



Life Cycle Assessment of Conventional and Self Compacting Concrete- A Cradle to Grave Approach

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Abstract

The construction industry in the developing country such as India is rapidly growing due to the infrastructural development. This growing demand leads to the consumption of material required for the construction. Concrete is one such material that is widely used all over the world. The concrete and the raw materials associated with it have been a concern due to the environmental issues related to their production. Among all the raw materials used for the production of concrete, cement generates a significant amount of CO₂ during its production. To determine the impact associated with concrete, it is important to understand the whole life cycle of its production. The current study is one such attempt to understand the cradle-to-grave life cycle assessment (LCA) of concrete. To quantify the impact associated with the whole life cycle of the concrete production an Excel-based tool is developed in this study. The tool is developed using Indian specific data. Using this tool, the present study compares conventional concrete with Self Compacting Concrete (SCC). The impact associated with cement type, mix design proportion, and End-of Life (EOL) scenarios were evaluated for both types of concrete. The results suggest that using blended cements such as Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC) are beneficial from environmental point of view than using Ordinary Portland Cement (OPC). Using blended cement can reduce the amount of clinkers generated during cement pyroprocessing by 58% and overall Global Warming Potential (GWP) by 40%. However in case of SCC, double the amount of binder content is required to achieve necessary strength and workability when PPC is used in place of the combination of OPC+ fly ash. Due to this the mix made using PPC cement has 27% higher GWP and 23% higher production cost than the OPC+ fly ash based mix. This outcome shows that choosing an alternative cement type and replacing Ordinary Portland Cement (OPC) alone does not ensure better performance unless the quantities are carefully optimized.

Keywords: Life Cycle Assessment (LCA), Conventional Concrete, Self-Compacting Concrete (SCC), Global Warming Potential (GWP), Supplementary Cementitious materials (SCMs).

Received: November 04th, 2025 / Revised: December 19th, 2025 / Accepted: December 26th, 2025 / Online: December 31st, 2025

I. INTRODUCTION

The construction industry is one of the most resource and energy intensive sectors worldwide. The growth of the construction industry is inevitable, as it provides the infrastructure that supports economic growth and better living standards. Concrete is used extensively as a construction material because of qualities such as strength, durability, versatility, and comparatively lower cost. The increasing demand for concrete and the primary raw material of cement is a major concern from an environmental perspective. Cement production is responsible for large amount of industrial greenhouse gas emissions. As per the data, cement production emits around 8% of total global CO₂ emissions [1]. Also, India is second largest producer of cement and produces around 430 million tonnes in the year of 2023-24 [2]. This demand is

expected to grow in the future due to rapidly expanding infrastructure.

Increasing demand for concrete has also raised serious concerns about long term availability of other raw materials used for the production. One such raw material is limestone. One survey predicts that several regions of India will run out of limestone in 3-4 decades [3]. The mining of natural aggregates that are used for concrete production have also caused significant environmental damage, such as landscape degradation and riverbed erosion. States like Gujarat are facing significant ecological pressure because of sand and aggregate extraction. [4]. It is important for the researchers and policymakers associated with the construction industry to find solutions to these problems. One of the solutions is to use Supplementary Cementitious Materials (SCMs), such as fly ash, slag, calcined clays, rice husk ash, and other materials. M. Tait and W. Cheung [5] conducted cradle to gate assessment of mixes

containing GGBS and flyash and found that mixes with GGBS have the lowest CO₂emissions. Other studies also suggested that incorporating waste materials as alternative binders can achieve meaningful reductions in global warming potential. [6], [7], [8]. B. Estanqueiroa et al. and M. Mah et al. [9], [10] observed that Recycle Concrete Aggregates (RCAs) can perform better than natural aggregates if transportation distances are minimized. Other studies also indicate that RCA can be a feasible and lower impact alternative to natural aggregates, provided that it is produced efficiently and does not have to be transported far [11-14]. The efforts to reduce the emissions associated with construction industries align with the initiatives run by the Indian government, such as the Waste to Wealth Mission and the National Resource Efficiency Policy. These programs encourage resource recovery and reuse practices. The systematic evaluation of these alternative solutions is essential. Many previous studies highlighted that the performance of alternative materials depends on local factors such as transportation distance, regional availability, mix proportions, and durability requirements.

Life Cycle Assessment (LCA) is a methodology standardized by ISO 14040 and ISO 14044. The environmental impacts at each stage of process or product life can be quantified using this framework. Previous research shows substantial variation in LCA outcomes. The variations are often caused by differences in system boundaries, functional units, software tools, and the widespread use of generalized datasets [15], [16],[17],[18],[19]. Most previous studies focus only on cradle to gate analysis. Very few studies include the full cradle to grave process. The full scale life cycle analysis would account for service life carbonation, demolition, waste processing, and end-of-life benefits apart from production. [20], [21]. Transportation impacts and regional energy profiles also play a major role in total emission [22], [23], [24]. The reliable primary data remain scarce in the Indian context. Most of the studies depend on European datasets, which often leads to inaccurate results, as they do not reflect real local conditions [19], [24].

The current study aims to provide a more accurate and thorough evaluation of concrete sustainability in India. The study evaluates the environmental and economic performance of conventional concrete mixes incorporating different cement types. It also analyzes Self Compacting Concrete (SCC) incorporating Portland Pozzolana Cement (PPC) and Ordinary Portland Cement (OPC) using a cradle to grave LCA approach. Primary industrial data related to cement production are collected from cement plants in Kutch, Gujarat. Concrete production details have been collected from Ready Mix Concrete (RMC) facilities in Rajkot, Gujarat. To analyze the impact based on these collected data, a customized Excel-based Concrete Life Cycle Assessment (CONLCA) tool was developed. The subsequent sections will discuss the details of inventory data and the tool development.

II. METHODOLOGY

This study employs a structured and systematic Life Cycle Assessment (LCA) methodology based on the internationally recognized standards ISO 14040 and ISO 14044. The methodology is organized into four key stages; Goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The study is supported

by a customized excel based model, the CONLCA tool, developed specifically for Indian conditions.

The assessment framework and system boundary of the study are presented in Fig.1. The key stages of the assessment are explained in subsequent sections.

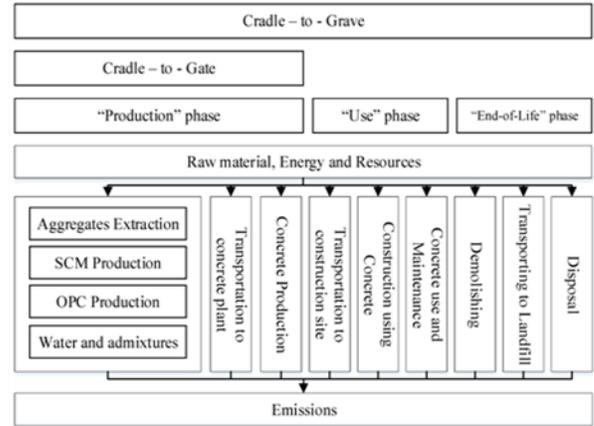


Fig. 1. Cradle to Grave LCA framework of Concrete [25]

A. Goal and Scope Definition

This section explains the primary aim and scope of the research. The present research aims to evaluate and compare the environmental impacts and production costs of conventional concrete mixes made using different types of cement. It also analyzes and compares Self Compacting Concrete (SCC) made with OPC and PPC cement. A cradle-to-grave system boundary is used in which evaluation is done for all stages right from raw material extraction to final disposal. The functional unit is defined as 1 m³ of concrete, designed to deliver equivalent structural performance and durability over a 50years of building life. Environmental impacts are calculated using the ReCiPe 2016 (H) method, with modeling carried out through the customized CONLCA tool.

B. Life Cycle Inventory (LCI)

This phase of life cycle assessment involves the collection of data. In the present study, detailed data related to raw materials, transportation, and energy input are collected for each stage of the concrete life cycle.

The information pertaining to cement manufacturing is gathered from plants located near the Kutch region in Gujarat. The data related to raw material extraction and processing, the type of fuel used in the kiln, the usage of electricity, and transportation within the cement plants are collected from these plants. Most of the cement plants in this region produce different types of cement, such as Ordinary Portland, Portland Slag, and Portland Pozzolana Cement. These plants supply cement to the concrete plants located in Rajkot city, Gujarat.

The Ready Mix Concrete (RMC) plant in Rajkot, Gujarat, provided the details related to mix design and energy requirements for batching and processing concrete. The material transportation distance and modes were collected through technical discussion.

The construction site related information, such as structural specifications, quantity of materials, equipment, maintenance cycle, and building life, is collected from an ongoing mid rise residential building site located in Rajkot City.

The secondary data concerning fuel and energy use were taken from recognized Indian organizations, such as the Bureau of Energy Efficiency (BEE) [26], Confederation of Indian Industry (CII) [2], The Energy and Resource Institute (TERI) [27], national statistics published by the Ministry of Statistics and Programme Implementation (MOSPI) [28] and Central Electricity Authority (CEA) [29]. These primary and secondary data sets are combined to establish a complete and consistent inventory, which is a base for emission calculation using the CONLCA tool.

C. Life Cycle Impact Assessment (LCIA)

This section of the Life Cycle Assessment (LCA) includes the calculation of impacts associated with the various stages using the collected data in the inventory section. After calculation, the collected data transforms into measurable impacts. The CONLCA tool is designed to calculate harmful gaseous emissions at each stage of LCA. These calculated emission values are then used to calculate environmental impacts using the ReCiPe 2016 method by applying appropriate impact factors. The CONLCA tool allows the user to enter mix design details, such as the type and quantity of raw materials. Users can also select different types of cement and Secondary Cementitious Materials (SCMs) from the listed choices. It also allows users to enter data regarding transport distances, modes of transportation, and site equipment. The percentage of waste that goes to landfill and recycling after demolition of the building can also be selected by the users. The tool calculates Global Warming Potential (GWP) and energy consumption at each stage. The midpoint and endpoint indicators can also be calculated using the ReCiPe method integrated with the tool.

The production cost is also calculated using this tool based on mix design details and the local market price of raw materials, as this is the primary cost considered by builders and contracts during mix selection. The production cost provides direct practical relevance when it comes to adoption of sustainable mixes. However, the full life cycle cost (LCC) was not included due to limited availability of consistent local financial details and regional variability. The production cost analysis enables combined environmental and economic evaluation and comparison.

D. Interpretation

The results derived under the LCIA section are discussed during interpretation. From the calculation one can interpret the environmental and economic performance of various mixes and compare them. Additionally, the influence of end-of-life processing and transport distances can be identified.

III. DEVELOPMENT OF CONLCA TOOL AND ANALYTICAL ANALYSIS

This section discusses the framework and analytical calculation procedures used for development of the Concrete Life Cycle Assessment (CONLCA) tool. This is an Excel-based tool that is designed to evaluate the environmental and economic performance of concrete mixes. The tool is based on Indian manufacturing and operational conditions. It evaluates emissions of major greenhouse gases and air pollutants (CO₂, CH₄, N₂O, NO_x, SO₂, CO, PM₁₀, and VOCs) and cumulative energy consumption per cubic meter of concrete across a cradle-

to-grave system boundary. The tool integrates midpoint and endpoint environmental impact indicators through the ReCiPe 2016 (H) method and enables the estimation of production cost per cubic meter for different cement types and supplementary cementitious material (SCM) combinations. The adopted system boundary analyzes stages such as raw material extraction, processing, transport, batching, onsite placement, service life operations, demolition, and end-of-life options, including recycling and landfilling. The functional unit considered is one cubic meter of concrete. The user can enter quantities per m³ (cement, SCMs, aggregates, admixtures, water), transport distance and mode for each material and process, onsite technology, and end-of-life distribution among recycling and landfill. The tool then generates stage wise and total Global Warming Potential (GWP) per m³, energy consumption per stage, midpoint, and endpoint environmental impacts. The tool can also analyze sensitivity for SCM substitution and transport variation. The following section shows the sample calculations and procedure for the emission and impact factor calculations.

A. Emission Calculation for Raw Material Excavation and Processing

CONLCA calculates emissions at each stage, using the standard activity × emission factor approach:

$$E_i = A_i \times EF_i \quad (1)$$

Where: E_i = Emissions of pollutant i (kg / cum)
 A_i = Activity data (e.g., fuel L, kWh, t-km)
 EF_i = Emission factor (kg / unit activity)

The emission factor for each process or material is derived using the equation shown below.

$$EF_{clinker} = EF_{process} + (E_{thermal} \times EF_{fuel}) + (E_{electric} \times E_{Felectric}) \quad (2)$$

For example, the emission factor for clinker production is calculated by considering both process emissions from calcinations and energy related emissions from fuel and electricity consumption during cement manufacture.

The first component, $EF_{process}$, represents CO₂ released during the decarbonation of limestone, contributing 0.530 kg CO₂/kg clinker [30]. The second component accounts for emissions from thermal energy consumed in the kiln, calculated as 3.2 MJ/kg clinker × 0.094 kg CO₂/MJ = 0.3008 kg CO₂/kg [28]. The third term represents emissions from electrical energy used in grinding, material handling, and cooling, determined as 0.045 MJ/kg × 0.22 kg CO₂/MJ = 0.0099 kg CO₂/kg, based on the Indian national grid emission factor of ~0.78 kg CO₂/kWh [29].

$$EF_{clinker} = 0.530 + 0.3008 + 0.0099 = 0.841 \frac{kg \text{ CO}_2}{kg} \quad (3)$$

This confirms that process emissions are the dominant contributor to clinker's carbon intensity, followed by thermal and electrical energy consumption, based on Indian cement industry averages. Similarly the emission factors associated with

other raw materials and processes are calculated. Table I shows emission factors and a sample calculation of CO₂ emission associated with a trial mix adopted in this study.

B. Emission Calculation Associated with Transportation at Each Stage

The emissions associated with the transportation of raw materials to cement and concrete plants, concrete to construction sites, and demolition waste to landfills and recycling sites are calculated. The emission factors are computed in kg/tonne.km, and the quantity of materials in tonnes is multiplied with these emission factors to arrive at the emission associated with each material or process. The tool includes mode and vehicle specific emission factors, enabling users to assign appropriate transport classes such as Low Duty Vehicles (LDV), Medium Duty Vehicles (MDV), Heavy Duty Vehicles (HDV), rail, and water transport for each material and process. The calculation of CO₂ emission for different types of transportation modes is shown in Table II. The default transport distance of 350 km is considered for all cement types. Due to its lower carrying capacity, LDV exhibits the highest CO₂ emission (0.38 kg/t.km). HDV and rail transport have significantly reduced emission intensities due to the benefits of bulk transport. The CO₂ emission values reduce as the mode of transportation changes from LDV to HDV.

TABLE I. MATERIAL/PROCESS WISE CO₂ EMISSION

Material/ Process	CO ₂ Emission Factor (kgCO ₂ /kg material)	Quantity (kg/cum)	CO ₂ Emission kg/cum
Clinker production	8.41E-01	207	1.70E+02
Cement packaging	2.00E-02	218	4.36E+00
Fine aggregates excavation+ processing	4.00E-03	970	3.88E+00
Coarse aggregates excavation+ processing	6.00E-03	711	4.27E+00
Fly ash Processing, handling	2.02E-02	156	3.15E+00
Water	5.00E-04	203	1.02E-01
Super Plasticizers (PCE)	5.50E+00	3.15	1.73E+01

TABLE II. CO₂ EMISSION FOR DIFFERENT TRANSPORT MODE

Transportation Mode	Avg. Load (tonnes)	CO ₂ Emission Factors (Kg /tonne .km)	Quantity of Cement (tonnes /cum)	Emission from Transport (kg/cum)
LDV	3.5 to 7.5	3.80E-01	0.218	2.90E+01
MDV	7.5 to 12	1.40E-01		1.07E+01
HDV	12 to 40	9.00E-02		6.87E+00
Rail		1.10E-02		8.39E-01
Water		2.00E-02		1.53E+00

C. Service Life Carbonation Calculation

Service life carbonation refers to the slow absorption of atmospheric CO₂ by hydrated cement during the operational life of reinforced concrete. In this study, carbonation during service life was calculated using a time dependant diffusion model used in durability studies. Carbonation depth x was estimated using the formula $x=kt^n$ [31], where k is the carbonation coefficient (mm.year⁻ⁿ), t is exposure time in years, and n is the time exponent. The square root model is generally used, where n is taken as 0.5. However, long term filed stuides conclulde that n=0.5 can overestimate carbonation at later ages [32], and hence n=0.4 is used in the present study. A service life of 50 years is assumed, which is commonly used in building LCA studies. The value of k is taken from the fib model code 2010 [33]. Mid range k values are selected to represent the moderate outdoor exposure. The exposed surface area was taken as 3 m² per cubic meter of concrete, which is generally adopted in beam-column type building elements. Carbonation is usually not complete because of painted, coated, or repaired concrete surfaces. That is why partial carbonation was considered while using a degree of carbonaiton (Dc). The carbonated concrete volume is calculated by multiplying carbonation depth with exposed surface area. CO₂ uptake was calculated using the follwing equation.

$$CO_2 \text{ uptake} = m_{cement, carb} \times Utcc \times Dc \quad (3)$$

Where, $m_{cement, carb}$ = The mass of cement in the carbonated zone Utcc= 0.25 kg CO₂ /kg (maximum theoretical CO₂ uptake capacity of cement) [33] and Dc= Fraction of cement that carbonates

The CO₂ uptake value is taken as a negative value, which gives a small reduction in net cradle to grave GWP.

D. Midpoint and Endpoint Environmental Impact Assessment

The impact at an intermediate stage is represented by midpoint indicators. Midpoint indicators measure the potential environmental consequences of emissions and resource consumption. The midpoint indicators measured using the ReCiPe 2016 (H) methodology are Global Warming Potential (GWP), Stratospheric Ozone Depletion, Human Health Ozone Formation Potentials (HOFP), Ecosystem Ozone Formation Potential (EOFP), Particulate Matter Formation, Terrestrial Acidification, Mineral Resource Scarcity, and Fossil Resource Scarcity. Firstly, the emissions are allotted to the relative midpoint indicators. The values of these harmful emissions, which are calculated using the CONLCA tool, are multiplied with the characterization factor defined in the ReCipe method to get the defined values of midpoint indicators. The value of midpoint indicators expresses the relative contribution to a specific environmental issue. For example, greenhouse gases such as CO₂, CH₄, and N₂O are converted into a single unit of kg CO₂ equivalent under the GWP category. Similarly, SO₂ and NOx emissions are converted into kg SO₂ equivalent to denote terrestrial acidification.

From the values of midpoint indicators, one can determine which pollutants or lifecycle stages exert the highest impact. The midpoint indicators are allotted to the relative endpoint damage

category and multiplied with the impact factor associated with the particular endpoint indicators. Endpoint indicators show damage to the final level. In the ReCipe method, three endpoint indicators are calculated: Human health, Terrestrial and Freshwater ecosystems, and Resources. The damage to human health is measured in DALYs (Disability-Adjusted Life Years). The value of this damage category denotes the number of healthy human life years lost due to diseases, disabilities, or premature death caused by environmental pollution. The categories of Terrestrial and Freshwater ecosystems are measured in species year. This unit predicts the loss of species due to factors such as land use, acidification, and ecotoxicity in a year’s time. The third damage category,

Resources refer to the limited availability of essential resources. It is represented in economic surplus cost (USD). This category of damage represents the extra financial burden on the future generations to extract remaining mineral and fossil resources. Fig. 2 presents the steps involved in the calculations using Recipe method integrating the CONLCA tool. Likewise, emissions and impacts are calculated at each stage of the LCA of concrete. The CONLCA tool offers a transparent assessment platform tailored to Indian concrete production scenarios. It enables quantification of environmental damages and energy consumption across cradle-to-grave life cycle stages.

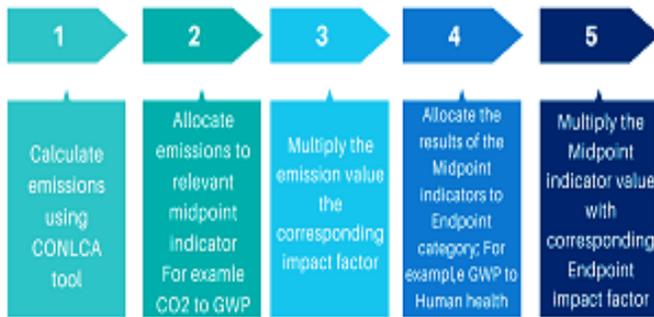


Fig. 2. Calculation Framework for Midpoint and Endpoint Indicators

E. Energy Consumption Assessment

Energy consumption in the CONLCA model is quantified separately for each lifecycle stage using activity data and stage specific energy intensity factors and then normalized per cubic meter of concrete. For the production stage, energy use for raw material excavation and processing, clinker burning, grinding, and cement and concrete manufacturing is calculated from literature based thermal and electrical energy intensities (MJ/kg) for each process and multiplied by the corresponding material quantities per m³ of concrete. Additional electricity for batching plant operations and onsite placing (mixers, pumps, conveyors, and controls) is then added to obtain the total production energy per m³.

Transport energy is estimated by combining material masses, transport distances, and mode specific energy factors (MJ/t·km) for LDV, MDV, HDV, rail, and water and summing the contributions for all inbound and outbound flows.

Operational energy cannot be directly attributed to concrete as it is primary by heating, air conditioning and ventilation. Therefore, the allocation approach is necessary. ISO 14044 recommends to use a physical basis, when allocation is

unavoidable. Hence, for the use stage, whole building’s operational energy in MJ/year is first allocated to the structural system using a mass allocation factor equal to the ratio of concrete mass to total structural mass (0.60 in this case). This approach is widely accepted in building and construction LCA practice. To identify the operational energy for 1 m³ of concrete, the annual energy is divided by the total volume of concrete and then multiplied by the building’s service life (50 years). Based on the mass allocation method, energy attributed to concrete is equivalent to 227 MJ/m³.yr over the 50 years of service life.

An alternative area based allocation is also evaluated by normalizing operational energy to carpet area and then converting it to a concrete volume basis. This results in 368.67 MJ/m³.yr over 50 years, which is higher than the value obtained from the mass allocation approach. It is also observed that several building LCA studies adopt a zero-allocation approach, where operational energy is not assigned to any materials. It is treated as building level parameter and not materially driven.

Demolition energy is calculated using an intensity of 12 kWh per tonne of concrete for mechanical demolition and primary crushing, converted to MJ with 1 kWh = 3.6 MJ. For land filling, energy is estimated based on landfill handling factor of 8 MJ/tonne and the mass of concrete per m³. For recycling, diesel and electricity demands for pre-crushing, crushing, magnetic separation, and washing are taken from typical Construction and Demolition (C&D) recycling plant data (MJ/m³) and summed to obtain the total recycling energy. The total life cycle energy consumption is the sum of all these stage wise energy contributions.

IV. RESULTS AND DISCUSSION

This section presents and discusses the results generated through the CONLCA tool, organized to highlight how material choices and end-of-life strategies influence the environmental performance of concrete. The analysis is divided into three key scenario groups: A. The influence of type of cement in conventional concrete B. The influence of type of cement in Self Compacting Concrete (SCC) C. Influence of End-of-Life (EOL) Scenarios and transportation distances.

A. The Influence of Type of Cement in Conventional Concrete

Under this section, Ordinary Portland Cement (OPC) is compared with several blended cements, which include Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC), and Portland Limestone Cement (PLC). Table III lists the type of cement incorporated in the CONLCA tool along with their specifications and corresponding mixes.

TABLE III. SPECIFICATION OF DIFFERENT CEMENT TYPES AND CORRESPONDING CONCRETE MIXES

Cement Types	Specification	Name of Mix
Ordinary Portland Cement	95% clinkers, 5% gypsum	CONOPC
Portland Pozzolana Cement-I	80% clinkers, 15% Pozzolanic material, 5% gypsum	CONPPC-I
Portland Pozzolana Cement-II	69% clinkers, 26% Pozzolanic material, 5% gypsum	CONPPC-II

Portland Pozzolana Cement-III	50% clinkers, 30% Calcined clay, 15%Limestone, 5% gypsum	CONPPC-III
Portland Slag Cement-I	65% clinkers, 30% GBFS, 5% gypsum	CONPSC-I
Portland Slag Cement-II	40%clinkers, 55%GBFS, 5% gypsum	CONPSC-II
Portland Limestone Cement	80% clinkers, 15% Limestone, 5% gypsum	CONPLC

To highlight the influence of cement type, other parameters, such as concrete mix proportions, transportation mode and distances, construction technologies, and End-of-Life (EOL) scenarios, were kept similar. The default transportation route and corresponding distances used for the analysis under this section are shown in Fig.3.

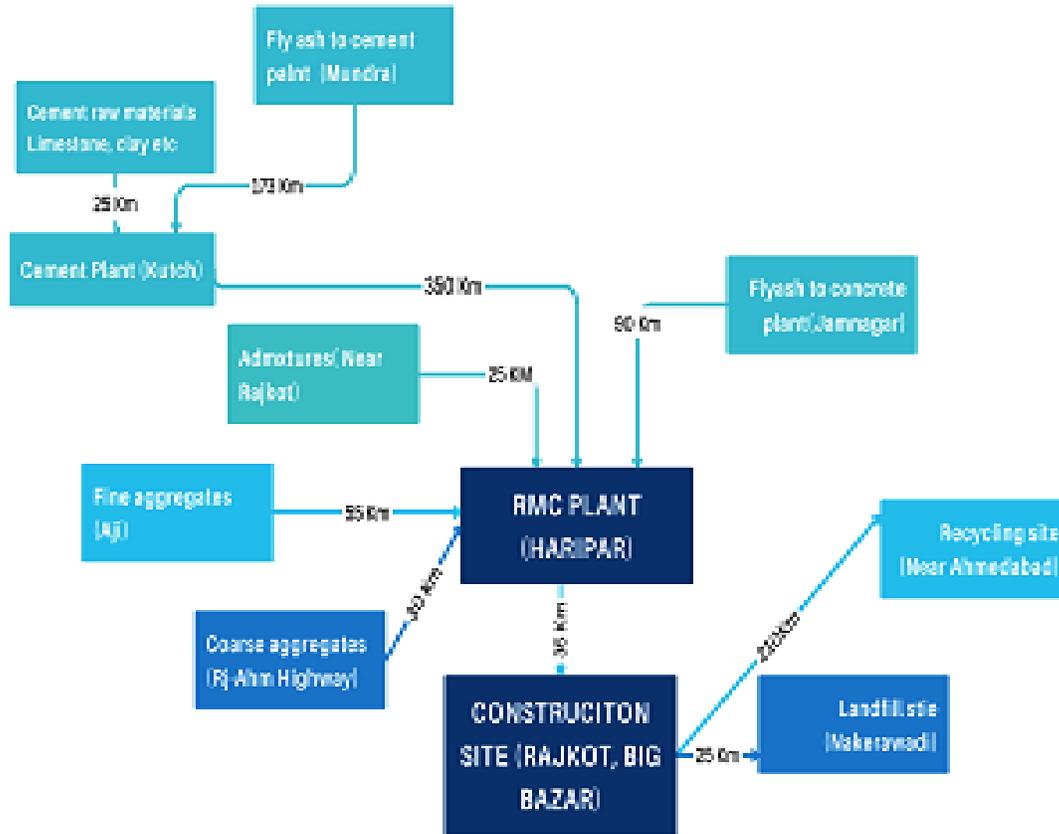


Fig. 3. Default Transportation Routes and Distances

The parameters, such as CO₂ emission, Global Warming Potential (GWP), energy consumption, and environmental impact categories based on the ReCiPe method, are calculated for all concrete mixes. From the results it is clear that the clinker ratio is the key factor that influences environmental impact across cement types. The technique for clinker production, cement pyroprocessing, requires the highest amount of energy and releases the maximum amount of CO₂. Table IV displays the comparative analysis of clinker ratios and CO₂ emissions for all different concrete mixes.

It is obvious from the results that blended cements generate a lesser amount of clinkers and corresponding emissions. As shown in Table IV, CONPSC-II shows a 58% reduction in both clinker content and CO₂ emissions compared to CONOPC. The mix with PPC cement, CONPPC-III, achieves reduction up to 47% in CO₂ emission. Fig.4 demonstrates that the lower clinker content directly leads to lower CO₂ emissions. The results demonstrate that blended cements can greatly reduce

environmental burden in the conventional concrete mixes. The GWP is also calculated based on the greenhouse gas emissions, and the results are summarized in Table V.

TABLE IV. COMPARATIVE ANALYSIS OF CLINKER RATIO AND CO₂ EMISSION

Concrete Mix	Clinker Ratio kg/cum	% Reduction in Clinker Ratio	CO ₂ Emission During Clinker Production kg/cum)	% Reduction in CO ₂ Emission
CONOPC	364	-	298	-
CONPPC-I	306	16	251	16
CONPPC-II	264	27	217	27
CONPPC-III	192	47	157	47
CONPSC-I	249	32	204	32
CONPSC-II	153	58	126	58
CONPLC	306	16	251	16

TABLE V. COMPARISON OF GWP AND ENERGY CONSUMPTION

Concrete Mix	GWP (kg CO ₂ e/cum)	% Reduction in GWP	Energy Consumption (MJ/cum)	% Reduction in Energy Consumption
CONOPC	434	0	13896	0
CONPPC-I	387	11	13700	1

CONPPC-II	352	19	13556	2
CONPPC-III	303	30	13054	6
CONPSC-I	340	22	13504	3
CONPSC-II	262	40	13177	5
CONPLC	384	12	13674	2

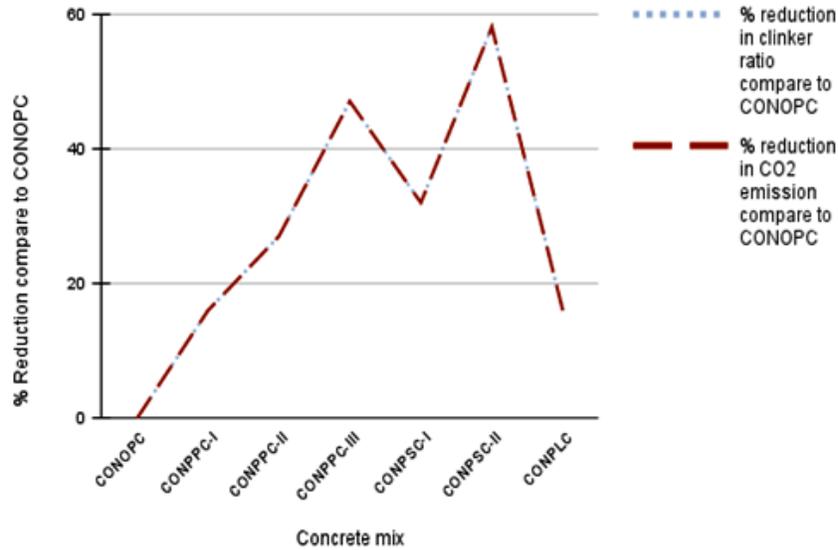


Fig. 4. Percentage Reduction in Clinker Ratio and CO2 Emission

The results display similar trends as those of previous results. It shows GWP reductions ranging from 11% to 40% when compared to the OPC mix (CONOPC). Smaller reductions in energy consumption are also observed between 1% and 6%. Fig.5 represents GWP and energy consumption together for all

the mixes. It is observed that PPC (PPC-III) and PSC based cements show noticeable improvement. The reduction in GWP and energy consumption in these two mixes is primarily due to their high use of supplementary cementitious materials (SCMs).

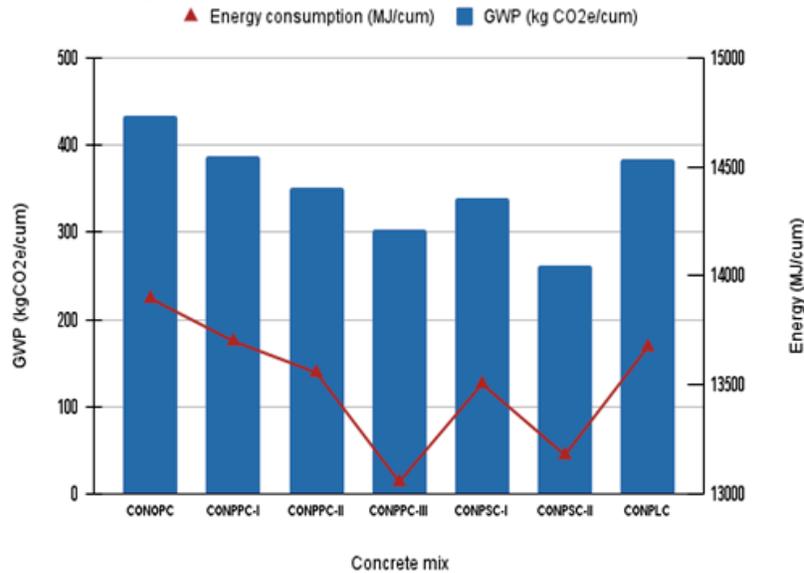


Fig. 5. Comparative Analysis of GWP and Energy Consumption

Reductions are also noticeable in midpoint impact categories, such as particulate matter formation, terrestrial acidification, and fossil resource scarcity, as shown in Table VI. The PSC mixes and PPC mixes particularly CONPPC-III, show the major improvements that demonstrate the advantages of replacing clinker with industrial byproducts like flyash and GGBS.

The endpoint results calculated using ReCipe method is listed in Table VII. These results reveal that impacts on human health measured in DALY remain same across mixes. However,

damages related to resource shows major changes. Resource damage decreases from damage decreases from USD 2.57 for OPC to only USD 0.82 for CONPPC-III. Overall, the findings suggest that type of cement used in concrete mix plays a crucial role in the environmental performance of concrete. Blended cements exhibit meaningful reductions across multiple impact categories. The results offer a practical pathway to more sustainable construction. Encouraging the regular use of blended cements in conventional concrete can significantly support decarbonization efforts within the construction sector.

TABLE VI. COMPARISON OF MIDPOINT INDICATORS FOR DIFFERENT CEMENT TYPES

Comparison of Midpoint Indicators for Concrete Mix	Midpoint Impact Indicator						
	Stratospheric Ozone Depletion (kg CFC11-eq/kg ODS)	Human health Ozone Formation Potentials (kg NOx-eq/kg)	Ecosystem Ozone Formation Potential (kg NOx-eq/kg)	Particulate Matter Formation (kg PM2.5-eq/kg)	Terrestrial Acidification (kg SO ₂ -eq/kg)	Mineral Resource Scarcity (kg Cu-eq/kg ore)	Fossil Resource Scarcity (kg oil-eq/kg resource)
CONOPC	0.001	3.557	0.333	10.824	1.247	6.606	30.563
CONPPC-I	0.001	3.423	0.319	10.652	1.105	5.563	25.738
CONPPC-II	0.001	3.325	0.309	10.526	1.000	4.798	22.199
CONPPC-III	0.000	3.148	0.291	10.233	0.826	1.158	16.086
CONPSC-I	0.000	3.289	0.306	10.480	0.962	4.520	20.912
CONPSC-II	0.000	3.066	0.283	10.194	0.725	2.781	12.869
CONPLC	0.001	3.376	0.315	10.471	1.099	5.563	25.738

TABLE VII. COMPARISON OF ENDPOINT INDICATORS FOR DIFFERENT CEMENT TYPES

Concrete Mix	Endpoint Impact Category	
	Human Health (Disability-Adjusted Life Years (DALY))	Resources (USD2013)
CONOPC	0.007	2.570
CONPPC-I	0.007	2.164
CONPPC-II	0.007	1.866
CONPPC-III	0.007	0.817
CONPSC-I	0.007	1.758
CONPSC-II	0.007	1.082
CONPLC	0.007	2.164

TABLE VIII. MIX DESIGN DETAILS OF SCC

Material	Quantity (Kg/m ³)	
	CONSCC-I	CONSCC-II
Cement	218 (OPC)	402 (PPC)
Fine aggregates (sand)	970	1078
Coarse aggregates	711	657
Fly ash	156	-
Water	203	205
Super Plasticizers	3.15	2.76
Total weight of concrete	2261	2345

B. The Influence of Type of Cement in Self Compacting Concrete (SCC)

This section explores how changing the type of cement affects the sustainability of Self Compacting Concrete (SCC). Two M20-grade SCC mixes were developed at the laboratory of Marwadi University, Rajkot, Gujarat. The mix details are shown in Table VIII. The design is done based on the European Federation of National Associations Representing for Concrete (EFNARC). Ordinary Portland Cement (OPC) produced the first mix, CONSCC-I, while Portland Pozzolana Cement (PPC) containing 15% fly ash produced CONSCC-II. The functional equivalence between conventional and self-compacting concrete mixes was established based on their mechanical strength, fresh state SCC performance criteria, and durability assumptions.

The experimental results show 28-day compressive strength around 29 MPa for both the mixes, confirming equivalent structural load-bearing performance based on IS 10262. The rheology of SCC mixes was validated using EFNARC acceptance limits. The SCC mixes under study report slump flow as 741 mm, V-funnel 12s, U-box 20 mm, and L-box ratio 0.90. All the results fall within EFNARC recommended limits. This outcome confirms adequate segregation resistance, passing and filling ability, and ensuring SCC performance beyond nominal compressive strength. Functional equivalence in durability was assumed based on identical service life (50 years) in the absence of accelerated durability test facilities.

Although PPC is commonly viewed as a more environmentally friendly option, the results from this study showed that the PPC based SCC mix required a much higher

quantity of cementitious material to meet the required flow and strength characteristics of SCC. CONSCC-II used 402 kg/m³ of binder, almost double the 218 kg/m³ used in CONSCC-I. This large increase in cement content significantly influenced the environmental results. The Life Cycle Assessment findings revealed that CONSCC-I performed considerably better in terms of carbon footprint, producing 285 kg CO₂e/m³, which is 27% lower than CONSCC-II (390 kg CO₂e/m³). A breakdown of GWP across different life cycle stages is presented in Table IX and illustrated in Fig.6, showing that the raw material production stage contributed the most to total emissions for both mixes.

TABLE IX. COMPARISON OF GWP AND PRODUCTION COST FOR SCC.

Concrete Mix	GWP (kg CO ₂ e/cum)	% Reduction in GWP	Production Cost (INR)	% Reduction in Cost
CONSCC-I	285	27	3890	23
CONSCC-II	390	-	5043	-

The cost assessment of both the mixes aligns with GWP results. It is observed that CONSCC-I was 23% cheaper to produce than CONSCC-II (Table X). The higher impact of PPC based SCC is attributed to the quantity of binder and not the cement type. This impact can be reduced by using additional SCM fillers while maintaining ENFARC criteria.

This analysis reflects the influence of cement content on the environmental impact and economic performance of concrete. The midpoint and endpoint indicator results are shown in Tables XI and XII respectively. The SCC concrete mix with OPC + fly ash as a binder performs better than the mix with PPC cement across all midpoint categories. In the case of endpoint indicators, the impact on human health (DALY) was similar for both mixes. The damage to the resource was almost double for the mix with PPC cement than that of the PPC + fly ash mix. Based on these observations, the study suggests that simply substituting Ordinary Portland Cement (OPC) does not guarantee sustainability benefits, particularly in Self Compacting Concrete (SCC) mixes.

TABLE X. LIFE CYCLE STAGE WISE COMPARISON OF GWP FOR SCC

Life Cycle stage	Concrete Mix / GWP (kg CO ₂ e/cum)	
	CONSCC-I	CONSCC-II
Raw material excavation and processing	214	314
Transportation at each stage	45	54
Concrete batching plan	4.35	4.35
Placing of concrete	8.09	8.09
Usage phase	4.65	0.84
Demolition	2.45	2.54
Land filling	0.49	0.51
Recycling	6.46	6.70
Total	285	390

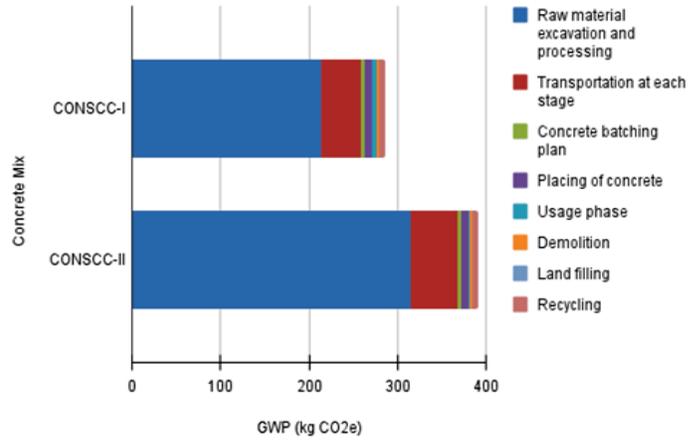


Fig. 6. Life Cycle Stage Wise Comparative Analysis of GWP

TABLE XI. MIDPOINT INDICATORS OF SCC

Midpoint Indicators	CONSCC-I	CONSCC-II
Stratospheric Ozone depletion (kg CFC11-eq/ kg ODS)	0.0004	0.0006
Human health Ozone formation potentials (HOFP) (kg NOx-eq/kg)	2.48	2.99
Ecosystem Ozone formation Potential (EOFP) (kg NOx-eq/kg)	0.023	0.028
Particulate matter formation (kg PM2.5-eq/kg)	8.14	8.59
Terrestrial acidification (kg SO ₂ -eq/kg)	0.80	1.11
Mineral resource scarcity (kg Cu-eq/kg ore)	3.76	5.84
Fossil resource scarcity (kg oil-eq/kg resource)	17.4	27

TABLE XII. ENDPOINT INDICATORS OF SCC

Endpoint Impact Indicator	SCC-I	SCC-II
Human Health (Disability-Adjusted Life Years (DALY))	0.0054	0.0057
Resources (USD2013)	1.46	2.27

C. Influence of End-of-Life (EOL) Scenarios and Transportation Distance

This section explores how different End-of-Life (EOL) strategies influence the environmental performance of concrete after demolition. Five scenarios were considered, ranging from complete landfilling to full recycling of concrete waste: i) 100% landfill ii) 70% landfill + 30% recycling iii) 50% landfill + 50% recycling iv) 30% landfill + 70% recycling and v) 100% recycling. To analyze the impact of transportation, two different distances to recycling facilities were considered: 40 km and 210

km. The distance to the landfill disposal site was maintained constant as 40 km. Based on the analysis presented in Table XIII, the recycling scenario shows a higher GWP even at a short distance of 40 km. To estimate the transport break-even distance, linear interpolation was performed between the two distances, 40 km and 210 km, assuming a linear relationship between transport distance and GWP. The interpolation gives break-even distance as -15 km. This negative value implies that recycling does not achieve GWP parity with landfilling, even at very short transport distances. Therefore, the end-of-life outcomes remain highly distance sensitive. The outcomes strongly depend on local recycling efficiency and the extent to which virgin material production is avoided.

TABLE XIII. COMPARISON OF DIFFERENT RECYCLING SCENARIOS

Concrete mix	Transport distance to recycling site (Km)	Re-cycling %	GWP (kg CO _{2e} /cum)	Energy consumption MJ/cum
CONSCC-II	210	0	384	13363
		30	410	13603
		50	427	13764
		70	444	13925
		100	470	14166
CONSCC-II	40	0	384	13363
		30	390	13356
		50	394	13352
		70	399	13347
		100	405	13341

V. SENSITIVITY AND UNCERTAINTY DISCUSSION

A sensitivity analysis was performed one by one for four different parameters to evaluate uncertainty propagation. The key inventory inputs affecting the global warming potential (GWP) of concrete are analyzed. The first parameter, clinker CO₂ emission factor, was perturbed by ±10% and ±20% to represent most likely plant wise variation caused by kiln efficiency, fuel mix, and calcinations accounting.

The second parameter, transport distances, was varied by ±20%, consistent with typical uncertainty in freight transport assumptions. The third parameter considered was energy intensity while placing the concrete, which varied by ±15% to reflect variability in on-site equipment use. The fourth parameter, service life of the building, which affects use phase contribution, was varied by (±50%). This variation mainly influences the carbonation related CO₂ uptake. A scenario analysis was carried out to evaluate alternate service lives (25 and 75 years) with the baseline service life of 50 years. For the CONOPC mix (GWP= 434 kgCO_{2e}/m³ baseline), the clinker emission factor was the dominant uncertainty driver. The ±10% variation resulted in a total GWP range of 404–464 kg CO_{2e}/m³ (±6.91%). The ±20% variation resulted in 373–495 kgCO_{2e}/m³ (±14%).

The uncertainty in transport distances caused a smaller variation of ±11 kgCO_{2e}/m³ (±2.53%). The energy intensity during the placing stage had a marginal influence of ±0.8 kg CO_{2e}/m³ (±0.2%). The service life variation has negligible influence on overall GWP. These findings indicate that clinker

related emission assumptions govern uncertainty in overall GWP results. The transport related parameters form the second most influential parameter. Table XIV summarizes the sensitivity analysis results for different parameters.

TABLE XIV. SENSITIVITY ANALYSIS FOR KEY PARAMETERS (CONOPC)

Parameter	Variation (%)	Overall GWP (Low)	Overall GWP (High)	Absolute Change (± kg CO _{2e} /m ³)	Relative Change (%)
EF Clinker (0.841 kg CO ₂ /kg clinker)	±10%	404	464	30	±6.91
EF Clinker (0.841 kg CO ₂ /kg clinker)	±20%	373	495	61	±14
Transport Distance	±20%	423	445	11	±2.53
Placing Energy Intensity	±15%	433.23	434.77	0.77	±0.18
Building Service Life	±50%	433.996	434.004	0.004	-

VI. VALIDATION OF CONLCA RESULTS

The results of the CONLCA tool were compared with the outputs from established LCA platforms. The cradle to grave GWP values results obtained from the CONLCA tool were compared with One Click LCA results. The functional unit (1 cum of concrete), system boundary, and inventory assumptions are kept the same. The results establish close agreement, with only small differences: 352 vs 343 kg CO_{2e}/m³ (3%) for CONPPC-II and 434 vs. 404 kg CO_{2e}/m³ (7%) for CONOPC. The results are shown in Table XV. Further, the validation was carried out by comparing CONLCA with SimaPro results, based on literature for three concrete mixes. The equivalent mix design adopted for the analysis is shown in Table XVI. The comparative analysis is summarized in Table XVII. It is observed that CONLCA slightly overestimated GWP for all three mixes (Mix I: 366 vs 339, Mix II: 255 vs 227, Mix III: 149 vs 127 kg CO_{2e}/m³). CONLCA, One Click LCA, and SimaPro showed reduction in GWP across mixes, confirming that CONLCA reliably captures the reduction in environmental impacts with lower clinker content and higher SCM replacement. The analysis makes CONLCA suitable for comparative LCA and scenario based decision support.

TABLE XV. COMPARISON OF GWP RESULTS (CONLCA VS. ONE CLICK LCA)

Concrete Mix	CONLCA Results (kgCO _{2e} /m ³)	One Click LCA Results (kgCO _{2e} /m ³)	Result Variation (%)
CONOPC	434	404	7
CONPPC-II	352	343	3

TABLE XVI. MIX DESIGN OF REFERENCE CONCRETE MIXES [5]

Material	Mix : CEM I (kg/m ³)	Mix : CEM II/B-V (kg/m ³)	Mix : CEM II/B (kg/m ³)
OPC	380	247	114
GGBS	0	0	266
FA	0	133	0
10/20 mm Limestone Aggregates	615	606	610
4/10 mm Limestone Aggregates	413	407	410
0-4mm Fine Aggregates	806	794	800
Plasticiser	2	2	2
Water	190	190	190
Total	2406	2379	2392

TABLE XVII. COMPARISON OF PRODUCTION STAGE GWP (CONLCA VS. SIMAPRO)

Mix	SimaPro (kgCO ₂ e/m ³) [5]	CONLCA (kgCO ₂ e/m ³)
I	339	366
II	227	255
III	127	149

VII. CONCLUSION AND RECOMMENDATIONS

The Life Cycle Assessment (LCA) approach is used to evaluate the environmental performance of conventional and self-compacting concrete mixes using different cement types. The production cost of different concrete mixes is also calculated using the composition and local market price of the materials. The main focus of the study is to identify how the type of cement, mix designs, and End-of-Life (EOL) waste management strategies influence outcomes. The results indicated that replacing Ordinary Portland Cement (OPC) with blended cements such as PPC and PSC in normal concrete can significantly reduce environmental impacts, mainly because of the reduced clinker content. Replacing OPC with blended cements led to notable drops in CO₂ emissions and Global Warming Potential (GWP). However, the study also demonstrated that not all cases guarantee improvements when OPC is replaced. For Self-Compacting Concrete (SCC), the mix produced using PPC required almost double the binder content to reach the desired structural performance. The higher binder content results in higher GWP and production cost compared to the OPC + fly ash based mix. The results suggest that the reduction in environmental impact of concrete mixes depends not only on choosing a cement type but also on carefully optimizing binder quantity and proportions. It is also observed that the environmental benefit of EOL recycling strongly depends on how close recycling facilities are to demolition sites.

Long transportation distances impose additional burden and may surpass the environmental advantages of recycling.

The outcome from the study suggests adopting low clinker blended cements for conventional concrete mixes. Furthermore, optimizing binder content at concrete batching is important even when blended cement is used. The policy measures that promote local C&D recycling facilities, regional waste processing and optimized logistics can improve LCA outcomes directly. Industrial implementation should prioritize (i) increasing availability of low clinker blended cements, (ii) encouraging SCM use through standards and incentives, and (iii) planning recycling infrastructure near urban demolition sites to minimize transport emissions and maximize circularity benefits.

VIII. FUTURE SCOPE

More concrete LCA studies should be carried out based on the actual industrial data and local construction conditions. Full life cycle costing (LCC) can be performed based on the reliable operational and end of life cost details. It would be advantageous if a tool that integrates the structural performance of concrete mixes along with environmental and economic analysis could be developed.

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