Tyre Stewardship Australia and Sunshine Coast Council

# Life Cycle Assessment of Crumb Rubber Asphalt

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# List of Abbreviations

| Abbreviation | Description |
|---|---|
| AusLCI | Australian life cycle inventory |
| BCC2 | Brisbane City Council |
| CR | Crumb rubber |
| DGA | Dense graded aggregate |
| LCA | Life cycle assessment |
| LGA | Local government authority |
| GGA7 | Gap graded aggregate 7 mm |
| GGA10 | Gap graded aggregate 10 mm |
| GHG | Greenhouse gas |
| NTRO | National Transport Research Organisation |
| OTR | Off-the-road |
| PMB | Polymer modified bitumen |
| SAT4P | Sustainability Assessment Tool for Pavements |
| TSA | Tyre Stewardship Australia |

# Summary

Off-the-road (OTR) tyres are durable and designed to be used in harsh environments such as in the agriculture, construction and mining sectors. Unlike passenger and truck tyres, OTR tyres are typically buried or stockpiled on-site at remote locations, causing negative environmental impacts and wasting useful resources. To mitigate these impacts, the Sunshine Coast Council oversaw a project to be one of the first to trial the use of crumb rubber (CR) made from OTR tyres in several pavements across their network in 2024.

The project compared unmodified (i.e. conventional local council reference) mixes to novel CR-modified mixes utilising OTR tyres from construction machinery. The findings of this project (12 months on from construction) demonstrated that OTR CR can be used interchangeably with traditional CR in bitumen.To close the loop of this trial, a cradle-to-grave life cycle assessment (LCA) focussed on greenhouse gas (GHG) emissions was undertaken on eight pavement sections comprising various local council reference mixes and novel CR-modified mixes installed across three sites in the Sunshine Coast.

The LCA assessed the environmental performance of CR-modified asphalt compared to conventional and polymer-modified mixes to understand the emissions reduction benefits of recycling OTR CR in asphalt. The eight treatments across the three trial sites are outlined in the table below.

| Site | Treatments |
|---|---|
| Perlan Street (Site 1) | a. Conventional BCC2 (C320)<br>b. CR-modified GGA7 (OTR CR 18%) – edge plane and overlay<br>c. CR-modified GGA7 (OTR CR 18%) – mill and fill |
| Railway Parade (Site 2) | a. Polymer-modified AC14 (A15E)<br>b. CR-modified GGA10 (OTR CR 18%) |
| Spalls Road (Site 3) | a. Conventional BCC2 (C320)<br>b. CR-modified Durapave Plus 7 mm (OTR CR 18%) – 35 mm thickness<br>c. CR-modified Durapave Plus 7 mm (OTR CR 18%) – 25 mm thickness |

The key results from the LCA show:

- Material production (modules A1-A3) accounts for approximately 65-85% of total upfront emissions, with transport to site (A4) and construction (A5) having less influence.
- For Sites 1 and 3, where asphalt thicknesses were similar, the CR-modified asphalt pavements exhibited higher upfront emissions than the conventional mixes, due to the higher embodied carbon intensity of the CR-modified binders.
- For Site 2, the polymer-modified mix (AC14 (A15E)) recorded higher upfront emissions, mainly because of its greater layer thickness, as the GHG intensities of the two asphalt mixes are comparable.

Although CR-modified mixes may have slightly higher upfront carbon emissions, their improved durability and reduced maintenance frequency can deliver GHG savings across the pavement's life cycle. The results demonstrate that CR from OTR vehicles can be recycled into asphalt and give similar performance and offer environmental benefits through reduced GHG emissions. CR-modified asphalt can enhance fatigue performance (i.e. cracking resistance and enhanced durability against oxidative aging) in a similar way to costly and high GHG emission polymer modified binders.

When extended pavement service life can be achieved, CR-modified asphalt demonstrates clear whole-of-life carbon savings:

- Perlan Street (Site 1):
  - Up to 12% GHG emission reductions at 40% additional service life.
- Railway Parade (Site 2):
  - Up to 20% GHG emission reductions at 40% additional service life.
- Spalls Road (Site 3):
  - Up to 9% GHG emission reductions (for the same pavement thickness) at 50% additional service life.
  - Up to 20% GHG emission reductions (for a thinner pavement) at 50% additional service life.

# Contents

1. Introduction ..... 7

2. Goal and Scope ..... 8
- 2.1 Goal ..... 8
- 2.2 Scope ..... 8
  - 2.2.1 Products ..... 8
  - 2.2.2 Declared Unit ..... 9
  - 2.2.3 System Boundaries ..... 9
- 2.3 Impact Categories, Indicators, Methodologies and Characterisation Factors ..... 10
- 2.4 Cut-off Criteria ..... 10

3. Life Cycle Inventory Analysis ..... 11
- 3.1 Data Collection ..... 11
- 3.2 Data Allocation ..... 11
- 3.3 Material Inventory Data ..... 11
- 3.4 Maintenance and Service Life ..... 18
  - 3.4.1 Additional Service Life ..... 19
- 3.5 Key Assumptions ..... 19
- 3.6 Data Quality Assessment ..... 20

4. Life Cycle Assessment ..... 21
- 4.1 Upfront Carbon ..... 21
- 4.2 Cradle-to-Grave Carbon ..... 22
  - 4.2.1 Site 1 Perlan Street ..... 22
  - 4.2.2 Site 2 Railway Parade ..... 24
  - 4.2.3 Site 3 Spalls Road ..... 27

5. Conclusions ..... 29

References ..... 31

# Tables

Table 2.1: The traditional and crumb rubber asphalt treatments assessed in this study ..... 9
Table 2.2: Life cycle assessment coverage by module ..... 10
Table 3.1: Material inventory data for asphalt mixes – extraction (wt.% per tonne of asphalt) ..... 12
Table 3.2: Annual usage and production volume of asphalt mixes ..... 12
Table 3.3: Material inventory data for each case at site 1 (Perlan Street) ..... 13
Table 3.4: Material inventory data for each case at Site 2 (Railway Parade) ..... 14
Table 3.5: Material inventory data for each case at Site 3 (Spalls Road) ..... 17
Table 3.6: Year of heavy patching and resurfacing under different service life extensions ..... 19
Table 4.1: Upfront GHG emissions for each case ..... 21
Table 4.2: GHG emissions by life cycle module and total for each case at site 1 ($kgCO_2$-e/$m^2$) ..... 24
Table 4.3: GHG emissions by life cycle module and total for each case at site 2 ($kgCO_2$-e/$m^2$) ..... 26
Table 4.4: GHG emissions by life cycle module and total for each case at site 3 ($kgCO_2$-e/$m^2$) ..... 28

# Figures

Figure 4.1: Upfront GHG emissions for each life cycle module of current work for each case at Site 1 ..... 22
Figure 4.2: Relative and total ‘cradle-to-grave’ GHG emissions under additional service life scenarios at Site 1 ..... 23
Figure 4.3: GHG emissions for each life cycle module under additional service life scenarios at Site 1 ..... 24
Figure 4.4: Total ‘cradle-to-grave’ GHG emissions under varying additional service life scenarios at Site 2 ..... 25
Figure 4.5: GHG emissions for each life cycle module under varying additional service life scenarios at Site 2 ..... 26
Figure 4.6: Total ‘cradle-to-grave’ GHG emissions under varying additional service life scenarios at Site 3 ..... 27
Figure 4.7: GHG emissions for each life cycle module under varying additional service life scenarios at Site 3 ..... 28

# 1. Introduction

Local roads managed by councils comprise around 77% of the Australian road network by length (ALGA 2024), and they are under increasing financial pressures to maintain adequate levels of service whilst ensuring their pavements last longer. Alongside these requirements, many councils have sustainability targets to reduce not only their greenhouse gas emissions, but also move towards a circular economy. As a result, local councils are keen to innovate and trial new technologies and materials that can meet their needs.

Incorporating crumb rubber (CR) from processed end-of-life truck and passenger car tyres has been used widely across Australia, especially in sprayed seal applications, but also within asphalt mixes. In these applications, it has been shown to provide many benefits, such as improved fatigue performance, better oxidation resistance and reduced moisture sensitivity when compared to unmodified bitumen and asphalt (Picado-Santos et al. 2020). Off-the-road (OTR) tyres are durable and designed to be used in harsh environments such as construction, agriculture and mining. However, their disposal is a significant challenge due to their size and remote locations, and only 15% of OTR tyres are recovered (TSA 2025). OTR tyres are typically buried or stockpiled on-site at these remote locations, causing negative environmental impacts and wasting useful resources (TSA 2023).

In 2024, the Sunshine Coast Council oversaw a project to trial the use of CR made from OTR tyres from construction machinery (used in quarry operations) in the construction of pavements across several of their roads. The project involved several partners, including the Australian Flexible Pavement Association (AfPA), Boral (and its subsidiary Allens Asphalt), Carroll Engineering Services, Puma Bitumen, RMIT University, and Tyre Stewardship Australia (TSA). This was one of the first trials to explore the use of CR from OTR tyres from the construction industry.

Eight different treatments were trialled across the three sites to compare conventional mixes (unmodified and polymer modified). The mixes selected for use at the three sites were as follows:

- **Site 1 (Perlan Street)** compared an unmodified local government dense graded asphalt mix (BCC2 (C320)) to CR-modified asphalt (gap graded asphalt (GGA7) with 18% OTR CR) with different application types (edge plane and overlay, mill and fill).
- **Site 2 (Railway Parade)** compared a polymer-modified asphalt (AC14 (A15E)) with a CR-modified asphalt (GGA10 with 18% OTR CR).
- **Site 3 (Spalls Road)** compared an unmodified local government dense graded asphalt mix (BCC2 (C320)) to a CR-modified asphalt (18% OTR CR) with different thicknesses (25 mm and 35 mm).

The findings of this project (12 months on from construction) demonstrated that OTR CR can be used interchangeably with traditional CR in bitumen, without requiring significant adjustments to binder blending, mix design or asphalt manufacturing processes (TSA 2025). CR-modified asphalt improves fatigue performance (i.e. cracking resistance and enhanced durability against oxidative aging).

To close the loop of this trial, the National Transport Research Organisation (NTRO) were engaged by TSA to perform a life cycle assessment (LCA) to quantify the whole-of-life greenhouse gas (GHG) emissions associated with each of the mixes.

# 2. Goal and Scope

## 2.1 Goal

The goal is to conduct a LCA of various CR and traditional asphalt treatments installed across three sites within the Sunshine Coast Council, Queensland. These LCAs provide an evidence base to support the increased use of CR in the Council's roads by:

- Providing the Council with credible and quantitative data of the GHG emissions across the entire pavement lifecycle (from raw material extraction to end-of-life) to support sustainable pavement management plans
- By demonstrating the environmental benefits of reusing end-of-life tyres in road infrastructure, the project reinforces council efforts to support circular economy initiatives and state and federal recycling targets.

This technical report and its findings can support councils to consider the GHG emissions savings of CR-modified mixes in their specifications, procurement policies and sustainability frameworks.

## 2.2 Scope

The LCA undertaken in this project covers the 'cradle-to-grave' life cycle of the treatments, focusing on GHG emissions. Its coverage includes:

- upstream emissions from the extraction and transportation of raw materials and the manufacturing of the product (at the manufacturing plant)
- construction emissions from equipment used to install the pavement
- maintenance emissions from equipment used to repair the pavement
- transportation of materials during the construction and maintenance
- end-of-life disposal.

### 2.2.1 Products

The LCA is conducted for various traditional and CR asphalt treatments installed across three of the Sunshine Coast Council's local roads using OTR tyres. The assessed treatments are outlined by their mix and application type and dimensions (Table 2.1). The three traditional asphalt treatments (indicated by an asterisk) represent typical local council pavements.

Table 2.1: The traditional and crumb rubber asphalt treatments assessed in this study

| Road Name | Case | Mix Type | Application Type | Application Area [$m^2$] | Thickness (mm) |
|---|---|---|---|---|---|
| Perlan Street | 1a | BCC2 (C320) [LGA DGA] * | Mill and fill | 2,738 | 32.5 |
| | 1b | GGA7 (OTR CR 18%) | Edge plane and overlay | 1,551 | 32.5 |
| | 1c | GGA7 (OTR CR 18%) | Mill and fill | 180 | 32.5 |
| Railway Parade | 2a | AC14 (A15E) * | Edge Plane, PMB Seal & Overlay | 2,194 | 50.0 |
| | 2b | GGA10 (OTR CR 18%) | Edge Plane, PMB Seal & Overlay | 2,918 | 35.0 |
| Spalls Road | 3a | BCC2 (C320) [LGA DGA] * | Overlay | 2,768 | 35.0 |
| | 3b | Durapave Plus 7 mm (OTR CR 18%) | Overlay | 930 | 35.0 |
| | 3c | Durapave Plus 7 mm (OTR CR 18%) | Overlay | 1,868 | 25.0 |

* Reference cases.

### 2.2.2 Declared Unit

The functional unit is kilograms of carbon dioxide equivalent per square metre of pavement ($kgCO_2$-e/$m^2$).

### 2.2.3 System Boundaries

The scope of the assessment is 'cradle-to-grave' and consists of the following key phases associated with pavements:

- extraction and production – embodied energy contained in pavement materials from extraction and production (i.e. 'cradle to gate')
- construction – the energy used during initial construction of pavements, including its manufacture and laying and use of construction vehicles and machinery. Construction phase can also include pre-construction removal of existing materials
- maintenance – use of construction vehicles, machinery and energy use while delivering maintenance treatments
- end of life – disposal[1], recycling or reuse of end-of-life materials
- transportation/materials haulage – use of heavy haulage vehicles in transporting materials to the project site for construction and maintenance, or from the project site to end of life disposal.

The LCA and its key phases are aligned with *EN 17472:2022* lifecycle modules A-C as shown in Table 2.2.

[1] While end of life disposal of pavements into landfill is rare (or perhaps even non-existent) in practice, it is important to include the phase in the lifecycle to demonstrate completeness and allow flexibility if needed (e.g. distressed roads that cannot be reused due to contamination, or inclusion of recycled content that hasn't yet been approved for reuse). Additionally, alignment with the IS ratings process requires the inclusion of end-of-life in the LCA.

Table 2.2: Life cycle assessment coverage by module

| Stage | Module | Declared |
|---|---|---|
| Product | A1 – Extraction and upstream production (extraction of virgin materials and sourcing of recycled materials) | ✓ |
| | A2 – Transport (to asphalt or manufacturing plant) | ✓ |
| | A3 – Manufacturing (production processes) | ✓ |
| Construction | A4 – Transport (materials to site) | ✓ |
| | A5 – Construction-installation process (mixing and placement) | ✓ |
| Use | B1 – Use (traffic) | × |
| | B2 – Maintenance (routine) | × |
| | B3 – Repair (periodic) | ✓ |
| | B4 – Replacement (rehabilitation) | × |
| | B5 – Refurbishment (resurfacing) | ✓ |
| | B6 – Operational energy use (not applicable) | × |
| | B7 – Operational water use (not applicable) | × |
| End of life | C1 – De-construction demolition (optional removal of existing pavement in preconstruction) | ✓ |
| | C2 – Transport to waste processing (including recycling facilities) or disposal | ✓ |
| | C3 – Waste processing (applicable only for in-situ reuse) | × |
| | C4 – Disposal | × |

Note: Modules A0 (pre-construction activities) and D (benefits from the reuse, recycling or recovery of materials) are out of scope for this LCA.

## 2.3 Impact Categories, Indicators, Methodologies and Characterisation Factors

The GHG emissions are calculated using the standard *EN 15804:2012+A2:2019* characterisation method, excluding long-term and infrastructure emissions, as well as the additional requirements of the PCR:2019 for construction products.

## 2.4 Cut-off Criteria

As per the *PCR 2019:14*, inventory flows from personnel-related activities, infrastructure, construction, production equipment, and tools that are not directly consumed in the production process can be excluded from the LCA, if not known to have the potential to cause significant impact.

# 3. Life Cycle Inventory Analysis

## 3.1 Data Collection

Foreground data has been sourced from Boral, Sunshine Coast Council and TSA, and background data has been sourced from the AusLCI and AusLCI shadow databases (v1.40) and the NTRO LCA Tool (see Section 4) database (last updated June 2024).

Boral provided foreground data on:

- project data, including area of the project site
- raw materials and material proportions contained in the asphalt mixes
- manufacturing processes of asphalt (including type of plant, electricity and fuel consumption and the production volumes)
- transport mode and distance from plant (asphalt, bitumen, and aggregate) to construction site, from bitumen plant to boral asphalt plant
- construction processes and activities (including equipment and hours).

Sunshine Coast Council provided foreground data on the target service life for the surface, base and subbase layers from their asset management plan.

TSA provided foreground data on the GHG emission factor for OTR CR.

Assumptions were made for:

- the treatment of materials from existing pavement removal and end-of-life pavement, including the proportion of materials re-used on site or recycled, and the transport mode and distance to processing or disposal facilities
- the maintenance schedule for periodic heavy patching (see Section 3.4)
- maintenance activities including existing pavement removal process and construction process
- the additional service life associated with CR-modified and polymer modified asphalt mixes.

## 3.2 Data Allocation

No co-product allocation has been used in this LCA analysis.

## 3.3 Material Inventory Data

Table 3.1 and Source: Personal communication with Carl Topp, Boral.

Table 3.2 present the material inventory data for asphalt extraction and production, respectively, with the data sourced from Boral.

Table 3.1: Material inventory data for asphalt mixes – extraction (wt.% per tonne of asphalt)

| Ingredients | 1a (Ref)<br>BCC2 (C320) [LGA DGA] | 1b & 1c<br>GGA7 (OTR CR 18%) | 2a (Ref)<br>AC14 (A15E) | 2b<br>GGA10 (OTR CR 18%) | 3a (Ref)<br>BCC2 (C320) [LGA DGA] | 3b & 3c<br>Durapave Plus 7mm (OTR CR 18%) |
|---|---|---|---|---|---|---|
| Sand | 12.5% | - | 10.0% | - | 12.5% | - |
| Coarse aggregate | 44.7% | 67.0% | 59.7% | 67.3% | 44.7% | 73.2% |
| Fine aggregate | 37.5% | 23.9% | 25.0% | 24.0% | 37.5% | 15.4% |
| Hydrated lime | - | 0.9% | 0.9% | 0.9% | - | 0.9% |
| Binder | 5.30%<br>(C320) | 6.59%<br>(C170) | 4.40%<br>(A15E) | 6.27%<br>(C170) | 5.30%<br>(C320) | 8.43%<br>(C170) |
| OTR CR | - | 1.476% | - | 1.402% | - | 1.898% |
| Sasobit | - | 0.134% | - | 0.128% | - | 0.172% |

Source: Personal communication with Carl Topp, Boral.

Table 3.2: Annual usage and production volume of asphalt mixes

| Energy Consumption Type | Parallel Flow Drum | Astec Double Barrel Drum |
|---|---|---|
| Electricity (kWh) | 408,746 | - |
| LPG (L) | 1,514,361 | - |
| Diesel oil (L) | - | 1,095,520 |
| Loader diesel consumption (L) | 162,369 | 175,695 |
| Production volume ($m^3$) | 108,246 | 117,130 |

Source: Personal communication with Carl Topp, Boral.

Table 3.3, Table 3.4 and

Table 3.5 presents all inputs for each assessed life cycle stage of the pavement for Site 1, Site 2 and Site 3, respectively.

Table 3.3: Material inventory data for each case at site 1 (Perlan Street)

| Life Cycle Stages/Item | Quantity | | |
|---|---|---|---|
| **Case** | **1a (Ref)** | **1b** | **1c** |
| Application | Mill & Fill | Edge Plane & Overlay | Mill & Fill |
| Asphalt mix type | BCC2 (C320) [LGA DGA] | GGA7 (OTR CR 18%) | GGA7 (OTR CR 18%) |
| Asphalt plant | Parallel Flow Drum | Astec Double Barrel Drum | Astec Double Barrel Drum |
| Project area | 2,738 $m^2$ | 1,551 $m^2$ | 180 $m^2$ |
| **Production Stage (A1-A3) – Raw material extraction, transport and production** | | | |
| Precoated aggregate | 30.98 t | 11.00 t | 2.02 t |
| C170 | 2.96 t | 1.05 t | 0.196 t |
| Asphalt – extraction | 223.2. t | 119.60 t | 15.60 t |
| Asphalt – production | 82.80 $m^3$ | 54.08 $m^3$ | 5.59 $m^3$ |
| Emulsion (CRS60) | - | 0.124 t | - |
| **Construction Stage (A4) – Transport (materials to site)** | | | |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 4,449.3 tkm | 1,577.9 tkm | 292.5 tkm |
| Trucking asphalt from plant to site, four axle truck | 13,479.7 tkm (60.4km) | 7,224.9 tkm (55.1km) | 764.9 tkm (55.1 km) |
| Trucking binder from plant to site, 112 km, four axle truck | 331.1 tkm | 125.5 tkm | 21.9 tkm |
| Trucking aggregate from plant to site, 78 km, four axle truck | 2,416.4 tkm | 858.0 tkm | 286.2 tkm |
| **Construction Stage (A5) – Construction-installation process (mixing and placement)** | | | |
| Removal – Milling machine, Wirtgen W200F (2023) | 3.5 hours | 1 hours | 0.5 hour |
| Removal – Two 3-axle rigid trucks | 3.5 hours | 2.5 hours | 0.5 hour |
| New pavement - Sprayer, DAF CF85 430 Sprayer (2005) | 1.5 hours | 1.5 hours | 0.5 hour |
| New pavement – Sealing equipment, CAT PS-200B multi roller | 2 hours | 2 hours | 1 hour |
| New pavement – Sealing equipment, Freightliner FL112 Series (1998) road truck | 2 hours | - | - |
| New pavement – Sealing equipment, Western Star 4700 model road truck | 2 hours | 2 hours | 2 hours |
| New pavement – Sealing equipment, John Deere 4320 Tractor Broom (2011) | 1 hours | 1 hours | 0.5 hours |
| New pavement – Asphalt Paver, Caterpillar AP600F (2022) | 5 hours | 2.5 hours | 0.5 hours |
| New pavement – Rollers, Dynapac CC224HF (2017) | 5 hours | 2.5 hours | 0.5 hours |
| New pavement – Rollers, Sakai Multi Tyre (2022) | 5 hours | 2.5 hours | 0.5 hours |
| New pavement – Rollers, Dynapac CC10 (2017) | 3 hours | 1 hours | 0.5 hours |
| New pavement – Emulsion, Iveco Euro Cargo MLI60 Day Cab 4X2 (2019) | - | 0.5 hours | - |
| **Use Stage (B3) – Periodic heavy patching (single treatment), including production, transport and disposal of necessary materials** | | | |
| Milling asphalt layer | 0.89 $m^3$ | 0.50 $m^3$ | 0.06 $m^3$ |

| | | | |
|---|---|---|---|
| Milling granular layer | 4.1 $m^3$ | 2.3 $m^3$ | 0.27 $m^3$ |
| Asphalt AC20 (C600) – Raw material extraction | 9.8 t | 5.5 t | 0.64 t |
| Asphalt AC20 (C600) – Production & construction | 4.1 $m^3$ | 2.3 $m^3$ | 0.27 $m^3$ |
| Precoated aggregate – Extraction & production | 0.56 t | 0.32 t | 0.037 t |
| C170 – Extraction & production | 0.028 t | 0.016 t | 0.0019 t |
| Spray seal – Construction | 27.38 $m^2$ | 15.51 $m^2$ | 1.80 $m^2$ |
| Asphalt – Extraction | 2.2 t | 1.2 t | 0.14 t |
| Asphalt – Production & construction | 0.85 $m^3$ | 0.48 $m^3$ | 0.056 $m^3$ |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 233.6 tkm | 130.9 tkm | 15.2 tkm |
| Trucking asphalt from plant to site, four axle truck | 723.9 tkm | 370.4 tkm | 43.0 tkm |
| Trucking binder from plant to site, 112 km, four axle truck | 3.2 tkm (60.4 km) | 1.8 tkm (55.1 km) | 0.21 tkm (55.1 km) |
| Trucking aggregate from plant to site, 78 km, four axle truck | 43.5 tkm | 24.7 tkm | 2.9 tkm |
| **Use Stage (B5) – Periodic resurfacing (single treatment), including production, transport and disposal of necessary materials** | | | |
| Milling Asphalt layer | 89.0 $m^3$ | 50.4 $m^3$ | 5.9 $m^3$ |
| Precoated aggregate – extraction & production | 55.8 t | 31.6 t | 3.7 t |
| C170 – extraction & production | 2.8 t | 1.6 t | 0.19 t |
| Spray seal – construction | 2738 $m^2$ | 1551 $m^2$ | 180 $m^2$ |
| Asphalt – extraction | 223.2 t | 119.6 t | 13.9 t |
| Asphalt – production & construction | 84.5 $m^3$ | 48.1 $m^3$ | 5.6 $m^3$ |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 4,463.5 tkm | 2,392.3 tkm | 277.6 tkm |
| Trucking asphalt from plant to site, four axle truck | 13,479.7 tkm (60.4 km) | 6,029.6 (55.1 km) | 765.0 (55.1 km) |
| Trucking binder from plant to site, 112 km, four axle truck | 315.9 tkm | 178.9 tkm | 20.8 tkm |
| Trucking aggregate from plant to site, 78 km, four axle truck | 4,353.4 tkm | 2,466.1 tkm | 286.2 tkm |
| **End of life (C1) – De-construction demolition** | | | |
| Milling asphalt layer | 89.0 $m^3$ | 50.4 $m^3$ | 5.9 $m^3$ |
| Milling granular layer | 410.7 $m^3$ | 232.7 $m^3$ | 27.0 $m^3$ |
| **End of life (C2) – Transport to waste processing (including recycling facilities) or disposal** | | | |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 23,355.7 tkm | 13,094.2 tkm | 1,519.6 tkm |

Table 3.4: Material inventory data for each case at Site 2 (Railway Parade)

| Life Cycle Stages/Item | Quantity | |
|---|---|---|
| **Case** | **2a (Ref)** | **2b** |
| Application | Edge Plane, PMB Seal & Overlay | Edge Plane, PMB Seal & Overlay |
| Asphalt mix type | AC14 (A15E) | GGA10 (OTR CR 18%) |
| Asphalt plant | Parallel Flow Drum | Astec Double Barrel Drum |
| Project area | 2,194 $m^2$ | 2,918 $m^2$ |
| **Production Stage (A1-A3) – Raw material extraction, transport and production** | | |
| Precoated aggregate | 31.54 t | 38.5 t |
| S25E | 3.5 t | 4.3 t |

| Life Cycle Stages/Item | Quantity | |
|---|---|---|
| CRS 170-60 | 0.66 t | 0.86 t |
| Asphalt – extraction | 277.9 t | 243.4 t |
| Asphalt – production | 103.9 $m^3$ | 95.4 $m^3$ |
| **Construction Stage (A4) – Transport (materials to site)** | | |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 1,665.0 tkm | 1,447.3 tkm |
| Trucking asphalt from plant to site, four axle truck | 7,724.8 tkm (27.8km) | 5,476.0 tkm (22.5km) |
| Trucking S25E from plant to site, 75 km, four axle truck | 264.3 tkm | 323.1 tkm |
| Trucking CRS 170-60 from plant to site, 41 km, four axle truck | 27.2 tkm | 35.3 tkm |
| Trucking aggregate from plant to site, 60 km, four axle truck | 1,833.7 tkm | 1,717.2 tkm |
| **Construction Stage (A5) – Construction-installation process (mixing and placement)** | | |
| Removal – Milling machine, Wirtgen W200F (2023) | 1 hour | 1 hour |
| Removal – Two 3-axle rigid trucks | 1.5 hours | 2 hours |
| New pavement - Sprayer, DAF CF85 430 Sprayer (2005) | 1.5 hours | 2 hours |
| New pavement – Sealing Equipment, CAT PS-200B Multi Roller | 4 hours | 4 hours |
| New pavement – Sealing Equipment, Freightliner FL112 Series (1998) Road Truck | 4 hours | 4 hours |
| New pavement – Sealing Equipment, Western Star 4700 model Road Truck | 4 hours | 4 hours |
| New pavement – Sealing Equipment, John Deere 4320 4320 Tractor Broom (2011) | 0.5 hour | 0.5 hour |
| New pavement – Asphalt Paver, Caterpillar AP600F (2022) | 3.5 hours | 2.5 hours |
| New pavement – Rollers, Dynapac CC224HF (2017) | 3.5 hours | 2.5 hours |
| New pavement – Rollers, Hamm HD+ 70i VO (2021) (2022) | 3.5 hours | 2.5 hours |
| New pavement – Rollers, Dynapac CC10 (2017) | 2 hours | 1 hour |
| New pavement – Emulsion, Iveco Euro Cargo MLI60 Day Cab 4X2 (2019) | 1 hour | 1 hour |
| **Use Stage (B3) – Periodic heavy patching (single treatment), including production, transport and disposal of necessary materials** | | |
| Milling Asphalt layer | 1.1 $m^3$ | 1.0 $m^3$ |
| Milling Granular layer | 3.3 $m^3$ | 4.4 $m^3$ |
| Asphalt AC20 (C600) – raw material extraction | 7.8 t | 10.4 t |
| Asphalt AC20 (C600) – production & construction | 3.3 $m^3$ | 4.4 $m^3$ |
| Precoated aggregate – extraction & production | 0.45 t | 0.59 t |
| S25E – extraction & production | 0.034 t | 0.045 t |
| Spray seal – construction | 21.94 $m^2$ | 29.18 $m^2$ |
| Asphalt – extraction | 2.8 t | 2.4 t |
| Asphalt – production & construction | 1.0 $m^3$ | 1.0 $m^3$ |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 207.0 tkm | 250 tkm |
| Trucking asphalt from plant to site, four axle truck | 294.5 tkm (27.8 km) | 236.2 tkm (22.5 km) |
| Trucking S25E from plant to site, 75 km, four axle truck | 2.5 tkm | 3.4 tkm |
| Trucking aggregate from plant to site, 41 km, four axle truck | 18.3 tkm | 24.4 tkm |
| **Use Stage (B5) – Periodic resurfacing (single treatment), including production, transport and disposal of necessary materials** | | |
| Milling Asphalt layer | 109.7 $m^3$ | 102.1 $m^3$ |
| Precoated aggregate – extraction & production | 44.7 t | 59.5 t |
| S25E – extraction & production | 3.4 t | 4.5 t |

| Life Cycle Stages/Item | Quantity | |
|---|---|---|
| CRS 170-60 – extraction & production | 0.21 t | 0.29 t |
| Spray seal – construction | 2,194 $m^2$ | 2,918 $m^2$ |
| Asphalt – extraction | 277.9 t | 243.4 t |
| Asphalt – production & construction | 103.9 $m^3$ | 95.4 $m^3$ |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 5,557.4 tkm | 4,867.5 tkm |
| Trucking asphalt from plant to site, four axle truck | 7,724.8 tkm (27.8 km) | 5,476.0 tkm (22.5 km) |
| Trucking S25E from plant to site, 75 km, four axle truck | 254.2 tkm | 338.1 tkm |
| Trucking CRS 170-60 from plant to site, 41 km, four axle truck | 8.4 tkm | 11.8 |
| Trucking aggregate from plant to site, 60 km, four axle truck | 1,833.7 tkm | 2,438.8 tkm |
| **End of life (C1) – De-construction demolition** | | |
| Milling Asphalt layer | 109.7 $m^3$ | 102.1 $m^3$ |
| Milling Granular layer | 329.1 $m^3$ | 437.7 $m^3$ |
| **End of life (C2) – Transport to waste processing (including recycling facilities) or disposal** | | |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 20,696.0 tkm | 25,001.7 tkm |

Table 3.5: Material inventory data for each case at Site 3 (Spalls Road)

| Life Cycle Stages/Item | Quantity | | |
|---|---|---|---|
| **Case number** | **Case 3a (Ref)** | **Case 3b** | **Case 3c** |
| Application | Overlay | Overlay | Overlay |
| Asphalt Mix Type | BCC2 (C320) [LGA DGA] | Durapave Plus 7mm (OTR CR 18%) | Durapave Plus 7mm (OTR CR 18%) |
| Asphalt Plant | Parallel Flow Drum | Astec Double Barrel Drum | Astec Double Barrel Drum |
| Project area | 2,798 $m^2$ | 930 $m^2$ | 1,868 $m^2$ |
| Thickness of paving | 32.5 mm | 35 mm | 25 mm |
| **Production Stage (A1-A3) – Raw material extraction, transport and production** | | | |
| Asphalt – extraction | 228.1 t | 75.9 t | 108.9 t |
| Asphalt – production | 86.4 $m^3$ | 31.0 $m^3$ | 44.5 $m^3$ |
| Emulsion CRS 170-60 | 0.68 t | 0.20 t | 0.49 t |
| **Construction Stage (A4) – Transport (materials to site)** | | | |
| Trucking asphalt from plant to site, four axle truck | 13,775.1 tkm (60.4 km) | 3,968.3 tkm (52.3 km) | 5,693.4 tkm (52.3 km) |
| Trucking CRS 170-60 from plant to site, 100 km, four axle truck | 68.5 tkm | 19.6 tkm | 48.9 tkm |
| **Construction Stage (A5) – Construction-installation process (mixing and placement)** | | | |
| New pavement – Asphalt Paver, Caterpillar AP600F (2022) | 3.5 hours | 1 hour | 3 hours |
| New pavement – Rollers, Dynapac CC224HF (2017) | 3.5 hours | 1 hour | 3 hours |
| New pavement – Rollers, Sakai Multi Tyre (2022) | 3.5 hours | 1 hour | 3 hours |
| New pavement – Rollers, Dynapac CC10 (2017) | 1 hour | 1 hour | 0.5 hour |
| New pavement – Emulsion, Iveco Euro Cargo MLI60 Day Cab 4X2 (2019) | 0.5 hour | 0.5 hour | 0.5 hour |
| **Use Stage (B3) – Periodic heavy patching (single treatment), including production, transport and disposal of necessary materials** | | | |
| Milling Asphalt layer | 0.91 $m^3$ | 0.33 $m^3$ | 0.47 $m^3$ |
| Milling Granular layer | 4.0 $m^3$ | 1.3 $m^3$ | 2.8 $m^3$ |
| Asphalt AC20 (C600) – raw material extraction | 10.0 t | 3.3 t | 6.7 t |
| Asphalt AC20 (C600) – production & construction | 4.2 $m^3$ | 1.4 $m^3$ | 2.7 $m^3$ |
| Precoated aggregate – extraction & production | 0.57 t | 0.19 t | 0.38 t |
| C170 – extraction & production | 0.029 t | 0.0096 t | 0.0019 t |
| Spray seal – construction | 27.98 $m^2$ | 9.30 $m^2$ | 18.68 $m^2$ |
| Asphalt – extraction | 2.3 t | 0.76 t | 1.1 t |
| Asphalt – production & construction | 0.86 $m^3$ | 0.31 $m^3$ | 0.45 $m^3$ |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 238.7 tkm | 70.7 tkm | 150.7 tkm |
| Trucking asphalt from plant to site, four axle truck | 739.8 tkm (60.4 km) | 213.0 tkm (52.3 km) | 405.0 tkm (52.3 km) |
| Trucking C170 from plant to site, 100 km, four axle truck | 2.9 tkm | 1.0 tkm | 1.9 tkm |
| Trucking aggregate from plant to site, 50 km, four axle truck | 28.5 tkm | 9.5 tkm | 19.0 tkm |
| **Use Stage (B5) – Periodic resurfacing (single treatment), including production, transport and disposal of necessary materials** | | | |
| Milling Asphalt layer | 90.9 $m^3$ | 32.6 $m^3$ | 108.9 $m^3$ |
| Precoated aggregate – extraction & production | 57.0 t | 19.0 t | 38.1 t |
| C170 – extraction & production | 2.9 t | 0.96 t | 1.9 t |

| Life Cycle Stages/Item | Quantity | | |
|---|---|---|---|
| CRS 170-60 – extraction & production | 0.68 t | 0.20 t | 0.49 t |
| Spray seal – construction | 2798 $m^2$ | 930 $m^2$ | 1868 $m^2$ |
| Asphalt – extraction | 228.1 t | 75.9 t | 108.9 t |
| Asphalt – production & construction | 86.4 $m^3$ | 31.0 $m^3$ | 44.5 $m^3$ |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 4,239.4 tkm | 1,517.5 tkm | 2,177.2 tkm |
| Trucking asphalt from plant to site, four axle truck | 13,775.1 tkm (60.4 km) | 3,968.3 tkm (52.3 km) | 5,693.4 tkm (52.3 km) |
| Trucking C170 from plant to site, 100 km, four axle truck | 288.2 tkm | 95.8 tkm | 192.4 tkm |
| Trucking CRS 170-60 from plant to site, 100 km, four axle truck | 68.5 tkm | 19.6 tkm | 48.9 tkm |
| Trucking aggregate from plant to site, 50 km, four axle truck | 2851.8 tkm | 947.9 tkm | 1903.9 tkm |
| **End of life (C1) – De-construction demolition** | | | |
| Milling Asphalt layer | 90.9 $m^3$ | 32.6 $m^3$ | 46.7 $m^3$ |
| Milling Granular layer | 419.7 $m^3$ | 139.5 $m^3$ | 280.2 $m^3$ |
| **End of life (C2) – Transport to waste processing (including recycling facilities) or disposal** | | | |
| Trucking removed material from site to recycling facilities, 20 km, two axle truck | 23,867.5 tkm | 8,049.7 tkm | 15,231.7 tkm |

## 3.4 Maintenance and Service Life

According to Sunshine Coast Council (personal communication, Cory Josland), the target service life for the surface is 20 years, while for the base and subbase layers is 60 years. These values are applicable to the conventional mix BCC2 (C320) [LGA DGA] in this LCA.

The maintenance schedule for the conventional mix is assumed to be the following:

- Heavy patching (1% of surface area repaired):
  - Periodic maintenance in 10 years
  - Removal of 32.5 mm asphalt and 150 mm of unbound granular base by profiling
  - construct new base layer (AC20 (C600)), waterproofing seal (10 mm C170 seal) and surfacing layer (BCC2 (C320) [LGA DGA]).
- Resurfacing (100% of surface area):
  - Periodic maintenance in 20 years
  - Removal of 32.5 mm asphalt by profiling
  - Waterproofing seal (10 mm C170 seal) and surfacing layer (BCC2 (C320) [LGA DGA]).
- Pavement end of life (100% of surface area):
  - Rehabilitation in 60 years
  - Removal of 32.5 mm asphalt and 150 mm of unbound granular base by profiling.

### 3.4.1 Additional Service Life

Compared to the unmodified mixes, polymer modified asphalt mixes can extend a pavement's service life by improving its fatigue and cracking resistance. For the AC14 (A15E) (case 2a), previous research has shown that these polymer-modified mixes have significantly improved performance, especially in fatigue, compared to unmodified mixes (Grenfell 2024). A conservative estimate of the additional service life of AC14 (A15E) is around 40% compared to the unmodified mixes (Grenfell 2024). For the CR-modified mixes, previous research has shown that the service life of these pavements can be extended (i.e. delaying maintenance activities compared to the conventional LGA mixes) due to the addition of CR (Grobler 2020). For site 3, the Durapave product has a much higher binder and CR content compared to the other CR-modified mixes, and so it is reasonable to assume that it could provide up to 50% additional service life.

The following service life extensions relative to the unmodified mix (BCC [LGA DGA]) were examined for the CR-modified mixes:

- Site 1: 0 to 40% additional service life (in 10% increments).
- Site 2: 0 to 40% additional service life (in 10% increments).
- Site 3: 0 to 50% additional service life (in 10% increments).

The service life extensions impact when the maintenance activities occur, as illustrated for heavy patching and resurfacing in Table 3.6.

Table 3.6: Year of heavy patching and resurfacing under different service life extensions

| Service Life Extension | Year of Heavy Patching | Year of Resurfacing |
|---|---|---|
| 0% | 10 | 20 |
| 10% | 11 | 22 |
| 20% | 12 | 24 |
| 30% | 13 | 26 |
| 40% | 14 | 28 |
| 50% | 15 | 30 |

Note: 0% service life extension corresponds to the conventional BCC [LGA DGA] mix.

## 3.5 Key Assumptions

- Materials from the removal of the existing pavement and end-of-life pavement are assumed to be fully recycled, with transportation carried out by a two axle truck over 20 km from site to the recycling plant.
- The equipment used to precoat the aggregate on site is assumed to have an insignificant impact and has been excluded from the LCA.
- The density of the existing pavement surface is assumed to be 2,500 kg/m$^3$.
- The application factor for all the equipment is assumed to be "Medium".
- The milling thickness for pavement removal is assumed to remain constant throughout the service life, taken as equal to the thickness of the paving layer.
- Two three axle rigid trucks are assumed to operate in conjunction with the profiler during the profiling process. The operating hours of the two trucks are assumed to be equal to those of the profiler.

## 3.6 Data Quality Assessment

The quality of the data used in this LCA ranges from good to very good quality data on specific processes (foreground data) and poor to good quality data for the generic data (background). The background inventory data used to conduct this LCA are primarily from the NTRO LCA Tool database which was last updated in June 2024. The GHG emission factor for OTR was sources from a TSA report "*Life Cycle Assessment of Agriculture and Mining Off-the-Road (OTR) Tyres*" and represents the average value across two tyre types evaluated under three scenarios (TSA 2024).

# 4. Life Cycle Assessment

This section outlines the LCA results of the eight treatments across the three sites. The LCA was performed using the NTRO's LCA Tool, a 'cradle-to-grave' assessment tool that supports the development of more sustainable pavements. The tool's methodology is aligned with the Sustainability Assessment Tool for Pavements (SAT4P), which both follow relevant international and Australian standards (e.g. ISO 14040, ISO 21930, EN 15804, etc.), and provide a range of outputs including GHG emissions, material usage quantities, and economic costs.

## 4.1 Upfront Carbon

The upfront carbon corresponds to the GHG emissions associated with the creation of the new pavements (life cycle modules A1–A5). The upfront GHG emissions for each case are presented in Table 4.1 and Figure 4.1. The upfront GHG emissions range from 4.86 to 10.51 $kgCO_2$-e/$m^2$, primarily influenced by the layer thickness and binder type. The extraction and production of the materials (A1–A3) accounts for 65-85% of total GHG emissions, with the remaining GHG emissions in transport to site (A4) and construction activities (A5).

Table 4.1: Upfront GHG emissions for each case

| Road Name | Case | Mix Type | Application Type | Application Area [$m^2$] | Thickness (mm) | GHG Emissions [$kgCO_2$-e/$m^2$] |
|---|---|---|---|---|---|---|
| Perlan Street | 1a * | BCC2 (C320) [LGA DGA] | Mill and fill | 2,738 | 32.5 | 6.02 |
| | 1b | GGA7 (OTR CR 18%) | Edge plane and overlay | 1,551 | 32.5 | 7.49 |
| | 1c | GGA7 (OTR CR 18%) | Mill and fill | 180 | 32.5 | 9.00 |
| Railway Parade | 2a * | AC14 (A15E) | Edge Plane, PMB Seal & Overlay | 2,194 | 50 | 10.51 |
| | 2b | GGA10 (OTR CR 18%) | Edge Plane, PMB Seal & Overlay | 2,918 | 35 | 7.41 |
| Spalls Road | 3a * | BCC2 (C320) [LGA DGA] | Overlay | 2,768 | 32.5 | 4.86 |
| | 3b | Durapave Plus 7mm (OTR CR 18%) | Overlay | 930 | 35 | 7.29 |
| | 3c | Durapave Plus 7 mm (OTR CR 18%) | Overlay | 1,868 | 25 | 5.39 |

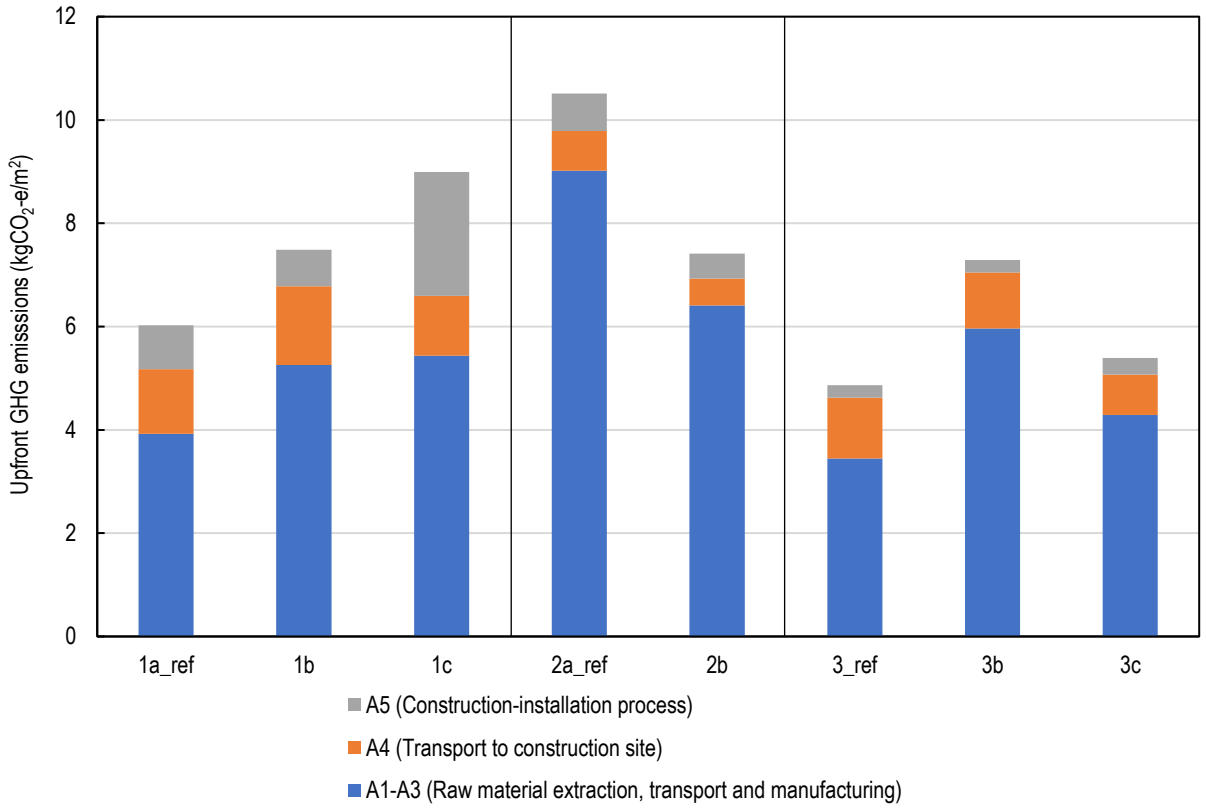
Note: * indicates the reference cases.

For Perlan Street (Site 1), case 1a with the reference mix BCC2 (C320) exhibits the lowest emissions (6.02 $kgCO_2$-e/$m^2$), whereas case 1b and 1c with the CR-modified mix GGA7 (OTR CR 18%) show higher emissions of 7.49 and 9.00 $kgCO_2$-e/$m^2$ respectively. The increase is primarily attributed to the higher GHG intensity of the CR-modified mixes. It is noted that the relatively high construction-installation process (A5) emissions for case 1c are likely influenced by the rough estimation of equipment operating hours associated with its small project area (180 $m^2$). This also contributes to the higher overall GHG emissions of case 1c compared with case 1b. Therefore, a more meaningful comparison can be drawn between cases 1a and 1b.

For Railway Parade cases (Site 2), case 2a with the polymer modified mix AC14 (A15E) yields higher emissions (10.51 $kgCO_2$-e/$m^2$) primarily due to its greater layer thickness (50 mm), as the GHG intensity of the two mixes is comparable. In contrast, case 2b with the CR-modified mix GGA7 (OTR CR 18%) had a lower emission of 7.41 $kgCO_2$-e/$m^2$ corresponding to its thinner layer of 35 mm.

On Spalls Road (Site 3), case 3a with the reference mix BCC2 (C320) exhibits the lowest GHG emissions (4.86 $kgCO_2$-e/$m^2$), whereas case 3b and 3c with the CR-modified mix Durapave Plus 7mm (OTR CR 18%) show higher emissions of 7.29 and 5.39 $kgCO_2$-e/$m^2$ respectively. The greater GHG emissions is primarily attributed to the higher embodied carbon associated with the materials and processing of the CR-modified mixes. As cases 3a and 3b have comparable paving thicknesses (32.5 mm and 35.0 mm, respectively), the comparison between these two cases is more meaningful.

Figure 4.1: Upfront GHG emissions for each life cycle module of current work for each case at Site 1



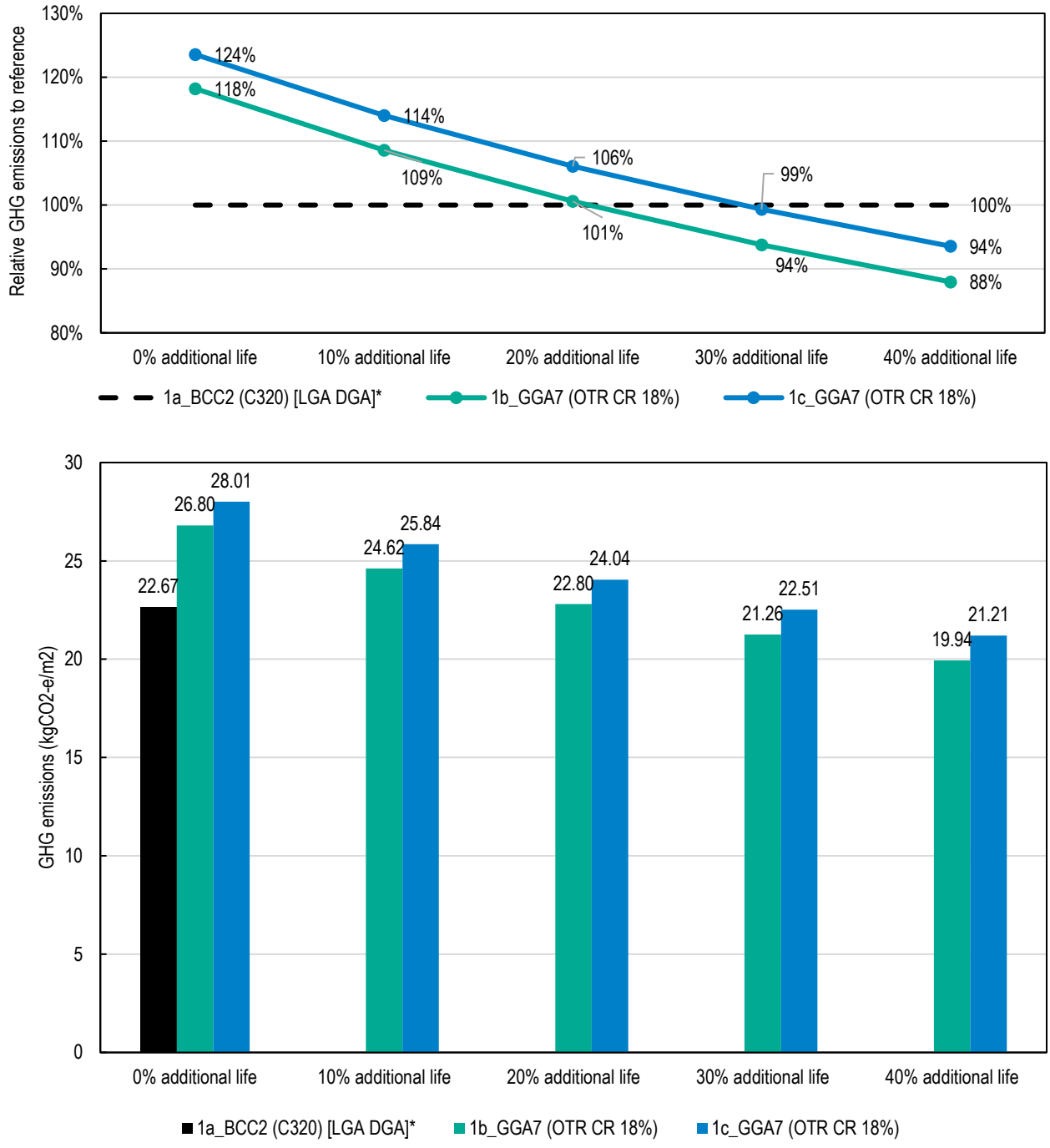

## 4.2 Cradle-to-Grave Carbon

A sensitivity analysis was conducted to evaluate the impact of the extended service life of the CR–modified asphalt mixes on cradle-to-grave GHG emissions of the pavement, considering service life extensions from 0% up to 50% compared to the reference mixes. The additional service life results in reduced maintenance over the life of the pavement (for further details on maintenance schedules see Section 3.4).

### 4.2.1 Site 1 Perlan Street

Figure 4.2 shows that when the CR-modified asphalt mixes (GGA7 (OTR CR 18%)) service lives are extended relative to the reference mix (BCC2 (C320) [LGA DGA]), total cradle-to-grave GHG emissions decrease progressively, achieving up to 12% and 6% lower emissions at 40% additional life for case 1b and 1c, respectively. When CR-modified asphalt mixes can achieve 20% additional service life, cases 1b and 1c exhibit comparable GHG emissions to the reference case 1a. As discussed in Section 4.1, the higher overall GHG emissions of case 1c compared with case 1b is influenced by the rough estimation of equipment operating hours associated with its small project area (180 $m^2$).

Figure 4.2: Relative and total 'cradle-to-grave' GHG emissions under additional service life scenarios at Site 1




Note: * Reference case does not have additional service life.

Table 4.2 and Figure 4.3 presents the the breakdown of emissions by life cycle stage. The majority of GHG emissions originate from production stage (A1-A3) and periodic resurfacing (B5). The reduction in maintenance frequency associated with the longer service life is the main contributor to the overall carbon savings for case 1b and 1c. The relatively high construction-installation process (A5) emissions for case 1c are again likely influenced by the rough estimation of equipment operating hours.

Figure 4.3: GHG emissions for each life cycle module under additional service life scenarios at Site 1

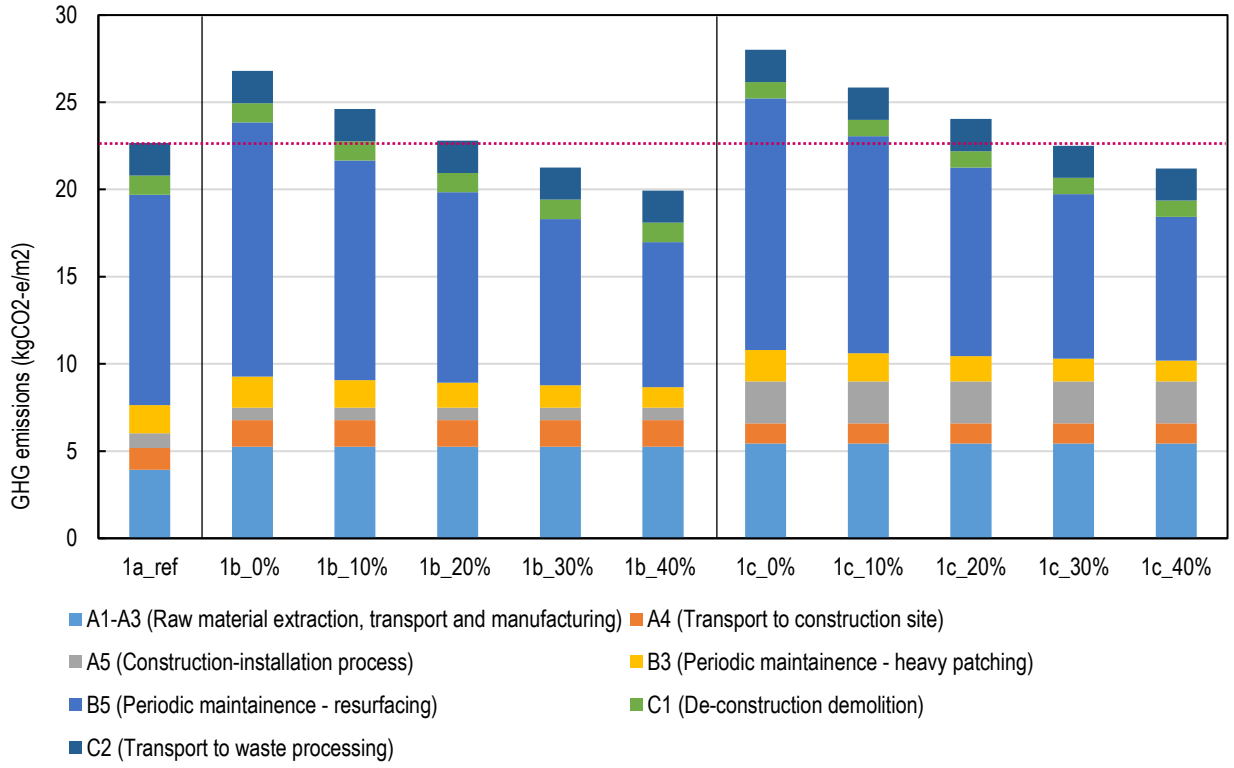



Table 4.2: GHG emissions by life cycle module and total for each case at site 1 ($kgCO_2$-e/$m^2$)

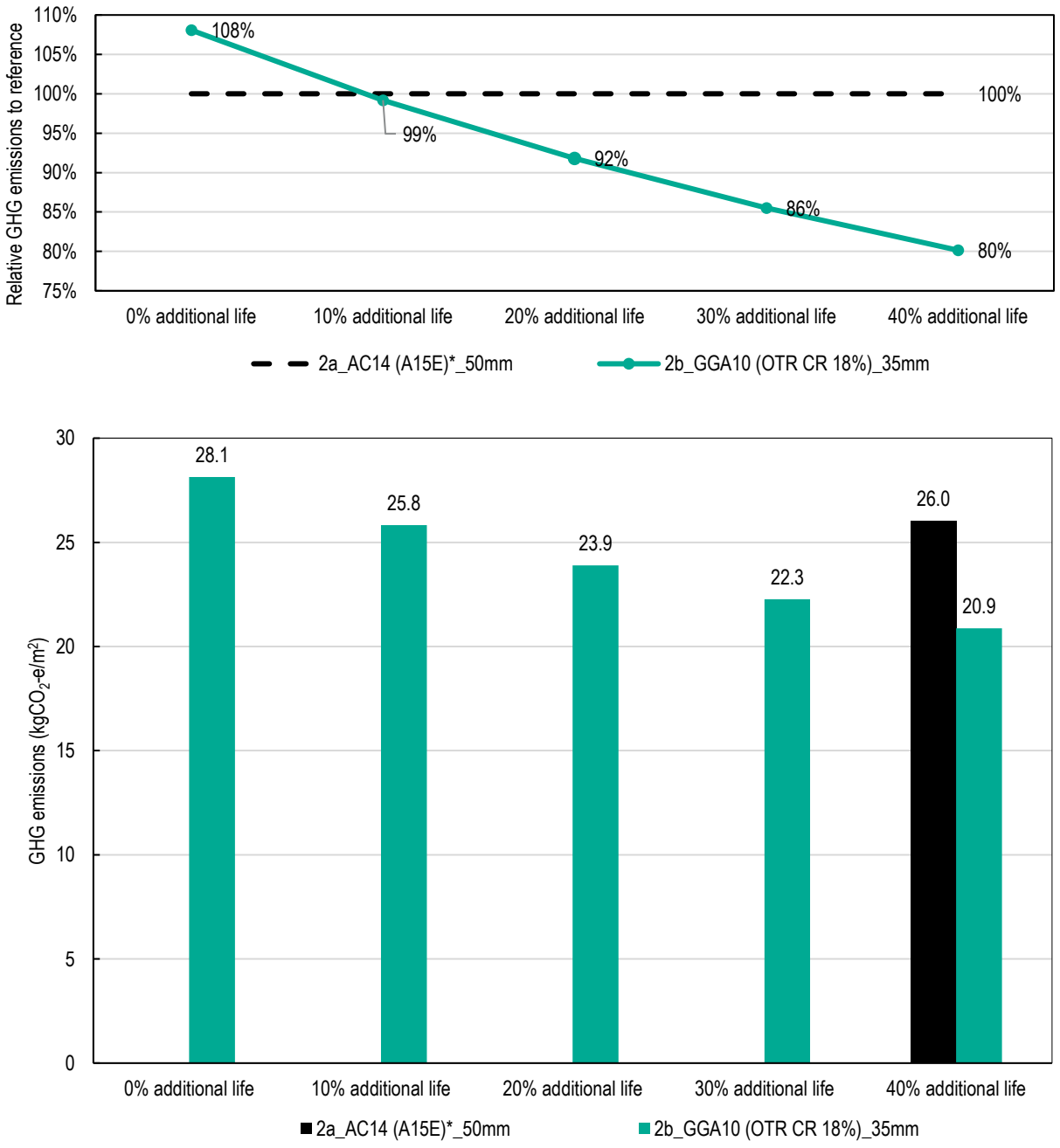
| Case | Additional Life | A1-A3 | A4 | A5 | B3 | B5 | C1 | C2 | Total |
|---|---|---|---|---|---|---|---|---|---|
| 1a (Ref) | 0% | 3.92 | 1.25 | 0.85 | 1.62 | 12.04 | 1.11 | 1.87 | 22.67 |
| 1b | 0% | 5.25 | 1.53 | 0.71 | 1.78 | 14.57 | 1.11 | 1.85 | 26.80 |
| | 10% | 5.25 | 1.53 | 0.71 | 1.59 | 12.58 | 1.11 | 1.85 | 24.62 |
| | 20% | 5.25 | 1.53 | 0.71 | 1.43 | 10.92 | 1.11 | 1.85 | 22.80 |
| | 30% | 5.25 | 1.53 | 0.71 | 1.29 | 9.52 | 1.11 | 1.85 | 21.26 |
| | 40% | 5.25 | 1.53 | 0.71 | 1.17 | 8.32 | 1.11 | 1.85 | 19.94 |
| 1c | 0% | 5.44 | 1.16 | 2.40 | 1.44 | 10.82 | 0.93 | 1.85 | 28.01 |
| | 10% | 5.44 | 1.16 | 2.40 | 1.81 | 14.43 | 0.93 | 1.85 | 25.84 |
| | 20% | 5.44 | 1.16 | 2.40 | 1.61 | 12.46 | 0.93 | 1.85 | 24.04 |
| | 30% | 5.44 | 1.16 | 2.40 | 1.31 | 9.43 | 0.93 | 1.85 | 22.51 |
| | 40% | 5.44 | 1.16 | 2.40 | 1.19 | 8.24 | 0.93 | 1.85 | 21.21 |

### 4.2.2 Site 2 Railway Parade

The AC14 (A15E) mix is assumed to have a 40% longer service life than the BCC2 (C320) [LGA DGA] mix and serves as the reference case 2a (see Section 3.4). Figure 4.4 shows that when the CR-modified asphalt

mixes GGA10 (OTR CR 18%) are assumed to have an extended service life, total cradle-to-grave GHG emissions of the pavement (case 2b) decrease progressively, achieving up to 20% lower emissions at 40% additional life compared to the reference case 2a. When CR-modified asphalt mixes can achieve 10% additional service life than the BCC2 (C320) [LGA DGA] mix, case 2b with CR-modified mix exhibits comparable GHG emissions to the reference case 2a with AC14 (A15E). This is mainly attributed to its thinner paving thickness of 35 mm, compared with 50 mm for case 2a.

Figure 4.4: Total 'cradle-to-grave' GHG emissions under varying additional service life scenarios at Site 2




Note: * Reference case has a 40% additional service life compared to the traditional BCC LGA DGA mix (see Section 3.4).

Table 4.3 and Figure 4.5 present the the breakdown of emissions by life cycle stage. Similar as Site 1, the majority of GHG emissions originate from production stage (A1-A3) and periodic resurfacing (B5). The

reduction in maintenance frequency and less paving thickness is the main contributor to the overall carbon savings for case 2b.

Figure 4.5: GHG emissions for each life cycle module under varying additional service life scenarios at Site 2

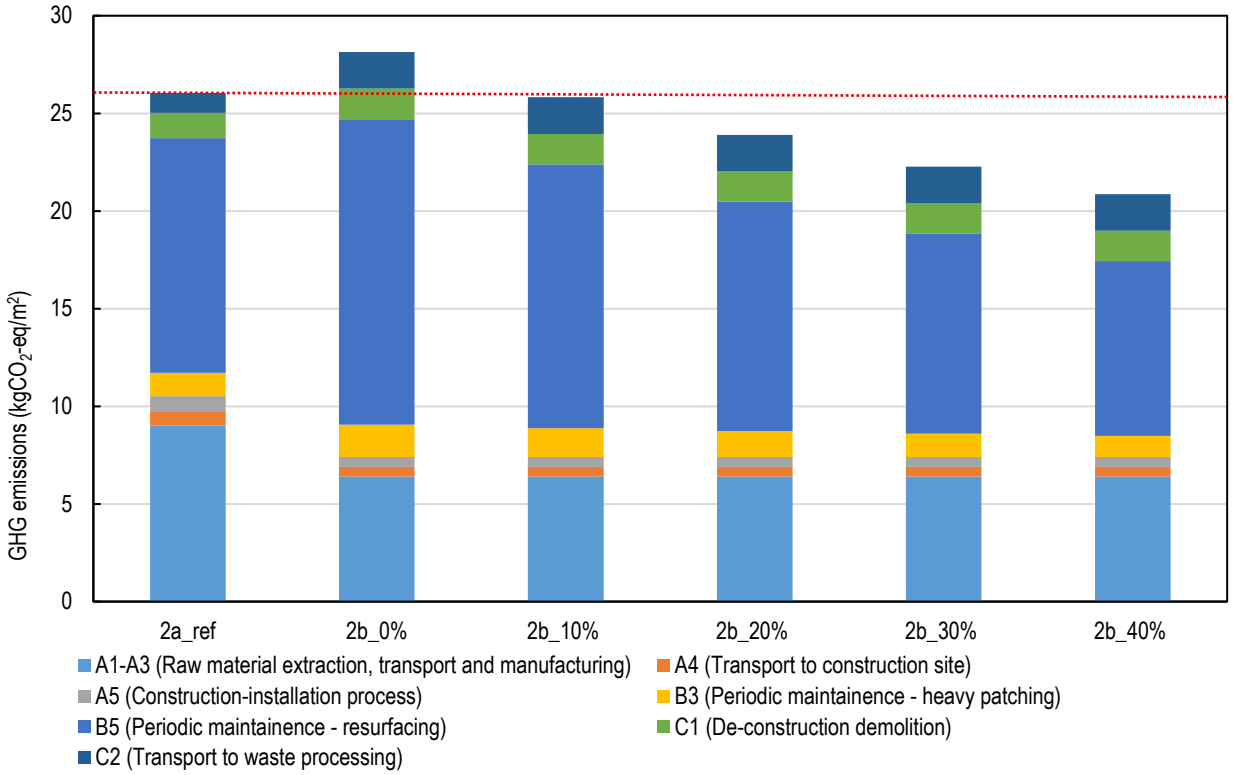



Table 4.3: GHG emissions by life cycle module and total for each case at site 2 ($kgCO_2$-e/$m^2$)

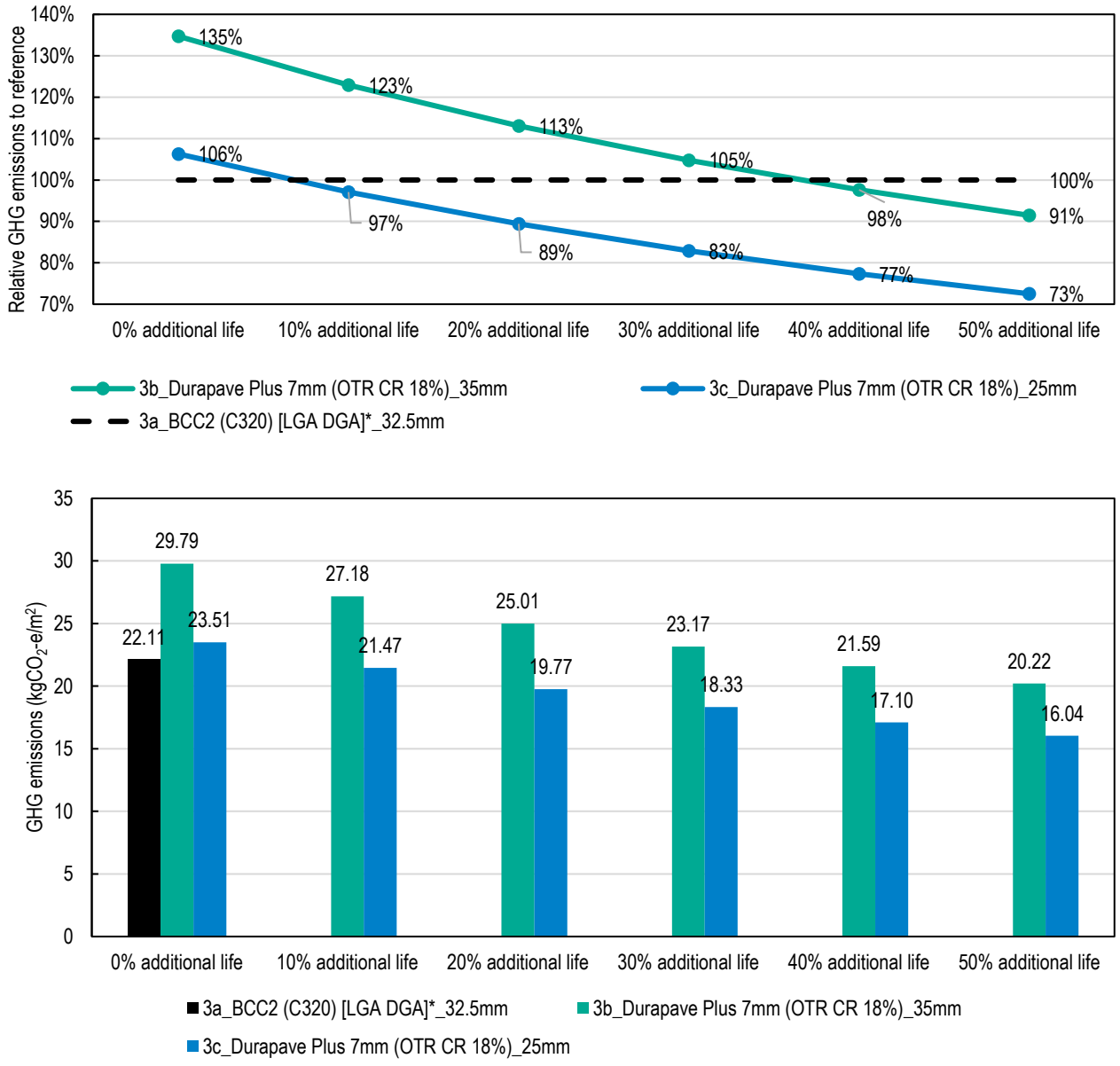
| Case | Additional Life | A1-A3 | A4 | A5 | B3 | B5 | C1 | C2 | Total |
|---|---|---|---|---|---|---|---|---|---|
| 2a (Ref) | 40% | 9.02 | 0.72 | 0.77 | 1.20 | 12.03 | 1.28 | 1.02 | 26.04 |
| 2b | 0% | 6.41 | 0.48 | 0.52 | 1.64 | 15.65 | 1.56 | 1.88 | 28.14 |
| | 10% | 6.41 | 0.48 | 0.52 | 1.47 | 13.52 | 1.56 | 1.88 | 25.84 |
| | 20% | 6.41 | 0.48 | 0.52 | 1.32 | 11.74 | 1.56 | 1.88 | 23.91 |
| | 30% | 6.41 | 0.48 | 0.52 | 1.19 | 10.23 | 1.56 | 1.88 | 22.27 |
| | 40% | 6.41 | 0.48 | 0.52 | 1.08 | 8.94 | 1.56 | 1.88 | 20.87 |

Note: The 2a_AC14 (A15E) mix is assumed to have a 40% service life compared to the traditional BCC LGA DGA mixes (see Section 3.4).

### 4.2.3 Site 3 Spalls Road

Figure 4.6 shows the relative cradle-to-grave GHG emissions (compared to the reference case) for varying additional service life. The CR-modified asphalt mixes Durapave Plus 7mm (OTR CR 18%) are assumed to have an extended service life relative to the reference mix (BCC2 (C320) [LGA DGA]). The total cradle-to-grave GHG emissions decrease progressively; when the CR-modified mixes achieve 40% and 10% additional service life for cases 3b and 3c, respectively, their cradle-to-grave GHG emissions are comparable to the reference case 3a. It should be noted that the paving thickness varies between cases, and so case 3c can achieve deeper GHG reductions due to the decreased thickness, if the service life can be extended. As cases 3a and 3b have similar thicknesses (32.5 mm and 35.0 mm, respectively), this provides a more direct comparison between the standard mix and the CR-modified mix, requiring approximately 35-40% additional service life to achieve parity with the reference.

Figure 4.6: Total 'cradle-to-grave' GHG emissions under varying additional service life scenarios at Site 3




Note: * Reference case does not have additional service life.

Table 4.4 and Figure 4.7 presents the breakdown of GHG emissions by life cycle stage. The periodic maintenance (B3 and B5) accounts for approximately 65% of total GHG emissions in case 3a and cases 3b and 3c under 0% additional life scenario. Extending the service life in 3b and 3c reduces its contribution to under 50% of total GHG emissions. This highlights the significant impact maintenance activities have on life cycle GHG emissions and how CR-modified mixes can reduce these impacts over conventional mixes.

Figure 4.7: GHG emissions for each life cycle module under varying additional service life scenarios at Site 3

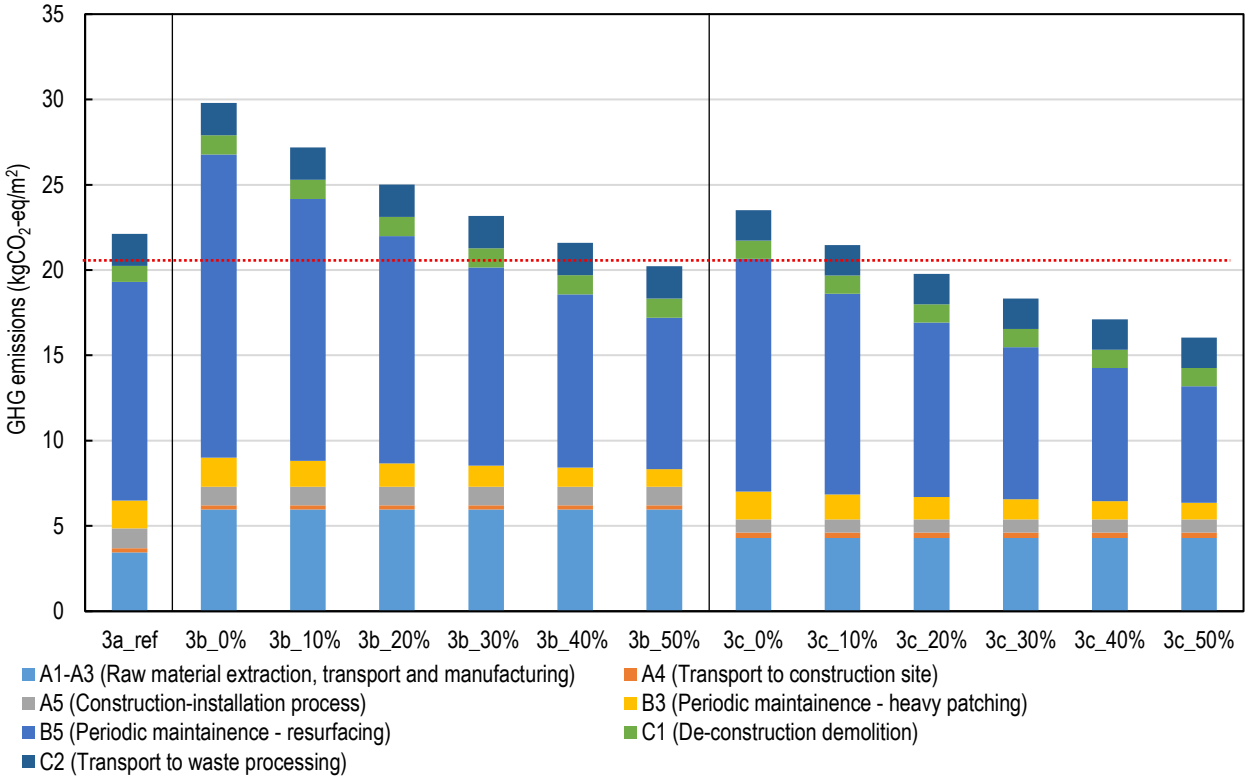



Table 4.4: GHG emissions by life cycle module and total for each case at site 3 ($kgCO_2$-e/$m^2$)

| Case | Additional Life | A1-A3 | A4 | A5 | B3 | B5 | C1 | C2 | Total |
|---|---|---|---|---|---|---|---|---|---|
| 3a (Ref) | 0% | 3.45 | 0.24 | 1.18 | 1.63 | 12.82 | 0.93 | 1.87 | 22.11 |
| 3b | 0% | 5.96 | 0.24 | 1.09 | 1.72 | 17.76 | 1.13 | 1.89 | 29.79 |
| | 10% | 5.96 | 0.24 | 1.09 | 1.53 | 15.34 | 1.13 | 1.89 | 27.18 |
| | 20% | 5.96 | 0.24 | 1.09 | 1.38 | 13.32 | 1.13 | 1.89 | 25.01 |
| | 30% | 5.96 | 0.24 | 1.09 | 1.25 | 11.61 | 1.13 | 1.89 | 23.17 |
| | 40% | 5.96 | 0.24 | 1.09 | 1.13 | 10.15 | 1.13 | 1.89 | 21.59 |
| | 50% | 5.96 | 0.24 | 1.09 | 1.03 | 8.88 | 1.13 | 1.89 | 20.22 |
| 3c | 0% | 4.29 | 0.32 | 0.78 | 1.63 | 13.64 | 1.07 | 1.78 | 23.51 |
| | 10% | 4.29 | 0.32 | 0.78 | 1.45 | 11.78 | 1.07 | 1.78 | 21.47 |
| | 20% | 4.29 | 0.32 | 0.78 | 1.30 | 10.23 | 1.07 | 1.78 | 19.77 |
| | 30% | 4.29 | 0.32 | 0.78 | 1.18 | 8.92 | 1.07 | 1.78 | 18.33 |
| | 40% | 4.29 | 0.32 | 0.78 | 1.07 | 7.79 | 1.07 | 1.78 | 17.10 |
| | 50% | 4.29 | 0.32 | 0.78 | 0.98 | 6.82 | 1.07 | 1.78 | 16.04 |

# 5. Conclusions

OTR tyres are durable and designed to be used in harsh environments such as construction, mining and agriculture. Unlike passenger and truck tyres, OTR tyres are typically buried or stockpiled on-site at remote locations, causing negative environmental impacts and wasting useful resources. To mitigate these impacts, the Sunshine Coast Council oversaw a project to be one of the first to trial the use of CR made from OTR tyres in several pavements across their network in 2024. The project compared unmodified (i.e. conventional local council reference) mixes to novel CR-modified mixes utilising OTR tyres from the construction industry. The findings of this project (12 months on from construction) demonstrated that OTR CR can be used interchangeably with traditional CR in bitumen. To close the loop of this trial, a cradle-to-grave LCA focussed on GHG emissions was undertaken on eight pavement sections comprising various local council reference mixes and novel CR-modified mixes installed across three sites in the Sunshine Coast.

The eight traditional and CR-modified pavements were examined across three sites:

- Site 1 (Perlan Street):
  - 1a: BCC2 (C320) [LGA DGA] – mill and fill (reference case).
  - 1b: GGA7 (OTR CR 18%) – edge plan and overlay.
  - 1c: GGA7 (OTR CR 18%) – mill and fill.
- Site 2 (Railway Parade):
  - 2a: AC14 (A15E) – edge plan, PMB seal and overlay (reference case).
  - 2b: GGA10 (OTR CR 18%) – edge plan, PMB seal and overlay.
- Site 3 (Spalls Road):
  - 3a: BCC2 (C320) [LGA DGA] – overlay (reference case).
  - 3b: Durapave Plus 7 mm (OTR CR 18%) – overlay (35 mm thickness).
  - 3c: Durapave Plus 7 mm (OTR CR 18%) – overlay (25 mm thickness).

The main outcomes from the LCA for the upfront carbon (i.e. constructing a new pavement) are:

- Upfront carbon is dominated by the input materials for the pavement (A1–A3), accounting for 65-85% of upfront GHG emissions.
- The CR-modified mixes have higher upfront carbon compared to the reference mixes for Sites 1 and 3.
- The AC14 (A15E) reference case has higher upfront carbon compared to the CR-modified mix for Site 2.

An examination of the impact of extended service life for the CR-modified mixes compared to the reference cases on the cradle-to-grave GHG emissions was undertaken, with the findings summarised for each site.

- Site 1 (Perlan Street):
  - At 0% additional service life, the CR-modified asphalt mixes have a higher carbon footprint by 4.13 to 5.34 $kgCO_2$-e/$m^2$ compared to the LGA DGA (BCC2).
  - When the service life is extended by 20-30%, the CR-modified asphalt mixes can achieve GHG parity with the LGA DGA (BCC2).
  - At 40% additional service life, the CR-modified asphalt mixes have a lower carbon footprint by 1.46 to 2.73 $kgCO_2$-e/$m^2$ compared to the LGA DGA (BCC2).
- Site 2 (Railway Parade):
  - At 0% additional service life, the CR-modified asphalt mix has a higher carbon footprint by 2.10 $kgCO_2$-e/$m^2$ compared to the AC14 (A15E).
  - When the service life is extended by 10%, the CR-modified asphalt mix can achieve GHG parity (–0.20 $kgCO_2$-e/$m^2$) compared to the AC14 (A15E).

  - At 40% additional service life, the CR-modified asphalt mix has a lower carbon footprint by 5.17 kgCO2-e/m2 compared to the LGA DGA (BCC2).
- Site 3 (Spalls Road):
  - At 0% additional service life, the CR-modified asphalt mixes have a higher carbon footprint by 1.40 to 7.68 $kgCO_2$-e/$m^2$ compared to the LGA DGA (BCC2).
  - When the service life is extended by 35%, the CR-modified asphalt mix with 35 mm thickness can achieve GHG parity compared to the LGA DGA (BCC2).
  - When the service life is extended by 35%, the CR-modified asphalt mix with 25 mm thickness can achieve GHG parity compared to the LGA DGA (BCC2).
  - At 50% additional service life, the CR-modified asphalt mixes have a lower carbon footprint by 1.89 to 6.07 $kgCO_2$-e/$m^2$ compared to the LGA DGA (BCC2).

The cradle-to-grave assessment demonstrates the potential GHG emissions reductions that can be achieved using CR-modified asphalt mixes compared to conventional mixes. Despite greater upfront GHG emissions (to construct the pavement), lower overall GHG emissions can be achieved by the CR-modified mixes due to the reduced maintenance activities.

The results demonstrate that CR from OTR vehicles (including construction vehicles) can be recycled into asphalt giving similar performance and environmental benefits to that of CR from end-of-life car and truck tyres. CR-modified asphalt has been shown to provide performance benefits over asphalt made with unmodified bitumen and can enhance fatigue performance in a similar way to costly, (high emission) polymer modified binders.

As these CR-modified mixes have only been installed relatively recently, their long-term performance should be monitored to understand the service life and maintenance requirements. As this information becomes available, this LCA can be revisited in the future for councils to assess GHG emissions savings from using CR-modified mixes with OTR tyres.

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