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Cradle-to-Cradle Environmental Assessment of Asphalt and Concrete Pavements under 100-Year Service-Life Scenarios in Australia

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Abstract

Pavement material selection plays a key role in reducing the environmental impacts of road infrastructure and supporting circular economy objectives. This study compares the environmental performance of asphalt and concrete pavements in Australia using a cradle-to-cradle life cycle assessment with a functional unit of 1 m². The analysis was performed in SimaPro using the ReCiPe 2016 (H) midpoint and endpoint methods and incorporated end-of-life recycling, along with a 100-year service-life sensitivity analysis. The results show that asphalt pavement has substantially lower environmental impacts than concrete across most categories. Global warming potential was 5.14 kg CO_2 eq for asphalt compared with 59.4 kg CO_2 eq for concrete, while the endpoint Single Score was 0.139 Pt and 1.484 Pt, respectively. Hotspot analysis identified cement production as contributing approximately 92% of the total impact for concrete, whereas transportation (49%), natural gas (18%), and electricity (14%) were the dominant contributors for asphalt. The sensitivity analysis further demonstrated that extending pavement service life reduced cumulative environmental impacts, although asphalt consistently maintained lower impacts than concrete under all service-life scenarios. The main contribution of this study is the integration of cradle-to-cradle modelling, midpoint and endpoint impact assessment, hotspot analysis, and long-term service-life sensitivity analysis within an Australia-specific framework. The findings provide practical evidence for selecting lower-impact pavement materials and highlight the importance of recycling, durability improvement, and reduced cement consumption in advancing circular economy strategies for sustainable road infrastructure.

1. Introduction

Road infrastructure is a critical enabler of economic development and logistics efficiency, supporting the movement of goods, services, and people across urban and regional networks. In Australia, increasing freight demand, population growth, urban expansion, and ageing pavement assets have intensified the need for road reconstruction and maintenance. While these developments enhance connectivity and economic productivity, they also impose substantial environmental burdens, including greenhouse gas emissions, resource depletion, and air pollutant releases associated with material production, construction activities, and end-of-life processes [1]. As a result, infrastructure decisions, particularly material selection, play a non-negligible role in shaping the environmental performance of road-based freight systems.

Concrete and asphalt remain the two dominant materials used in pavement construction, each characterised by distinct structural and environmental attributes. Concrete pavements are typically associated with high durability, longer service life, and reduced maintenance frequency, making them suitable for high-traffic freight corridors [2]. In contrast, asphalt pavements are widely adopted due to their lower initial costs, rapid construction, and ease of rehabilitation [3]. Despite these advantages, both materials are inherently resource, and energy-intensive. Concrete production is largely driven by Portland cement manufacturing, a major contributor to global CO_2 emissions due to limestone calcination and high-temperature kiln operations [4]. Conversely, asphalt production depends heavily on petroleum-derived bitumen and fossil-fuel-based thermal energy, leading to increased fossil resource depletion and associated emissions [5]. These contrasting characteristics highlight a fundamental trade-off between emission-intensive and resource-intensive material systems.

With Australia's commitment to emissions reduction and sustainable infrastructure development, there is a growing need for robust evaluation frameworks that support environmentally informed material selection. Conventional approaches based on economic cost or single indicators, such as carbon footprint, are insufficient to capture the multidimensional nature of environmental impacts, including effects on human health, ecosystem

quality, and resource scarcity [6]. This limitation introduces uncertainty into infrastructure decision-making and may lead to suboptimal outcomes from a sustainability perspective.

Life Cycle Assessment (LCA), as standardised by ISO 14044 and ISO 14040, provides a comprehensive methodology for evaluating environmental impacts across the entire life cycle of infrastructure systems, from raw material extraction to end-of-life treatment. By integrating life cycle inventory (LCI) data with life cycle impact assessment (LCIA) models, LCA enables the identification of environmental hotspots and facilitates consistent comparison between alternative materials [7]. Although numerous LCA studies have been conducted on pavement systems [8, 9], their findings are highly context-dependent, varying with regional energy mixes, material production pathways, transport logistics, and maintenance practices. In the Australian context, comprehensive comparative studies that integrate both midpoint and endpoint indicators within a consistent cradle-to-cradle framework remain limited, constraining the availability of robust, region-specific evidence.

More importantly, existing studies have largely treated pavement systems as isolated material systems, with limited consideration of their role within broader transport and logistics performance. While advancements in vehicle technologies have been extensively investigated for transport decarbonisation, the influence of infrastructure materials on logistics efficiency, particularly their effects on durability, maintenance frequency, and associated traffic disruptions, remains underexplored. This disconnect limits LCA studies' ability to inform integrated strategies for sustainable logistics.

To address these gaps, this study conducts a comparative life cycle assessment of asphalt and concrete pavements under Australian conditions, using a cradle-to-cradle system boundary (excluding the use phase). The analysis applies the ReCiPe 2016 (H) method at both midpoint and endpoint levels to enable a comprehensive evaluation of environmental performance. A 1 m² pavement functional unit is adopted, incorporating realistic material compositions, energy consumption, transport distances, and end-of-life scenarios.

Therefore, the specific objectives of this study are to:

1. quantify and compare the life-cycle environmental impacts of asphalt and concrete pavements;
2. identify key environmental hotspots and dominant impact drivers; and
3. propose material-specific mitigation strategies to support sustainable road reconstruction practices in Australia.

The cross-sectional configurations of the concrete and asphalt pavement systems evaluated in this study are illustrated in Fig. 1.

2. Methodology

This study employed the Life Cycle Assessment (LCA) methodology to quantify and compare the environmental performance of asphalt and concrete pavements used for road reconstruction in Australia. The assessment was conducted in accordance with the ISO 14040 and ISO 14044 standards, which comprise four sequential phases: (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) interpretation [10–13]. An attributional LCA approach was adopted to quantify the environmental burdens associated with representative Australian pavement production systems.

2.1. Goal and Scope Definition

The objective of this study was to compare the environmental performance of conventional asphalt and concrete pavements and to identify the principal environmental hotspots throughout their life cycles. The results are intended to support environmentally informed material selection during pavement design and infrastructure planning.

A cradle-to-cradle system boundary was adopted, encompassing raw material extraction, material production, transportation, pavement manufacturing, construction, recycling, and final disposal. The use phase, including traffic loading, vehicle–pavement interaction, rolling resistance, lighting, and operational maintenance, was excluded from the assessment because these processes are highly dependent on traffic conditions, climate, pavement deterioration, and maintenance strategies, resulting in substantial uncertainty and limited availability of Australia-specific inventory data.

Previous pavement LCA studies have similarly isolated the production and end-of-life stages when the objective is to compare material-related environmental burdens [14, 15]. Consequently, the results presented herein should be interpreted as comparisons of pavement material systems rather than complete whole-life environmental assessments.

Environmental impacts were evaluated using the ReCiPe 2016 (Hierarchist) life cycle impact assessment method at both midpoint and endpoint levels. Midpoint indicators describe individual environmental mechanisms, whereas endpoint indicators aggregate impacts into damage to human health, ecosystems, and resource availability, thereby facilitating comparison of the overall environmental performance of the pavement systems.

2.2. Functional Unit and Reference Analysis Period

The functional unit (FU) was defined as 1 m^2 of pavement providing equivalent structural capacity under representative Australian road design practice. A unit area was selected rather than a unit mass because pavement systems are designed and constructed based on surface area and layer thickness, while material mass varies according to density and composition. Consequently, expressing the functional unit on an area basis provides a consistent basis for comparing pavement systems constructed from materials with different physical properties and is widely adopted in pavement life cycle assessment studies. Concrete pavement was represented by a 200 mm slab (480 kg m^{-2}), whereas asphalt pavement was represented by a 100 mm layer (235 kg m^{-2}). These pavement structures were adopted from Austroads pavement design guidance and were assumed to provide equivalent structural performance for comparative environmental assessment over the reference analysis period [16, 17].

Because the two pavement systems have different design service lives, a 100-year reference analysis period was adopted to ensure functional equivalence over the assessment horizon. Under baseline conditions, the design service life of asphalt pavement was assumed to be 25 years, whereas that of concrete pavement was assumed to be 40 years [18]. Consequently, asphalt pavement required four replacement cycles over the reference period, while concrete pavement required 2.5 replacement cycles.

2.3. System Boundary

The system boundary comprised the following life cycle stages:

1. raw material extraction;
2. raw material transportation;

3. material production;
4. pavement manufacturing;
5. construction;
6. end-of-life recycling; and
7. final landfill disposal.

The foreground system included all major material and energy flows associated with pavement production, whereas background processes such as electricity generation, fuel production, transportation services, and waste management were modelled using the Ecoinvent database.

The use phase was excluded because deterioration mechanisms, traffic loading, rolling resistance, maintenance scheduling, and user-delay effects vary considerably depending on road function and operational conditions. Excluding these processes enabled the comparison to focus specifically on the environmental implications of pavement material production and end-of-life management while maintaining consistent modelling assumptions between the two pavement alternatives. The overall system boundary and life cycle processes considered in this study are illustrated in Fig. 2.

2.4. Life Cycle Inventory (LCI) Analysis

LCI modelling was performed using SimaPro 10.2.02 with the Ecoinvent v3.11. Concrete pavement was modelled using the material composition recommended by Austroads (2017), consisting of coarse aggregate (48%), fine aggregate (32%), cement (12%), fly ash (3%), and water (6%) [17, 19]. Because an appropriate standalone fly ash dataset was unavailable in the selected background database, the fly ash fraction was represented by an equivalent cement content to maintain the pavement's total binder content and mechanical characteristics. This modelling assumption is recognised as a source of uncertainty and is discussed in the limitations section. For the functional unit of 480 kg m^{-2}, the concrete inventory included 67.2 kg of cement, 230.4 kg of coarse aggregate, 153.6 kg of fine aggregate, and 28.8 kg of water. Electricity consumption during production was assumed to be 0.50 kWh per functional unit. Material transportation was modelled using transport distances of 10.08 tkm for cement, 9.22 tkm for coarse aggregate, and 6.14 tkm for fine aggregate. Meanwhile, asphalt pavement consisted of approximately 94% mineral aggregate and 6% bitumen, consistent with previous pavement studies [20]. Due to database limitations, bitumen was represented using the closest available hot-applied bituminous product. Therefore, for the functional unit of 235 kg m^{-2}, the inventory comprised 220.9 kg of aggregate and 14.1 kg of bitumen. Energy requirements included 1.73 m^3 of natural gas for aggregate heating and 0.94 kWh of electricity for crushing, screening, conveying, and mixing operations. Transportation requirements were represented by 11.05 tkm for aggregates and 4.23 tkm for bitumen.

Both pavement systems incorporated a 5% allowance for production waste during manufacturing. At the end of the service life, a 95% recycling rate and 5% landfill disposal were assumed for both pavement systems to reflect contemporary material recovery practices, while maintaining consistent end-of-life assumptions for comparative analysis [21]. The complete LCI is presented in Tables 1 and 2.

Table 1
LCI of concrete pavement (1 m² functional unit)

Inputs	Amount	Unit	Output	Amount	Unit
Cement	67.20	kg	Concrete pavement	480.0	kg
Coarse aggregate (gravel, crushed)	230.40	kg	Gravel, crushed (95% recycling)	218.88	kg
Fine aggregate (sand)	153.60	kg	Sand (95% recycling)	145.92	kg
Water	28.80	kg	Waste concrete (5% landfill)	24.00	kg
Transport (cement)	10.08	tkm			
Transport (gravel)	9.22	tkm			
Transport (sand)	6.14	tkm			
Electricity	0.50	kWh			
Assumptions: thickness 0.20 m; density 2400 kg m^{-3}, 480 kg concrete per m²					

Table 2
LCI of asphalt pavement (1 m² functional unit)

Inputs	Amount	Unit	Output	Amount	Unit
Coarse aggregate (gravel, crushed)	220.90	kg	Asphalt pavement (reference flow)	235.0	kg
Bitumen (hot bitumen adhesive compound)	14.10	kg	Gravel, crushed (95% recycling)	209.86	kg
Transport (aggregate)	11.05	tkm	Bitumen (95% recycling)	13.40	kg
Transport (bitumen)	4.23	tkm	Waste asphalt (5% landfill)	11.75	kg
Electricity	0.94	kWh			
Natural gas	1.73	m³			
Assumptions: thickness 0.10 m; density 2350 kg $m^{-3,}$ 235 kg asphalt per m²					

2.5. Data Quality and Assumptions

Foreground inventory data were compiled from Australian pavement engineering practice [16] and published literature [22], while background processes were obtained from the Ecoinvent database. Inventory data were considered technologically representative of conventional pavement production systems and, where local datasets were available, geographically representative of Australian conditions. Where Australian-specific datasets were unavailable, internationally recognised proxy datasets were adopted.

Several modelling assumptions introduce uncertainty into the analysis, including the representation of fly ash using equivalent cement content, assumed transportation distances, production waste factors, and end-of-life recycling

rates. These assumptions were applied consistently across both pavement systems to maintain comparability and were further evaluated through sensitivity analysis.

2.6. Life Cycle Impact Assessment (LCIA)

Environmental impacts were evaluated using the ReCiPe 2016 (Hierarchist) impact assessment method implemented in SimaPro. The hierarchist perspective adopts a 100-year time horizon and represents the consensus viewpoint most commonly applied in comparative LCA studies.

Midpoint indicators included climate change, freshwater eutrophication, marine eutrophication, terrestrial acidification, human toxicity, ecotoxicity, land use, water consumption, and resource scarcity. Endpoint indicators were expressed as damage to human health (DALYs), ecosystems (species·year), and resource availability (USD). In addition to characterisation results, aggregated endpoint single-score results (Pt) were reported to facilitate overall comparison of environmental performance between the pavement systems.

2.7. Sensitivity Analysis of Pavement Service Life

To evaluate the robustness of the comparative LCA, a sensitivity analysis was conducted to examine the influence of pavement service life on cumulative environmental impacts over the 100-year reference period. Service life was selected because it is one of the most influential engineering parameters governing pavement replacement frequency and long-term material demand.

The baseline analysis assumed service lives of 40 years for concrete pavement and 25 years for asphalt pavement. Additional scenarios were evaluated by varying concrete service life from 35 to 45 years and asphalt service life from 20 to 30 years, representing conservative and optimistic durability scenarios reported in the literature. The environmental burdens associated with each scenario were adjusted using a multiplication factor calculated as:

$$MF = \frac{T}{SL}$$

1

where:

MF is the multiplication factor,

T is the reference analysis period (100 years),

SL is the assumed pavement service life.

Accordingly, multiplication factors of 5.00, 4.00, and 3.33 were applied to asphalt pavements with service lives of 20, 25, and 30 years, respectively, whereas factors of 2.86, 2.50, and 2.22 were applied to concrete pavements with service lives of 35, 40, and 45 years, respectively. Each service-life scenario was modelled independently in SimaPro while maintaining identical material compositions, transportation distances, recycling rates, and impact assessment methods. Only the replacement frequency varied between scenarios, allowing the influence of pavement durability on cumulative environmental performance to be isolated. Finally, the sensitivity analysis focused only on GWP (kg CO_2-eq) and the aggregated endpoint single-score indicator (Pt) because these indicators provide complementary measures of climate change impacts and overall environmental burden.

3. Results and Discussion

This section presents and interprets cradle-to-cradle system-boundary LCA results (excluding the use phase) for asphalt and concrete pavements, using a functional unit of 1 m². Environmental impacts are evaluated using the ReCiPe 2016 (H) midpoint and endpoint methods to capture climate, human health, ecosystem, and resource-related effects. Network contribution diagrams are first analysed to identify dominant material and energy hotspots, followed by midpoint and endpoint comparisons to highlight key trade-offs between pavement systems. The discussion links quantified impacts to underlying production processes to inform material-specific mitigation strategies for sustainable road reconstruction.

3.1. Network Contribution

The network contribution analysis (Fig. 3) reveals distinct structural differences in the environmental profiles of the two pavement systems under a cradle-to-cradle boundary (excluding use phase). For concrete pavement (Fig. 3A), cement production is by far the largest contributor, accounting for approximately 92% of the total environmental impact. Transportation contributes around 7%, while all other processes combined account for only 1%. This dominant contribution from cement production is expected, as clinker manufacturing is both energy-intensive and carbon-intensive. During clinker production, large quantities of CO_2 are released through limestone calcination and fuel combustion, making cement the primary source of greenhouse gas emissions. By comparison, transportation has a much smaller influence, indicating that the environmental burden associated with cement manufacture greatly outweighs that of material delivery.

The contribution profile for asphalt pavement (Fig. 3B) is more evenly distributed across several processes. Transportation is the largest contributor, representing 49% of the total impact, followed by natural gas consumption (18%), electricity use (14%), bitumen production (12%), waste asphalt management (4%), and gravel production (3%). The high contribution from transportation reflects the considerable environmental burden associated with moving aggregates and asphalt mixtures between production facilities and construction sites. In addition, asphalt production requires heating aggregates and bitumen, resulting in significant natural gas consumption.

Previous studies have similarly identified bitumen production and heating energy as the principal contributors to asphalt-related environmental impacts, particularly in terms of fossil resource use and air emissions [23, 24]. Electricity is primarily used to operate crushing, screening, conveying, and mixing equipment, while bitumen production contributes because it relies on petroleum refining, an energy-intensive process with substantial greenhouse gas emissions. Gravel extraction contributes relatively little, as its production requires considerably less energy than the manufacture of bitumen and the thermal processing involved in asphalt production.

A comparison of the two pavements reveals distinctly different environmental hotspots. For concrete pavement, the environmental impact is overwhelmingly driven by cement production, whereas asphalt pavement is influenced by a combination of transportation, thermal energy use, electricity consumption, and bitumen production. These findings suggest that different mitigation strategies are needed for each pavement type. Reducing the clinker content in concrete through the use of supplementary cementitious materials offers significant potential to lower environmental impacts. Potential environmental improvements may be achieved through increased use of reclaimed asphalt pavement (RAP), optimisation of transportation logistics, improved plant energy efficiency, and adoption of warm-mix asphalt technologies, as demonstrated in previous studies [25]. Focusing on these key hotspot processes provides the most effective pathway for reducing the environmental impacts associated with pavement construction.

3.2. Midpoint Impact Comparison of Concrete and Asphalt Pavements

Table 3 and Fig. 4 present the ReCiPe 2016 (H) midpoint impact results for 1 m² of concrete and asphalt pavement. The results show clear differences in environmental performance, with concrete pavement exhibiting higher impacts across nearly all impact categories. The most notable difference is observed in global warming potential. Concrete pavement generates 59.5 kg CO_2 eq, compared with only 5.14 kg CO_2 eq for asphalt pavement, making its climate change impact more than 11 times greater. This result is largely driven by cement production, in which clinker manufacturing releases substantial amounts of CO_2 through limestone calcination and fossil fuel combustion. This trend is consistent with previous LCA studies, which identify cement production as the primary source of greenhouse gas emissions in concrete systems [26, 27]. Similar trends are observed in ozone and fine particulate matter formation, as well as in terrestrial acidification, reflecting upstream combustion emissions and pollutant releases associated with high-temperature cement processing.

Concrete pavement also records considerably higher impacts in several air pollution categories. Ozone formation affecting human health reaches 0.138 kg NO□ eq, while fine particulate matter formation and terrestrial acidification increase to 0.0447 kg $PM_{2.5}$ eq and 0.108 kg SO_2 eq, respectively. These results are linked to emissions of heavy metals and other pollutants during cement production and raw material extraction, which have been identified in previous LCA studies as key contributors to toxicity-related impact categories [28]. The consistently higher values across these categories indicate that concrete pavement imposes a broader environmental burden beyond climate change alone.

A similar pattern is found for toxicity-related impacts. Terrestrial ecotoxicity is 118 kg 1,4-DCB eq for concrete pavement, compared with 45.6 kg 1,4-DCB eq for asphalt pavement. Likewise, human non-carcinogenic toxicity increases from 0.719 kg 1,4-DCB eq for asphalt to 2.9 kg 1,4-DCB eq for concrete. These findings indicate that cement production is a major source of emissions that affect both ecosystems and human health. An interesting exception is water consumption. Asphalt pavement shows a negative value (-0.0355 m³), indicating a net environmental credit that is likely associated with recycling and avoided-product allocation at the end of its life cycle. In contrast, concrete pavement consumes 0.107 m³ of water, primarily due to the water required for concrete mixing and material production. These findings are consistent with broader LCA literature, which identifies cement-based materials as resource-intensive across multiple environmental dimensions [29].

Generally, the midpoint assessment demonstrates that concrete pavement has a substantially larger environmental footprint than asphalt pavement. The greatest differences occur in global warming potential, air pollutant emissions, toxicity, and resource scarcity, highlighting cement production as the dominant environmental hotspot. By comparison, the lower impacts of asphalt pavement suggest greater opportunities for improvement through enhanced recycling practices, shorter transport distances, improved plant energy efficiency, and increased use of reclaimed asphalt pavement (RAP).

Table 3
ReCiPe 2016 (H) midpoint life cycle impact comparison of concrete and asphalt pavements per 1 m² functional unit (cradle-to-cradle (excluding use phase)).

Impact category	Concrete pavement	Asphalt pavement	Unit
Global warming	5.14×10^{0}	5.94×10^{1}	kg CO_2 eq
Stratospheric ozone depletion	2.29×10^{-6}	6.04×10^{-6}	kg CFC_{11} eq
Ionizing radiation	2.40×10^{-3}	3.31×10^{-2}	kBq Co-60 eq
Ozone formation, Human health	1.37×10^{-2}	1.37×10^{-1}	kg NO□ eq
Fine particulate matter formation	4.07×10^{-3}	4.48×10^{-2}	kg $PM_{2.5}$ eq
Ozone formation, Terrestrial ecosystems	1.53×10^{-2}	1.40×10^{-1}	kg NO□ eq
Terrestrial acidification	9.90×10^{-3}	1.08×10^{-1}	kg SO_2 eq
Freshwater eutrophication	1.62×10^{-4}	6.69×10^{-4}	kg P eq
Marine eutrophication	4.22×10^{-5}	7.14×10^{-5}	kg N eq
Terrestrial ecotoxicity	4.56×10^{1}	1.18×10^{2}	kg 1,4-DCB
Freshwater ecotoxicity	6.91×10^{-3}	2.40×10^{-2}	kg 1,4-DCB
Marine ecotoxicity	3.38×10^{-2}	9.40×10^{-2}	kg 1,4-DCB
Human carcinogenic toxicity	6.05×10^{-3}	8.88×10^{-2}	kg 1,4-DCB
Human non-carcinogenic toxicity	7.19×10^{-1}	2.91×10^{0}	kg 1,4-DCB
Land use	4.04×10^{-2}	-2.71×10^{-1}	m²a crop eq
Mineral resource scarcity	8.00×10^{-4}	1.62×10^{-1}	kg Cu eq
Fossil resource scarcity	3.51×10^{0}	7.24×10^{0}	kg oil eq
Water consumption	-3.55×10^{-2}	1.61×10^{-1}	m³

3.3. Endpoint Impact Comparison

The endpoint results (Fig. 5) present the endpoint impact assessment of concrete and asphalt pavements using the ReCiPe 2016 Endpoint (H) method. The damage assessment, normalisation, and weighting analyses provide an integrated view of the potential impacts on Human health, Ecosystems, and Resources. The damage assessment (Fig. 5A) shows a clear contrast between the two pavement systems. Concrete pavement recorded the highest impact in all three damage categories (100%), whereas asphalt pavement contributes only 9% to both human health and ecosystems, and 60% to resources. This outcome is consistent with previous studies identifying cement manufacturing as a major contributor to health and ecosystem-related impacts associated with construction materials [30, 31].

The normalisation results (Fig. 5B) reinforce this pattern. Human health is the most affected category, with concrete pavement scoring 0.00353 Pt, compared with 0.00031 Pt for asphalt pavement. Concrete also produces

higher impacts on ecosystems (0.00014 Pt) than asphalt (0.00001 Pt). Although the difference is less pronounced for resources, concrete (0.00008 Pt) still exceeds asphalt (0.00005 Pt). These findings suggest that emissions associated with cement manufacturing remain the primary driver of the overall environmental burden.

The weighting analysis (Fig. 5C) provides the final comparison of the endpoint impacts. Human health contributes the largest share of the total weighted score for both pavement types, reaching 1.41038 Pt for concrete and 0.12422 Pt for asphalt. Impacts on ecosystems are considerably lower, with scores of 0.05771 Pt and 0.00513 Pt, respectively, while resources contribute the smallest share, at 0.01600 Pt for concrete and 0.00954 Pt for asphalt. This indicates that damage to human health is the dominant contributor to the overall endpoint impact, followed by ecosystem quality and resource depletion.

In general, the endpoint assessment demonstrates that concrete pavement has a substantially greater environmental impact than asphalt pavement across all three endpoint damage categories. The consistently higher scores highlight cement production as the principal environmental hotspot throughout the concrete life cycle. By contrast, the lower endpoint impacts of asphalt pavement suggest greater opportunities for environmental improvement through increased use of reclaimed asphalt pavement (RAP), improved plant energy efficiency, and more efficient transportation and construction practices.

3.4. Single-Score Impact Comparison

Figure 6 compares the weighted endpoint scores (Pt) of the five most influential impact categories for asphalt and concrete pavements. Only these five categories are presented because the remaining impact categories contributed negligibly to the total environmental impact and had little influence on the final results. Among the selected categories, global warming related to human health is the most significant contributor for both pavement systems. Concrete pavement records a weighted score of 0.9208 Pt, which is more than 11 times higher than that of asphalt pavement (0.0796 Pt). This substantial difference is mainly attributed to the high greenhouse gas emissions from cement clinker production, in which CO_2 is released through both limestone calcination and fossil fuel combustion.

The second largest contributor is fine particulate matter formation, with concrete pavement reaching 0.4684 Pt, compared with 0.0427 Pt for asphalt pavement. These impacts are primarily linked to emissions generated during cement manufacturing, including fuel combustion and raw material processing. A similar pattern is observed for global warming affecting terrestrial ecosystems, where concrete records 0.0450 Pt, while asphalt contributes only 0.0039 Pt.

The remaining categories, fossil resource scarcity and human non-carcinogenic toxicity, make comparatively smaller contributions to the total weighted score. Concrete pavement records 0.0157 Pt and 0.0110 Pt, respectively, whereas asphalt pavement produces 0.0095 Pt and 0.0027 Pt. Although these values are much lower than those associated with climate change and particulate matter formation, they further demonstrate the greater environmental burden of concrete production.

The results indicate that the environmental performance of both pavement systems is largely determined by global warming and fine particulate matter formation, while the remaining impact categories contribute only a minor share of the total endpoint score. The consistently higher weighted scores for concrete pavement highlight cement production as the principal environmental hotspot throughout its life cycle. In contrast, the lower impacts of asphalt pavement suggest that further environmental improvements can be achieved by increasing the use of

reclaimed asphalt pavement (RAP), improving plant energy efficiency, and optimising material transportation and construction practices.

3.5. Sensitivity Analysis of Pavement Service Life

A sensitivity analysis was performed to examine how variations in service life influence the environmental performance of asphalt and concrete pavements over a 100-year assessment period. Service life was selected as the key sensitivity parameter because it directly determines the number of pavement replacement cycles required during the analysis period. For asphalt pavement, service-life scenarios of 20, 25, and 30 years were evaluated, corresponding to multiplication factors of 5.00, 4.00, and 3.33, respectively. For concrete pavement, service lives of 35, 40, and 45 years were assessed using multiplication factors of 2.86, 2.50, and 2.22, respectively. As shown in Fig. 7, a shorter service life led to higher environmental impacts because more frequent replacement increased the cumulative material and energy requirements over the 100-year period. For asphalt pavement, reducing the service life from 25 to 20 years increased the global warming potential from 20.57 to 25.71 kg CO_2 eq, representing a 25.0% increase, while the Single Score rose from 0.556 to 0.694 Pt. In contrast, extending the service life to 30 years reduced the global warming potential to 17.13 kg CO_2 eq and the Single Score to 0.462 Pt, corresponding to a 16.75% reduction relative to the base scenario. Whereas concrete pavement exhibited the same overall trend, although the magnitude of change was less pronounced. Reducing the service life from 40 to 35 years increased the global warming potential from 148.72 to 170.13 kg CO_2 eq (+ 14.40%) and raised the Single Score from 3.710 to 4.244 Pt. Extending the service life to 45 years lowered the global warming potential to 132.06 kg CO_2 eq and the Single Score to 3.295 Pt, representing an 11.20% reduction compared with the base case.

In general, the results show that asphalt pavement is more sensitive to changes in service life than concrete pavement, as reflected by the larger percentage variation in both global warming potential and Single Score. This greater sensitivity is primarily attributable to asphalt's shorter design life, which results in more frequent replacement over the 100-year assessment period. Despite these variations, asphalt consistently produced lower environmental impacts than concrete across all scenarios, indicating that the comparative conclusions remain robust under realistic service-life assumptions.

3.6. Comparison with previous pavement LCAs

Compared to studies that focus on single indicators (e.g., GWP) or adopt narrower system boundaries (e.g., cradle-to-gate), the present study integrates midpoint, endpoint, and single-score analyses within a consistent Australia-specific framework. This enables a more comprehensive evaluation of environmental trade-offs between emission-related and resource-related impacts, which are often not captured simultaneously in conventional pavement LCA studies.

Table 4 summarises previous studies indicating that concrete pavement exhibits a substantially higher global warming potential than asphalt pavement, primarily due to emissions associated with Portland cement production. This finding aligns with literature, such as Loijos et al. [32], which identifies cement manufacturing as the dominant contributor to greenhouse gas emissions in concrete pavement systems. However, unlike studies that include long-term use-phase effects, which may alter comparative outcomes, the present analysis isolates production and end-of-life stages to provide a controlled comparison of material-related impacts.

In contrast, asphalt pavement exhibits significantly higher fossil resource scarcity than concrete pavement, reflecting its reliance on petroleum-derived bitumen and fossil-fuel-based thermal energy. This observation aligns

with findings reported by Milad et al. [23], which highlight the strong dependence of asphalt production on fuel consumption and binder content. Beyond climate change and resource depletion, the midpoint results further show that concrete pavement has higher impacts across multiple categories, including particulate matter formation, terrestrial acidification, and toxicity-related indicators, whereas asphalt pavement exhibits higher impacts in marine eutrophication and fossil resource use. Compared to previous studies that focus primarily on individual indicators or limited system boundaries, the integrated approach adopted in this study provides a more comprehensive understanding of these trade-offs. In particular, combining midpoint and endpoint analyses enables the identification of both process-level hotspots and overall damage implications, thereby improving the robustness of comparative assessments.

The exclusion of the use phase in this study enables a consistent evaluation of material production and end-of-life processes; however, it may lead to different conclusions compared to studies that incorporate traffic-related effects. Previous research by Trupia et al. [14] and Araújo et al. [15] demonstrates that use-phase factors, such as rolling resistance, can significantly influence total life-cycle emissions, although these effects are highly uncertain and variable. Therefore, the present results should be interpreted within the defined system boundary, while recognising that inclusion of use-phase impacts may alter the relative performance of pavement systems.

Table 4
Comparative analysis of the present study and selected published LCA studies on asphalt and concrete pavements

Study	Geography / Context	Pavement Alternatives	Functional Unit (FU)	System Boundary	LCIA / Indicators	Key Findings
This study	Australia (road reconstruction)	Asphalt vs concrete	1 m² (0.20 m concrete; 0.10 m asphalt)	Cradle-to-cradle (excluding use phase)	ReCiPe 2016 (H) midpoint + endpoint + single score	Concrete shows higher impacts across most categories (e.g., GWP), while asphalt exhibits higher fossil resource scarcity; cement dominates concrete impacts, whereas bitumen and thermal energy dominate asphalt
Loijos at al. [32]	USA; variability across design, traffic, and climate	Asphalt vs concrete	1 m² (50-year service life)	Full life cycle (including use phase and maintenance)	GWP-focused with sensitivity analysis	Demonstrates that inclusion of use-phase effects (e.g., rolling resistance) can significantly influence comparative outcomes
Santero at al. [33]	Global review	Multiple pavement systems	Not applicable	Varies across studies	Review of LCA methodologies	Highlights methodological inconsistencies, particularly in system boundaries and omission of use-phase impacts
De Pascale et al. [34]	Italy	Porous asphalt mixtures with recycled aggregates	1 kg mixture	Cradle-to-gate	ReCiPe 2016 midpoint + endpoint	Shows that alternative binders and recycled aggregates can reduce impacts at the material production stage

Study	Geography / Context	Pavement Alternatives	Functional Unit (FU)	System Boundary	LCIA / Indicators	Key Findings
Milad et al. [23]	Global review	Warm-mix vs hot-mix asphalt	Varies	Varies across studies	Energy use and emissions	Demonstrates that reduced production temperatures lower energy consumption and emissions in asphalt production
Araújo et al. [15]	Portugal	Asphalt pavement alternatives	Not specified	Includes use phase	Energy and emissions focus	Emphasises the importance of including use-phase impacts in pavement LCA
Trupia et al. [14]	UK case study	Pavement systems	Case-specific	Expanded boundary including rolling resistance	Carbon footprint	Shows that rolling resistance can significantly influence total life-cycle emissions, but introduces modelling uncertainty

3.7. Policy and practical implications

Policy recommendations should therefore focus on incentivising the adoption of recycled content in pavement materials and promoting research into novel, lower-impact binders and aggregates, given the substantial environmental benefits demonstrated by such approaches [35, 36]. For example, in Australia, government initiatives promote the use of recycled asphalt pavement in new construction, showcasing a commitment to circular economy principles in infrastructure development [37]. In other countries such as China, policies encourage the efficient use of cement and concrete to reduce reliance on supply-side technologies for net-zero emissions, highlighting the global trend towards sustainable pavement practices [38]. This includes a focus on innovative material formulations, such as warm-mix asphalt and bio-based binders, which have demonstrated measurable reductions in life-cycle environmental indicators [39]. Additionally, the development of comprehensive lifecycle management guidelines, as seen in European initiatives like PavementLCM, can facilitate the integration of sustainability assessments and circular economy principles into routine road pavement management practices [40]. This includes integrating advanced modelling techniques to quantify long-term performance under varying environmental conditions and traffic loads.

Incorporating future climate scenarios into these LCAs is crucial for providing robust decision support for engineers, ensuring that pavement designs are resilient and sustainable over their operational lifetimes [41]. Therefore, the selection of road pavement materials is increasingly influenced by national sustainability goals, LCA, and specific traffic requirements. Table 5 compares pavement materials and policies across several countries based on recent research and regulatory frameworks. These guidelines emphasise the importance of context-specific LCA to accurately account for local material properties, transportation logistics, and rehabilitation techniques, ensuring the applicability of findings to diverse geographical and operational settings [42].

Table 5
Comparison of road pavement materials by country and policy

Country / Region	Primary Policy or Framework	Policy Objective & Implementation	Comparative Material Considerations	Implication for logistics sustainability
Canada	MTQ Pavement Selection Policy	Network-level allocation of asphalt ("black") and concrete ("white") pavements	Material selection based on 50-year LCCA + LCA	Enables long-term optimisation of high-volume freight corridors
China	Dual Carbon Policy	Emission reduction via material efficiency and low-carbon production	Continued asphalt dominance with focus on reducing cement and construction emissions	Limits carbon intensity in rapidly expanding freight networks
United States	FHWA Climate Challenge; EPD mandates	Carbon-informed procurement using Environmental Product Declarations	Asphalt: higher energy and waste; Concrete: higher GWP	Supports low-carbon infrastructure decisions in freight systems
European Union	PavementLCM; EN 15643/15804	Standardised LCA-based pavement management	Context-specific material selection based on lifecycle performance	Integrates circular economy principles into logistics infrastructure planning
Switzerland	National Road LCA/LCCA	Long-term (75-year) lifecycle optimisation using ecological indicators	Concrete preferred for high-traffic routes due to lower lifecycle energy demand	Improves durability and reduces maintenance-related freight disruptions

A comparative analysis of international policy frameworks reveals a consistent shift towards integrating life cycle thinking into pavement material selection, albeit with region-specific priorities. While developed regions such as the European Union and Canada emphasise lifecycle optimisation through standardised LCA/LCCA frameworks, rapidly developing economies such as China prioritise emission reduction through material efficiency and supply-side interventions. Despite these differences, a common trend emerges: the increasing reliance on data-driven decision-making tools to balance environmental performance, cost, and operational efficiency in transport infrastructure systems.

Material selection in pavement systems is increasingly guided by key policy drivers that balance performance requirements with environmental considerations. One of the primary factors is the trade-off between durability and emissions. Concrete pavements are often prioritised for high-traffic highways due to their superior structural resilience under intense vehicular loading and their lower long-term maintenance requirements [37]. In contrast, asphalt pavements are frequently favoured for their lower initial global warming potential and higher recyclability, which can enhance their overall sustainability performance.

In parallel, there has been a policy shift from conventional "cradle-to-gate" assessments towards comprehensive "cradle-to-cradle" life cycle frameworks that incorporate circular economy. This transition is critical, as factors such as pavement–vehicle interaction, rolling resistance, and maintenance frequency can substantially influence the total carbon footprint of road infrastructure [41, 43]. Furthermore, the integration of recycled materials has become a central policy strategy in many regions. The incorporation of Recycled Asphalt Pavement (RAP) and recycled

concrete aggregates is increasingly incentivised, as these approaches can significantly reduce resource depletion and improve overall environmental performance across multiple impact categories [36, 39].

From a logistics perspective, these policy developments highlight the need to move beyond material-level optimisation towards integrated infrastructure–transport system strategies. Policies that simultaneously address material selection, maintenance scheduling, and traffic management can deliver significantly greater emission reductions than isolated interventions. Therefore, future regulatory frameworks should explicitly incorporate logistics performance indicators, such as freight flow efficiency and congestion-related emissions, into pavement design and material selection processes.

4. Conclusions

This study compared the environmental performance of asphalt and concrete pavements in Australia using a cradle-to-cradle LCA framework, with a functional unit of 1 m^2 and the ReCiPe 2016 (H) midpoint and endpoint methods. The assessment covered material production, transportation, construction, recycling, and final disposal while excluding the use phase. The pavement systems were represented by a 100 mm asphalt layer (235 kg m^{-2}) and a 200 mm concrete slab (480 kg m^{-2}), with a 95% end-of-life recycling rate applied to both systems. generally, asphalt showed substantially lower environmental impacts than concrete across most impact categories. The results reported in the manuscript give a global warming potential of 5.14 kg CO_2 eq for asphalt and 59.4 kg CO_2 eq for concrete, indicating an approximately 11.6-fold higher climate impact for concrete. Hotspot analysis showed that cement production accounted for about 92% of the concrete pavement impact. In contrast, asphalt impacts were more distributed, with transportation (49%), natural gas (18%), electricity (14%), and bitumen production (12%) as the main contributors.

The endpoint assessment supported the midpoint findings. Human health was the dominant damage category, with weighted scores of 1.410 Pt for concrete and 0.124 Pt for asphalt, while the five-category single-score analysis identified global warming–human health and fine particulate matter formation as the leading contributors. These results indicate that reducing clinker-intensive cement use is particularly important for concrete, whereas asphalt improvement should focus on transport optimisation, lower-energy production, and greater use of reclaimed asphalt pavement. Service life also had a clear influence on long-term performance. Over the 100-year assessment period, extending asphalt service life from 25 to 30 years reduced GWP by 16.75%, whereas shortening it to 20 years increased GWP by 25.0%. For concrete, extending service life from 40 to 45 years reduced GWP by 11.20%, while a 35-year life increased it by 14.40%. Despite these variations, asphalt remained environmentally preferable under all scenarios considered, demonstrating that the main comparative finding is robust to reasonable changes in pavement service life.

The key novelty of this study is the integration of cradle-to-cradle modelling, midpoint and endpoint assessment, process-level hotspot analysis, circular economy approach, and a 100-year service-life sensitivity analysis within a single Australia-specific framework. Rather than relying solely on carbon emissions or short-term material production, the approach captures broader environmental trade-offs together with the effects of recycling and pavement durability. The findings provide a practical basis for lower-impact pavement selection and suggest that combining material decarbonisation, high recycling rates, efficient production and transportation, and longer service life can support more circular and environmentally sustainable road infrastructure in Australia.

Declarations

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT 5.2 to improve content clarity and tone, while maintaining consistency. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Competing Interests

The authors declare no competing interests.

Author Contribution

Authors ContributionsBidattul Syirat Zainal: Investigation, Methodology, Resources, Validation, Data curation, Conceptualisation, Visualisation, Formal analysis, Writing – original draft; Noor Faizah Che Harun: Writing – review & editing; Normaniza Osman: Supervision. T.M.I. Mahlia: Software, Supervision.

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Data Availability Statement

The primary life-cycle inventory data generated during this study were subjected to confidentiality restrictions. As a result, these datasets are not publicly available but can be made available from the corresponding author upon reasonable request for academic, non-commercial purposes. Secondary life-cycle inventory data supporting the analysis were obtained from the ecoinvent database and implemented in SimaPro; access to these datasets is subject to third-party licensing restrictions and cannot be redistributed openly. All assumptions, system boundaries, functional units, and methodological parameters used in the life cycle assessment model are fully described in the manuscript to ensure transparency and reproducibility.

References

1. BITRE. Road: The Economics of Road Maintenance. Bureau of Infrastructure and Transport Research Economics, Australia; 2023.
2. Yaqoob S, Silfwerbrand J, Strömberg L. Evaluation of Rapid Repair of Concrete Pavements Using Precast Concrete Technology: A Sustainable and Cost-Effective Solution. Nordic Concrete Research 2021;65(2):107–28.

3. Milad A, Taib AM, Ahmeda AG, Solla M, Yusoff NIM. A review of the use of reclaimed asphalt pavement for road paving applications. Jurnal Teknologi (Sciences & Engineering) 2020;82(3).
4. Barbhuiya S, Kanavaris F, Das BB, Idrees M. Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development. Journal of Building Engineering 2024;86:108861.
5. Liu Y, Liu Z, Zhu Y, Zhang H. A Review of Sustainability in Hot Asphalt Production: Greenhouse Gas Emissions and Energy Consumption. Applied Sciences 2024;14(22):10246.
6. Laurent A, Olsen SI, Hauschild MZ. Limitations of Carbon Footprint as Indicator of Environmental Sustainability. Environmental Science & Technology 2012;46(7):4100–8.
7. Hellweg S, Milà i Canals L. Emerging approaches, challenges and opportunities in life cycle assessment. Science 2014;344(6188):1109–13.
8. Chen Y, Pei Z, Feng D, Yi J. Environmental impact and comprehensive value assessment of epoxy-based binder for asphalt pavement recycling based on LCA and LCC. Chemical Engineering Journal 2025;511:161973.
9. Chen Q, Yu B, Wang Y, Shao X, Pang Z, Zhang Y. Multidimensional automated decision support for asphalt pavement maintenance using the BIM-LCA-LCCA method. International Journal of Pavement Engineering 2025;26(1):2508343.
10. Kaynak E, Piri IS, Das O. Revisiting the Basics of Life Cycle Assessment and Lifecycle Thinking. Sustainability 2025;17(16):7444.
11. Li A, Li X, Chan Y, Ma W. Using life cycle assessment to evaluate the environmental impact of the thermal power industry. Carbon Management 2025;16(1):2522082.
12. Pacañot VDJ. Evaluating environmental impacts with life cycle assessment. Nature Reviews Earth & Environment 2022;3(4):224-.
13. Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel H-J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. The international journal of life cycle assessment 2006;11(2):80–5.
14. Trupia L, Parry T, Neves LC, Lo Presti D. Rolling resistance contribution to a road pavement life cycle carbon footprint analysis. The International Journal of Life Cycle Assessment 2017;22(6):972–85.
15. Araújo JPC, Oliveira JRM, Silva HMRD. The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. Transportation Research Part D: Transport and Environment 2014;32:97–110.
16. Austroads. Guide to Pavement Technology Part 2: Pavement Structural Design. Austroads: Austroads; 2026.
17. Austroads. Cycling Aspects of Austroads Guides (2017 Edition). 3 ed. Austroads.gov.au; 2017.
18. C&CAA. Guide to Residential Streets and Paths. 2nd ed.; 2004.
19. Vorobieff G, Moffatt M. Guide to pavement technology: part 4c: materials for concrete road pavements. 2017.
20. Milad A, Babalghaith AM, Al-Sabaeei AM, Dulaimi A, Ali A, Reddy SS, et al. A Comparative Review of Hot and Warm Mix Asphalt Technologies from Environmental and Economic Perspectives: Towards a Sustainable Asphalt Pavement. Int J Environ Res Public Health 2022;19(22).
21. Wang Z, Bell MGH, Bhattacharjya J, Geers G. The Dynamics of Concrete Recycling in Circular Construction: A System-Dynamics Approach in Sydney, Australia. Sustainability 2025;17(10):4282.
22. Khamil KN, Mohd Sabri MF, Yusop AM. Thermoelectric energy harvesting system (TEHs) at asphalt pavement with a subterranean cooling method. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2024;46(1):10662–78.

23. Milad A, Babalghaith AM, Al-Sabaeei AM, Dulaimi A, Ali A, Reddy SS, et al. A Comparative Review of Hot and Warm Mix Asphalt Technologies from Environmental and Economic Perspectives: Towards a Sustainable Asphalt Pavement. International Journal of Environmental Research and Public Health 2022;19(22):14863.
24. Hao G, Ong GP, He M. Asphalt emissions during pavement construction: a comprehensive review of analytical metrics, methods, and influencing factors. Transportation Research Record 2026;2680(3):262–85.
25. Mariyappan R, Palammal JS, Balu S. Sustainable use of reclaimed asphalt pavement (RAP) in pavement applications—a review. Environmental Science and Pollution Research 2023;30(16):45587–606.
26. Amato I. Concrete solutions: cement manufacturing is a major source of greenhouse gases. But cutting emissions means mastering one of the most complex materials known. Nature 2013;494(7437):300–2.
27. Sbahieh S, McKay G, Nurdiawati A, Al-Ghamdi SG. The sustainability of partial and total replacement of Ordinary Portland Cement: A deep dive into different concrete mixtures through life cycle assessment. Journal of Building Engineering 2025;108:112830.
28. Pizoń J, Poranek N, Horňáková M. Life Cycle Assessment of Concrete Containing Crushed Concrete Paving Blocks as a Sustainable Replacement for Natural Aggregates. Sustainability 2026;18(6):2703.
29. Ige OE, Moloi K, Kabeya M. Sustainability assessment of cement types via integrated life cycle assessment and multi-criteria decision-making methods. Sci 2025;7(3):85.
30. Mandal A, Rajput SP, Choudhary H. Life Cycle Assessment of Concrete with Ceramic Waste Powder and Stone Dust: A Central India Case Study. Environ Res 2026:123857.
31. Shukla A. A study on the assessment of the environmental footprint of cement production in India: potential challenges towards achieving UN-SDGs. Engineering, Construction and Architectural Management 2026:1–25.
32. Loijos A, Akbarian, M., Sahni, S.,Ochsendorf, J. Sensitivity Analysis of the Life Cycle Environmental Performance of Asphalt and Concrete Pavements *2010 Concrete Sustainability Conference* National Ready Mixed Concrete Association 2010.
33. Santero NJ, Masanet E, Horvath A. Life-cycle assessment of pavements. Part I: Critical review. Resources, Conservation and Recycling 2011;55(9):801–9.
34. De Pascale B, Tataranni P, Bonoli A, Lantieri C. Comparative Life Cycle Assessment (LCA) of Porous Asphalt Mixtures with Sustainable and Recycled Materials: A Cradle-to-Gate Approach. Materials 2023;16(19):6540.
35. Plati C, Tsakoumaki M. Life Cycle Assessment (LCA) of Alternative Pavement Rehabilitation Solutions: A Case Study. Sustainability 2023;15(3):2129-.
36. Thapa I, Baral NP, Adhikari KR. Comprehensive review of LCA studies in Civil Engineering. Bibechana 2023;20(3):326–38.
37. Gundogdu H, Cansiz ÖF, Can MF. The Evolution of Classical and Soft Computing Methods in Predicting Road Maintenance and Repair Costs: Approaches in the Literature and Future Perspectives. The Baltic Journal of Road and Bridge Engineering 2025;20(3):57–89.
38. Zhang H, Zhang Q, Luo C, Liu N, Wang K. Life cycle assessment and sensitivity analysis of carbon emissions in full depth reclamation with portland cement and conventional pavement repair. Scientific Reports 2025;15(1):18593-.
39. Afshin A, Behnood A. Sustainability of Asphalt Pavements: The role of life cycle assessment (LCA) and emerging technologies. Cleaner Materials 2025;18:100346.
40. Presti DL, Carrión AJdB, Parry T, Neves Ls, Keijzer E, Kalman B, et al. A Framework for Life Cycle Management of Road Pavements in Europe. Transportation research procedia 2023;72:1552–9.

41. Dave EV, Haslett KE, Mo W, Chabot A. Life Cycle Assessment Based Framework for Design and Maintenance of Roadways in the Cities of Tomorrow. HAL (Le Centre pour la Communication Scientifique Directe) 2021.
42. Schmitt LC, Levasseur A, Vaillancourt M, Lachance-Tremblay É. Life cycle assessment of various pavement rehabilitation techniques: A case study. Transportation Research Part D Transport and Environment 2024;139:104476-.
43. Vargas-Farias A, Santos J, Hartmann A, Pijl FVd. A life-cycle assessment framework for pavement management considering uncertainties. CRC Press eBooks. Informa; 2023, p. 965–72.

Figures



Figure 1

Typical concrete (rigid) and asphalt (flexible) road pavements and schematic representation of their principal structural layers.

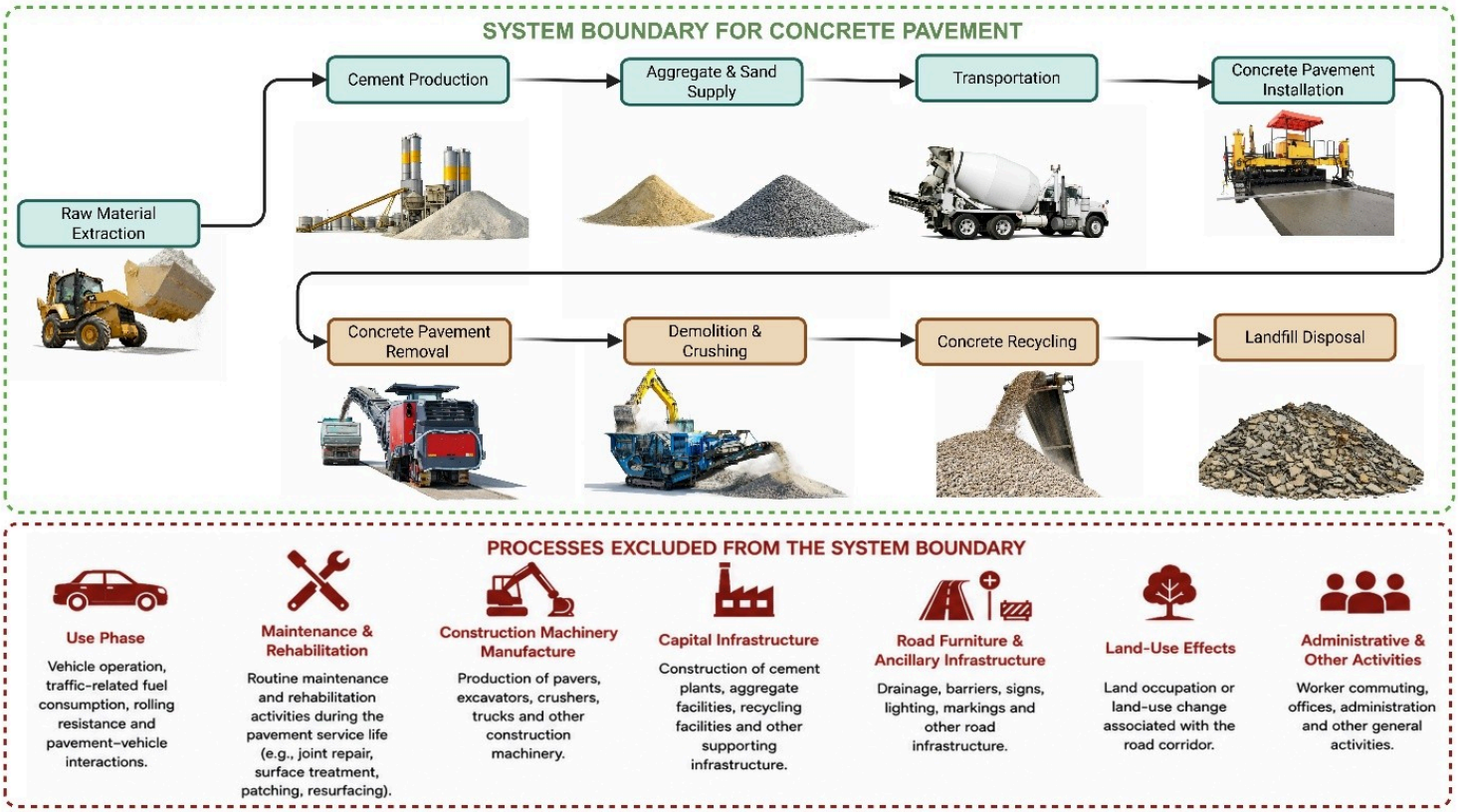


Figure 2

Cradle-to-cradle system boundaries for (A) concrete and (B) asphalt pavements, including key processes and exclusions.

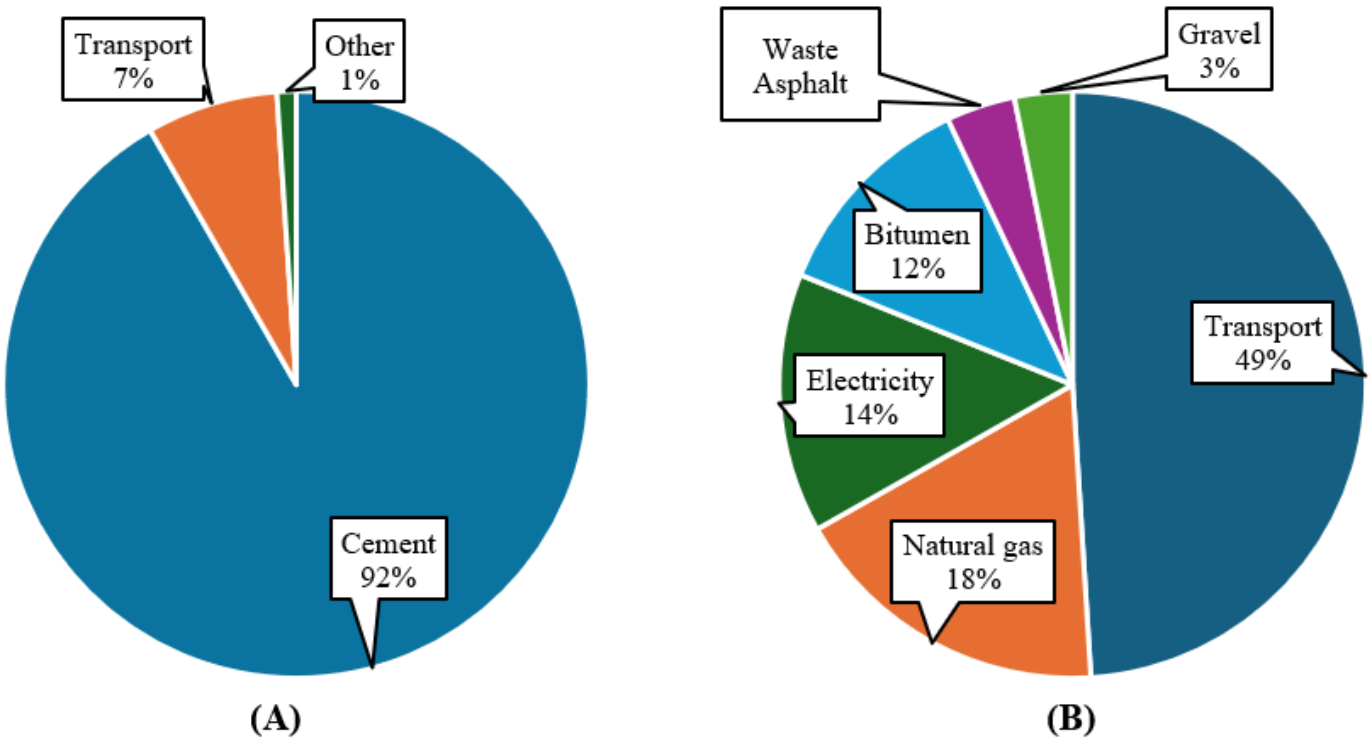


Figure 3

Network contribution diagram midpoint of the top contributing processes to the total environmental impact of pavement production (1 m² functional unit) **(A)** Concrete, **(B)**Asphalt.

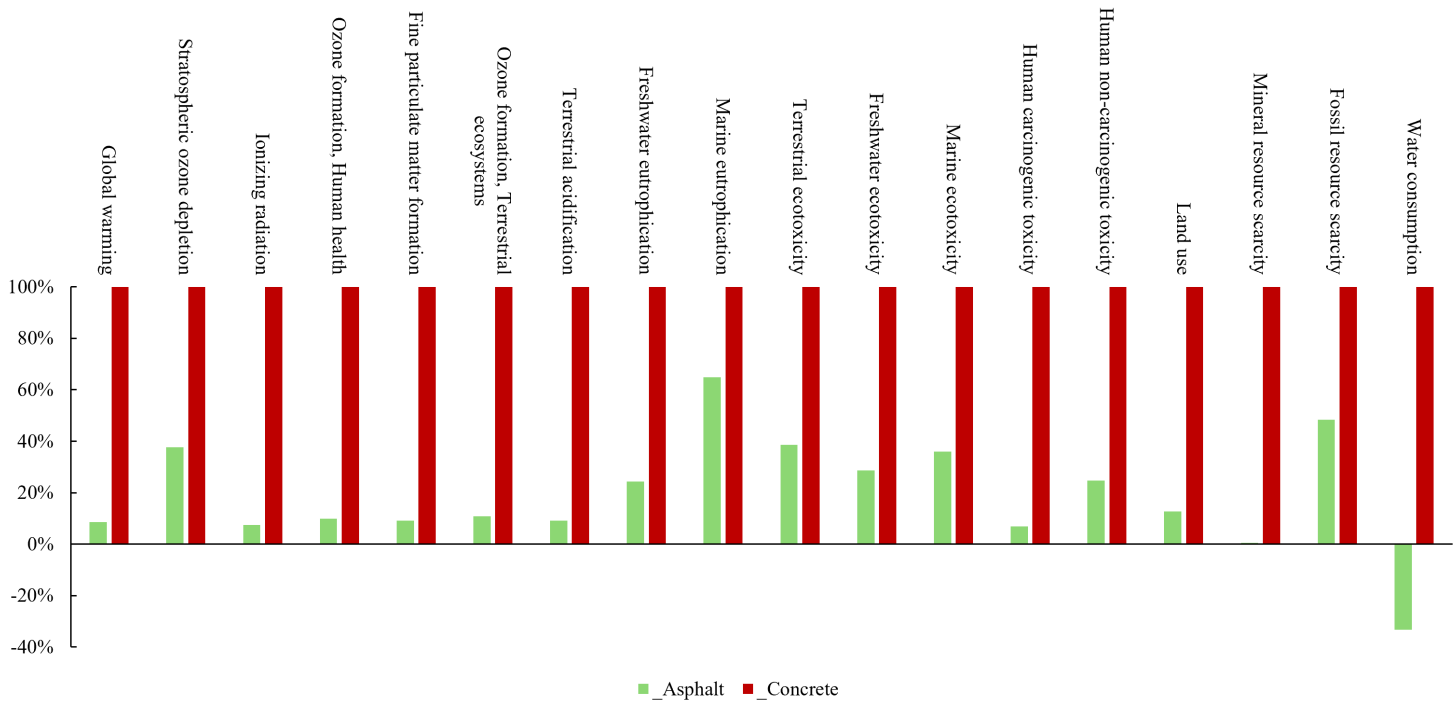


Figure 4

ReCiPe 2016 (H) midpoint characterisation results comparing concrete and asphalt pavements per 1 m² functional unit (cradle-to-cradle (excluding use phase)).

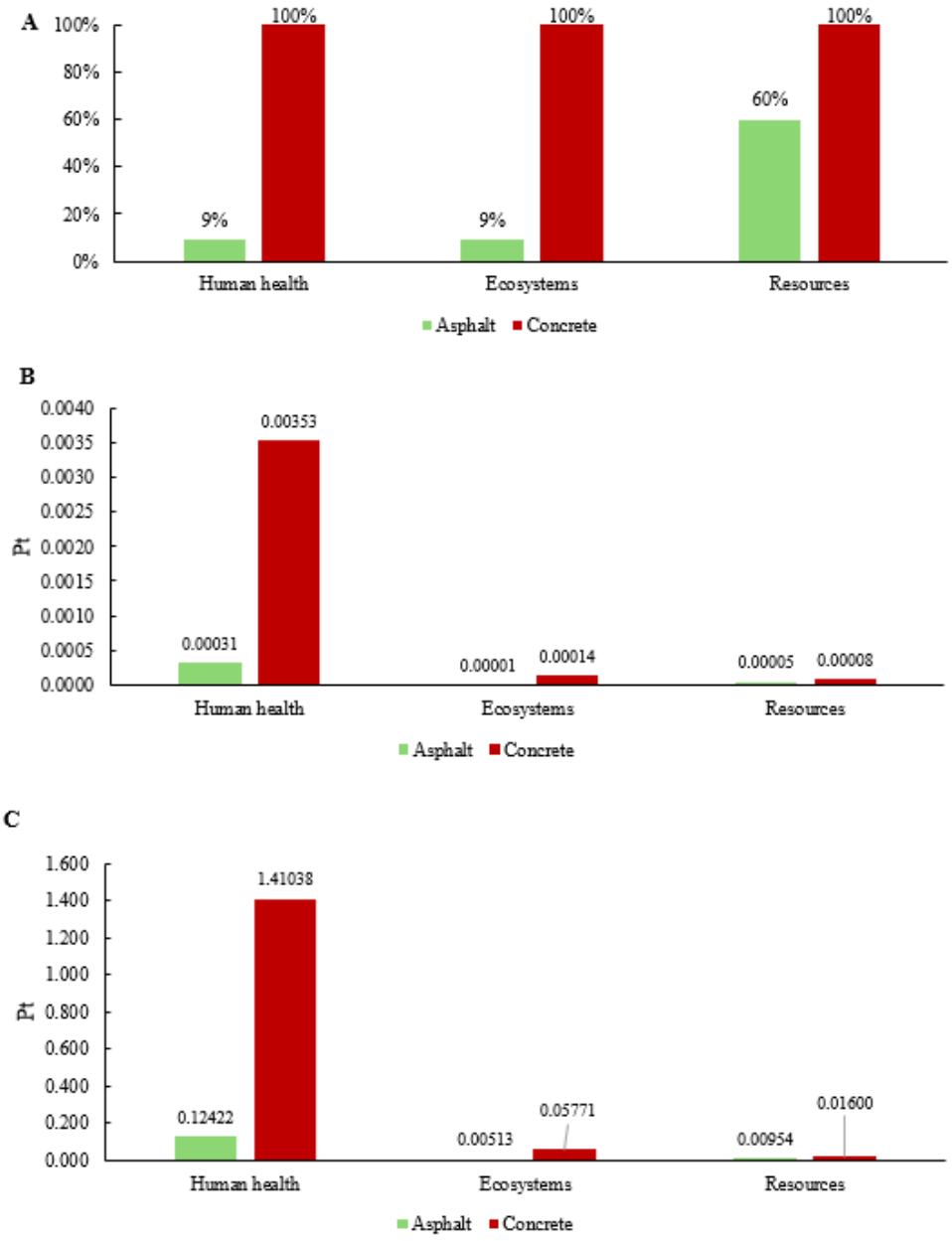


Figure 5

Endpoint impact assessment of concrete and asphalt pavements: (A) damage assessment, (B) normalisation, and (C) weighting results using ReCiPe 2016 Endpoint (H).

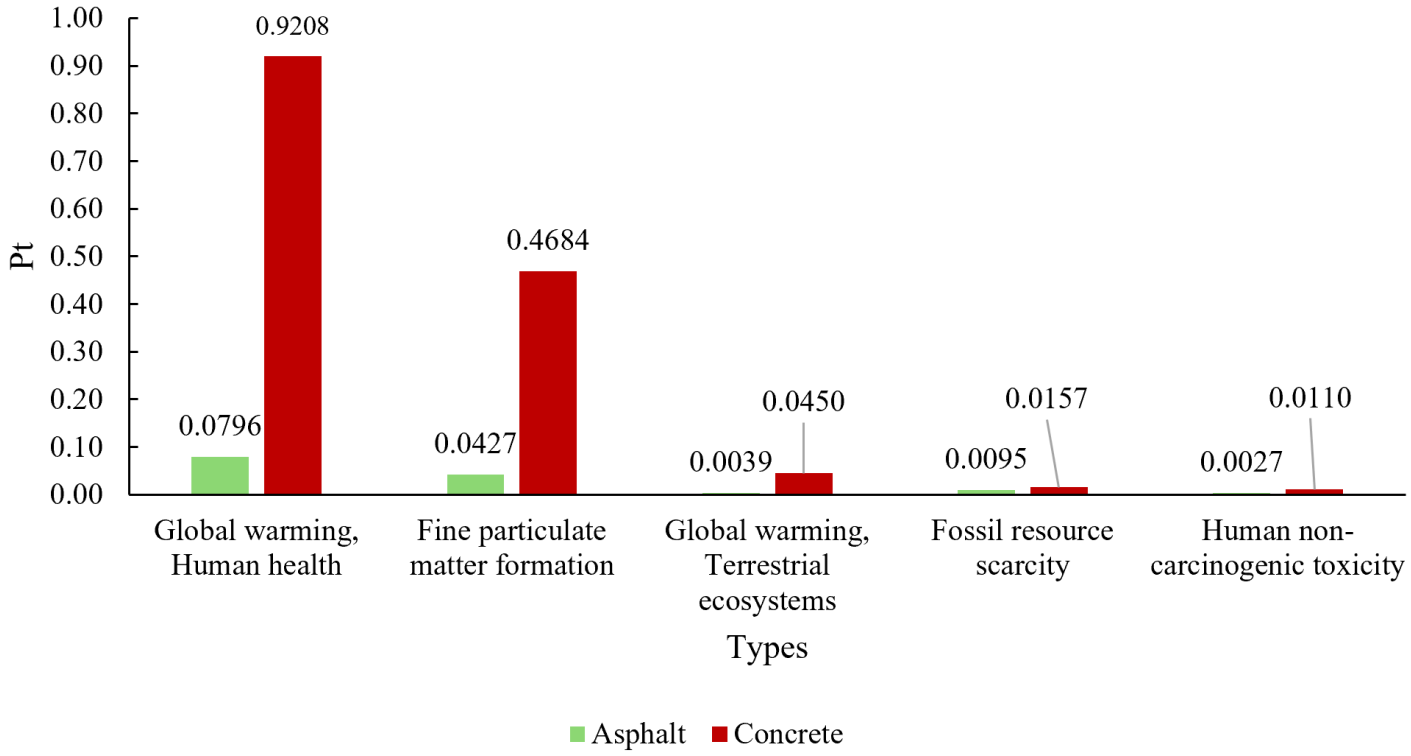


Figure 6

ReCiPe 2016 (H) endpoint single-score results comparing asphalt and concrete pavements per 1 m² functional unit.



Figure 7

Sensitivity analysis of asphalt and concrete pavements over a 100-year service period