particularly the cement and SCMs. Replacing cement with fly ash (CONOPC FA-I & II, CONOPC FA, RCA) or ceramic powder (CONOPC, CTWP) results in substantial emission reductions between 16% and 24%. Using SCM reduces use of cement and subsequent clinker production, a significant CO₂ emitter during cement production. C. R. Orozco et al. (2023) [25] have reported similar results with a 25-30% GWP reduction when cement is replaced by 25% fly ash. On the other hand, mixes like CONPPC, RCA, and CONOPC, CTWA had 1% to 8% more emissions because they needed more energy for transporting and processing recycled aggregates, which matches what I. Marie and H. Quiasrawi (2012) [26] found. The study reported that RCA production can increase demand for energy by 5–10% due to crushing, screening, and washing processes.

3.2.2. Construction Stage

The cement type, SCM usage, and concrete workability influence the GWP during construction. CONPPC-I, CONPPC-II, and CONPPC RCA have similar GWPs of 309 kgCO₂e/m³ due to their similar raw material composition and workability properties. CONOPC FA-I, CONOPC FA-II, and CONOPC FA, RCA show a reduction of 24% due to reduced cement content. CONOPC, CTWA demonstrates an 18% reduction, while CONOPC, CTWP achieves the lowest emissions with a 28% reduction. The decrease in emissions is attributed to improved workability and reduced energy consumption.

3.2.3. End-of-Life Scenario

This stage's emissions depend on whether concrete is landfilled or recycled at the End of its life. For mixes CONPPC-I and CONOPC FA-I, where it is assumed that waste is landfilled after demolition, the highest GWP value of

13 kgCO_{2e}/m³ is observed. Energy-intensive transportation and methane emissions during waste decomposition in landfills are responsible for this higher value.

GWP for the mixes CONPPC-II, CONOPC FA-II, CONOPC FA, RCA, and CONPPC RCA is 8 kgCO_{2e}/m³, which is 38% lower than CONPPC-I due to the assumption that waste is recycled at the End of life. Recycling reduces landfill dependency, which reduces CO₂ emissions associated with material transportation and disposal. The mixes CONOPC, CTWA, and CONOPC, CTWP, demonstrate the

lowest GWP among all mixes, with a value of 7 kgCO_{2e}/m³, which is 46% lower than CONPPC-I. This statistic indicates a strong potential for sustainable waste management in construction practices.

Similar observations were established by Backes et al. (2022) [27], who reported that mechanical recycling of carbon reinforced concrete results in an end-of-life GWP of 7.0 kgCO_{2e}/m³. The comparison of GWP at each stage is shown in Figures 2 and 3.

Table 4. Stage-specific GWP analysis of concrete mixes

Life cycle stage	Concrete Mix	GWP KgCO _{2e} /m ³	Percentage reduction/ increase compared to CONPPC-I
Production	CONPPC-1, PPC-II	354	
	CONOPC FA-I, FA-II	270	-24
	CONOPC FA, RCA	271	-23
	CONPPC, RCA	359	+ 1
	CONOPC,CTWA	381	+8
	CONOPC, CTWP	298	-16
Construction	CONPPC-1, PPC-II	309	-
	CONOPC FA-I, FA-II	235	-24
	CONOPC FA, RCA	236	-24
	CONPPC, RCA	309	0
	CONOPC,CTWA	255	-18
	CONOPC,CTWP	223	-28
End of life	CONPPC-1, CONOPC FA-I	13	-
	CONPPC-II, CONOPC FA-II CONOPC FA, RCA CONPPC, RCA	8	-38
	CONOPC,CTWA, CONOPC,CTWP	7	-46

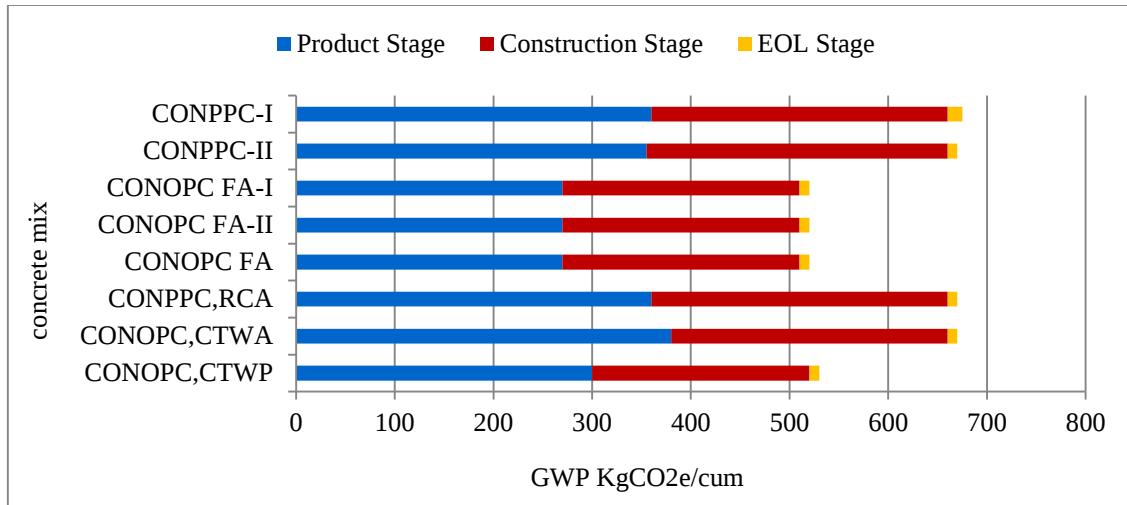


Fig. 2 Comparison of GWP across life cycle stages

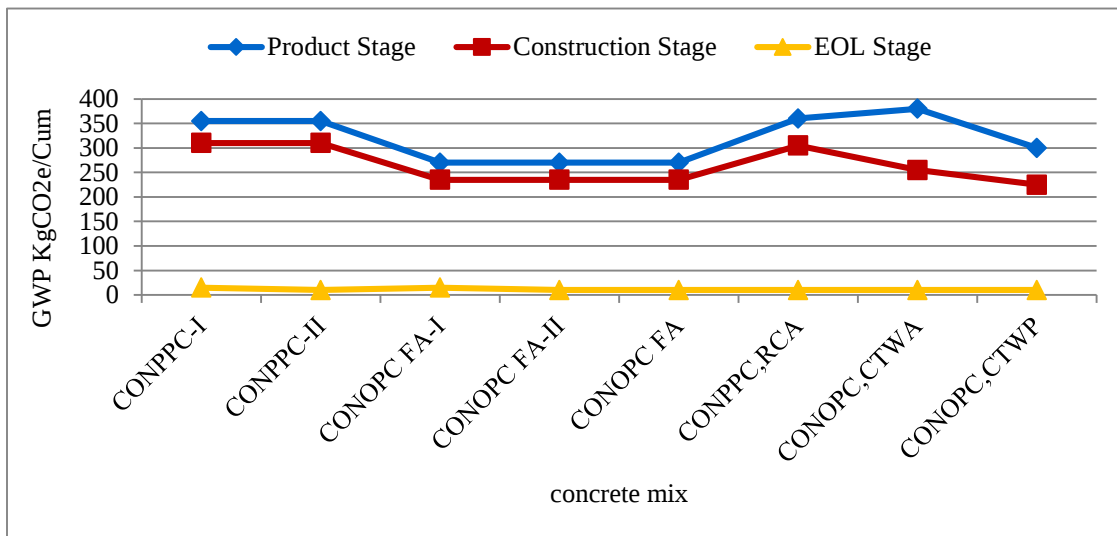


Fig. 3 GWP trend across concrete mixes

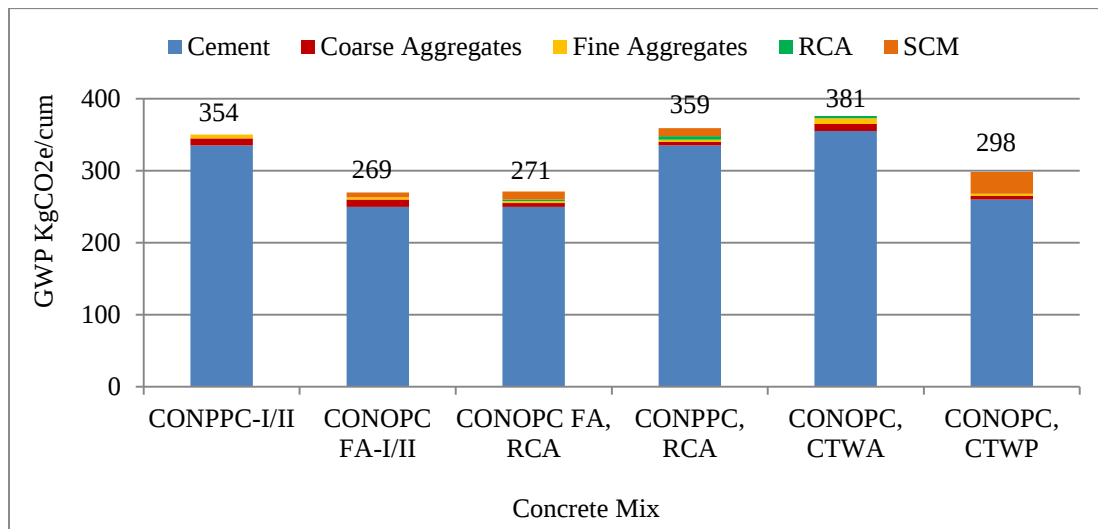


Fig. 4 Material-wise contribution to GWP

Table 5. Material-specific GWP in concrete mixes

Concrete Mix	Material	GWP KgCO _{2e} /m ³	% contribution to GWP of the production stage
CONPPC-I/II	Cement	335	95
	Fine Aggregates	6	2
	Coarse Aggregates	12	3
CONOPC FA-I/II	Cement	246	91
	Fine Aggregates	6	2
	Coarse Aggregates	13	5
	SCM (fly ash)	4	2
CONOPC FA, RCA	Cement	246	91
	Fine Aggregates	6	2
	Coarse Aggregates	10	4
	RCA	4	1.5
	SCM (fly ash)	4	1.5
CONPPC, RCA	Cement	335	93
	Fine Aggregates	6	2
	Coarse Aggregates	9	2.5
	RCA	9	2.5
CONOPC,CTWA	Cement	364	96
	Fine Aggregates	6	2
	Coarse Aggregates	9	2
	RCA (Ceramic tiles waste)	1	-
CONOPC,CTWP	Cement	254	85
	Fine Aggregates	6	2
	Coarse Aggregates	14	5
	SCM (Ceramic tiles waste Powder)	24	8

3.3. Material-Wise GWP Analysis

The Global Warming Potential (GWP) has been quantified based on the contribution of individual raw materials during the production stage. Cement remains the dominant contributor to emissions across all mixes. In mixes containing Portland Pozzolana Cement (PPC), namely CONPPC-I, CONPPC-II, and CONPPC RCA, the GWP is estimated at 335 kg CO_{2e}/m³, accounting for approximately 93% to 95% of total emission during the production stage. In comparison, mixes incorporating Ordinary Portland Cement (OPC), such as CONOPC FA-I, CONOPC FA-II, CONOPC FA RCA, and CONOPC CTWP, show a GWP value between 246 and 254 kgCO_{2e}/m³, accounting for 85% to 91% of the overall GWP during the production stage. CONOPC CTWA exhibits the highest GWP at 381 kgCO_{2e}/m³, with OPC alone contributing 95% of total emissions. This elevated impact is due to the high OPC content in the mix.

Incorporating Supplementary Cementitious Materials (SCMs) such as fly ash and Ceramic Tile Waste Powder (CTWP) reduces cement-related emissions significantly. Fly ash in CONOPC FA-I, CONOPC FA-II, and CONOPC FA, RCA contributes around 1.5% of the total GWP of the production stage, which helps to lower the overall cement footprint. Similarly, ceramic tiles waste powder in CONOPC, CTWP accounts for 8% of the GWP, which is higher than fly

ash but lower than cement. Figure 4 shows the material-wise analysis of GWP for each concrete mix. Table 5 presents a detailed breakdown of the material-wise GWP contribution across eight concrete mixes.

3.4. Material Cost Analysis

The cost of different concrete mixes was evaluated, considering solely the production stage while excluding expenses associated with other life cycle stages. Local market rates for raw materials are considered to ensure the contextual relevance of the cost analysis.

The production cost of CONPPC-I and CONPPC-II was determined to be INR 3687/m³. Among all constituent materials, Portland Pozzolana Cement (PPC) accounted for the highest cost contribution to the mix with INR 2,614/m³, followed by fine aggregates (INR 562/m³) and coarse aggregates (INR 511/m³). These figures indicate the dominance of cement in overall production cost.

In comparison, the production cost of CONOPC FA-I & FA-II was determined as INR 3419/m³, with a cost reduction of 7% compared to CONPPC-I & II. The cost reduction is attributed to the replacement of cement with fly ash. The cost breakdown indicates

The contribution of Ordinary Portland Cement (OPC) is INR 1716/m³ and fly ash is INR 585/m³.

Furthermore, cost optimization was observed in the CONOPC FA, RCA mix, which combines both fly ash and recycled aggregates. This mix recorded the lowest production cost at INR 3365/m³, which is almost 9% lower than CONPPC-I. The cost savings are largely due to a significant reduction in cement content.

Conversely, mixes such as CONPPC, RCA, and CONOPC, CTWA, which utilize RCA or Ceramic Tile Waste Aggregates (CTWA) without substantially reducing cement content, reported production costs of INR 3683/m³ and INR 3677/m³, respectively, values that are nearly equivalent to CONPPC-I. This finding indicates that recycled aggregates do not significantly alter the cost of coarse aggregates, thus limiting overall production cost.

The mix CONOPC, CTWP, which includes ceramic tile waste powder as SCM, has a production cost of INR 3441/m³, which is almost 7% less than CONPPC-I. This demonstrates the potential of ceramic waste as an alternative binder. The comparative analysis shows that the incorporation of fly ash, either alone or in combination with recycled aggregates, yields the most economical mix design. Replacing coarse aggregates alone does not significantly reduce the cost.

Figure 5 graphically presents the findings and compares each concrete mix's production cost and GWP. This figure serves as a valuable reference for stakeholders seeking to balance economic and environmental objectives. The results indicate that mixes incorporating fly ash and ceramic tile waste powder as SCM lower the production cost and contribute to the lower environmental impact, thus aligning with sustainable construction practices.

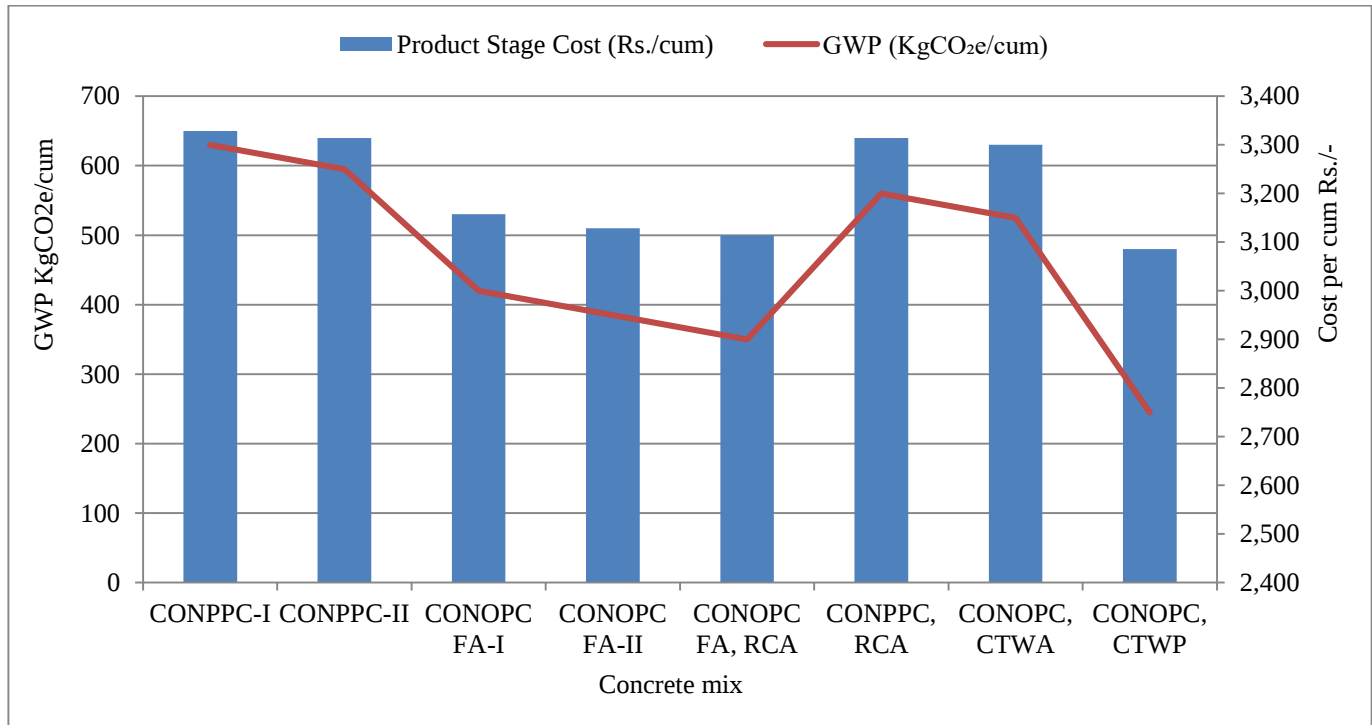


Fig. 5 Comparative analysis of GWP and production cost

4. Conclusion and Recommendations

This study presents the environmental and economic benefits of adopting sustainable concrete mix designs in the Indian construction sector. The incorporation of fly ash and ceramic waste powder as Supplementary Cementitious Materials (SCMs) has substantially reduced Global Warming Potential (GWP) by approximately 23-25% and production costs by 7-9% per cubic meter of concrete. A key finding of the study is the higher GWP associated with mixes made using

Portland Pozzolana Cement (PPC), such as CONPPC-I and CONPPC-II, which already contain 26–30% fly ash, compared to mixes made with Ordinary Portland Cement (OPC) and a similar proportion of fly ash blended separately at the batching plant (i.e., CONOPC FA-I and II). This can be attributed to the high clinker-to-cement ratio in PPC-based mixes, in which fly ash is blended with clinker during cement manufacturing. Fly ash is added at the batching plant in the case of OPC-based mixes, effectively reducing the clinker proportion and, hence, the clinker-to-cement ratio.

Replacing part of coarse aggregates alone with Recycled Concrete Aggregates (RCA) yields minimal environmental benefit, while the combined use of RCAs and SCMs can achieve a reduction in GWP up to 25%. However, the adoption of RCA in developing countries like India, particularly in smaller cities and towns, remains limited due to a lack of segregation and recycling facilities for Construction and Demolition (C&D) waste, the absence of standardized guidelines, and low awareness among stakeholders. Recycling construction and demolition waste consistently outperforms landfilling in terms of sustainability. Although India's 2016 rules for managing construction and demolition waste mandate the reuse and recycling of materials, enforcement remains weak. To implement the policies for sustainable construction practices, strict regulations should be enforced, and incentives should be introduced to the stakeholders who adopt these policies. Strengthening the infrastructure for C&D

waste collection, segregation, and processing is recommended. The collaboration of the private and government sectors is suggested to promote research and development of innovative waste utilization technologies in construction.

4.1. Future Scope

Further research related to concrete with different grades can be done. Furthermore, the long-term durability and structural performance of concrete made with sustainable materials can be explored. Other geographical regions that have an abundant supply of industrial byproducts can be studied. The integration of locally available industrial waste into construction materials would not only reduce GWP but also support India's circular economy initiatives.

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