

Environmental Impact Analysis of Traditional Concrete Road and Ash-based Concrete Road Construction

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SUMMARY

This study compares the environmental performance of two pavement types: conventional concrete using cement, gravel, and crushed stone, and an ash-based mix incorporating legacy ash and ground granulated blast furnace slag (GGBFS). The ash-based option supports circular economy principles by repurposing waste and reducing dependence on virgin raw materials. Using life cycle assessment (LCA) in SimaPro, greenhouse gas emissions were evaluated across the pavements' life cycles. Results show that conventional concrete generates about 66% more CO₂ emissions, mainly from cement production and aggregate processing. In contrast, the ash-based road achieved a 66% reduction in embodied carbon, highlighting its potential as a sustainable alternative. These findings demonstrate the value of circular economy strategies in road construction and confirm the role of secondary materials in lowering the sector's carbon footprint.

KEYWORDS

Legacy-ash, Life cycle Analysis, circular economy, environmental assessment.

1. INTRODUCTION.

The construction industry is a major source of greenhouse gas emissions and resource consumption, with road infrastructure contributing heavily due to its reliance on cement, gravel, and crushed stone. Concrete, the most widely used pavement material, has high environmental impacts, mainly from energy-intensive cement production and virgin aggregate extraction. Growing concerns over climate change and resource depletion highlight the need for sustainable alternatives. The circular economy approach—emphasising waste reuse, reduced resource demand, and extended material lifecycles—offers a pathway forward. In concrete production, incorporating industrial by-products such as legacy ash and ground granulated blast furnace slag (GGBFS) both diverts waste from ash disposal facilities and reduces demand for clinker-based cement, thereby cutting CO₂ emissions. This study applies life cycle assessment (LCA) using SimaPro software to compare two road construction scenarios: (i) conventional concrete using cement and natural aggregates, and (ii) ash-based concrete incorporating legacy ash and GGBFS. The primary focus is on CO₂-equivalent emissions. The objective is to quantify the environmental benefits of ash-based roads and evaluate trade-offs within a circular economy framework. The findings contribute to sustainable infrastructure research and provide guidance for policymakers, engineers, and industry stakeholders in advancing low-carbon, resource-efficient construction practices.

2. LITERATURE REVIEW

2.1. ENVIRONMENTAL IMPACT ANALYSIS

Concrete production is a major contributor to CO₂ emissions, largely due to cement manufacture and virgin aggregate use. Cement production alone accounts for about 8% of global CO₂ emissions, mainly from limestone calcination and fossil fuel combustion (Scrivener et al., 2018). Supplementary binding materials such as fly ash, ground granulated blast furnace slag (GGBFS), and silica fume can partially replace cement without compromising strength (Mehta & Monteiro, 2014). These by-products also enhance durability and reduce embodied energy (Thomas, 2007).

2.2. BENEFITS OF LEGACY ASH

Legacy ash, often stored in ash dams or landfills, reduces disposal burdens while replacing a portion of cement, thereby lowering emissions. Studies report that incorporating fly ash and GGBFS can cut CO₂ emissions by 30–50% compared to ordinary portland cement (OPC), depending on replacement level and curing conditions (Joshi et al., 2020; Ghosh et al., 2019).

2.3. LIFE CYCLE ASSESSMENT (LCA)

LCA is widely used to evaluate environmental impacts of construction materials throughout their life cycle, from raw material extraction to disposal (ISO 14040 & 14044, 2006). Tools like SimaPro, GaBi, and OpenLCA consistently show cement and aggregate production as dominant impact contributors (Santero et al., 2011). Incorporating industrial by-products improves outcomes, especially in global warming potential, acidification, and eutrophication. Figure 1 illustrates pavement life cycle stages.

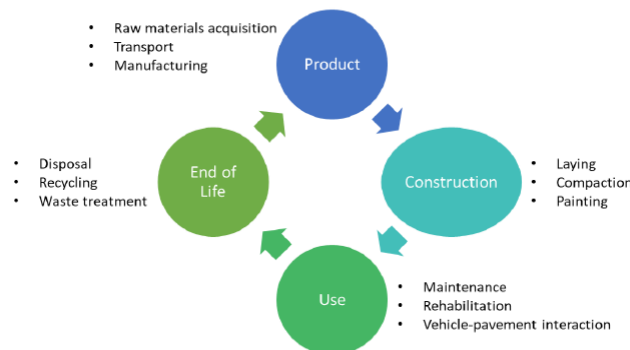


Figure 1: Pavement life cycle stages (CEDR, 2021).

In an LCA study, environmental impacts are assessed by examining resource use (energy, land, water, and materials) and emissions to air, water, and soil. The methodology analyses inputs and outputs to identify environmental “hotspots” and trade-offs. LCA is iterative, allowing refinement and improvement. The general framework is outlined in ISO 14040:2006 and ISO 14044:2006 (ISO/SANS, 2006), though sector-specific guidelines, such as the FHWA Pavement Life Cycle Assessment Framework (FHWA-HIF-16-014, 2016), provide more detailed application.

LCA consists of four main phases (Figure 2):

- **Goal and scope definition** – Define study purpose, system boundaries, functional unit, assumptions, and limitations.
- **Inventory analysis** – Collect and model data on resource inputs and environmental releases.

- **Impact assessment** – Calculate potential impacts across selected categories, with optional normalization and weighting.
- **Interpretation** – Analyse and present results, drawing conclusions and recommendations.

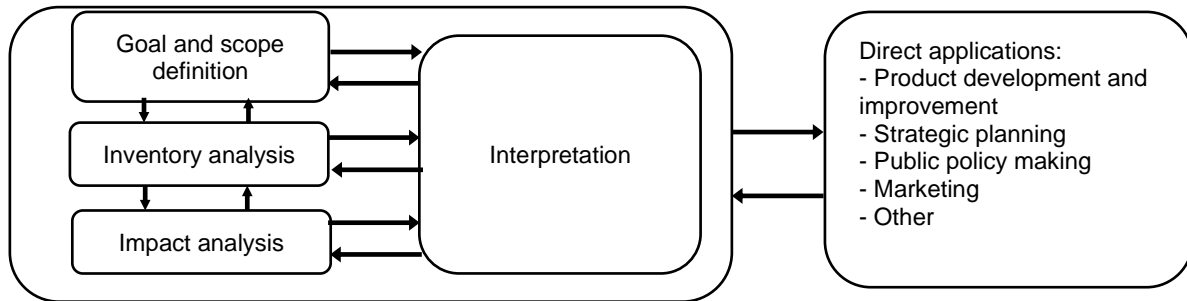


Figure 2 : Life cycle assessment Framework (ISO/SANS, 2006)

The **circular economy** promotes continuous material use, waste minimisation, and natural system regeneration (Ellen MacArthur Foundation, 2015). Using industrial by-products such as fly ash and slag in concrete exemplifies these principles by reducing reliance on virgin raw materials. Studies (Pomponi & Moncaster, 2017) show that circular strategies in the built environment lower environmental impacts and improve efficiency. Despite clear benefits, large-scale use of ash-based concrete in road construction is still limited due to material variability, performance concerns, and regulatory barriers. However, pilot projects increasingly demonstrate feasibility. For example, Zhang et al. (2021) found that high-volume fly ash concrete met durability and structural requirements while offering superior environmental performance. This literature establishes ash-based concrete as a viable innovation pathway for sustainable infrastructure. While conventional concrete dominates due to established standards and supply chains, this study builds on prior work by comparing the life cycle impacts of conventional and ash-based roads within a circular economy framework.

3. METHODOLOGY

A life cycle assessment (LCA) was conducted to compare CO₂ emissions from a conventional concrete road (natural gravel, cement, crushed stone) and an ash-based road using legacy ash and ground granulated blast furnace slag. This aligns with circular economy principles by reducing waste and reliance on virgin materials. The study adopted a **cradle-to-site** approach (Figure 3), covering raw material processing, design, construction, and transportation, but excluding use, maintenance, rehabilitation, and end-of-life phases. System boundaries included material production, transport to site, on-site mixing, and pavement placement. The functional unit was a road 8 m wide and 400 m long, with thicknesses of 1300 mm (conventional) and 1250 mm (ash-based).

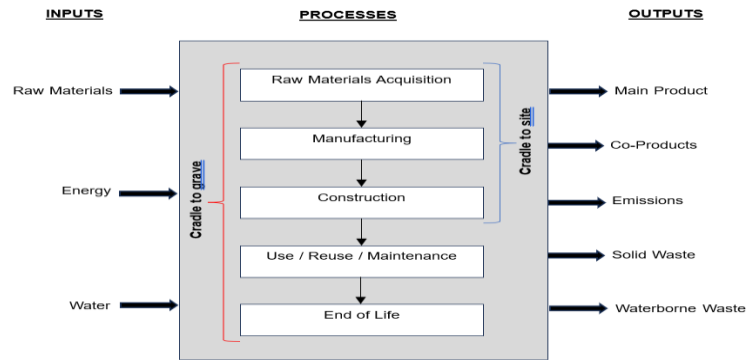


Figure 3: System boundaries (Environmental Protection Agency (EPA), 1993).

3.1. LIFE CYCLE INVENTORY ANALYSIS

The life cycle inventory (LCI) phase covers data collection and calculations. It compiles inputs (energy, water, materials) and outputs (emissions, wastes), scaled to the functional unit. The inventory was first prepared qualitatively, then quantitatively for all cradle-to-site processes. Data quality is critical, as it determines study reliability.

3.1.1. Data Sources

The LCI dataset was compiled using the SimaPro software with Ecoinvent Database 3, Blaauw and Maina's (2021) South African pavement LCI study, and environmental product declarations (EPDs). The conventional road design used natural gravel, cement, and crushed stone (Table 1).

Table 1 : Concrete road constructed using traditional construction materials – Option 1

| Layer | Material |
|---------------------------------------|----------------------|
| Concrete surface | Concrete slab |
| Upper subbase | C3 stabilised cement |
| Lower subbase | C3 stabilised cement |
| Upper Selected-Subgrade | C4 stabilised cement |
| Lower Selected-Subgrade | G5 |
| Upper subgrade | G7 |
| Lower subgrade | G9 |
| Rip & Compact 150 mm In-Situ Material | G10 |

Concrete mixture composed of cement, sand, natural coarse aggregate was used as a reference in this study. The LCI data for ordinary portland cement (CEM I), sand, water, natural coarse aggregates were sourced from the study reported by Blaauw and Maina (2021) and Ecoinvent Database 3 as shown in Table 2.

Table 2 : LCI data of concrete slab surfacing layer

| Materials | KgCO ₂ eq/ton | Data Source |
|-----------|--------------------------|--|
| CEM I | 997 | Ecoinvent Database 3 Cement, Portland {ZA} cement production, Portland Cut-off, U |
| Water | 0.12 | Blaauw and Maina (2021) |
| Sand | 5.49 | Ecoinvent Database 3 Sand {ZA} gravel and quarry operation Cut-off, U |

| | | |
|--------------------------|-------|-------------------------|
| Natural coarse Aggregate | 14.38 | Blaauw and Maina (2021) |
|--------------------------|-------|-------------------------|

Blaauw and Maina (2021), reported a typical energy requirement of 65.4 MJ for the concrete mixing process, with an energy split of 75% diesel and 25% electricity. The emission factors for diesel and electricity were reported by Blaauw and Maina, 2021, as shown in Table 3. In this study, the emissions for concrete mixing on site was then calculated to be 8.53 kgCO₂eq/m³.

Table 3 : Emission factors for generation of one megajoule of energy in South Africa.

| Energy | KgCO ₂ eq/MJ |
|-------------|-------------------------|
| Electricity | 0.075 |
| Diesel | 0.297 |

The assumed transportation distances of materials to the pavement construction site are reported in Table 4. It was assumed that the capacity of the truck used to transport the materials is 32 short tons. The emission factor for a 32-ton short distance of 0.031 kgCO₂eq/ton-km was used in the study and was reported by Blaauw and Maina (2021).

Table 4 : Assumed transportation distances and location

| Material | Location | Distance (km) |
|--------------------------|---|---------------|
| CEM I | Centurion Cement manufacturing site, South Africa | 40 |
| Sand | eMalahleni Quarry, South Africa | 20 |
| Natural coarse aggregate | eMalahleni Quarry, South Africa | 20 |

In the construction stage, the environmental impacts of concrete pavement placement using suitable equipment were considered. These impacts arise from fuel consumption by various types of equipment. The emission factors associated with the operation of each construction equipment were sourced from Blaauw and Maina (2021), who reported LCI data that accounts for most of the typical activities required to construct a concrete pavement road (refer to Table 5).

Table 5 : Emission factor for construction activities per square meter in South Africa.

| Pavement construction activities | kgCO ₂ eq/m ² |
|----------------------------------|-------------------------------------|
| Paver | 0.05 |
| Grader | 0.01 |
| Concrete sawing and sealing | 0.04 |

Subbase (upper and lower) and Upper Selected – Subgrade: C3 & C4 Cement Stabilised. LCI data for C3 & C4 Cement stabilised are summarised in Table 6.

Table 6 : LCI data of C3 & C4 cement stabilised

| Material | kgCO ₂ eq/ton | Data Source |
|-----------------------|--------------------------|----------------------|
| Cement CEM I (42.5 N) | 997 | Ecoinvent Database 3 |

| | | |
|-------------------|------|---|
| | | Cement, Portland {ZA} cement production, Portland Cut-off, U |
| Water | 0.12 | Blaauw and Maina (2021) |
| G5 Natural Gravel | 6.35 | Blaauw and Maina (2021) |
| G7 Natural Gravel | 6.35 | Blaauw and Maina (2021) |

The LCI data for the concrete mixing and construction activities are the same as reported in the concrete slab surfacing section abovementioned. LCI data for the remaining layers the base and sub-base grades were considered in this study. The LCI data are represented in Table 7.

Table 7 : LCI data of for the rest of the layers of the concrete road

| Layer | Material | Constituent | kgCO ₂ eq/ton | Data Source |
|---------------------------------------|----------|----------------|--------------------------|-------------------------|
| Lower Selected-Subgrade | G5 | Natural gravel | 6.35 | Blaauw and Maina (2021) |
| Upper subgrade | G7 | Natural gravel | 6.35 | Blaauw and Maina (2021) |
| Lower subgrade | G9 | Natural gravel | 6.35 | Blaauw and Maina (2021) |
| Rip & Compact 150 mm In-Situ Material | G10 | Natural gravel | 6.35 | Blaauw and Maina (2021) |

The transportation distances of the materials to the pavement construction site are assume and presented in Table 8, along with the emission factor for a 30 short tons truck reported by Blaauw and Maina (2021).

Table 8: Assumed transportation distances and emission factor.

| Material | Location | Distance (km) | kgCO ₂ eq/ton-km |
|----------------|-----------------------------|---------------|-----------------------------|
| Crushed stone | Howard Quarry, South Africa | 20 | 0.031 |
| Natural gravel | Howard Quarry, South Africa | 20 | 0.031 |

The emission factors associated with the operation of each construction equipment were sourced from Blaauw and Maina (2021), who reported LCI data that accounts for most of the typical activities required to construct base and sub-base grades layers of a pavement road (refer to Table 9).

Table 9 : Emission factor for construction activities per square meter in South Africa.

| Pavement construction activities | Value (kgCO ₂ eq/m ²) |
|----------------------------------|--|
| Compactor - soil | 0.04 |
| Paver | 0.05 |
| Grader | 0.01 |

The water requirements for granular pavement layer compaction were sourced from Blaauw and Maina (2021) as summarised in Table 10.

Table 10 : Water requirements for granular layer compaction in South Africa.

| Layer | Water requirement (l/m ²) |
|-----------------------|---------------------------------------|
| Crushed stone G1 base | 27.79 |
| All other layers | 20.83 |

3.1.2. Ash-based Concrete Road

Ash-based concrete road constructed using industrial by-products such as legacy ash and ground granulated blast slag as shown in Table 11.

Table 11 : Ash-based concrete road made using industrial by-products – Option 2

| Layer | Material |
|---------------------------------------|---------------------------|
| Ash Concrete Surfacing | Legacy Ash-Based Concrete |
| Upper subbase | C3 Ash Stabilised |
| Lower subbase | C3 Ash stabilised |
| Upper Selected-Subgrade | C4 Ash Stabilised |
| Lower Selected Subgrade | G5 |
| Upper subgrade | G7 |
| Lower subgrade | G9 |
| Rip & Compact 150 mm In-Situ Material | G10 |

Ash-based concrete mixture composed of industrial by-products such as Eskom Legacy Ash and ground granulated blast slag. The LCI data for each material is shown in Table 12.

Table 12 : LCI data of ash-based concrete

| Material | kgCO ₂ eq/ton | Data Source |
|------------------------------|--------------------------|---|
| Legacy ash (waste material) | 0 | N/A |
| Ground granulated blast slag | 238 | Ecoinvent Database 3 Ground granulated blast furnace slag {ZA} ground granulated blast furnace slag production Cut-off, U |
| Quarry stones | 14.38 | Blaauw and Maina (2021) |
| Sand | 5.49 | Ecoinvent Database 3 Sand {ZA} gravel and quarry operation Cut- off, U |
| Water | 0.12 | Blaauw and Maina (2021) |
| Activators | 230 | Ecoinvent Database 3 |
| Superplasticiser | 925 | Environmental Product Declaration Mapei |
| Fiber reinforced | 2280 | Environmental Product Declaration Mapei |

Legacy ash was used in the ash-based concrete mixture and treated as waste since it is dumped ash with no economic value, unlike fly ash which can be marketed as a supplementary binder. Therefore, no economic or mass allocation was applied. The activator was assumed to be a blend of fly ash (economic allocation), GGBFS, sodium hydroxide, and sodium silicate. Emission factors for each component were obtained from the Ecoinvent Database 3 and combined to determine the overall value. Concrete mixing required 65.4 MJ of energy (75% diesel, 25% electricity), as reported by Blaauw

and Maina (2021). Using their emission factors (Table 13), the calculated emissions from ready-mix concrete production were 8.53 kg CO₂eq/m³.

Table 13 : Emission factors for generation of one megajoule of energy in South Africa.

| Energy | KgCO ₂ eq/MJ |
|-------------|-------------------------|
| Electricity | 0.075 |
| Diesel | 0.297 |

Transportation distances are shown in Table 14. A 32-ton truck was assumed, with an emission factor of 0.031 kgCO₂eq/ton-km (Blaauw & Maina, 2021). The superplasticizer (UAE) and polypropylene fiber (Italy) were shipped to Durban Harbor and then transported to eMalahleni Power Station. Distances from manufacturing sites to ports and shipping routes were included, calculated using the Sea Rates Distance Calculator.

Table 14 : Assumed transportation distances

| Material | Location | Distance (km) |
|------------------------------|--|---------------|
| Legacy Ash (waste material) | eMalahleni Ash Disposal Facility (ADF), South Africa | 0.1 |
| Ground granulated blast slag | Mpumalanga chrome company, South Africa | 30 |
| 19 mm quarry stones | eMalahleni Quarry, South Africa | 20 |
| Sand | eMalahleni Quarry, South Africa | 20 |
| Activators | Benoni, South Africa | 85 |
| Superplasticer | Mapei Construction LLC to Jebel Ali Port | 30 |
| | Jebel Ali Port to Durban Harbour | 7 354 |
| | Durban Harbour to eMalahleni, South Africa | 650 |
| Fiber reinforced | Mapei S.p.A. San Cesario sul Panaro to Port of Ravenna | 120 |
| | Port of Ravenna to Durban Harbour | 10 799 |
| | Durban Harbour to eMalahleni, South Africa | 650 |

The environmental impacts for the ash concrete surfacing layer placement with suitable equipment was considered. Blaauw and Maina (2021) reported LCI data that accounts for most of the typical activities required to construct a concrete pavement road (Table 15).

Table 15 : Emission factor for construction activities per square meter in South Africa.

| Pavement construction activities | KgCO ₂ eq/m ² |
|----------------------------------|-------------------------------------|
| Paver | 0.05 |
| Grader | 0.01 |
| Concrete sawing and sealing | 0.04 |

Base and Upper Selected – Subgrade: C3 & C4 Ash Stabilised LCI data for ash stabilised layers with cement, replacing traditional materials as reported in Table 16.

Table 16 : LCI data of C3 & C4 Ash stabilised

| Material | kgCO ₂ eq/ton | Data Source |
|-----------------------------|--------------------------|-------------|
| Legacy ash (waste material) | 0 | N/A |

| | | |
|-----------------|------|--|
| Water | 0.12 | Blaauw and Maina (2021) |
| Activator HC | 728 | Ecoinvent Database 3 C3 hydrocarbon production, mixture, petroleum refinery operation ZA |
| Cement (42.5 N) | 997 | Ecoinvent Database 3 |

The assumed transportation distances to the pavement construction site are reported in Table 17. It was assumed that the capacity of the truck used to transport the materials is 32 short tons. The emission factor for a 32-ton short distance of 0.031 kgCO₂eq/tonne-km was used in the study and was reported by Blaauw and Maina (2021).

Table 17 : Assumed transportation distances

| Material | Location | Distance (km) |
|-----------------------------|--|---------------|
| Legacy ash (waste material) | eMalahleni Ash Disposal Facility (ADF), South Africa | 0.1 |
| Activator HC | Benoni | 85 |
| Cement (42.5 N) | Centurion Cement Company | 40 |

The LCI data for the concrete mixing and construction activities are the same as reported in the Legacy Ash-based Concrete section abovementioned and the LCI data for the remaining layers for the subgrades (G5, G7, G9 and G10) are the same as those reported in the concrete road analysis.

4. RESULTS & DISCUSSION

4.1. ENVIRONMENTAL IMPACTS OF CONCRETE ROAD

The CO₂ emissions for each layer of the concrete road evaluated in the study are illustrated in Figure 4 and Table 18. The results show that the concrete surfacing layer is the highest contributor to environmental impacts compared to the other layers. This is attributed by the production of cement.

Table 18: CO₂ emissions for each of the layer of the concrete road evaluated in the study

| Layer | Material | kgCO ₂ eq/FU |
|---------------------------------------|----------------------|-------------------------|
| Concrete surface | Concrete slab | 342 349 |
| Upper subbase | C3 stabilised cement | 50 883 |
| Lower subbase | C3 stabilised cement | 50 883 |
| Upper Selected-Subgrade | C4 stabilised cement | 27 960 |
| Lower Selected-Subgrade | G5 | 6 249 |
| Upper subgrade | G7 | 6 249 |
| Lower subgrade | G9 | 6 249 |
| Rip & Compact 150 mm In-Situ Material | G10 | 6 249 |

Transport and construction contributed only a minimal portion to the total CO₂ emissions. These findings emphasize the need to focus on material processing and production phases to reduce CO₂ emissions in concrete pavement, consistent with previous studies (Gulotta et al., 2015; Praticò et al., 2020).

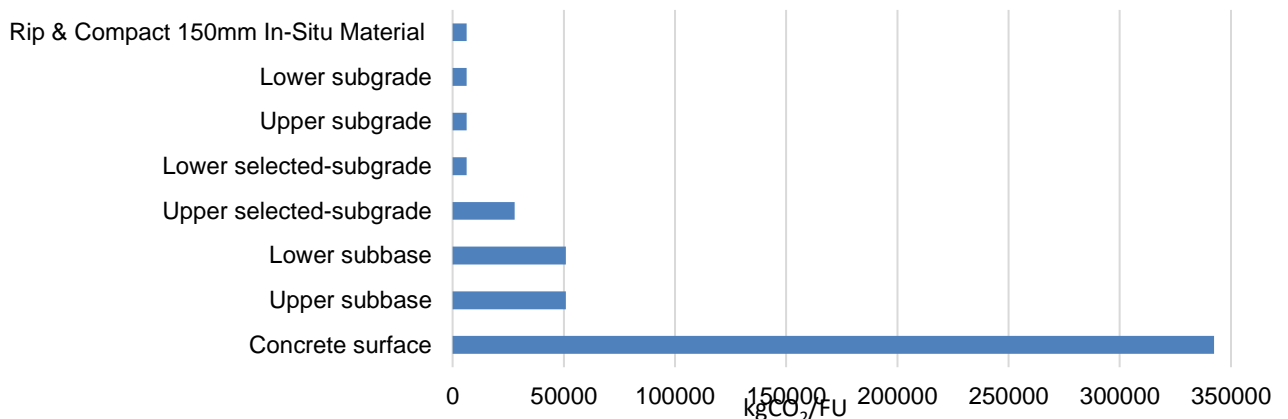


Figure 4 : Traditional concrete road CO₂ emissions for each layer

4.2. ENVIRONMENTAL IMPACTS OF ASH-BASED CONCRETE ROAD

The CO₂ emissions for each layer of the ash-based concrete road evaluated in the study are illustrated in Figure 5 and Table 19. The results indicate that the ash-concrete surfacing layer is the highest contributor, followed by the base and upper selected-subgrade layers.

Table 19: CO₂ emissions for each of the layer of the ash-based concrete road evaluated in the study

| Layer | Material | kgCO ₂ eq/FU |
|---------------------------------------|--------------------|-------------------------|
| Ash Concrete Surfacing | Ash-Based Concrete | 58 117 |
| Upper subbase | Ash stabilised | 31 863 |
| Lower subbase | Ash stabilised | 31 863 |
| Upper Selected-Subgrade | Ash stabilised | 21 497 |
| Lower Selected Subgrade | G5 | 6 249 |
| Upper subgrade | G7 | 6249 |
| Lower subgrade | G9 | 6249 |
| Rip & Compact 150 mm In-Situ Material | G10 | 6249 |

This is attributed to the fact that these layers contain activators, petroleum-based products and cement, both of which are energy-intensive materials with high CO₂ emissions during their production and processing. The findings highlight the environmental impact of the material composition, particularly the use of activators and cement, in the ash-concrete layers.

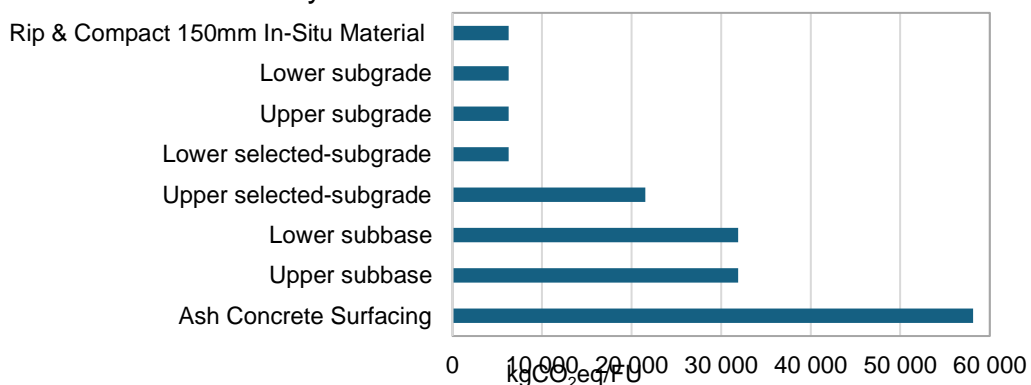


Figure 5: Ash-based concrete road CO₂ emissions for each layer

5. CONCLUSION

The CO₂ emissions results for the concrete road and ash-based concrete road obtain are 497 072 kgCO₂eq/FU and 168 336 kgCO₂eq/FU respectively. The findings show that the concrete road generates significantly higher CO₂ emissions than the ash-based alternative, primarily due to the carbon-intensive production of cement and the extraction and processing of crushed stone. Cement production is a major contributor due to the energy-intensive calcination process and the release of CO₂ from limestone decomposition. Alternatively, the ash-based concrete road incorporates industrial by-products, such as Eskom legacy ash and ground granulated blast furnace slag, which have lower embodied carbon since they utilise waste materials. This substitution reduces the reliance on virgin materials like cement and minimizes the overall carbon footprint of the road, enhancing sustainability. The study underscores the importance of sustainable material choices in construction, demonstrating that the use of waste by-products and the reduction of reliance on carbon-intensive binders like portland cement can significantly contribute to environmentally friendly infrastructure development. Adopting such approaches could help mitigate the environmental impact of the construction industry and promote long-term sustainability.

6. RECOMMENDATIONS

This study recommends prioritising ash-based concrete roads due to their lower CO₂ emissions and improved environmental performance. Using legacy ash and GGBFS reduces reliance on carbon-intensive cement and supports the circular economy. To enable wider adoption, construction standards should be updated to promote low-carbon materials, supported by long-term performance monitoring for durability and cost-effectiveness. Future research should focus on optimising mix designs, assessing supply chain emissions, and conducting life cycle cost analyses. In addition, studies on social acceptance, policy barriers, and industry readiness will be vital for scaling up ash-based concrete roads.

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