SSROC - Life Cycle Assessment and Potential Environmental Benefits of Crumb Rubber Asphalt using Field Data

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Document Summary

Selected Councils	Northern Beaches Council Project location: The Circle, Narraweena Burwood Council Project location: Park Ave, Burwood City of Sydney Project location: Sussex St, Haymarket
Product(s)	Pavement laid with/without crumb rubber modified asphalt
Declared functional unit	Per square meter (m^2) of pavement (asphalt layer only)
Analysis period	40 years
Standards	ISO 14040-14044, ISO 21930:2017, EN 15978:2011
Life Cycle Assessment (LCA) scope	Cradle-to-Grave
LCA study details	Dr. Quddus Tushar & Professor Filippo Giustozzi Royal Melbourne Institute of Technology RMIT University, Australia
Year of primary data collection	2023
LCA software	SimaPro version 9.2
LCA database	Australian Life Cycle Inventory (AusLCI)
LCA methodology Applicable regions	ReCiPe Midpoint (H) V1.12 / World Recipe H Australia

Important Note: The results and analysis presented in this report represent the relative expressions of the data sets obtained from the contractors at the specific construction site under consideration. It is important to note that these findings do not estimate the impacts category at the endpoint of the products and/or associated risks.

Acknowledgment: The authors would like to express their gratitude to Boral Asphalt NSW for collecting primary data on site.

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Executive Summary

This study evaluates the environmental impacts associated with incorporating crumb rubber (CR) from end-of-life tyres into bitumen for asphalt pavement construction. In 2023, the Southern Sydney Regional Organisation of Councils (SSROC) spearheaded a nationally significant initiative in New South Wales, aiming to pave asphalt roads using crumb rubber. Each of the eleven participating SSROC councils resurfaced a road using a CR-modified asphalt mix and compared its performance over time with a conventional asphalt mix (without crumb rubber) laid at the same location, exposed to similar traffic and weather conditions.

From the SSROC crumb rubber asphalt demonstration project, three councils—Northern Beaches Council, Burwood Council, and City of Sydney—were selected for a more in-depth investigation into the potential environmental benefits of using crumb rubber in council asphalt roads. The study conducted a comprehensive project-level Life Cycle Assessment (LCA) to evaluate the carbon footprint (kg CO2 eq) and other environmental impacts at all life cycle stages (including production, construction, and maintenance) of CR asphalt pavements compared to traditional ones.

The LCA analysed impacts related to the production of raw materials, including recycled materials like Reclaimed Asphalt Pavement (RAP) and recycled crushed glass, asphalt production processes, transportation, and paving operations during construction and maintenance phases. Additionally, a sensitivity analysis was conducted to assess the effectiveness of CR asphalt in reducing pavement emissions while enhancing pavement durability over the road asset's service life.

Key findings of the LCA study include:

1. Incorporating CR into asphalt mixes through the wet method (CR in bitumen as a modifier) can reduce environmental impacts during the production and construction phase compared to conventional asphalt, provided that part of the bitumen content is replaced by crumb rubber. For example, adding 10% CR by weight of the total binder (meaning that 100 grams of CR are added to 900 grams of virgin bitumen to manufacture 1 kg of CR modified binder) results in lower environmental impacts compared to using 1 kg of virgin bitumen, leading to reduced emissions during the construction phase.
2. Improvements in pavement performance due to CR-modified asphalt result in fewer maintenance interventions during the service life, consequently reducing environmental impacts (up to approximately 30%) associated with the maintenance phase of the road asset.
3. Indirect environmental benefits, such as recovering steel from end-of-life tyres during CR production and diverting waste tyres from landfills, can further decrease greenhouse gas emissions associated with using CR asphalt.

The extended service life and reduced environmental impacts underscore the importance of incorporating recycled materials, like CR, in asphalt for sustainable infrastructure development. The study's outcomes support the adoption of CR in asphalt mixes through policy incentives and awareness programs promoting sustainable practices in local council roads.

1. Introduction

1.1 Rationale behind the study

The rationale for undertaking this LCA study is in harmony with SSROC's dedication to sustainability. SSROC is committed to promoting the practical use of recycled materials in council roads by employing environmental assessment methodologies. These methodologies are designed to facilitate sustainable development and informed decision-making, ultimately enhancing waste management practices.

1.2 Standards

The methodology outlined in this report adheres to established LCA standards, including ISO 14040-14044, ISO 21930:2017, and EN 15978:2011. The analytical process incorporates terminology and techniques associated with the use of the Simapro 9.2 software tool for conducting Life Cycle Assessments (LCA) for road products, construction, and maintenance activities. The integration of the Australian Life Cycle Inventory (AusLCI) database proved instrumental in evaluating the environmental footprint of products, pinpointing areas for enhancing sustainability, and enabling informed decision-making related to resource management and strategies for reducing environmental impact (Grant, 2016).

1.3 Technical data

This study analyses technical data from conventional asphalt mixes and crumb rubber-modified asphalt pavements obtained from asphalt contractors through SSROC. The data includes asphalt mix composition, production processes, energy consumption, transportation, and paving operations. The information on the conventional asphalt mix design (i.e. without crumb rubber) includes quantities of various components such as sand, aggregates, filler, bitumen, Reclaimed Asphalt Pavement (RAP) material, and recycled crushed glass used in the three projects, as detailed in **Table 1**. Different councils adjusted these proportions based on local conditions, traffic loads, project characteristics, and other design considerations. The data sets from three councils were transmitted to RMIT University by SSROC. Specifically, the Burwood Council project involved paving both the base asphalt layer and wearing course using a dense graded (DG) mix. The City of Sydney resurfaced the wearing course with a dense graded heavy-duty asphalt mix, and the Northern Beaches Council opted for a conventional dense graded asphalt mix. Northern Beaches Council used C320 bitumen in their mixes, while C450 bitumen was used for the other two councils. As per the project guidelines developed by the Australian Flexible Pavement Association (AfPA), various contents of RAP and recycled crushed glass (GS) aggregate were included in the asphalt mix when anticipated.

Table 1 Composition of the control asphalt mixes used at SSROC councils

	Council	Burwood Council (base layer)	Burwood Council (wearing course)	City of Sydney	Northern Beaches Council
	Project Location	Park Ave, Burwood	Park Ave, Burwood	Sussex St, Haymarket	The Circle, Narraweena
	Date	1/06/2023	20/06/2023	21/06/2023	23/06/2023
	Total tonnes of Asphalt	261.3	271.4	116.58	128.34
	Contractor Product ID	DG20 C450 15% RAP 10% GS	DG14 C450 2.5% GS	DG14 C450 HD 20% RAP 2.5% GS	DG10 C320 AUSPEC
1	**Materials used in the project (%)**				
a)	Total sand content	21.8	46.8	26.8	57.9
b)	Total coarse aggregate content	47.3	43.6	45.0	34.3
c)	Filler content/type - (Auspec Mixes = Baghouse Fines; *Heavy Duty mixes = Hydrated Lime)	2.0	2.0	*1.5	2.0
d)	RAP content (RAP Size ≤ 14 mm)	15.0	-	20.0	-
e)	Bitumen content (Excluding binder recovered from RAP)	3.9	5.1	4.2	5.8
f)	Recycled crushed glass content	10.0	2.5	2.5	-
2	**Asphalt production (electricity in kWh, LPG in MJ)**				
a)	Type of plant:	Astec T300 Drum Plant (Boral Asphalt NSW)			
b)	Electricity consumption per project (Astec advised value - 5.7 kWh/ton asphalt)	1489.41	1546.98	664.51	725.72
c)	LPG consumption per project (Astec advised value - 100 MJ/ton of asphalt)	26130	27140	11658	12834
3	**Transportation (km)**				
a)	Distance from asphalt plant to site (km)	6.2	6.2	19.5	33.5
b)	Distance from bitumen plant (SAMI Bitumen, NSW) to Boral asphalt plant (km)	23.2			
4	**Paving operations**				
a)	Type of intervention and layer thickness	Mill & Fill (150 mm) in particular areas	Mill & Fill (50 mm)	Mill & Fill (50 mm)	Mill (20 mm) & Fill (30 mm) (Overlay)
b)	Milling machine: brand model, time of operation (h) or fuel consumption (L)	Wirtgen – approx. 6 hours			
c)	Asphalt paver: brand/model, time of operation (h) or fuel consumption (L)	Roadtek - RP175EX- approx. 8 hours	Roadtek - RP175EX- approx. 8 hours	Roadtek - RP175EX- approx. 8 hours	Vogele 5100 – approx. 8 hours
d)	Rollers: brand/model, time of operation (h) or fuel consumption (L)	Hamm HD70 (Steel), Dynapac CP142 (Multi), Hamm HD10C (Steel) – approx. 8 hours			
5	**Project data as transmitted by the Contractor**				
a)	Length of paving section/s (m)	60 m	145 m	180 m	170 m
b)	Width of paving section/s (m)	11 m	11 m	5.2 m	7 m
c)	Thickness of paving section/s (m)	0.15 m	0.05 m	0.05 m	0.05 m

Crumb Rubber (CR) modified asphalt was prepared using three crumb rubber binders (S9R, S15R, and A18R) in accordance with the latest Austroads specifications. Additionally, a warm mix asphalt additive (Sasobit) was incorporated. The binder classifications S9R, S15R, and A18R align with the Austroads standards for polymer-modified binders in ATS3110. Specifically, S9R contains approximately 9%

crumb rubber content by weight of the binder, while S15R and A18R contain 15% and 18% crumb rubber, respectively.

The incorporation of crumb rubber serves the purpose of enhancing pavement performance and durability by providing additional resistance to cracking, rutting, and binder ageing. Details regarding aggregate grading (DG = Dense Graded and GGA = Gap Graded), the type of bitumen (C450, C320), as well as information about asphalt production processes and pavement construction machinery, can be found in **Table 2**.

Table 2 Composition of the crumb rubber modified asphalt mixes used at SSROC councils

	Council	Burwood Council (base layer)	Burwood Council (wearing course)	City of Sydney	Northern Beaches Council
	Project Location	Park Ave, Burwood	Park Ave, Burwood	Sussex St, Haymarket	The Circle, Narraweena
	Date	6/06/2023	19/06/2023	28/06/2023 & 29/06/2023	22/06/2023
	Total tonnes of Asphalt	174.6	176.82	117.22	100.5
	Contractor Product ID	GGA20 A18R, 2% WMA additive	GGA14 A18R, 2% WMA additive	DG14 S45R, 2% WMA additive, 2.5% GS	DG10 S9R, 2% WMA additive, 20% RAP, 2.5% GS
1	**Materials used in the project (%)**				
a)	Total sand content	17.1	16.6	39.7	34.9
b)	Total coarse aggregate content	74.4	74.4	50.5	36.1
c)	Filler content (GGA mixes = hydrated lime; DG mixes = baghouse fines)	1.0	1.0	2	1.5
d)	RAP content (RAP size ≤ 14 mm)	-	-	-	20
e)	Total binder content	7.5	8	5.3	5.0
f)	Crumb rubber content	S18R	S18R	S15R	S9R
g)	Recycled crushed glass	-	-	2.5	2.5
2	**Asphalt production (electricity in kWh, LPG in MJ)**				
a)	Type of plant:	Astec T300 Drum Plant (Boral Asphalt NSW)			
b)	Electricity consumption per project (Astec advised value - 5.7 kWh/ton of asphalt)	995.22	1007.87	668.15	572.85
c)	LPG consumption per project - (Astec advised value - 100 MJ/ton of asphalt)	17460	17682	11722	10050
3	**Transportation**				
a)	Distance from asphalt plant to site (km)	6.2	6.2	19.5	33.5
b)	Distance from bitumen plant (SAMI Bitumen, NSW) to Boral asphalt plant (km)	23.2			
4	**Paving Operations**				
a)	Type of intervention and layer thickness	Mill & Fill (150 mm) in particular areas	Mill & Fill (50 mm)	Mill & Fill (50 mm)	Mill (20 mm) & Fill (30 mm) (Overlay)
b)	Milling machine: brand model, time of operation (h) or fuel consumption (L)	Wirtgen – approx. 6 hours			
c)	Asphalt paver: brand/model, time of operation (h) or fuel consumption (L)	Roadtek - RP175EX- approx. 8 hours	Roadtek - RP175EX- approx. 8 hours	Roadtek - RP175EX- approx. 8 hours	Vogele - 5100 – approx. 8 hours
d)	Rollers: brand/model, time of operation (h) or fuel consumption (L)	Hamm HD70 (Steel), Dynapac CP142 (Multi), Hamm HD10C (Steel) – approx. 8 hours			
5	**Project DATA**				
a)	Length of paving section/s (m)	40 m	145 m	140 m	170 m
b)	Width of paving section/s (m)	11 m	11 m	5.2 m	7 m
c)	Thickness of paving section/s (m)	0.15 m	0.05 m	0.05 m	0.05 m

2. Goal and Scope Definition

This study conducted a comprehensive Life Cycle Assessment (LCA) to assess the environmental impact of integrating crumb rubber (CR) in road construction, using primary data provided by both the asphalt contractor and SSROC. The analysis included various phases, including raw materials extraction, manufacturing, asphalt and crumb rubber production, transportation, pavement construction operations, and diverse maintenance scenarios throughout the road's service life.

The study focused on the analysis of Carbon Footprint (measured in kg CO2-eq) and compared it between projects, considering the Life Cycle Inventory (LCI) of conventional and crumb rubber asphalt mixes employed in the SSROC demonstration project. Three distinct roads from SSROC councils—Burwood Council, Northern Beaches Council, and City of Sydney—were evaluated to yield valuable insights into the environmental implications of opting for CR as a sustainable pavement material.

2.1 Methodology

Attributional LCA was employed in this study to comprehend and quantify the direct environmental impacts associated with the use of asphalt material modified with crumb rubber (CR) in pavement construction operations. Attributional LCA relies on specific data about the processes and materials involved in the product's life cycle. In contrast to consequential LCA, which involves assessing potential systemic changes and global environmental consequences, attributional LCA provides an accurate evaluation of carbon emissions at the project level.

The Australian Life Cycle Inventory (AusLCI) incorporates inputs and outputs of pavement materials' energies and emissions related to production, operation, transportation, and other processes throughout their life cycle. The impact category *climate change* (measured in kg CO_2-eq) was employed in this study to facilitate comparisons between alternatives. This impact indicator expresses the impact on global warming potential of each greenhouse gas in terms of the amount of CO_2 that would create the same level of warming. In essence, in an LCA study examining climate change impacts, emissions of other greenhouse gases, such as methane (CH_4) or nitrous oxide (N_2O), are converted into CO_2 equivalents.

While this report primarily compares construction alternatives using the climate change indicator (CO2-eq), additional environmental impact indicators are also detailed in the Appendix.

2.2 Functional unit

The functional unit in LCA studies provides a standardised basis for comparing the environmental impacts associated with a particular product or process. In this study, the construction and maintenance of one square meter (1 m^2) of asphalt pavement using crumb rubber were compared to conventional asphalt. The length, width, and thickness of the asphalt pavements laid were extracted from the specified project data for the three SSROC councils analysed.

Various life cycle stages were examined to identify environmental impacts related to electricity and fuel consumption, greenhouse gas (GHG) emissions, and other relevant factors, all referred to the functional unit of 1 m^2. Specifically, the following phases were considered:

1. Extraction of raw materials;
2. Manufacturing of products;
3. Transportation of materials;
4. Pavement construction operations;
5. Pavement maintenance.

2.3 Assumptions on the durability of CR modified asphalt

Incorporating crumb rubber (CR) into asphalt pavements has demonstrated promising results in enhancing pavement durability while reducing maintenance needs, thereby offering significant environmental benefits for the recycling of end-of-life tyres (Joohari and Giustozzi, 2022). In this study, an analysis period of 40 years was considered to assess emissions associated with pavement maintenance operations. The chosen pavement maintenance strategy involves periodic milling and filling of the pavement surface layer (i.e. removal and replacement of the same thickness) every ten (10) years, resembling a typical pavement maintenance strategy. Additionally, an extension of pavement service life ranging from 10% to 40% was considered for CR-modified asphalt compared to conventional asphalt, aiming to evaluate potential changes in environmental impacts over the pavement's lifespan due to the addition of CR.

The extended durability of CR-modified asphalt pavements finds support in a substantial body of literature indicating the following benefits:

1. Resistance to Cracking: CR enhances resistance to cyclic loading and bottom-up cracking.
2. Resistance to Rutting: CR improves mix resistance to permanent deformation under heavy traffic, thanks to the improved elasticity of the mix at high temperatures.
3. Resilience to Temperature Variations: CR-modified asphalt performs well in both high and low-temperature environments, reducing the risks of damage due to thermal cycles.
4. Improved Resistance to Moisture Damage: CR-modified binder can provide additional coating to the aggregate, thereby reducing the risks of water-related pavement damage.
5. Resistance to Ageing: CR slows down the ageing process of asphalt, mitigating oxidative hardening, photooxidation due to UV radiations, and maintaining overall pavement flexibility over an extended period compared to conventional asphalt.

2.4 System boundary

The system boundary for this LCA is Cradle-to-Grave, excluding the end-of-life disposal of the road material. Life-cycle stages defined by EN 15978 are incorporated into this analysis, as illustrated in **Figure 1**.

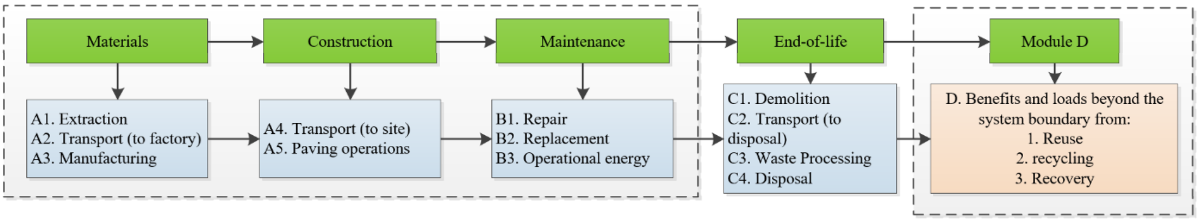


Figure 1 System Boundary of the LCA; the dotted line represents the boundaries of this LCA study (i.e. processes considered in the analysis)

2.4.1 Materials (EN 15978 A1-A3)

Materials production includes the extraction of raw materials, transportation, and manufacturing. In the case of recycled materials, the collection, sorting, and processing become significant factors to consider. The manufacturing of recycled materials, such as crumb rubber production from end-of-life tyres, involves various steps, including collection, sorting, shredding, grinding, and removing steel wires, as documented in a previous study by the authors (refer to Section 3.2).

2.4.2 Construction (EN15978 A4-A5)

The paving data supplied by the asphalt contractors includes recorded time and fuel usage during pavement construction and maintenance operations using various types of machinery, including the profiler (milling machine), paver, and rollers. Additionally, transportation distances and fuel usage from the asphalt plant to the pavement construction site were taken into account. The assessment of environmental impacts also incorporated the fuel consumption of trucks per kilometre of travel.

2.4.3 Maintenance (EN15978 B1-B3)

The conventional maintenance strategy employed in this study involves replacing the wearing course (40 mm) every ten years over the 40-year analysis period, resulting in four maintenance interventions for conventional asphalt pavements. In the LCA, a modelled service life extension (ranging from 10% to 40%) due to the addition of CR in the asphalt mix was considered. For example, a 10% extension in the durability of CR-modified pavement would lead to one maintenance intervention every 11 years instead of every 10 years. Each maintenance intervention includes the manufacturing of new asphalt mix, whether conventional or CR-modified asphalt, transportation to the site, and the subsequent use of machinery to lay the asphalt.

2.4.4 Module D (EN15978 D)

This LCA explores the potential recovery opportunities for by-products from end-of-life tyres (excluding crumb rubber) beyond the system's boundaries and examines their corresponding reduction in environmental impacts.

2.5 Cut-off criteria

The construction machinery, equipment, and recycling facilities utilized in this project are treated as reusable systems. Following each use, these versatile systems can be redeployed for producing new products. As a result, the environmental impacts associated with the installation of an asphalt plant and other manufacturing and recycling facilities are excluded from the project scope.

2.6 Allocation procedures

The allocation procedures in this study adhere to the ISO 14040/44 guidelines. Specifically, only raw materials manufacturing was considered when analysing asphalt production processes, eliminating the need for allocation based on co-products. However, the study also evaluated the redirection of recycled materials, such as steel and other by-products of end-of-life tyre recycling, to other applications.

Inputs for asphalt production, including materials (tonnes), electricity (kWh) and LPG (MJ) usage, and fuel consumption (L), were calculated using a physical mass basis for allocation purposes to assess the impacts of the manufacturing process.

The method followed in this study to model the recycling of end-of-life tyres involves tyre collection, shredding, sorting steel and textile fibre, and other processing activities. This method excludes impacts and benefits related to the previous life of a raw material derived from recycled sources within the system boundary. However, it considers the additional benefit of avoiding end-of-life tyre disposal in landfills and the potential recycling of steel.

3. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) of pavement materials entails evaluating the input and output flows associated with their life cycle. To assess the sustainability of various pavement materials, a comprehensive account of volumes, energy consumption, machinery, fuel consumption, and resource usage at each stage of a product's life cycle is essential.

3.1 Materials production

The Life Cycle Inventory (LCI) of raw materials involves extracting or obtaining materials, such as mining aggregates or extracting bitumen from crude oil. Aggregates for base layers and wearing courses in pavements include sand, gravel, and recycled crushed glass. Bitumen, binding aggregates together, is derived from crude oil. Crumb rubber from end-of-life tyres is used as an additive/polymer to modify the original bitumen (wet method), enhancing its durability and performance, thereby promoting sustainability. Filler, such as natural aggregate or hydrated lime, is added as a supplementary material to improve asphalt performance. The Australian Life Cycle Inventory (AusLCI) was used in this study to identify the associated impacts of these materials. **Table 3** lists some sources for manufacturing these products according to the AusLCI inventory.

Table 3 Life Cycle Inventory (LCI) of pavement materials as per the Australian Life Cycle Inventory (AusLCI). Other primary data sets were acquired directly from recycling facilities (i.e. to analyse crumb rubber and recycled crushed glass).

Materials production	Amount	Unit
Production of bitumen (1 ton)		
Electricity, low voltage, Australian	133.59	kWh
Liquefied petroleum gas, combusted in industrial boiler	0.916	ltr
Natural gas, combusted in industrial boiler	8.850	m^3
Residual fuel oil, combusted in industrial boiler	21.71	ltr
Transport, ocean freighter, average fuel mix	4582	tkm
Production of gravel (1 ton)		
Lubricating oil at the plant	0.0025	kg
Diesel, burned in building machine	14.3	MJ
Electricity, low voltage, Australian	9.06	kWh
Heat, light fuel oil, at boiler 10 kW	4.91	MJ
Transport, lorry 20-28 t, fleet average	0.0172	tkm
Tap water at the user	12.2	kg
Production of limestone (1 ton)		
Diesel, burned in building machine	18	MJ
Light fuel oil, burned in boiler 100 kW	0.594	MJ
Energy from fuel oil	91.9	MJ
Electricity, low voltage, Australian	32.5	kWh
Production of hydrated lime (1 ton)		
Limestones milled at plant	2000	kg
Transport, lorry 20-28 t, fleet average	490	tkm
Electricity, low voltage, Australian	124	kWh
Energy from natural gas	5400	MJ
Production of sand (1 ton)		

Materials production	Amount	Unit
Diesel, burned in building machine	14.7	MJ
Electricity, low voltage, Australian	2.72	kWh
Heat, light fuel oil, at boiler 10 kW	2.44	MJ
Water, drinking, Australia	10.1	ltr
Transport, truck, 28 t, fleet average	0.0172	tkm
Transport, van 3,5 t	0.0155	tkm
Reclaimed Asphalt Pavement (RAP) preprocessing (1 ton)		
Diesel consumption, on-site milling	0.29	ltr
Diesel consumption, transportation to the plant	0.25	ltr
Diesel consumption, crushing and sieving at the plant	0.63	ltr
Production of paraffin wax (1 ton)		
Electricity medium voltage, Australian grid	87	kWh
Heavy fuel oil in an industrial furnace	1810	MJ
Natural gas at an industrial furnace	2780	MJ
Transport, lorry > 16 t, fleet average	415	tkm
Landfill of waste (1 ton)		
Diesel used in Industrial machinery (0.001 m^3)	38.6	MJ
Transport truck 3.5 to 16 t, fleet average	40	tkm
Production of Recycled Crushed Glass (1 ton)		
Electricity, washing process	1.33	kWh
Electricity, crushing process	1.5	kWh
Bobcat, diesel consumption	0.46	ltr
Transportation (Fuel consumption in litre)	0.086	ltr
Water	50	ltr

3.2 Recycled materials: Crumb Rubber and Recycled Crushed Glass

Data pertaining to the input and output flows in the production processes of crumb rubber (CR) from end-of-life tyres were systematically collected directly from the recycling plant, as detailed in **Table 4** (Tushar et al., 2022). Determining the electricity consumption during CR production involved cross-referencing facility primary data with technical specifications outlined in the recycling machines' datasheets. The machinery operating time at the tyre recycler (shredder, rasper, granulator, and cracker mill) and fuel consumption were monitored to calculate the energy consumption and associated emissions to produce 1 ton of CR from end-of-life tyres.

The Life Cycle Inventory (LCI) of recycling waste glass includes washing and crushing processes (Tushar et al., 2023), as indicated in **Table 3**. Typically, about 90 tonnes of recycled glass aggregate are generated from 100 tonnes of collected waste glass during crushing. Approximately 5% of deleterious and non-recoverable materials, such as container tops, wood, foil, and other materials, are directed to landfills. The remaining 5% consists of bricks, plasters, and ceramics that are recovered and can be used as aggregates in construction.

Table 4 Life Cycle Inventory (LCI) for the production of 1-ton crumb rubber (CR)

Step1: Recycled waste tyres are transported to the recycling plant	
Process	Fuel consumption
Transportation (45 km)	8.28 L
Input: fuel consumption	**8.28 Litres of diesel**
Output: recyclable waste tyres (1.25 ton)	
Step2: Recycled tyres conveyed into the shredder (20 minutes)	
Barclay shredder	Energy consumption
Barclay shredder motor	25 kWh
Classifier	1.25 kWh
4 Conveyor belts	2 kWh
Input: Energy consumption from national grid	**28.25 kWh**
Output: 6-inch tyre shreds (1.25 ton)	
Step3: Shredded tyres conveyed into the rasper (15 minutes)	
Rasper	Energy consumption
Rasper Motor	45 kWh
2 Conveyor belts	0.75 kWh
Bobcat (diesel-operated)	1.88 L
Input: Electricity and fuel consumption	**45.75 kWh and 1.88 Litres of diesel**
Output: 25 mm tyre chunks (1 ton), steel (0.2 ton), and fibres (0.05 ton)	
Step4: Tyre chunks are conveyed into the granulator (15 min)	
Granulation	Energy consumption
Granulator motor	27.5 kWh
Air Conveyor	1.25 kWh
Input: Electricity consumption	**28.75 kWh**
Output: tyre granules (1 ton)	
Step5: Tyre granules are processed through the cracker mill (120 min)	
Cracker mill	Energy consumption
Cracker mill motor	220 kWh
Air conveyor	10 kWh
Cooler	62.5 kWh
Industrial sieve	11 kWh
Forklift (diesel-operated)	0.1 L
Input: Electricity consumption	**303.5 kWh and 0.1 litres of diesel**
Output: crumb rubber (1 ton)	

3.3 Materials used over the LCA analysis period

Quantifying pavement materials throughout the entire life cycle of a road requires considering both the initial construction and subsequent quantities needed for maintenance interventions, such as rehabilitation and/or resurfacing. The life cycle impact analysis also takes into account the environmental impacts associated with the extraction, manufacturing, transportation, and paving of these materials.

3.3.1 Life Cycle Inventory (LCI) - Construction Phase

Throughout the construction process, the Life Cycle Inventory (LCI) of both conventional asphalt and crumb rubber asphalt was considered to assess the materials used and the electricity, natural gas, and fuel consumed, as outlined in **Table 5** and **Table 6**. The amount of electricity (kWh) and LPG (MJ) required to heat and mix aggregates with bitumen to produce asphalt was estimated for the three council projects. The transportation of asphalt from the plant to the construction site was also documented to quantify fuel consumption and analyse emissions.

The time for site preparation, milling activities, etc., was recorded by the contractor to estimate fuel consumption due to the use of heavy machinery. Asphalt laying and compaction were also evaluated to quantify the energy consumption of paving machinery, such as rollers and pavers, and their fuel usage.

The Life Cycle Inventory of materials during construction provides insights into the mix design of CR asphalt with a warm mix additive (2% by weight of the binder). The analysis of data from this inventory can identify opportunities for improving construction practices, optimizing resource use, and reducing the carbon footprint for more sustainable road operations.

Table 5 Life Cycle Inventory of the conventional asphalt mixes at SSROC councils as transmitted by the contractor

Council name and dimensions (m)	Burwood wearing course (145×11×0.05)		Burwood base course (60×11×0.15)		Northern Beaches (170×7×0.05)		City of Sydney (180×5.2×0.05)	
Materials	**%**	**Tonnes**	**%**	**Tonnes**	**%**	**Tonnes**	**%**	**Tonnes**
Sand	46.80	127.02	21.80	56.96	57.94	74.35	26.80	31.24
Coarse aggregate	43.60	118.33	47.30	123.59	34.33	44.05	45.00	52.46
Natural filler	2.00	5.43	2.00	5.23	1.98	2.55	-	-
Hydrated lime	-	-	-	-	-	-	1.50	1.75
RAP	-	-	15.00	39.20	-	-	20.00	23.32
Bitumen	5.10	13.84	3.90	10.19	5.75	7.38	4.20	4.90
Crumb Rubber (CR)	-	-	-	-	-	-	-	-
Recycled Crushed Glass (RG)	2.50	6.79	10.00	26.13	-	-	2.50	2.91
WMA additive	-	-	-	-	-	-	-	-
Summation (Total materials)	100.00	271.40	100.00	261.30	100.00	128.34	100.00	116.58
Production	**Electricity consumption (5.7 kWh/ton) and LPG consumption (100 MJ/ton)**							
Electricity (kWh)	1546.98		1489.4		725.7		664.5	
LPG (MJ)	27140		26130		12834		11658	
Paving Operations	**Fuel consumption in Litres**							
Milling	29.85		28.74		14.01		12.82	
Paving (asphalt paver)	78.16		64.69		61.09		64.69	
Roller 01	53.74		44.47		42.00		44.47	
Roller 02	20.74		17.17		16.21		17.17	
Roller 03	37.83		31.31		29.57		31.31	
Transportation	**Fuel consumption in Litres**							
From plant to site	75.67		88.73		120.72		95.45	

Table 6 Life Cycle Inventory of the CR modified asphalt mixes at SSROC councils as transmitted by the contractor

Council name and dimensions (m)	Burwood wearing course(145×11×0.05)		Burwood base layer (40×11×0.15)		Northern Beaches (170×7×0.05)		City of Sydney (140×5.2×0.05)	
Materials	**%**	**Tonnes**	**%**	**Tonnes**	**%**	**Tonnes**	**%**	**Tonnes**
Sand	16.60	29.35	17.10	29.86	34.90	35.07	39.70	46.54
Coarse aggregate	74.40	131.55	74.40	129.90	36.10	36.28	50.50	59.20
Natural filler	-	-	-	-	1.50	1.51	2.00	2.34
Hydrated lime	1.00	1.77	1.00	1.75	-	-	-	-
RAP	-	-	-	-	20.00	20.10	-	-
Binder (%) Bitumen (B)	8.00	11.60	7.50	10.74	5.00	5.03	5.30	5.28
Binder (%) Crumb Rubber (CR)	A18R	2.55	A18R	2.36	S9R	0.45	S15R	0.93
Recycled Crushed Glass (RG)	0.00	0.00	0.00	0.00	2.5	2.51	2.50	2.93
WMA additive	2% binder	0.28	2% binder	0.26	2% binder	0.10	2% binder	0.12
Summation (Total materials)	100.00	176.82	100.00	174.60	100.00	100.50	100.00	117.22
Production	**Electricity consumption (5.7 kWh/ton) and LPG consumption (100 MJ/ton)**							
Electricity (kWh)	1007.87		995.2		572.9		668.2	
LPG (MJ)	17682		17460		10050		11722	
Paving Operations	**Fuel consumption in Litres**							
Milling	19.45		19.21		11.06		12.89	
Paving (Asphalt paver)	78.16		43.12		61.09		32.34	
Roller 01	53.74		29.65		42.00		22.24	
Roller 02	20.74		11.44		16.21		8.58	
Roller 03	37.83		20.87		29.57		15.65	
Transportation	**Fuel consumption in Litres**							
From plant to site	65.19		65.19		177.34		130.47	

3.3.2 Life Cycle Inventory (LCI) - Maintenance Phase

A comparative analysis was conducted to model the maintenance phase of road pavements using conventional and CR modified asphalt, as detailed in **Table 7** and **Table 8**. Specifically, it was assumed that any maintenance intervention during the service life of the pavement involved milling a 40 mm existing wearing course and resurfacing with 40 mm of asphalt. The asphalt mix used for maintenance is either *a)* CR modified asphalt at 9% CR content (S9R) or *b)* a conventional asphalt mix without CR.

Regular maintenance interventions (mill and fill) are scheduled every ten years to preserve the pavement's condition. However, following recent literature, the incorporation of CR into the asphalt mix was modelled to extend the pavement's life expectancy due to increased resistance to rutting, cracking, and overall pavement ageing. Due to uncertainty surrounding the extent of the service life extension of asphalt pavements due to CR and external conditions affecting the accuracy of this prediction at each project site, this study assumed that CR would result in at least a 10% increase in pavement durability (worst-case scenario) and up to 40% (best-case scenario). However, a nil increase in pavement durability due to the addition of CR in the asphalt mix was also modelled in the LCA. The analysis period was set at 40 years. The environmental impacts associated with these strategies are further detailed in Section 4 of this report. Refer to Section 2.4.3 for more information on the assumptions related to the maintenance phase.

The tables below present the volume of material, mix design, machinery consumptions, and energy consumptions for maintenance interventions in the case of milling and filling using conventional asphalt and CR-modified asphalt.

Table 7 Maintenance intervention (LCI) using conventional asphalt

Council name and pavement dimension (m)		Burwood (145×11×0.04)	Burwood (40×11×0.04)	Northern Beaches (170×7×0.04)	City of Sydney (140×5.2×0.04)
Materials	**(%)**	**Quantity of materials in Tonnes**			
Sand	58.10	88.96	24.54	66.37	40.60
Coarse aggregate	34.60	52.98	14.62	39.53	24.18
Natural filler	1.50	2.30	0.63	1.71	1.05
Bitumen	5.80	8.88	2.45	6.63	4.05
Summation (Total materials)	100.00	153.12	42.24	114.24	69.89
Production	**Electricity consumption (5.7 kWh/ton) and LPG consumption (100 MJ/ton)**				
Electricity (kWh)		872.78	240.77	651.17	398.36
LPG (MJ)		15312.00	4224.00	11424.00	6988.80
Paving Operations		**Fuel consumption in Litres**			
		207.31	109.73	161.44	130.29
Transportation		**Fuel consumption in Litres**			
From plant to site		59.26	17.78	224.14	93.19

Table 8 Maintenance intervention (LCI) using CR modified asphalt

Council name and pavement dimension (m)			Burwood (145×11×0.04)	Burwood (40×11×0.04)	Northern Beaches (170×7×0.04)	City of Sydney (140×5.2×0.04)
Materials		**%**	**Quantity of materials in Tonnes**			
Sand		58.10	88.96	24.54	66.37	40.60
Coarse aggregate		34.60	52.98	14.62	39.53	24.18
Natural filler		1.50	2.30	0.63	1.71	1.05
Binder (%)	Bitumen (B)	5.80	8.08	2.23	6.03	3.69
	Crumb Rubber (CR)	S9R	0.80	0.22	0.60	0.36
WMA additive		2% binder	0.18	0.05	0.13	0.08
Summation (Total materials)		100.00	153.12	42.24	114.24	69.89
Production			**Electricity consumption (5.7 kWh/ton) and LPG consumption (100 MJ/ton)**			
Electricity (kWh)			872.78	240.77	651.17	398.36
LPG (MJ)			15312.00	4224.00	11424.00	6988.80
Paving Operations			**Fuel consumption in Litres**			
			207.31	109.73	161.44	130.29
Transportation			**Fuel consumption in Litres**			
Plant to site			59.26	17.78	224.14	93.19

4. Life Cycle Impact Assessment (LCIA)

The LCA tool SimaPro 9.2 was employed to analyse the datasets collected in the LCI phase, thereby quantifying the environmental impacts for each project. Input materials for both the conventional asphalt mix and CR modified asphalt mix, as well as transportation and paving operations during construction and maintenance over the analysis period, were previously identified in the LCI phase (Section 3). The impact assessment method, ReCiPe 2016 v1.1, was used to evaluate the climate change indicator (kg CO2 eq), considering a time horizon of 100 years (Huijbregts et al., 2017).

Table 9 Life Cycle Impact Assessment (LCIA) indicator

Impact Category	Method	Unit
Climate Change	ReCiPe Midpoint (H) V1.12 / World Recipe H	kg CO_2 eq

The assessment evaluates the climate change impact category, hereafter referred to as *carbon footprint*, for each component and process. The goal is to identify areas where the most significant environmental impacts occur and consider opportunities for more sustainable pavement operations.

4.1 Environmental Impacts Assessment - Construction Phase

The carbon footprint (kg CO_2eq) of constructing a pavement using conventional and crumb rubber-modified asphalt for one square meter (1 m^2) is detailed in **Table 10**. The analysis includes raw materials extraction, manufacturing, transportation to the site, and paving operations. Overall, incorporating crumb rubber (CR) with a Warm Mix Asphalt (WMA) additive as a partial replacement or in conjunction with bitumen in pavement construction has the potential to enhance the environmental sustainability of the pavement.

A 22.34% reduction in environmental impacts was observed for the project at the Northern Beaches Council (50 mm thickness) when using CR asphalt compared to a conventional asphalt (CA) pavement during production and construction operations, as shown in **Figure 2**. However, in the case of Burwood Council (50 mm thickness), where a gap-graded asphalt mix (GGA) was used, a smaller decrease (2.85%) in CO_2eq was observed for using CR. For this project, the use of hydrated lime in the CR modified asphalt mix, instead of natural filler, contributed to a substantial increase in the carbon footprint. Hydrated lime generates significantly more environmental impacts than natural quarry filler in asphalt pavement construction. Specifically, hydrated lime (1.5% by weight of the total mix) in asphalt increases the carbon footprint by 1558.85 kg CO_2-eq compared to natural filler (98.86 kg CO_2-eq) for the City of Sydney. However, by incorporating 20% Reclaimed Asphalt Pavement (RAP) in the asphalt mixture, the council reduced the carbon footprint of the project, resulting in 8.12 kg CO_2 eq per m^2 of pavement.

The incorporation of Reclaimed Asphalt Pavement (RAP) material in the conventional asphalt mix at the City of Sydney provided a substantial environmental benefit by reducing raw resource consumption, energy use, emissions, waste generation, and overall environmental impacts associated with the pavement construction project. Compared to the CR asphalt alternative that did not include RAP, adding 20% RAP reduced the carbon footprint by 30.40% at the City of Sydney during production and construction operations. The use of RAP in the asphalt mix produces similar trends for Burwood Council.

Table 10 Environmental impacts (kg CO_2 eq) of the asphalt mixes per square meter (1 m^2) during production and construction operations. In the table, CA is conventional asphalt, CR is crumb rubber asphalt, and t is the asphalt thickness (quantities of materials and production details are included in **Table 5** and **Table 6**).

Council name and pavement thickness in mm		Burwood wearing course (t = 50 mm)		Burwood base layer (t = 150 mm)		Northern Beaches (t = 50 mm)		City of Sydney (t =50 mm)	
No	**Design Mixture**	**CA**	**CR**	**CA**	**CR**	**CA**	**CR**	**CA**	**CR**
1	Sand	629.35	145.44	282.25	147.94	368.42	173.79	154.81	230.58
2	Coarse aggregate	1485.1	1651.07	1551.17	1630.34	552.88	455.34	658.41	742.94
3	Natural filler	228.88	-	220.36	-	107.37	63.57	-	98.86
4	Hydrated lime	-	1576.23	-	1556.44	-	-	1558.85	-
5	RAP	-	-	155.05	-	-	79.51	92.23	-
6	Bitumen	7613.93	6380.64	5605.74	5906.75	4062.13	2515.4	2693.41	2904.86
7	Crumb Rubber (CR)	-	880.16	-	814.79	-	156.33	0.00	322.13
8	Recycled Glass (RG)	27.58	-	106.22	-	-	10.21	11.85	11.91
9	WMA additive	-	247.05	-	228.71	-	87.76	0.00	108.46
10	Materials (1+9)	9985	10881	7921	10285	5091	3542	5169.56	4420
11	Electricity (kWh)	1822.18	1187.16	1754.37	1172.26	854.82	674.76	782.72	787.01
12	LPG (MJ)	1734.64	1130.14	1670.09	1115.95	813.76	642.34	745.12	749.21
13	Production (11+12)	3557	2317	3424	2288	1669	1317	1528	1536
14	Paving Operations	744.92	709.74	630.13	420.24	550.69	540.72	576.31	310.07
15	Transportation	255.84	220.39	300.01	220.39	408.16	599.6	322.72	441.11
16	Summation (10+13+14+15)	14542	14128	12275	13214	7718	5999	7596	6707
17	Area (m^2)	(145×11)	(145×11)	(60×11)	(40×11)	(170×7)	(170×7)	(180×5.2)	(140×5.2)
18	kg CO_2eq per m^2 (16÷17)	9.12	8.86	18.6	30.03	6.49	5.04	8.12	9.21

4.1.1 Environmental Impacts Assessment - Construction Phase (Including Other End-Of-Life Tyre By-products)

Crumb rubber, derived from end-of-life tyres that often contain some form of steel reinforcement, is commonly processed to separate the steel from the rubber. The separated steel is typically reused by the steel industry, making the production of crumb rubber generate valuable by-products (**Table 4**) that can be considered as environmental 'credits.' Notably, recycling steel from end-of-life tyres generally requires less energy and emits fewer greenhouse gases than producing virgin steel from iron ore through traditional methods like mining and smelting.

LCA data suggests that incorporating crumb rubber by-products in the LCA can result in a significant reduction in CO_2eq emissions. Specifically, for Burwood Council mixes, considering crumb rubber by-products in the LCA can lead to a reduction of around 5.96% (base layer) and 6.09% (wearing course) of CO_2eq emissions per m^2 of pavement construction. In the case of the wearing course CR asphalt mix, a reduction from 8.86 to 8.32 kg CO_2eq per m^2 was achieved at Burwood Council, for instance. Similarly, the carbon emission reduction when the LCA considered recovering steel from end-of-life tyres was 8.78 and 4.91 kg CO_2eq per m^2 for the City of Sydney and Northern Beaches Council, respectively.

Vehicle tyres are not easily decomposable due to the presence of synthetic rubber designed to be durable and long-lasting, and other fillers. Therefore, another significant environmental benefit of recovering and recycling end-of-life tyres is the diversion of these tyres from landfills. Using crumb rubber in asphalt roads instead of landfilling end-of-life tyres can save CO_2eq emissions associated with landfill activities. The carbon emission reduction achieved by considering the recycling of steel from end-of-life tyres plus the avoidance of landfills is estimated to be 6.32% (Burwood Council, base layer), 6.43% (Burwood Council, wearing course), 5.53% (City of Sydney), and 3.17% (Northern Beaches Council).

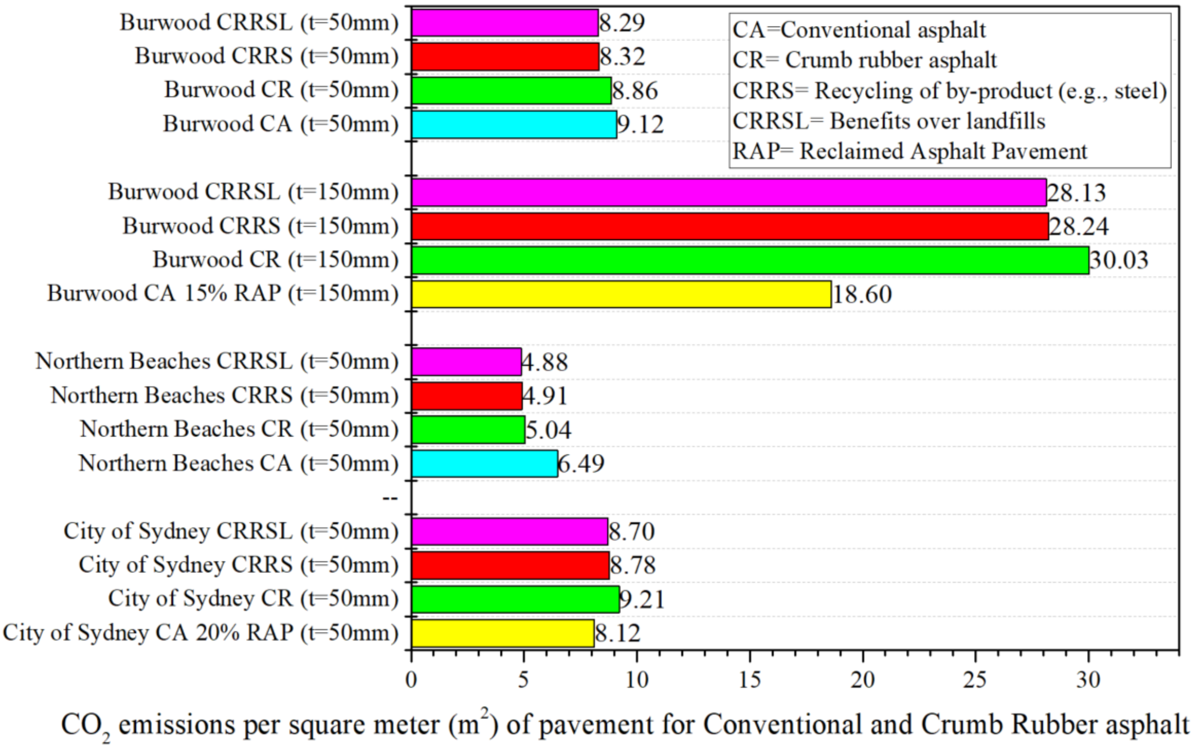


Figure 2 Environmental impacts (kg CO_2 eq) for the production and construction of asphalt pavements per square meter (1 m^2) at the three councils where *CR* is Crumb Rubber asphalt, *t* is the asphalt thickness, *CRRS* is the alternative that includes recycling of steel from tyres, *CRRSL* is the alternative

that includes recycling steel plus landfills avoidance, and *RAP* is the presence of Reclaimed Asphalt Pavement.

4.2 Impact Assessment - Maintenance Phase

The operation of resurfacing asphalt pavements through milling and filling with new asphalt aims to restore pavement smoothness and functionality, as signs of wear can emerge with ageing. Maintenance of road pavements, whether constructed with conventional asphalt or CR asphalt, involves similar fundamental procedures, with some differences due to the specific properties of the materials. In this study, CR modified asphalt was employed for maintenance on CR-modified asphalt roads, while conventional asphalt was used for roads originally paved with conventional asphalt. Specifically, the CR asphalt mix used in this study for resurfacing interventions (mill and fill) consists of 9% CR content and a Warm Mix Asphalt (WMA) additive (further details in Section 2.4.3).

Similar maintenance strategies were modelled, involving the resurfacing of 40 mm of pavement at regular intervals of 10 years. In the case of CR modified asphalt, a potential extension of service life by 10%, 20%, 30%, and 40% was modelled in the LCA.

Table 11 Environmental impacts (kg CO_2 eq) of asphalt mixture per square meter (1 m^2) during maintenance operations; maintenance conducted using conventional asphalt over the analysis period of 40 years (material quantities and production details are shown in **Table 7**).

Council name and pavement dimension		%	Burwood (185×11×0.04)	Northern Beaches (170×7×0.04)	City of Sydney (140×5.2×0.04)
1	Sand	58.1	562.4	328.87	201.19
2	Coarse aggregate	34.6	848.33	496.08	303.48
3	Natural filler	1.5	2612.25	72.25	44.2
4	Bitumen	5.8	6232.93	3644.81	2229.76
5	Materials (1 to 4)	100	10255.94	4542.03	2778.65
6	Electricity (kWh)		1311.64	767.01	469.22
7	LPG (MJ)		1248.63	730.16	446.68
8	Production (6 to 7)		2560.28	1497.16	915.91
9	Paving Operations		1071.94	545.83	440.51
10	Transportation		260.47	757.81	315.08
11	Summation (5+8+9+10)		14148.62	7342.83	4450.15
20	Periodic maintenance over the analysis period (40 yrs)		56594.48	29371.32	17800.62
21	kg CO_2-eq per m^2		27.81	24.68	24.45

The carbon footprint associated with the maintenance scenarios of the three projects over the analysis period of 40 years is 27.81, 24.68, and 24.45 kg CO_2eq per m^2 of pavement for Burwood Council, Northern Beaches Council, and City of Sydney, respectively, as shown in **Table 11**. If CR modified asphalt is used for maintenance and no improvement in service life is observed due to the addition of CR in the asphalt mix, the emissions per m^2 are 27.79, 24.66, and 24.43 kg CO_2eq for Burwood Council, Northern Beaches Council, and City of Sydney, respectively (**Table 12**). There is a significant potential for greater environmental savings if a 10 to 40% extension of service life is attributed to the use of CR in asphalt. The calculation of emissions includes materials used for maintenance resurfacing interventions, construction machinery, and transportation.

Table 12 Environmental impacts (kg CO_2eq) of asphalt mixture per square meter (1 m^2) during maintenance operations; maintenance conducted using CR modified asphalt over the analysis period of 40 years (material quantities and production details are shown in **Table 8**).

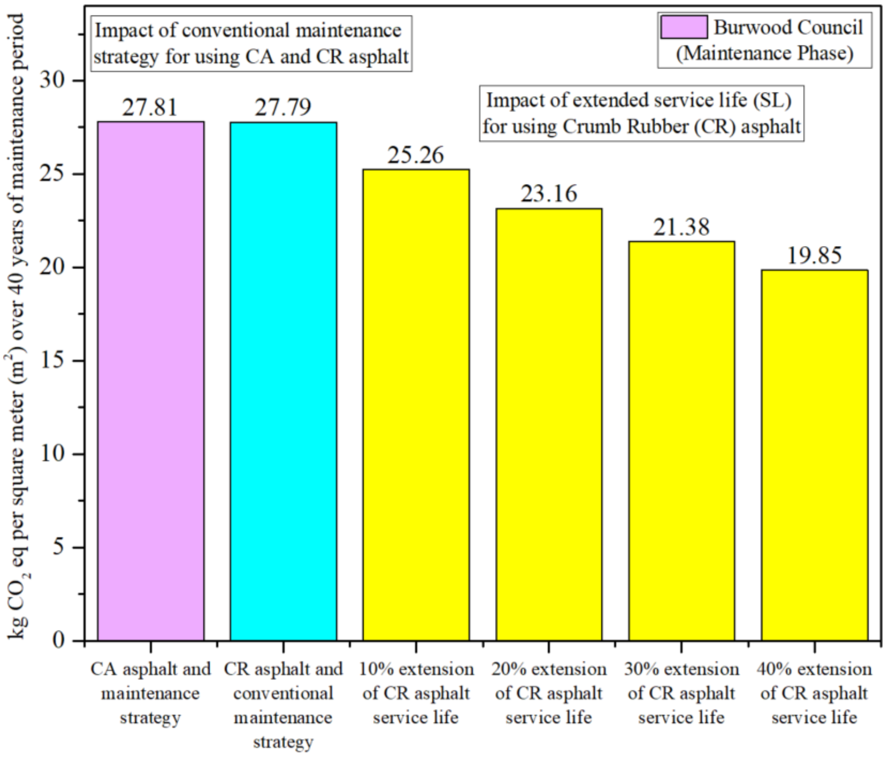
Council name and pavement dimension		%	Burwood (185×11×0.04)	Northern Beaches (170×7×0.04)	City of Sydney (140×5.2×0.04)
1	Sand	58.1	562.4	328.88	201.19
2	Coarse aggregate	34.6	848.35	496.08	303.49
3	Natural filler	1.5	2612.25	72.26	44.2
4	Bitumen	5.8	5671.97	3316.78	2029.09
5	Crumb Rubber (S9R)		352.51	206.14	126.11
6	WMA additive	2% binder	197.9	115.73	70.8
7	Materials (1 to 6)	100	10245.39	4535.86	2774.88
8	Electricity (kWh)		1311.65	767.01	469.23
9	LPG (MJ)		1248.64	730.16	446.69
10	Production (8 to 9)		2560.28	1497.17	915.91
11	Paving Operations		1071.94	545.83	440.51
12	Transportation		260.47	757.81	315.08
13	Summation (7+10+11+12)		14138.07	7336.66	4446.38
14	Conventional maintenance over the analysis period (40 years)		56552.27	29346.63	17785.51
15	kg CO_2-eq per m^2		27.79	24.66	24.43
16	10% extension of service life		25.26	22.42	22.21
17	20% extension of service life		23.16	20.55	20.36
18	30% extension of service life		21.38	18.97	18.79
19	40% extension of service life		19.85	17.62	17.45

A comprehensive discussion on the potential improvements of CR in extending the service life of the pavement and the associated environmental benefits is included in the following section.

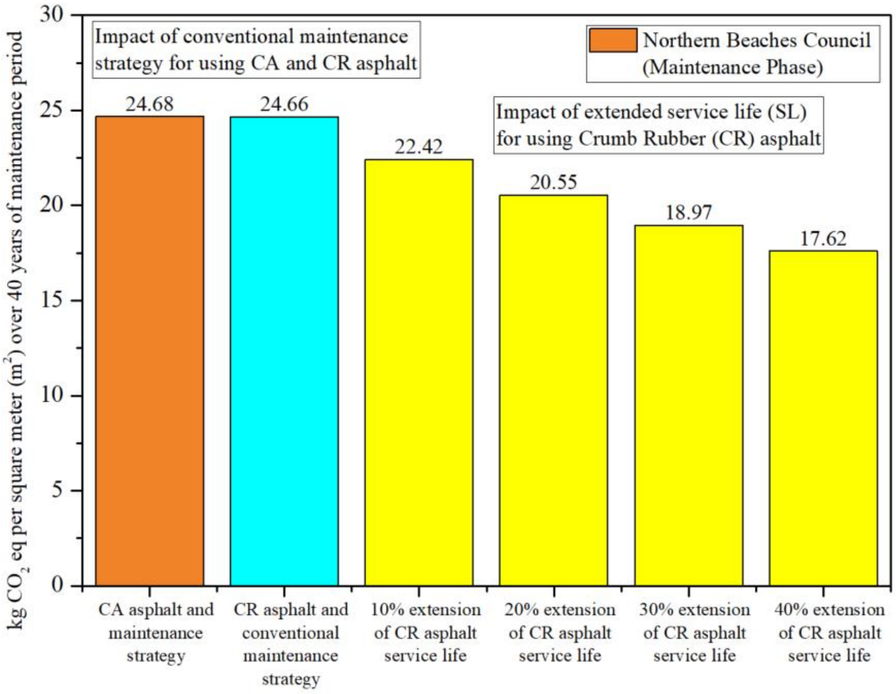
4.2.1 Scenario Analysis of CR Asphalt Durability

The use of CR in asphalt has demonstrated advantages in improving pavement durability under various circumstances. However, assigning an exact figure to the number of years a pavement's life is extended is challenging due to several concurrent assumptions on future traffic loads, weather conditions, and the deterioration rate of other pavement sub-layers during the road asset's service life. For this reason, a sensitivity analysis that considers the uncertainty associated with the extension of service life provided by CR was conducted in this study. The analysis assesses how variations in the durability of the pavement can affect environmental impacts over an analysis period of 40 years. Over this period, a longer service life between maintenance treatments has the potential to reduce the overall frequency of maintenance, thereby lowering energy consumption and associated emissions. A possible extension of 10%, 20%, 30%, and 40% to the pavement service life between resurfacing treatments was modelled in this LCA study. For the purposes of this study, the standard duration of a conventional asphalt resurfacing treatment (mill and fill, 40 mm, no crumb rubber used) was assumed to be 10 years. This means that over the analysis period of 40 years, the first maintenance intervention is scheduled at Year 10, the second at Year 20, the third at Year 30, and the last one at Year 40. A 20% increase in durability given by CR in the asphalt mix, for instance, would move the maintenance schedule to Year 12 (first intervention), Year 24 (second intervention), and Year 36 (third intervention). A fraction of the full maintenance cycle (i.e. 4/12 = 0.33) was used for the remaining four years of service life within the analysis period of 40 years.

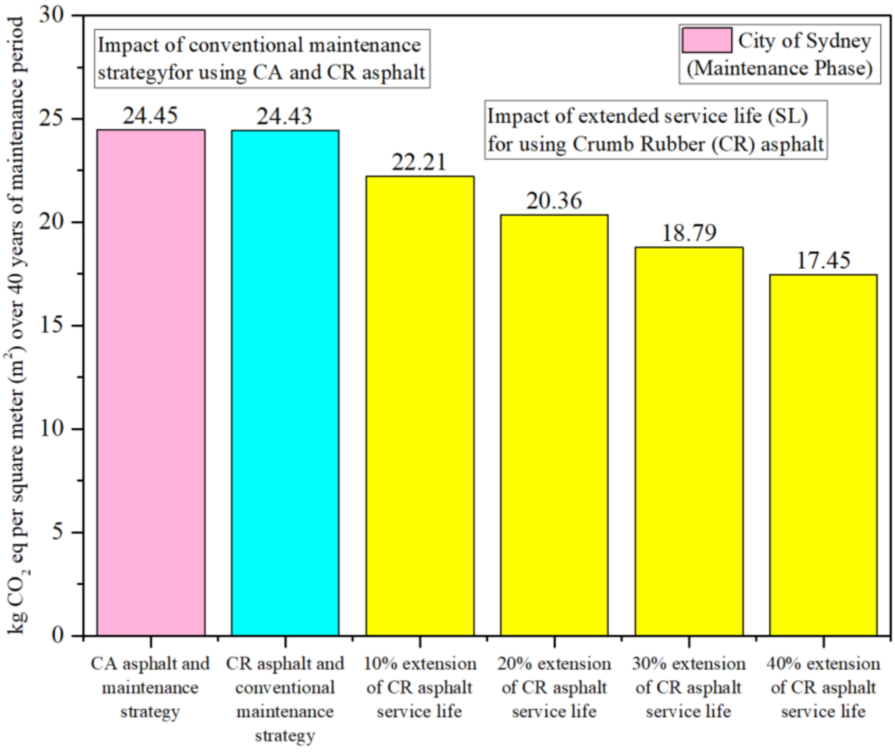
Overall, it was found that a 40% extension of service life with CR asphalt generates a decrease in CO_2eq emissions of approximately 29% per square meter of pavement, as shown in **Figure 3**. This figure becomes a 9%, 17%, and 23% reduction in CO_2eq for 10%, 20%, and 30% extensions of the pavement service life due to CR, respectively.



3(a) Burwood Council (Maintenance Phase)



3(b) Northern Beaches Council (Maintenance Phase)



3(c) City of Sydney (Maintenance Phase)

Figure 3 Environmental impacts (kg CO_2 eq) per square meter (1 m^2) for various maintenance scenarios. The conventional maintenance strategy considers a period of 10 years between maintenance treatments. The other scenarios consider an extension of the pavement service life due to the addition of Crumb Rubber (CR) in the asphalt mix.

4.3 Environmental Impacts Assessment Over the Entire Life Cycle - Initial Construction plus Maintenance

In this section, the carbon footprint of the three asphalt pavements was estimated throughout their life cycle stages. This involved accounting for emissions and energy consumption during the initial raw material extraction and production at the plant, transportation, field construction processes, and subsequent maintenance until the end of the analysis period.

The total carbon footprint of conventional asphalt (CA) – both construction and maintenance operations – for Burwood Council, Northern Beaches Council, and City of Sydney are 83,411, 37,089, and 25,397 kg CO_2eq, respectively, as shown in **Table 13**. Note that the volume of asphalt laid at the three locations are significantly different.

If CR asphalt is used during construction and maintenance interventions, and considering a nil improvement of its service life, the total amount of kg CO_2eq emissions is 83,894, 35,346, and 24,493 for Burwood Council, Northern Beaches Council, and City of Sydney, respectively. Meanwhile, if a pavement initially constructed with CR asphalt is maintained using CA, the total environmental impacts are 83,936, 35,371, and 24,508 kg CO2eq emissions for Burwood Council, Northern Beaches Council, and City of Sydney, respectively.

However, by considering a possible improvement in pavement service life from 10% to 40% due to the addition of CR in the initial asphalt mix and continuing to maintain the road asset using CR asphalt, the following reductions in carbon footprint can be achieved at the three councils over an analysis period of 40 years: from 5.6% to 18.9% at Burwood Council, from 11.9% to 27.3% at Northern Beaches Council, and from 9.9% to 23.6% at the City of Sydney.

Table 13 Total carbon footprint (kg CO_2eq) for construction and maintenance operations at the three councils.

No.		Burwood	Northern Beaches	City of Sydney	Source
1	Construction of Conventional Asphalt (CA)	26817	7718	7596	**Table 10**
2	Maintenance using CA	56594	29371	17801	**Table 11**
3	Life cycle of CA (1+2)	83411	37089	25397	
4	Construction of Crumb Rubber asphalt (CR)	27342	5999	6707	**Table 10**
5	Maintenance using CA (every 10 yrs)	56594	29371	17801	**Table 11**
6	Maintenance using CR (every 10 yrs)	56552	29347	17786	**Table 12**
7	Total impact of CR with CA maintenance (4+5)	83936	35371	24508	
8	Total impact of CR with CR maintenance (4+6)	83894	35346	24493	
9	CR asphalt + 10% extension of service life	78753	32678	22876	**Table 10** and **Table 12**
10	CR asphalt + 20% extension of service life	74469	30455	21528	
11	CR asphalt + 30% extension of service life	70844	28574	20388	
12	CR asphalt + 40% extension of service life	67736	26961	19411	

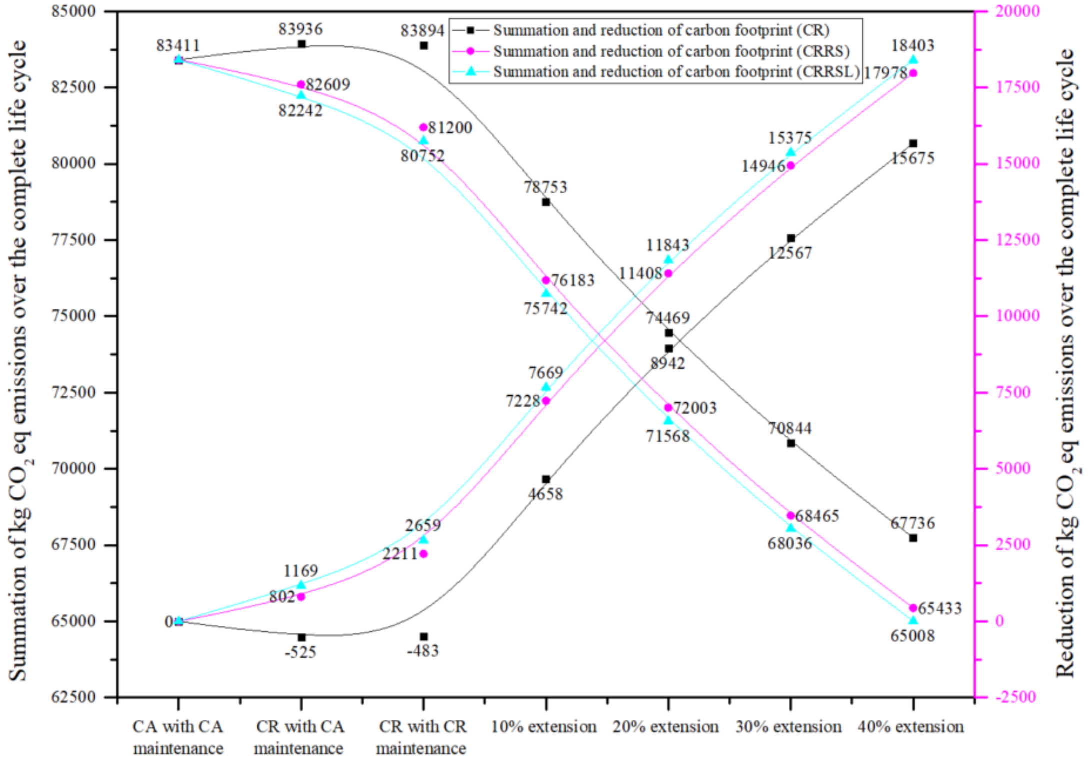
Additionally, a further reduction in environmental impacts can be achieved by considering the recycling of by-products from tyres (i.e. steel) and avoiding sending tyres to landfills (**Table 14**).

Table 14 Total carbon footprint (kg CO_2eq) for construction and maintenance operations at the three councils including the recycling of tyre processing by-products and the avoidance of landfills.

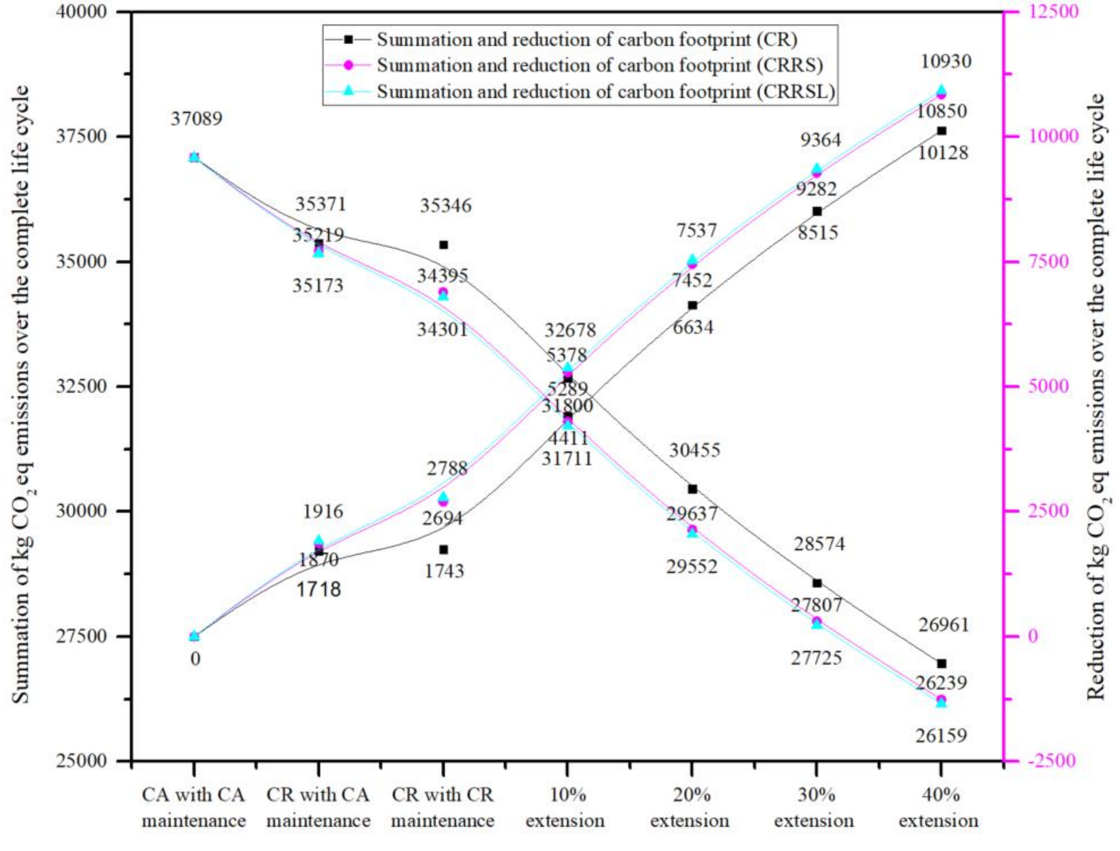
Total carbon footprint	CR only		Recycling by-product (steel)		Recycling by-product (steel) and avoidance of landfills	
	Life cycle emissions (kg CO_2eq)	Reduction compared to CA (kg CO_2eq)	Life cycle emission (kg CO_2eq)	Reduction compared to CA (kg CO_2eq)	Life Cycle emissions (kg CO_2eq)	Reduction compared to CA (kg CO_2eq)
Burwood Council Section (145 × 11 × 0.05 m) and (40 × 11 × 0.15 m)						
CA with CA maintenance	83411	0	83411	0	83411	0
CR with CA maintenance	83936	-525	82609	802	82242	1169
CR with CR maintenance	83894	-483	81200	2211	80752	2659
CR asphalt + 10% extension of service life	78753	4658	76183	7228	75742	7669
CR asphalt + 20% extension of service life	74469	8942	72003	11408	71568	11843
CR asphalt + 30% extension of service life	70844	12567	68465	14946	68036	15375
CR asphalt + 40% extension of service life	67736	15675	65433	17978	65008	18403
Northern Beaches Council (170 × 7 × 0.05 m)						
CA with CA maintenance	37089	0	37089	0	37089	0
CR with CA maintenance	35371	1718	35219	1870	35173	1916
CR with CR maintenance	35346	1743	34395	2694	34301	2788
CR asphalt + 10% extension of service life	32678	4411	31800	5289	31711	5378
CR asphalt + 20% extension of service life	30455	6634	29637	7452	29552	7537
CR asphalt + 30% extension of service life	28574	8515	27807	9282	27725	9364
CR asphalt + 40% extension of service life	26961	10128	26239	10850	26159	10930
City of Sydney Section (140 × 5.2 ×0.05 m)						
CA with CA maintenance	25397	0	25397	0	25397	0
CR with CA maintenance	24508	889	24191	1206	24134	1263
CR with CR maintenance	24493	904	23687	1710	23601	1796
CR asphalt + 10% extension of service life	22876	2521	22115	3282	22031	3366
CR asphalt + 20% extension of service life	21528	3869	20805	4592	20723	4674
CR asphalt + 30% extension of service life	20388	5009	19696	5701	19616	5781
CR asphalt + 40% extension of service life	19411	5986	18745	6652	18667	6730

Note: a '-' sign means an increase in the total emissions compared to conventional asphalt

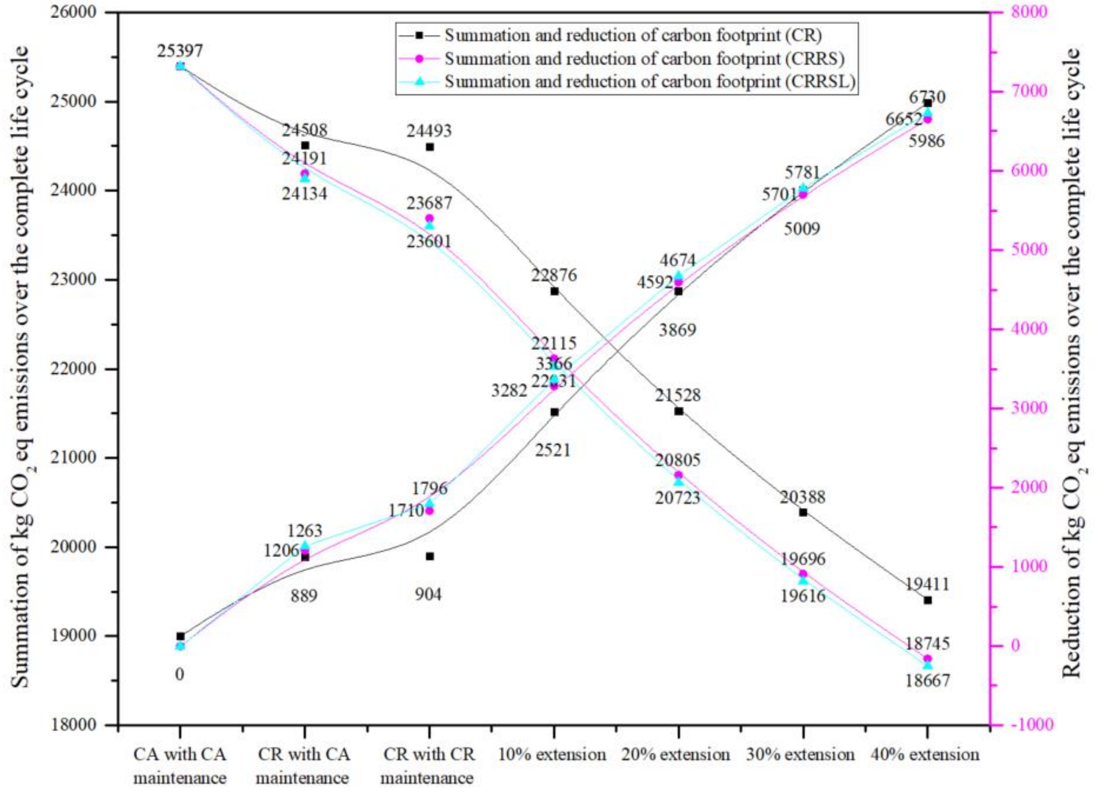
As mentioned in previous sections, steel from end-of-life tyres recycling is often in the form of wires or fibres embedded within the tyres for reinforcement. Tyre recyclers that produce CR have a separate mechanism that removes the steel before shredding tyre chunks into fine powder. Reprocessing recovered steel wires/fibres into steel or steel-related products reduces emissions by averting some energy-intensive steps in the steel production cycle. The carbon footprint reduction considering the by-product steel of CR production is higher than that of CR asphalt alone. A total decrease in emissions of 17,978, 10,850, and 6,652 kg CO_2eq was observed for Burwood Council, Northern Beaches Council, and City of Sydney, respectively, as shown in **Table 14** and **Figure 4**.



4(a) Burwood Council



4(b) Northern Beaches Council



4(c) City of Sydney

Figure 4 Total sum and reduction of kg CO_2eq emissions over the analysis period; CR is Crumb Rubber, CRRS includes the recycling of steel from tyres, and CRRRSL incorporates the environmental benefits when avoiding landfill.

The greatest benefit of using CR in asphalt is obtained by simultaneously considering the recycling of steel from tyres and avoiding landfills. A maximum decrease of 18,403, 10,930, and 6,730 kg CO_2eq was achieved in this case for Burwood Council, Northern Beaches Council, and City of Sydney, respectively.

5. Conclusion

Conventional asphalt paving relies on non-renewable resources, such as bitumen and quarry aggregate. Additionally, asphalt manufacturing involves electricity and gas consumption at the plant, using specialised equipment like asphalt pavers, rollers, and trucks for transportation and placement of the asphalt mixture. To address environmental concerns, the asphalt industry is increasingly incorporating recycled materials into the mix, reducing dependence on non-renewable resources and enhancing overall pavement performance.

In this context, the Southern Sydney Regional Organisation of Councils (SSROC) undertook one of Australia's largest multi-council demonstration projects, using crumb rubber from end-of-life tyres as a polymer (wet method) to enhance asphalt durability, performance, and environmental sustainability. Three projects from different councils—Burwood, Northern Beaches, and the City of Sydney—were selected for a comprehensive life cycle assessment (LCA) to analyse the carbon footprint of CR asphalt compared to conventional asphalt. Primary data on fuel consumption, energy consumption during production, transportation, etc., were obtained from the contractor through SSROC.

The LCA extended beyond the typical cradle-to-gate or cradle-to-construction analyses, including the maintenance phase over a 40-year period. CR asphalt, known for its durability and resistance to cracking, rutting, and ageing, requires less frequent maintenance, leading to longer-lasting pavements. A sensitivity analysis was performed, reducing the frequency of planned maintenance activities when CR asphalt was used, resulting in extended pavement service life, reduced demand for raw materials, and lowered environmental impacts.

Key conclusions from the LCA study include:

- Incorporating recycled end-of-life tyre material (CR) into bitumen reduces the demand for virgin materials, lowering the carbon footprint during construction.
- Further environmental gains can be achieved by recovering by-products from end-of-life tyre processing, such as steel fibres, for use in other applications.
- Diverting end-of-life tyres from landfills by incorporating them into asphalt roads as CR reduces emissions associated with tyre disposal, contributing to lower overall carbon emissions.
- The use of Reclaimed Asphalt Pavement (RAP) material yields substantial environmental savings, while alternatives to hydrated lime, such as antistripping agents, should be considered for improving the environmental sustainability of road projects.
- CR asphalt pavements require fewer maintenance activities due to improved durability, weather resistance, reduced rutting, and enhanced cracking resistance. The sensitivity

analysis shows significant carbon footprint reductions (5.6% to 27.3%) with a 10-40% extension of pavement service life due to CR.

In summary, the environmental benefits of using CR in asphalt pavement construction and maintenance operations make a substantial contribution to low-carbon infrastructure, minimising long-term maintenance costs, maximizing performance, and promoting a more sustainable approach.

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Appendix A

Appendix 1 Carbon emission (kg CO_2 equivalent) per unit of product

Materials or Product	Unit	kg CO_2 equivalent
Gravel, crushed, at mine.	1 tonne	12.550
Sand, at mine	1 tonne	4.954
Bitumen, at consume	1 tonne	550.084
Natural filler, Limestone, milled	1 tonne	42.167
Hydrated Lime	1 tonne	891.432
Warm mix asphalt additive (Paraffin, at plant)	1 tonne	873.277
Reclaimed asphalt pavement (RAP)	1 tonne	3.955
Recycled glass (washing and crushing)	1 tonne	4.065
Recycled glass (recycled by-product as aggregate)	1 tonne	2.640
Recycled glass (avoiding landfill plus recycling by-products)	1 tonne	-10.623
Crumb Rubber (CR) production	1 tonne	345.674
Crumb Rubber (CRS) (recycling steel as by-product)	1 tonne	10.618
Crumb Rubber (CRRSL) (avoiding landfill plus recycling by-products)	1 tonne	-9.411
Landfills of waste	1 tonne	20.030
Electricity consumption	1 kWh	1.1778
LPG consumption	1 MJ	0.064
Diesel consumption	1 Litre	3.381

Appendix 2 Environmental impact per ton of Gravel, Sand and Bitumen

Impact category	Unit	Gravel	Sand	Bitumen
Climate change	kg CO_2 eq	12.550	4.955	550.084
Ozone depletion	kg CFC-11 eq	8.55E-08	2.26E-07	4.697E-07
Terrestrial acidification	kg SO_2 eq	0.079	0.030	2.838
Freshwater eutrophication	kg P eq	6.00E-04	2.45E-04	3.30E-03
Marine eutrophication	kg N eq	2.18E-03	1.09E-03	1.05E-01
Human toxicity	kg 1,4-DB eq	3.852	1.044	2060.964
Photochemical oxidant formation	kg NMVOC	0.053	0.030	1.924
Particulate matter formation	kg PM10 eq	0.024	0.012	0.850
Terrestrial ecotoxicity	kg 1,4-DB eq	4.17E-04	1.81E-04	5.67E-03
Freshwater ecotoxicity	kg 1,4-DB eq	0.082	0.030	17.285
Marine ecotoxicity	kg 1,4-DB eq	0.077	0.029	17.408
Ionising radiation	kBq U235 eq	0.010	0.005	0.036
Agricultural land occupation	m^2a	0.383	0.183	1.798
Urban land occupation	m^2a	0.859	0.570	3.931
Natural land transformation	m^2	0.014	0.008	0.007
Water depletion	m^3	1.403	1.409	0.591
Metal depletion	kg Fe eq	1.082	0.499	3.975

Impact category	Unit	Gravel	Sand	Bitumen
Fossil depletion	kg oil eq	3.427	1.409	1254.327

Appendix 3 Environmental impact per ton of natural filler (Limestone, milled), Hydrated Lime and Warm Mix Additives (Paraffin)

Impact category	Unit	Natural filler (Limestone)	Hydrated Lime	WMA (Paraffin)
Climate change	kg CO_2 eq	42.167	891.433	873.277
Ozone depletion	kg CFC-11 eq	5.92E-08	9.43E-06	3.19E-05
Terrestrial acidification	kg SO_2 eq	0.377	0.790	4.988
Freshwater eutrophication	kg P eq	1.30E-03	3.95E-05	5.81E-02
Marine eutrophication	kg N eq	9.06E-03	2.92E-02	1.22E-01
Human toxicity	kg 1,4-DB eq	12.995	13.015	165.843
Photochemical oxidant formation	kg NMVOC	0.238	1.037	4.253
Particulate matter formation	kg PM10 eq	0.152	0.272	1.648
Terrestrial ecotoxicity	kg 1,4-DB eq	8.28E-04	5.07E-03	5.84E-02
Freshwater ecotoxicity	kg 1,4-DB eq	0.220	0.014	3.824
Marine ecotoxicity	kg 1,4-DB eq	0.213	0.051	4.304
Ionising radiation	kBq U235 eq	0.015	11.501	0.975
Agricultural land occupation	m^2a	0.764	3.897	43.407
Urban land occupation	m^2a	1.486	4.635	7.090
Natural land transformation	m^2	0.001	0.004	0.130
Water depletion	m^3	0.081	0.515	31.653
Metal depletion	kg Fe eq	1.716	0.175	60.509
Fossil depletion	kg oil eq	11.862	91.193	1307.607

Appendix 4 Environmental impact per ton of Reclaimed Asphalt Pavement (RAP), Electricity per kWh and LPG per MJ.

Impact category	Unit	RAP	Electricity (kWh)	LPG (MJ)
Climate change	kg CO_2 eq	3.956	1.178	0.064
Ozone depletion	kg CFC-11 eq	4.60E-10	1.01E-09	5.74E-12
Terrestrial acidification	kg SO_2 eq	0.0270	0.0071	0.0003
Freshwater eutrophication	kg P eq	2.91E-06	2.38E-06	5.11E-09
Marine eutrophication	kg N eq	1.65E-03	1.50E-04	1.96E-05
Human toxicity	kg 1,4-DB eq	2.291	0.206	0.000
Photochemical oxidant formation	kg NMVOC	0.044	0.004	0.001
Particulate matter formation	kg PM10 eq	0.010	0.002	0.000
Terrestrial ecotoxicity	kg 1,4-DB eq	5.24E-06	1.18E-05	4.99E-08
Freshwater ecotoxicity	kg 1,4-DB eq	0.0192	0.0052	0.0000
Marine ecotoxicity	kg 1,4-DB eq	0.0191	0.0048	0.0000
Ionising radiation	kBq U235 eq	3.05E-05	1.44E-05	4.85E-08

Impact category	Unit	RAP	Electricity (kWh)	LPG (MJ)
Agricultural land occupation	m^2a	0.0016	0.0239	0.0000
Urban land occupation	m^2a	0.0034	0.0405	0.0000
Natural land transformation	m^2	6.15E-06	3.7E-06	5.91E-08
Water depletion	m^3	0.0006	0.0022	0.0000
Metal depletion	kg Fe eq	0.0034	0.0013	0.0000
Fossil depletion	kg oil eq	1.3920	0.2869	0.0241

Appendix 5 Environmental impact per ton of Recycled Crushed Glass (RCG).

(1) Recycled Crushed Glass, Washing and Crushing RCG (W&C)

(2) Recycled Crushed Glass, recycled by-product as aggregate, RCG (BPA)

(3) Recycled Crushed Glass, avoiding landfill and recycling by-product, RCG (L&R)

Impact category	Unit	RCG (W&C)	RCG (BPA)	RCG (L&R)
Climate change	kg CO_2 eq	4.065	2.640	-10.624
Ozone depletion	kg CFC-11 eq	8.18E-09	8.14E-08	-1.19E-06
Terrestrial acidification	kg SO_2 eq	0.024	0.016	-0.065
Freshwater eutrophication	kg P eq	3.88E-06	4.01E-06	-1.68E-04
Marine eutrophication	kg N eq	1.03E-03	7.09E-04	-2.65E-03
Human toxicity	kg 1,4-DB eq	1.084	0.653	-0.972
Photochemical oxidant formation	kg NMVOC	0.027	0.020	-0.089
Particulate matter formation	kg PM10 eq	0.008	0.005	-0.024
Terrestrial ecotoxicity	kg 1,4-DB eq	2.59E-05	2.56E-05	-4.19E-04
Freshwater ecotoxicity	kg 1,4-DB eq	0.0090	0.0053	-0.0066
Marine ecotoxicity	kg 1,4-DB eq	0.0090	0.0056	-0.0112
Ionising radiation	kBq U235 eq	2.32E-05	1.07E-06	-2.26E-03
Agricultural land occupation	m^2a	0.0501	0.0171	-0.1498
Urban land occupation	m^2a	0.0901	0.0407	-0.3852
Natural land transformation	m^2	4.27E-05	-3.94E-04	-4.22E-03
Water depletion	m^3	0.0682	-0.0587	0.0012
Metal depletion	kg Fe eq	0.0067	0.0036	-0.7661
Fossil depletion	kg oil eq	1.2467	0.8636	-3.7814

Appendix 6 Environmental impact per ton of Crumb Rubber (CR) production.

(1) Crumb Rubber (CR) production

(2) Crumb Rubber (CRS) (recycling steel as a by-product)

(3) Crumb Rubber (CRRSL) (avoiding landfill and recycling by-products)

Impact category	Unit	CR	CRS	CRRSL
Climate change	kg CO_2 eq	345.674	10.619	-9.412
Ozone depletion	kg CFC-11 eq	1.09E-06	-1.40E-05	-1.56E-05
Terrestrial acidification	kg SO_2 eq	1.887	0.612	0.490

Impact category	Unit	CR	CRS	CRRSL
Freshwater eutrophication	kg P eq	3.83E-04	-1.23E-02	-1.25E-02
Marine eutrophication	kg N eq	5.09E-02	2.06E-02	1.55E-02
Human toxicity	kg 1,4-DB eq	22.937	-2.284	-5.089
Photochemical oxidant formation	kg NMVOC	1.266	-0.299	-0.457
Particulate matter formation	kg PM10 eq	0.553	-0.834	-0.877
Terrestrial ecotoxicity	kg 1,4-DB eq	2.94E-03	-9.06E-03	-9.66E-03
Freshwater ecotoxicity	kg 1,4-DB eq	0.182	0.113	0.091
Marine ecotoxicity	kg 1,4-DB eq	0.193	0.021	-0.007
Ionising radiation	kBq U235 eq	1.93E-03	-3.68E+00	-3.68E+00
Agricultural land occupation	m^{2}a	5.294	1.739	1.466
Urban land occupation	m^{2}a	12.322	8.866	8.218
Natural land transformation	m^2	0.005	-0.030	-0.036
Water depletion	m^3	1.407	0.798	0.7064
Metal depletion	kg Fe eq	0.466	-237.993	-239.0468
Fossil depletion	kg oil eq	96.038	25.988	19.132

Appendix 7 Environmental impact per litre of diesel consumption and per ton of waste disposed in landfills.

Impact category	Unit	Diesel	Landfills
Climate change	kg CO_2 eq	3.381	20.030
Ozone depletion	kg CFC-11 eq	3.93E-10	1.63E-06
Terrestrial acidification	kg SO_2 eq	0.0231	0.1219
Freshwater eutrophication	kg P eq	2.49E-06	2.34E-04
Marine eutrophication	kg N eq	1.41E-03	5.01E-03
Human toxicity	kg 1,4-DB eq	1.958	2.805
Photochemical oxidant formation	kg NMVOC	0.037	0.158
Particulate matter formation	kg PM10 eq	0.009	0.043
Terrestrial ecotoxicity	kg 1,4-DB eq	4.48E-06	6.06E-04
Freshwater ecotoxicity	kg 1,4-DB eq	0.0164	0.0213
Marine ecotoxicity	kg 1,4-DB eq	0.0164	0.0275
Ionising radiation	kBq U235 eq	2.61E-05	3.12E-03
Agricultural land occupation	m^{2}a	0.0013	0.2726
Urban land occupation	m^{2}a	0.0029	0.6482
Natural land transformation	m^2	5.26E-06	5.81E-03
Water depletion	m^3	5.18E-04	9.12E-02
Metal depletion	kg Fe eq	0.003	1.054
Fossil depletion	kg oil eq	1.190	6.856