

Quantifying the Fly Ash Dividend: A Cradle-to-Gate Life Cycle Assessment of M30 Concrete Paver Blocks under Indian Sourcing Conditions

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Abstract. Concrete paver blocks dominate non-traffic pedestrian pavement in Indian cities, yet their environmental footprint has not been systematically quantified using geographically specific life cycle inventory. This paper reports a cradle-to-gate Life Cycle Assessment (LCA) of six M30 grade I-shaped paver block mix variants produced with Class F fly ash (0% and 10% of OPC) and directly sourced Construction and Demolition (C&D) waste (0%, 15%, 30% of natural coarse aggregate). The LCA was executed in openLCA v1.11 with the Ecoinvent 3.8 database and the ReCiPe Midpoint (H) method across four impact categories (Climate Change, Fossil Energy, Particulate Matter, Water Use) for two functional units: one paver block and a 1 km road stretch (118,997 blocks). Fly ash substitution at 10% reduced GWP per block by 8.1–11.6%, fossil energy by 6.3–12.7%, PM by 7.3–12.2%, and water use by 5.9–10.9%. By contrast, C&D waste substitution alone altered GWP by less than 0.12%. Cement production accounts for approximately 87% of control GWP, confirming binder-side substitution as the principal decarbonisation lever. Filtering by IS 15658:2021 mechanical compliance identifies M30-FA10-RCA0 as the overall optimum, saving 8,349 kg CO₂ eq. per km of paved road.

Keywords: Life Cycle Assessment · openLCA · Concrete paver blocks · Fly ash · Construction and demolition waste · Global warming potential · ReCiPe Midpoint · IS 15658:2021.

1 Introduction

Cement manufacture accounts for approximately 7–8% of global anthropogenic CO₂ emissions, with each tonne of clinker releasing 0.80–0.95 tonnes of CO₂ through limestone calcination and kiln-fuel combustion [1, 2]. In India, annual cement production exceeds 330 million tonnes and continues to expand with urbanisation; concrete paver blocks consume a significant fraction of this output, together with large volumes of natural coarse aggregate (NCA) and river sand [3]. Two mitigation strategies dominate the sustainability discourse: partial replacement of OPC with Class F fly ash, and partial substitution of NCA with recycled aggregate derived from Construction and Demolition (C&D) waste [4–6]. Individually, both routes are technically validated; however, the comparative environmental payoff from cement-side versus aggregate-side substitution in real-world paver block production has not been explicitly quantified under Indian sourcing conditions. Published Life Cycle Assessment (LCA) studies on concrete paving overwhelmingly originate from European or North American supply chains, where cement clinker factors, aggregate transport distances, and electricity mixes differ substantially from Indian practice [7, 8].

Three gaps motivate the present investigation. First, openLCA-based assessments of concrete paver blocks using geographically specific Indian inventory — measured transport distances, Indian electricity mix, regional fly ash sourcing — remain scarce. Second, studies that couple LCA with the mandatory mechanical compliance envelope of IS 15658:2006 (First Revision 2021) [9] are absent: environmental benefit is typically reported without reference to whether the optimised mix is legally deployable. Third, the relative contribution of fly ash and C&D waste substitution has not been rigorously decoupled within a single factorial frame. The present paper addresses these gaps through a cradle-to-gate LCA of six M30 paver block mixes, reported for two functional units and cross-referenced against IS 15658:2021 compliance. The specific objectives are: (i) to develop a geographically specific cradle-to-gate LCA model

in openLCA; (ii) to quantify environmental impacts across four ReCiPe Midpoint (H) categories; (iii) to decouple cement-side and aggregate-side contributions; and (iv) to identify the mix that simultaneously satisfies mechanical compliance and delivers the greatest environmental dividend.

2 Materials and LCA Framework

2.1 Materials and Mix Variants

The binder system employs OPC 43 Grade (IS 8112:2013) and Class F fly ash (IS 3812 (Part 1):2003). Fine aggregate is natural river sand from the Narmada Zone II (specific gravity 2.65); coarse aggregate is crushed granite of 12 mm nominal size (specific gravity 2.74; water absorption 0.5%); the C&D waste aggregate is sourced directly from local demolition sites in Bhopal without processing (specific gravity 2.40; water absorption 5.0%). A 2×3 full factorial matrix was adopted: two fly ash levels (0%, 10% of OPC mass) and three C&D waste levels (0%, 15%, 30% of NCA mass), producing six mix variants designated M30-FA[X]-RCA[Y]. Mix proportions were established per IS 10262:2019 with cement content 390 kg/m³, water 172 kg/m³, w/c = 0.441.

2.2 Goal, Scope, and Functional Units

The LCA goal is to quantify and compare the cradle-to-gate environmental impact of six paver block mixes under Indian sourcing conditions. Two functional units enable multi-scale interpretation: (i) one I-shaped paver block of 200 × 160 × 60 mm (mass ≈ 4.68 kg); and (ii) a 1 km road stretch of 3.75 m width, requiring 118,997 blocks (5% wastage included). Four ReCiPe Midpoint (H) categories are reported: Climate Change (GWP, kg CO₂ eq.), Non-Renewable Fossil Energy (kg oil eq.), Particulate Matter Formation (kg PM_{2.5} eq.), and Water Use (m³). A cradle-to-gate boundary covers four unit processes — raw-material extraction, processing, transportation, and fabrication (mixing and vibro-compaction). Use-phase, maintenance, and end-of-life impacts lie outside the boundary. The system boundary is illustrated in Fig. 1.

Fig. 1. Cradle-to-gate system boundary for the LCA of M30 paver block production.

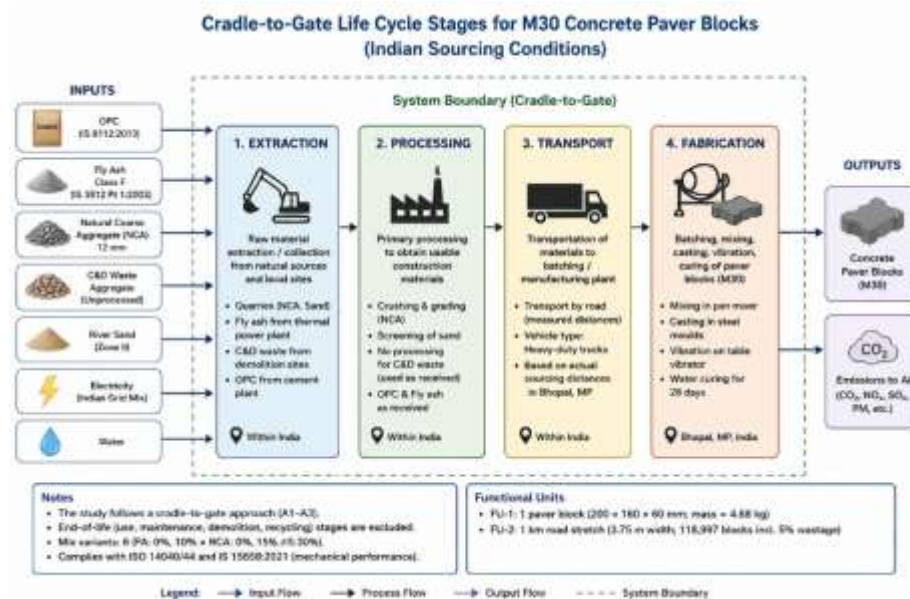


Fig. 1. Cradle-to-gate system boundary and unit-process flow for sustainable M30 concrete paver block production under Indian sourcing conditions.

2.3 Inventory, Impact Assessment, and Allocation

Inventory data were compiled from measured production-facility values (transport distances, mix proportions, fabrication energy), Ecoinvent 3.8 unit processes (clinker production, electricity, aggregate extraction, freight transport), and published LCA literature [7, 10]. Material transport distances are summarised in Table 1. Mixing and vibro-compaction together consume 0.00788 kWh per block. The ReCiPe Midpoint (H) 2016 method was applied for characterisation in openLCA v1.11. Fly ash and C&D waste are secondary materials; the cut-off allocation rule (ISO 14044:2006 [11]) was adopted — production burdens of parent processes are not reallocated to secondary materials, which carry only collection, conditioning, and transport burdens.

Table 1. Material transport distances and vehicle classes for the LCA inventory.

Material	Source	Distance (km)	Vehicle Class
OPC 43 Grade	UltraTech Dhar Works	320	16–32 MT lorry
Class F Fly Ash	Regional thermal plant	188	7.5–16 MT lorry
River Sand	Narmada River	80	7.5–16 MT lorry
Natural Coarse Aggregate	Local quarry	1	7.5–16 MT lorry
C&D Waste Aggregate	Demolition sites, Bhopal	20	7.5–16 MT lorry
PCE Superplasticizer	Regional supplier	765	7.5–16 MT lorry

3 Results and Discussion

3.1 Climate Change Impact at the Block Scale

The GWP per paver block is presented in Fig. 2. The FA0 series records GWP values of 0.862, 0.862, and 0.861 kg CO₂ eq. per block at 0%, 15%, and 30% C&D replacement — a variation of less than 0.12%. Aggregate-side substitution alone produces essentially no GWP movement because cement, which dominates the inventory, is unchanged. The FA10 series drops to 0.792, 0.792, and 0.762 kg CO₂ eq. per block, reductions of 8.1%, 8.1%, and 11.6% relative to the control. The step-change between the FA0 and FA10 series is the signature of binder-side substitution: a 10% OPC replacement removes ≈ 39 kg of cement per m³ of concrete, translating into a saving of ≈ 0.070 kg CO₂ per block at an emission factor of 0.83 kg CO₂ per kg of clinker. The additional reduction in FA10-RCA30 arises from the modest cement-content reduction accompanying aggregate substitution in the FA10 matrix.

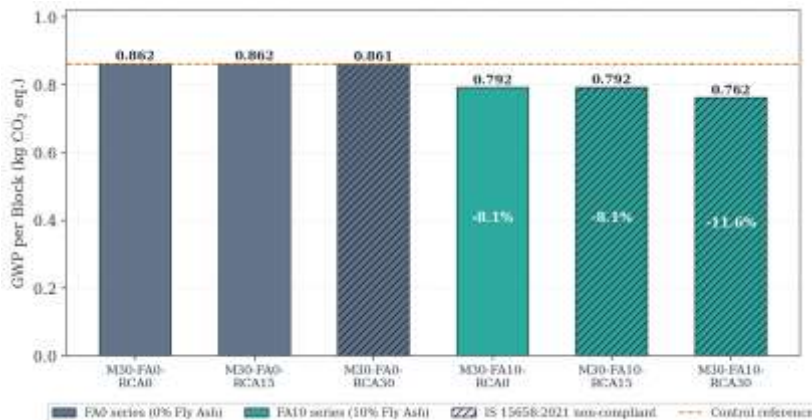


Fig. 2. GWP per paver block for the six mix variants; orange dashed line denotes the control GWP; hatched bars denote IS 15658:2021 mechanical non-compliance.

3.2 Four-Category Environmental Profile

Results for the four ReCiPe Midpoint (H) categories at the block scale are summarised in Table 2 and visualised in Fig. 3. Across all four categories the FA0 series exhibits near-zero sensitivity to C&D waste content, while the FA10 series delivers consistent, sizeable reductions: fossil energy from 0.13907 to 0.12134 kg oil eq. (6.3–12.7% reduction); PM_{2.5} from 0.00082 to 0.00072 kg PM_{2.5} eq. (7.3–12.2%); water use from 0.00101 to 0.00090 m³ (5.9–10.9%). The percentage-reduction pattern (Fig. 4) makes the decoupling between aggregate-side and binder-side substitution immediately visible: within each impact category, the three FA0 mixes cluster around zero reduction while the three FA10 mixes register negative values of comparable magnitude.

Table 2. LCA results per paver block — four ReCiPe Midpoint (H) impact categories.

Mix	GWP (kg CO ₂ eq.)	Energy (kg oil eq.)	PM _{2.5} (kg eq.)	Water (m ³)
M30-FA0-RCA0	0.86182	0.13907	0.00082	0.00101
M30-FA0-RCA15	0.86213	0.13940	0.00082	0.00101
M30-FA0-RCA30	0.86085	0.13924	0.00081	0.00101
M30-FA10-RCA0	0.79164	0.12995	0.00076	0.00094
M30-FA10-RCA15	0.79195	0.13027	0.00076	0.00095
M30-FA10-RCA30	0.76181	0.12134	0.00072	0.00090

Green: IS 15658:2021 compliant; red: non-compliant.



Fig. 3. Four-category environmental profile per paver block: (a) Climate Change, (b) Fossil Energy, (c) Particulate Matter, (d) Water Use.

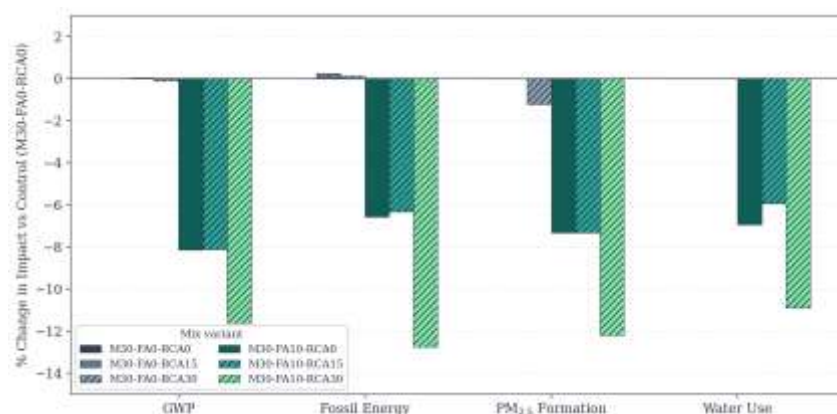


Fig. 4. Percentage change in environmental impact relative to the control mix (M30-FA0-RCA0).

3.3 Infrastructure-Scale Results and Hotspot Analysis

Scaling to a 1 km paved stretch (3.75 m width; 118,997 blocks) converts the fly ash dividend into quantities directly interpretable by infrastructure planners. The control releases 102,554 kg CO₂ eq. per km; the FA10 series achieves 94,161–94,278 kg CO₂ eq. per km — savings of 8,276–8,393 kg CO₂ eq. per km, roughly equivalent to the annual carbon uptake of 400+ mature trees. Decomposition of the control GWP by unit process (Fig. 5) shows cement production contributes ≈ 87% of GWP for the control and ≈ 80% for the optimum mix; transport contributes 8–10%; aggregate extraction 4–5%; fabrication < 1%. Cement is the single largest environmental lever — contributing 75–87% of every

impact category across every mix — confirming binder-side substitution as the only high-leverage decarbonisation strategy within the cradle-to-gate boundary.

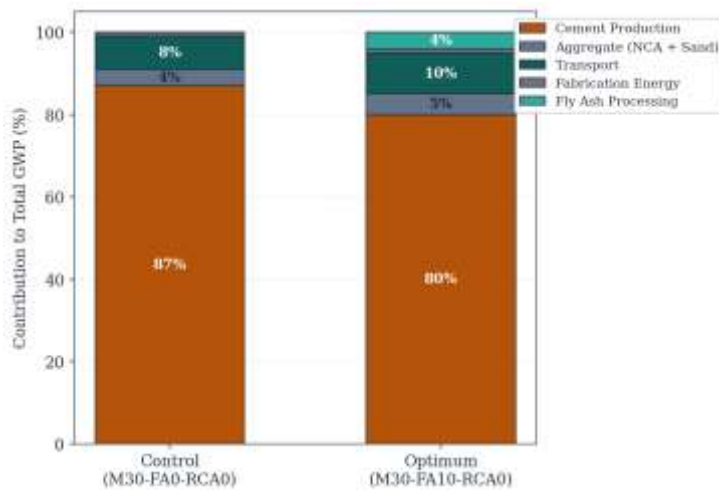


Fig. 5. GWP hotspot breakdown by unit process — control versus optimum sustainable mix.

3.4 Integrated Assessment: Environmental Benefit Filtered by Compliance

Three of the six mixes — M30-FA0-RCA30, M30-FA10-RCA15, M30-FA10-RCA30 — fail IS 15658:2021 mechanical requirements, with flexural strength below 3.30 MPa as the dominant limiting parameter. Although FA10-RCA30 delivers the single greatest environmental benefit per block (11.6% GWP reduction), its non-compliance precludes commercial deployment. Restricted to compliant mixes (Table 3), M30-FA10-RCA0 is the overall optimum: 8.1% GWP reduction, 6.6% fossil energy saving, 7.3% PM reduction, 6.9% water-use reduction, while simultaneously delivering the highest mechanical performance (40.8 MPa compressive, 4.68 MPa flexural). M30-FA0-RCA15 is the alternative optimum when waste-diversion is the primary objective: it incorporates 154 kg of unprocessed C&D waste per m³ ($\approx$ 35 tonnes per km of paved road) while retaining full mechanical compliance.

Table 3. Integrated technical–environmental assessment across all six mix variants.

Mix	IS 15658:2021	GWP Block	Δ GWP	Deployable?
M30-FA0-RCA0	Compliant	0.862	0.0%	Yes (baseline)
M30-FA0-RCA15	Compliant	0.862	0.0%	Yes (waste-diversion opt.)
M30-FA0-RCA30	Non-compliant	0.861	−0.1%	No (FS fail)
M30-FA10-RCA0	Compliant	0.792	−8.1%	Yes (overall optimum)
M30-FA10-RCA15	Non-compliant	0.792	−8.1%	No (FS fail)
M30-FA10-RCA30	Non-compliant	0.762	−11.6%	No (CS + FS fail)

4 Conclusions

A cradle-to-gate LCA of six M30 paver block mixes was executed in openLCA v1.11 with Ecoinvent 3.8 and ReCiPe Midpoint (H) under Indian sourcing conditions. The principal conclusions are:

(i) Cement production is the overwhelming environmental hotspot, contributing $\approx$ 87% of GWP for the control and $\approx$ 80% for the optimum sustainable mix. No aggregate-side intervention, in isolation, can meaningfully reduce cradle-to-gate impact.

(ii) Class F fly ash at 10% of OPC is the principal decarbonisation lever, delivering 8.1–11.6% GWP reduction, 6.3–12.7% fossil energy savings, 7.3–12.2% PM reduction, and 5.9–10.9% water-use reduction per block. Scaled to infrastructure: 8,276–8,393 kg CO₂ eq. saved per km of paved road.

(iii) C&D waste substitution in isolation produces near-zero change in cradle-to-gate impact (< 0.12% GWP variation). Its sustainability value lies in landfill diversion and virgin-aggregate conservation — benefits outside the cradle-to-gate boundary.

(iv) Filtering through IS 15658:2021 mechanical compliance, three of the six mixes — including the highest-environmental-benefit mix — are undeployable. M30-FA10-RCA0 is the overall optimum (40.8 MPa CS, 4.68 MPa FS, 8.1% GWP reduction). M30-FA0-RCA15 is the waste-diversion optimum ($\approx$ 35 tonnes of unprocessed C&D waste per km of paved road, full compliance retained). The study provides the first openLCA-based environmental benchmark for M30 paver block production under Indian sourcing conditions that explicitly couples LCA outcomes with IS 15658:2021 compliance.

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