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Development of an Assessment and Implementation Framework for the Use of Recycled Materials in the South Australian Road Network Project – Part 3 Life Cycle Assessment

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Summary

This project has been undertaken with support and funding from Green Industries South Australia as well as in collaboration with the Institute of Public Works Engineering Australasia, City of Mitcham, City of Burnside, Port Pirie Regional Council and the Adelaide Hills Council. The project is supervised by a project steering committee comprised of representatives from GISA, the Department of Infrastructure and Transport SA, Local Government Association SA and the Australian Road Research Board.

The project has three main components: knowledge capture, a review of environmental implications and a life cycle assessment (LCA) of SA roads containing recycled materials. This report is the third deliverable of the project comprising an LCA of pavements containing recycled materials: crushed glass (RCG), crumb rubber (CR) and recycled plastic (RP) compared with a conventional pavement (with no recycled materials). The objective of the study is to quantify the environmental impacts of local councils' roads containing recycled materials over a 40-year assessment period.

LCA is a standardised approach to quantifying the potential environmental impacts of a product or process. The study conducted LCA on three alternative cases containing recycled materials (RCG, CR and RP) and one base case (with no recycled materials). The LCA covered the pavement's life cycle including the embodied energy of its materials, construction, maintenance and rehabilitation processes. Environmental impacts were quantified as GHG emissions in tCO_2-eq[1] (tonnes carbon dioxide equivalent - a unit for GHG emission) for the lifecycle of a pavement over the assessment period of 40 years. Recycled materials' environmental impacts were also quantified in accordance with the Infrastructure Sustainability Council (ISC) framework, through seven impact categories/indicators: global warming, ozone depletion, acidification, eutrophication, photochemical oxidation, abiotic depletion (minerals), and abiotic depletion (fossil fuels).

LCA is performed using the Sustainability Assessment Tool (SAT) – a lifecycle assessment tool developed as a joint Western Australian Road Research and Innovation Program (WARRIP) and the National Assets Centre of Excellence (NACOE) program as a collaboration between ARRB, Main Roads Western Australia and the Queensland Department of Transport and Main Roads (TMR). The SAT allows the identification of the key drivers for the impacts of interest (e.g. GHG emissions) and enables the comparison of the quantified whole-of-life impacts between roads built from different materials. In this project, SA-specific data has been generated and incorporated into the SAT. This -state-specified data recognises SA's unique energy mix compared with the rest of Australia. Data used for the LCA was sourced from AusLCI and modified using SimaPro software to calculate emissions based on the South Australian energy market.

The LCA compared three alternative cases against a conventional dense-graded asphalt wearing course pavement. The pavement designs are:

- Base case: Conventional dense-graded asphalt wearing course.
- Alternative Case 1: 5 wt.% of RCG in dense-graded asphalt wearing course.
- Alternative Case 2: 1 wt.% of CR in dense-graded asphalt wearing course.
- Alternative Case 3: 0.5 wt.% RP in dense graded asphalt wearing course.

The assessment was based on a single 3.5 m wide road lane over a 1 km road length, for a period of 40 years. LCA results show that the addition of 5 wt.% RCG in the wearing course as an aggregate replacement has no significant effect on overall GHG emissions as compared to conventional dense graded asphalt. CR and RP are added in the wearing course as binder modifiers through wet and hybrid methods respectively. The addition of 1 wt.% CR in asphalt wearing course reduced GHG emissions by 2.54% whilst 0.5 wt% RP in asphalt wearing course reduced GHG emissions by 1.1%. The emissions linked with maintenance activities accounted for the major differences in lifecycle GHG emissions among four pavements (alternative and base cases). Material (embodied) emissions are another significant contributor to

[1] A carbon dioxide equivalent or CO_2 equivalent, abbreviated as CO_2-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP).

the overall GHG emissions. Further GHG reductions can be made by using renewable energy sources for the production of road construction materials which can significantly reduce the embodied energy of the materials used and cut down the lifecycle emissions of pavements.

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1. Introduction

1.1 Context

Climate change due to the emission of greenhouse gases (GHG) from human activities is one of, if not the most critical challenge the world is facing today. A key strategy to address this challenge is recycling: a process of converting waste material into new products. The principle behind this strategy is that recycling can save the energy used to produce new products from raw materials and consequently save the GHG emissions associated with raw materials extraction and production. In the context of road construction, recycled materials can be based on a range of source materials including recycled crushed glass (RCG), crumb rubber (CR) and recycled plastics (RP). The environmental impacts of using recycled materials in the road industry are not always clear. This uncertainty stems from the fact that transforming these materials into suitable road construction materials requires an understanding of manufacturing processes and optimised quantities of recycled materials used in road construction. The milestone 3 'knowledge capture' study had established the platform to identify the potential applications of recycled materials in road construction and their optimised content in the different pavement layers.

The purpose of this report is to investigate the environmental impacts of using recycled materials in the construction of a road. This study covers the life cycle assessment of three pavements incorporating recycled materials i.e. RCG, CR and RP compared with a conventional base case. The assessment scope covers the material, asphalt manufacturing, construction, maintenance and rehabilitation emissions of roads containing recycled material in their wearing course.

The study quantifies the immediate and long-term environmental impacts of using recycled materials on roads. The following impacts are considered:

- immediate environmental impact including the reduction of GHG emissions during the manufacturing of road construction materials
- long-term environmental impacts including emissions during the life cycle of the road which also includes construction, maintenance and rehabilitation processes.

The key benefits of using recycled materials on roads are:

- reduced environmental damage from sending waste to landfills which results in the land, water and air pollution
- reduced need for combusting waste as a waste management strategy (i.e. as an alternative fuel or energy-from waste management pathway) that causes significant atmospheric pollution and emissions
- reduced need for waste disposal facilities due to the practice of recycling.

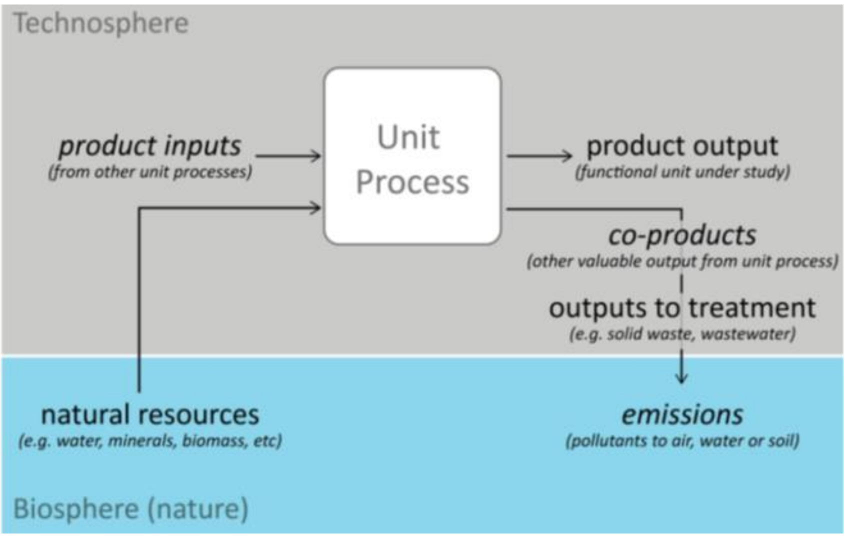
1.2 Life Cycle Assessment

Life cycle assessment (LCA) is a systematic, standardised approach to quantifying the potential environmental impacts of a product or process. LCA is an analysis technique to assess environmental impacts associated with all the stages of a product's life, from raw material extraction through materials processing, manufacture, distribution, use and disposal.

The methodologies for LCA are defined by the International Organization for Standardization (ISO) 14,040 series (ISO 2006a; ISO 2006b).

LCA measures the mass and energy exchange between biosphere (nature) and technosphere (human activities), through extracting natural resources or emitting pollutants to air, water, and soil as a result of human activities. The flow of the process is defined as a unit process that takes input and provides output products. Unit processes are combined to form a unit system process that encapsulates all activities from cradle to gate[2]. A single unit is illustrated in Figure 1.1. It shows the flow of material and energy to and from the biosphere as well as flow to and from the technosphere.

Figure 1.1: Input and output of a unit process in LCA



Source: Muralikrishna and Manickam (2017).

1.2.1 LCA Benefits

An LCA will enable SA local councils to:

- assess the full life cycle impact of infrastructure assets
- identify savings in environmental impacts and resources
- compare alternative materials, designs, and application scenarios
- communicate the benefits of investing in sustainability to stakeholders
- prioritise investments in sustainability improvements and mitigations of risks
- benchmark sustainability performance.

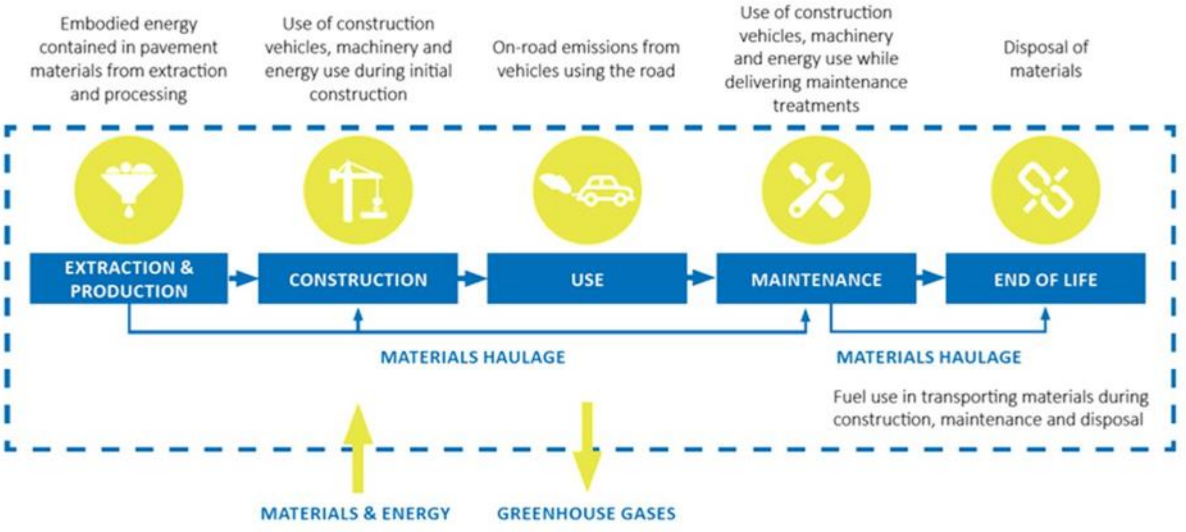
1.3 LCA Methodology

1.3.1 ARRB's Pavement Sustainability Assessment Tool (SAT)

The methodology for assessing the GHG and sustainability impacts in this project is based on the framework of ARRB's SAT- a life cycle assessment tool developed as a joint Western Australian Road Research and Innovation Program (WARRIP)-National Assets Centre of Excellence (NACOE) program as a collaboration between ARRB, Main Roads Western Australia and the Queensland Department of Transport and Main Roads (TMR). The SAT is designed to compare the life cycle environmental impact and financial costs of different road technologies and designs. Thus, it can assist with determining the potential environmental impacts of using RCG, CR and RP on roads. The SAT is designed to calculate and compare the accumulated environmental impacts of pavements based on different pavement materials, pavement designs, construction methods, maintenance requirements, transportation needs and usage scenarios. Figure 1.2 illustrates an overview of the phases over the life of a pavement that can be analysed in the SAT to calculate the lifecycle GHG emissions.

[2] Cradle-to-gate is an assessment of a partial product life cycle from manufacture (cradle) to the factory gate, i.e., before it is transported to the consumer.

Figure 1.2: Overview of the phases over the life of a pavement that can be analysed in the SAT to calculate the lifecycle GHG emissions

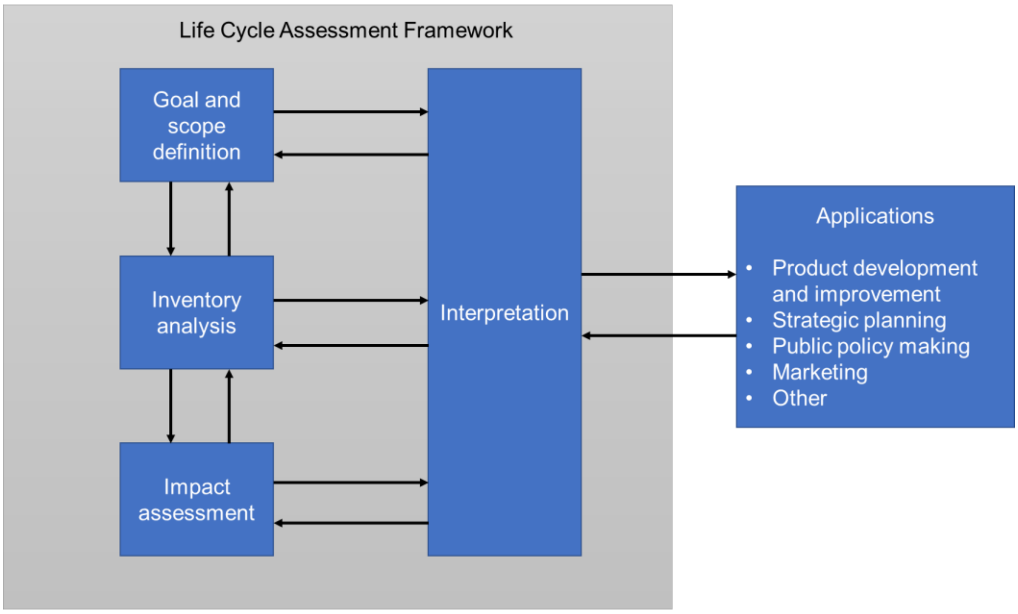


Source: Brownjohn et al. (2019).

1.4 LCA Framework

The LCA framework contains four stages: goal and scope definition, inventory analysis and impact analysis, each stage being followed by an interpretation of results (Muralikrishna & Manickam 2017) (see Figure 1.3).

Figure 1.3: Framework for life cycle assessment



Source: Muralikrishna and Manickam (2017).

Each stage of an assessment interacts with other stages:

- **The goal and scope** definition describes the reasons for the LCA, the scenarios, boundaries and indicators used.
- **The inventory analysis** builds a model of the production systems involved in each scenario and describes how each stage of the production process interacts with the environment.
- **Impact assessment** assesses the inventory data against key indicators to produce an environmental profile of each scenario.
- **Interpretation** analyses the results and undertakes systematic checks of the assumptions and data to ensure robust results.

2. Goal and Scope

The goal of the LCA study is to ascertain whether the use of RCG, CR and RP as raw materials are environmentally viable options when compared with conventional road construction materials. Herein, the report presents the life cycle assessment of roads incorporating recycled materials to quantify its impact on the environment. The study aims to present a comparative study of using recycled materials in road construction compared with the base cases (conventional materials).

The specific objectives of the study are as follows:

1. To quantify the environmental impacts associated with the use of 5% of RCG in asphalt wearing course compared with conventional roads.
2. To quantify the environmental impacts of using 1 wt.% of CR in asphalt wearing course compared with conventional roads.
3. To quantify the environmental impacts of using 0.5 wt.% RP of asphalt compared with conventional roads.

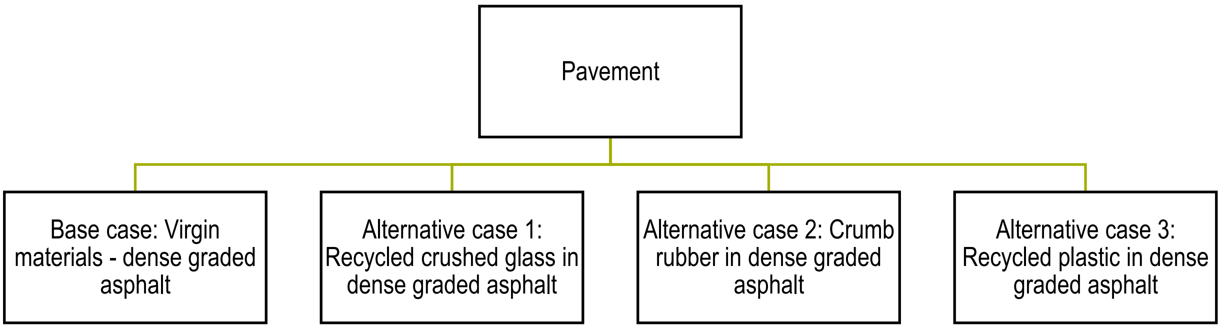
2.1 Intended Audience

The report is intended to inform Green Industries South Australia (GISA) about the potential environmental impacts of using recycled materials in road construction. The targeted audience for this study is road asset owners, state and local road agencies, sustainability managers and strategy decision-makers within the road construction industry.

2.2 Scenario Design

Scenario design refers to the establishment of design for the relevant alternative case that provides a meaningful comparison with base cases. This report discusses three alternative cases. Each recycled material represents an individual design scenario where an alternative case (i.e. a pavement design incorporating recycled materials and specified performance characteristics) is compared with a conventional base case containing only virgin materials. Figure 2.1 illustrates the scenario designs for alternative and base cases discussed in this report.

Figure 2.1: Scenario designs for alternative and base cases



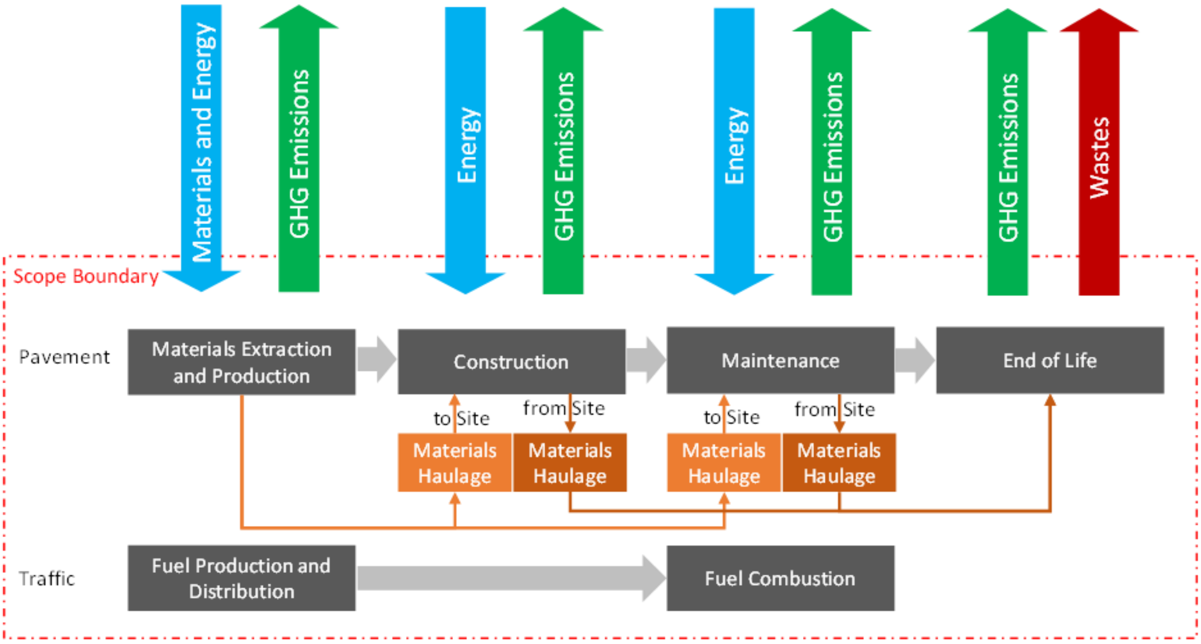
2.3 System Boundaries

This study provides the LCA of the roads containing recycled material (RCG, CR or RP). The lifecycle of recycled materials starts with the extraction and production of materials and finishes with the recycling or reuse of end-of-life materials. The extraction and production of materials are calculated through SimaPro[3] software. The outputs are then linked into SAT to calculate the whole life cycle emissions of road construction, maintenance, end-of-life and transportation of materials to the site. Figure 2.2 shows the assessment boundary for a lifecycle of a pavement.

The lifecycle assessment boundary consists of five interlinked phases:

- Extraction and production – Embodied energy contained in pavement materials from extraction and production (i.e. 'cradle to gate').
- Construction – The energy used during the initial construction of pavements, including its manufacture, and laying and use of construction vehicles and machinery. The construction phase can also include preconstruction removal of existing materials.
- Maintenance – Use of construction vehicles, machinery and energy use while delivering maintenance treatments.
- End of life – Disposal, 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.

Figure 2.2: Cradle to cradle[4] boundary of the system for pavements under study



Source: Brownjohn et al. (2019).

2.3.1 Focusing on the Surface Layer

The SAT is capable of undertaking assessments based on the full pavement structure (all pavement layers), in addition to assessments based on a single or specific set of pavement layers. Because CR and RP asphalt is typically designed as wearing course material, this analysis, therefore, focuses on the emissions impact on the surface layer of the pavement. To promote the use of RCG in the wearing course and for comparison purposes, RCG is incorporated into the wearing course as an aggregate replacement.

Table 2.1 presents the assessment basis applied in this analysis. In this example, the assessment was based on a lane-kilometre basis with a 3.5 m wide road lane over a 1 km road length, representing a total

[3] SimaPro is the professional tool to collect, analyse and monitor the sustainability performance data of products and services.

[4] Cradle-to-cradle is a specific kind of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process.

pavement area of 3,500 m^2. This area described in the assessment basis is known as a functional unit – the unit of pavement based on which the lifecycle emissions are assessed.

Table 2.1: Assessment basis

Assessment basis	Value
Assessment period [years]	40
Lane length [km]	1
Lane width [m]	3.5
Number of lanes	1

Table 2.2 shows the road life cycle variations of the alternative cases (i.e. use of recycled material) compared to the base case (virgin material). The three alternative cases have different recycled materials attributed to different extraction and production processes and maintenance phases of the life cycle. Depending on the type of recycled materials, the alternative pavement may require different levels of maintenance during its life period. CR and RP are added as a binder modifier to enhance their durability and thus require less maintenance. Whereas RCG is added as an aggregate replacement and does not have a significant effect on the durability of the pavement, therefore the maintenance schedule remains the same as the base case

Table 2.2: Comparison of SAT input parameters for recycled material containing asphalt to conventional asphalt

Assessment stages	RCG	RP	CR
Assessment basis	Same as the base case	Same as the base case	Same as the base case
Materials extraction and production	Recycled crushed glass is added as aggregate replacement.	PE-modified binder as pavement material generated through blending with bitumen in the asphalt plant	CR-modified binder as pavement material generated through blending with bitumen in asphalt plant
Construction	Hot mix asphalt	Hot mix asphalt	Hot mix asphalt
Maintenance	Same as base case Routine (years): 5, 15, 25, 35 Periodic (years): 10 (patch), 20 (resurface), 30 (patch) Rehabilitation (years): 40	Routine (years): 6, 18, 30, 36 Periodic (years): 12 (patch), 24 (resurface) Rehabilitation(years): 40	Routine (years): 7, 21, 35 Periodic (years): 14 (patch), 28 (resurface) Rehabilitation(years): 40
End-of-life	Same as Conventional	Same as Conventional	Same as Conventional
Transportation	Haulage distance between the locations of material production (virgin and recycled) and pavement construction site is assumed 25 km.	Haulage distance between the locations of material production (virgin and recycled) and pavement construction site is assumed 25 km..	Haulage distance between the locations of material production (virgin and recycled) and pavement construction site is assumed 25 km.

2.4 Assumptions

1. Assessment period of 40 years is assumed.
2. Recycled materials are only added to the surface/wearing course of the pavement.
3. AUS LCI[5] database is used for electricity and water usage emissions.

[5] The Australian National Life Cycle Inventory Database (AusLCI) is a national, publicly accessible database with authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services over their life cycle. The database brings together stakeholders from industry, government and academia to develop a methodology to standardise the interpretation of ISO 14040 in Australia and is an important resource for those involved in environmental assessment and particularly life cycle assessment (LCA). The inventory data is estimated by assuming Australian-average processes and input parameters. This assumption may lead to either under or overestimating state-specific lifecycle emissions.

4. Global unit processes from Ecoinvent 3[6] library are used for RCG and RP recovery. However, the CR recovery process is modelled in SimaPro software based on South Australian data.
5. South Australian electricity and water usage emissions are used for modelling alternative and base cases.
6. Recycled polyethylene plastics are assumed to be used in the alternative case for RP in the wearing course asphalt. RP was added as a binder modifier using the hybrid method.
7. Finely pulverised crumb rubber (< 0.7 mm) is assumed to be used in the case of CR in the wearing course asphalt. CR is added as a binder modifier using the wet method.
8. RP and CR are assumed to enhance asphalt durability
9. RCG is added as a partial aggregate replacement in the wearing course and is assumed to have the same durability and performance as conventional pavement.
10. Dense graded asphalt (DGA) is used in the wearing course for all pavement designs. Hot mix asphalt is manufactured for all cases.
11. Materials from all pavement options are recycled as recycled asphalt pavement (RAP) at the end of their design lives.
12. Transport emissions are estimated on the basis that all materials will be transported in four-axle articulated trucks with 100% payload and travelling at 70 km/h.

[6] Ecoinvent is the world's leading LCI database containing over 16,000 unique datasets. The datasets in Ecoinvent cover a wide array of products, services and processes, from building materials to food and from resource extraction to waste management.

3. Life Cycle Inventory (LCI) Analysis

The life cycle inventory analysis is the stage of an LCA where the system under study is broken down into individual unit processes, in accordance with the system boundary in Figure 2.2. The life cycle inventory analysis is the process of collecting the data required to quantify the physical inputs and outputs associated with the processes taking place within the system boundary of the entire product system.

3.1 Data Collection

The most demanding task in performing LCA is data collection. Depending on the complexity of the processes there are many different strategies for data collection. Data can be acquired from available peer-reviewed life cycle inventory databases and through consultation with stakeholders. On these bases, data can be categorised as, Foreground data and Background Data.

Foreground data refers to very specific data needed to model the system. Foreground data used for the study is collected through consultation with local councils. Data for unit operations such as mixing drums, machinery, heavy vehicles, rollers, generators, heating units etc. are obtained from their product data sheets or in some instances assumptions are made to calculate energy requirements. Background data is data for generic materials, energy, transport, and waste management systems. The background data is sourced from the AUS LCI database and Ecoinvent 3 database.

The SAT contains reference databases for the following:

- pavement materials, including emissions, consumption and environmental impact factors, material densities and a library of verified material products
- emission factors for construction, maintenance, transportation and disposal processes.

The supporting data that need to be established to enable the SAT to undertake the assessment are listed in Table 3.1.

Table 3.1: Data required to calculate life cycle GHG emissions

Data category	Input data [unit]	Description
Materials	Material density [kg/m^3]	The density of the pavement material
	Mass-fraction [%]	Percentage of mass of the pavement material in the asphalt mixture
	Mine to end of production emissions [tCO_2-eq/tonne]	GHG emission factor for virgin materials
	Recycling to end of production emissions [tCO_2-eq/tonne]	GHG emission factor for recycled materials
	Transport mode	The type of vehicles used to transport virgin material and recycled materials
	Haulage distance [km]	The total haulage distance between the source of material to the pavement construction site.
Manufacturing process	Asphalt density [tonnes/m^3]	The density of manufactured asphalt mixture
	Natural gas [MJ/tonne]	The amount of natural gas used in the process of manufacturing a tonne of asphalt mixture
	Diesel [L/tonne]	The amount of diesel used in the process of manufacturing a tonne of asphalt mixture
	Electricity [kWh/tonne]	The amount of electricity used in the process of manufacturing a tonne of asphalt mixture

Data category	Input data [unit]	Description
Rehabilitation regime	Resurfacing frequency [years]	The number of years between resurfacing the pavement
	Repair frequency [years]	The number of years between repairing the pavement
Location of the recycling facility	Distance to recycling facility [km]	The distance between the pavement site to the recycling facility
Location of the disposal facility	Distance to disposal facility (landfill) [km]	The distance between the pavement site to the disposal facility

3.2 State-specific Materials Emission Data

Pre-existing life cycle inventory data and emissions factors were only available for a limited number of pavement materials and asphalt products. In some instances where a sourced material was a near equivalent to the constituent material, the inventory data from the similar material were used. For materials where there were no equivalent data, ARRB used SimaPro to disaggregate and interrogate the AusLCI data and then re-model them using additional data from Ecoinvent and information sourced directly from suppliers. Once the comprehensive materials database was established, ARRB adjusted the background inventory data to specify them for South Australia. Adjustments were made to apply South Australian emissions from electricity generation, water and fuel usage. These state-specified emissions were fed into SAT to calculate overall GHG emissions.

Table 3.2 shows the material emission data sourced from the AusLCI database (background data) used to model new products in SimaPro. The material's embodied emissions are adjusted according to the South Australian energy market.

Table 3.2: Background inventory of material and energy processes

Materials	Unit process label in SimaPro	GHG (tCO_2-eq/tonne)
Natural gravel	Gravel, round, at mine, SA/AU U	0.0028
Crushed gravel	Gravel, crushed, at mine, SA/AU U	0.0063
Crushed rock base	Gravel, crushed {AU}, SA| production at the mine	0.0141
Recycled sand	Recycled aggregate, at the plant, AU U	0.0037
Rock fill	Gravel, crushed {AU}, SA| production at mine	0.0141
Crushed brick	Recycled aggregate, at plant, AU U	0.0036
Crushed aggregate	Gravel, crushed {AU}, SA| production at mine	0.0141
Crusher dust	Gravel, crushed {AU}, SA| production at mine	0.0141
Fine aggregate	Sand, at mine/SA/AU U	0.0028
Natural sand	Sand, at mine/SA/AU U	0.0028
Binder	Bitumen, at port, SA/AU U	0.3842
Recycled crushed glass	Glass cullet, sorted SA, AU| treatment of waste glass from unsorted public collection, sorting | Cut-off, U	0.0136
Crumb rubber	Rubber from waste tyres, SA, fine pulverised crumb rubber (< 0.7 mm)/AU U	0.1693

Materials	Unit process label in SimaPro	GHG (tCO_2-eq/tonne)
Recycled plastics	Waste polyethylene, for recycling, sorted {Europe without Switzerland} | treatment of waste polyethylene, for recycling, unsorted, sorting | Cut-off, U	0.2371

3.3 Construction and Maintenance Process Emission Data

3.3.1 Manufacturing Emissions

The AusLCI database was used to determine the emissions associated with the manufacture of asphalt. This source provided a breakdown of the natural gas, diesel and electricity used to manufacture asphalt in a typical batch plant. These values were used and then multiplied by the state-specific energy factors detailed in the Department of the Environment and Energy (2019) to determine the tCO_2-eq/tonne of the manufactured product.

3.3.2 Process Emissions

A first principles approach was used to determine the emissions related to the construction and maintenance processes. This approach estimated the amount of work that can be completed in a single shift, identified the construction plant used to complete the work during the shift and calculated the diesel usage using the fuel consumption rates (Skolnik et al. 2013 and Transport Authorities Greenhouse Group 2013). The fuel usage per cubic metre of work was then calculated by dividing the fuel usage by the assumed cubic metres that can be completed in a shift. The emissions per cubic metre were then calculated by multiplying this number by the emission factor (in tCO_2-eq/kL of diesel) outlined in Transport Authorities Greenhouse Group (2013). These values were then compared to the values detailed in Transport Authorities Greenhouse Group (2013) and back-calculated values obtained from outputs of the Carbon Gauge tool (a GHG assessment calculator for road projects developed by Transport for NSW).

3.3.3 Machinery (Mobile Plant) Emissions

The emission factors per unit of measurement (typically hours) for each mobile plant were calculated using the diesel usage per unit of measurement detailed in Transport Authorities Greenhouse Group (2013), multiplied by the emissions factor for diesel in tCO_2-eq/kL of diesel from the AusLCI database.

3.4 Input Data for Pavement Design

Pavement design values were sourced from related literature or based on assumptions when other data sources were unavailable. Some data was based on ARRB's in-house analysis. Pavement designs were established in consultation with partner councils. The LCA analysis compared three alternative cases against a conventional dense-graded asphalt wearing course pavement:

Design scenario	Description	Label
Base case	Conventional dense-graded asphalt wearing course	Conventional DGA
Alternative case 1	5% of RCG in DGA wearing course	RCG-DGA
Alternative Case 2	1 wt.% of CR in DGA wearing course	CR-DGA
Alternative Case 3	0.5 wt.% of RP in DGA wearing course	RP-DGA

3.4.1 Base Case: Conventional DGA

The design of a conventional dense graded asphalt pavement (base case) is shown in Table 3.3.

Table 3.3: Pavement design for the base case

Layer	Layer name	Description/material type	Unit of measurement	Thickness [mm]	Material 1	% by mass of mix	Material 2	% by mass of mix	Material 3	% by mass of mix
1	Surface	Dense graded asphalt	Mass-%	30	C170	5%	10 mm crushed aggregate	94%	Hydrated lime	1%
2	Intermediate	150 mm in situ asphalt base	Mass-%	150	In situ material	100%				
3	Base	250 mm in situ lightly bound at 2% granular material	Mass-%	250	In situ material	100%				
4	Select fill	200 mm in situ unbound granular material	Mass-%	200	In situ material	100%				

3.4.2 Alternative Case 1: RCG-DGA

The design of a recycled crushed glass dense graded asphalt pavement is shown in Table 3.4.

Table 3.4: Pavement design for alternative case 1

Layer	Layer name	Description/material type	Unit of measurement	Thickness [mm]	Material 1	% by mass of mix	Material 2	% by mass of mix	Material 3	% by mass of mix	Material 4	% by mass of mix
1	Surface	Dense graded asphalt with crushed glass???	Mass-%	30	C170	5%	10 mm crushed aggregate	89%	Recycled crushed glass	5%	Hydrated lime	1%
2	Intermediate	150 mm in situ asphalt base	Mass-%	150	In situ material	100%						
3	Base	250 mm in situ lightly bound at 2% granular material	Mass-%	250	In situ material	100%						
4	Select fill	200 mm in situ unbound granular material	Mass-%	200	In situ material	100%						

3.4.3 Alternative Case 2: CR-DGA

The design of a crumb rubber-dense graded asphalt pavement is shown in Table 3.5.

Table 3.5: Pavement design for alternative case 2

Layer	Layer name	Description/material type	Unit of measurement	Thickness [mm]	Material 1	% by mass of mix	Material 2	% by mass of mix	Material 3	% by mass of mix	Material 4	% by mass of mix
1	Surface	Dense graded asphalt with crumb rubber modified binder	Mass-%	30	C170	4.5%	10 mm crushed aggregate	93.5%	Crumb rubber (as part of binder)	1%	hydrated lime	1%
2	Intermediate	150 mm in situ asphalt base	Mass-%	150	In situ material	100%						
3	Base	250 mm in situ lightly bound at 2% granular material	Mass-%	250	In situ material	100%						
4	Select fill	200 mm in situ unbound granular material	Mass-%	200	In situ material	100%						

3.4.4 Alternative Case 3: RP-DGA

The design of a recycled plastic dense graded asphalt pavement is shown in Table 3.6.

Table 3.6: Pavement design for alternative case 3

Layer	Layer name	Description/material type	Unit of measurement	Thickness [mm]	Material 1	% by mass of mix	Material 2	% by mass of mix	Material 3	% by mass of mix	Material 4	% by mass of mix
1	Surface	Dense graded asphalt with recycled plastic modified binder	Mass-%	30	C170	4.8%	10 mm crushed aggregate	93.7%	Recycled ldpe (as part of binder)	0.5%	Hydrated lime	1%
2	Intermediate	150 mm in situ asphalt base	Mass-%	150	In situ material	100.0%						
3	Base	250 mm in situ lightly bound at 2% granular material	Mass-%	250	In situ material	100.0%						
4	Select fill	200 mm in situ unbound granular material	Mass-%	200	In situ material	100%						

3.4.5 Maintenance Assumptions

Asphalt containing CR and RP are assumed to require fewer maintenance interventions due to their superior durability (Picado-Santos et al. 2020; Sasidharan et al. 2019). RCG added as a replacement for aggregates is assumed to have the same durability and performance as conventional asphalt. The assumptions listed below are based on research findings from ARRB's ongoing projects with local councils on the use of RCG in asphalt wearing courses. The number of maintenance activities and periods are based on NACOE and WARRIP analysis, including a review of over 20 individual Transport of Main Roads Queensland and Main Roads Western Australia maintenance schedules and material performance research.

1. Maintenance activities of RCG pavement are assumed same as the base case. Conventional pavements generally undergo four routine and three periodic maintenances over 40 years.

2. RP is added as an alternative to polymers therefore it is assumed that the RP requires less periodic maintenance (two) as compared to conventional pavement.

3. CR pavement has high durability as compared to conventional pavement therefore, it requires three routine maintenances and two periodic maintenances over the period of 40 years.

The maintenance schedules used in the LCA are presented in Appendix A Table A.1.

4. LCA Impact Analysis

LCA impact analysis evaluates the pavement options' life cycle contribution to a range of environmental impacts. The potential environmental impacts of recycled materials were estimated in accordance with the EN 15804:2012 method which uses impact categories from the CML[7] baseline impact assessment method. The assessment method uses the following impact categories: climate change (GHG emissions), acidification, eutrophication, ozone layer depletion and photochemical oxidation (see Table 4.1). The characterisation[8] is the first step and involves the calculation of potential impacts on the basis of the LCI results.

Table 4.1: Impact categories/indicators are established under the EN15804 framework

Impact category/indicator	Unit	Description
Climate change (GHG emissions)	Kg CO_2-eq	Indicator of potential global warming due to emissions of greenhouse gases to the air.
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that causes the destruction of the stratospheric ozone layer
Acidification	kg mol H^+	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
Eutrophication	kg PO_4-eq	Indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds
Photochemical ozone formation	kg NMVOC-eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Abiotic depletion (minerals)	kg Sb eq	The depletion of nonliving (abiotic) resources such as fossil fuels, minerals, clay, and peat.
Abiotic depletion (fossil fuels)	MJ	

Figure A.1, Figure A.2 and Figure A.3 show the source of emissions for the production of RCG, RP and CR. The glass sorting and crushing process emit 0.0136 kg CO_2-eq of GHG for the production of 1 kg of RCG. Sorting of recycled plastic produces 0.237 kg CO_2-eq of GHG to recover 1kg of polyethylene. The recovery process of RP is sourced from the international Ecoinvent library which calculates emissions based on Europe's average electricity consumption for plastic recycling. Therefore, reported GHG emissions and other enviropoints for RP are indicative and estimated values. The GHG emissions for materials should be reported and interpreted in conjunction with other environmental impact indicators as shown in Table A.2.

The seven environmental impact indicators including GHG emissions are calculated for the production phase of recycled materials using SimaPro software. This provides an indication of the overall environmental impact of the production phase of recycled materials. For the remaining life cycle phases (i.e., construction, maintenance, rehabilitation and end-of-life) only GHG emissions were calculated and reported. GHG emission is a key impact category during the life cycle of the pavement that provides sufficient evidence to guide the council's managers in decision making. The remaining impact indicators are out of scope for this project and can be included in future/follow-up research.

4.1 GHG Emissions for the Life Cycle of a Pavement

For all three alternative cases and a base case, DGA with a C170 binder was used. Figure 4.1 presents the life cycle GHG emissions of the surface layer for each of the four pavement design options over an assessment period of 40 years. The GHG emissions are broadly aggregated into four categories based on their source of emissions:

- materials (embodied)

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[7] *CML*-IA is a database that contains characterisation factors for life cycle impact assessment (LCIA) and is easily read by the CMLCA software program.

[8] All inputs and outputs are measured for their potency, and the sum of contributing impacts is expressed in an appropriate unit (e.g. kg CO_2-eq for global warming potential).

- construction
- maintenance
- transport.

Table 4.2 describes sources of emissions under each emission category. Material (embodied) emissions account for the highest GHG emissions for all alternative and base cases. The second highest source of GHG emissions is from maintenance activities which include materials manufacturing emissions and maintenance processes emissions. Maintenance types and frequency depend on the performance and durability of the pavement. Fewer maintenance interventions over the life cycle of the pavement can result in fewer overall emissions.

Figure 4.1: Lifecycle GHG emissions excluding use-phase and end-of-life emissions (in tonnes of CO_2 equivalent)

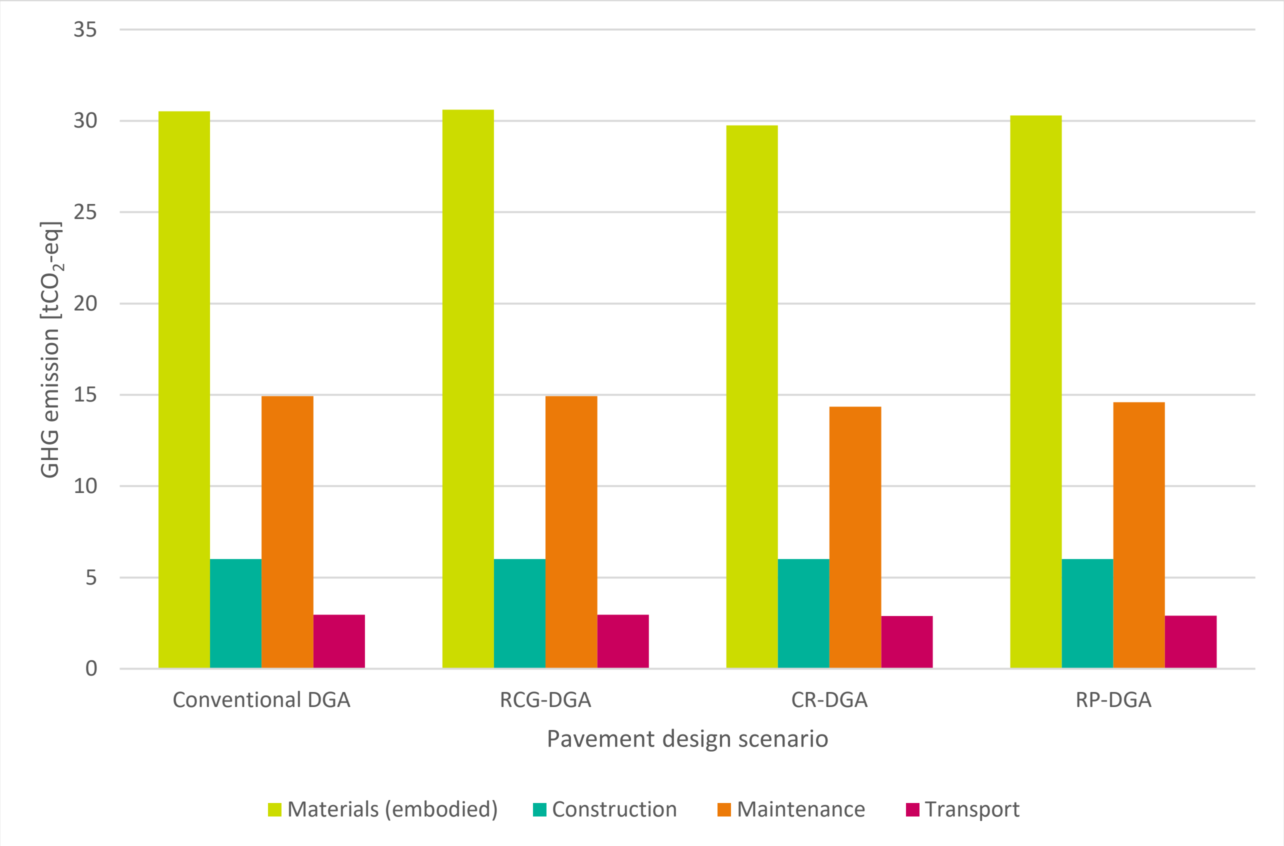


Table 4.2: Sources of emissions under each emission category

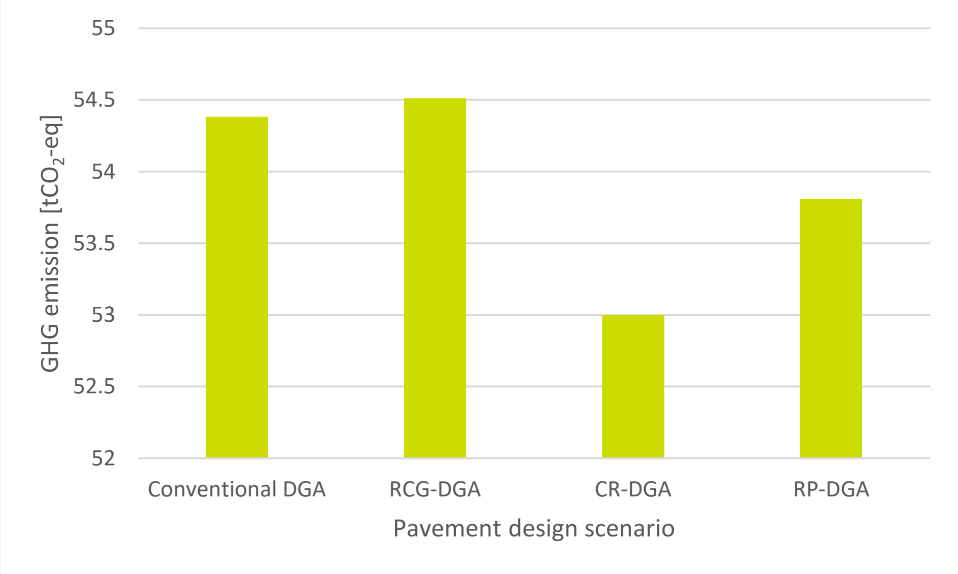
Emission category	Description
Materials for construction and maintenance	Construction and maintenance materials (embodied emissions)
Construction	Construction materials manufacturing Construction processes/equipment
Maintenance	Maintenance materials manufacturing Maintenance processes/equipment
Transportation	Transport to site: construction materials Transport to site: maintenance materials Transport off-site: recycling

The LCA does not include the recycling of the pavement at the end-of-life. Therefore, GHG emissions at the end of the pavement life are not assessed because they are added as embodied emissions in the subsequent pavement life cycle (in which the recycled materials are reused).

4.1.1 Comparison

Figure 4.2 shows that the conventional DGA and RCG-DGA have the highest GHG emissions of 54.5 tCO_2-eq and 54.4 tCO_2-eq respectively. RP-DGA accounts for 53.8 tCO_2-eq while CR has the lowest GHG emissions (53.0 tCO_2-eq) as compared to other recycled materials. Contributional analysis for GHG emissions from each phase is discussed in the following section.

Figure 4.2: Overall GHG emissions over the assessment period of 40 years



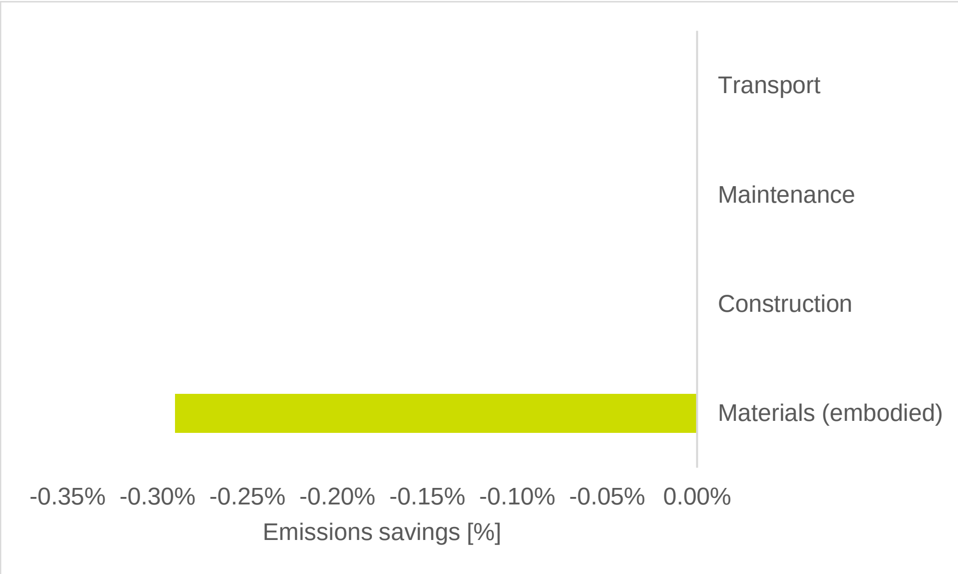
4.1.2 Contribution Analysis

Alternative case 1 (RCG-DGA) vs base case

RCG was incorporated into the wearing course of the pavement as aggregate replacement. Maintenance types and frequencies for pavements containing RCG were assumed to be the same as a base case (maintenance chart is given in Table A.1). Figure 4.3 shows the contribution analysis of GHG emissions during different stages of the life cycle. Use of 5% RCG in wearing course has no significant impact on overall emissions as compared to conventional materials. However, RCG has slightly higher embodied emissions as compared to conventional aggregates. Overall RCG-DGA produces 0.1 tCO_2-eq more emissions than a conventional DGA over the period of 40 years. The slight difference can be recovered by improvements in RCG sorting and recycling process efficiencies. Figure 4.4 shows a slight increase (i.e. negative savings) in the embodied emissions of materials used in the RCG-DGA design as compared to the base case.

Figure 4.3: **Contribution analysis of pavement containing RCG compared with conventional pavement (base case)**

Figure 4.4: **Percentage change in life cycle GHG emissions from RCG-DGA as compared to conventional DGA**



Alternative case 2 (CR-DGA) vs base case

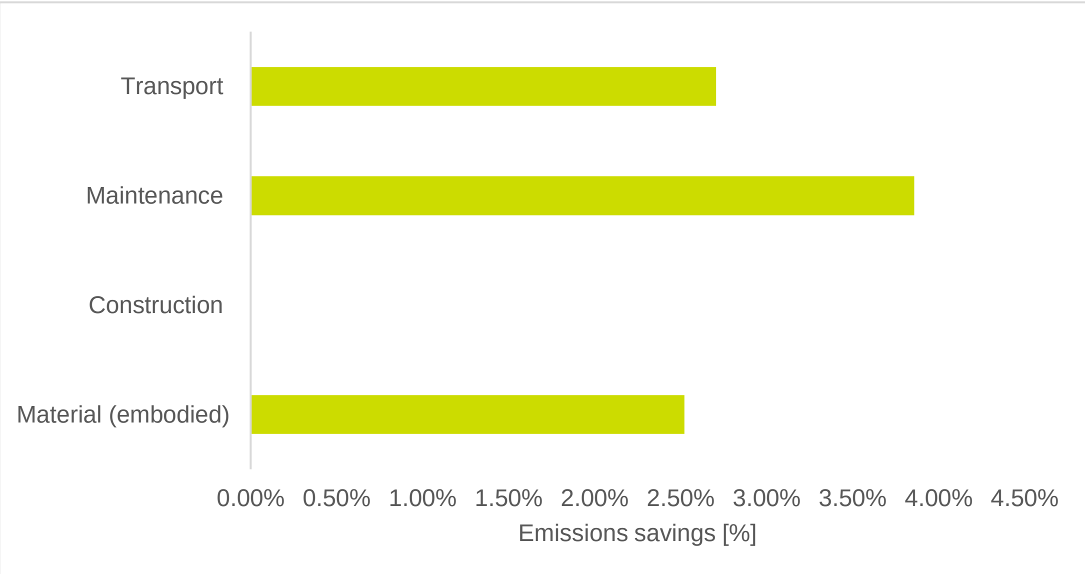
CR (1 wt.% of asphalt) was added into the wearing course as a binder modifier or enhancer through the wet method[9]. It was assumed that the CR requires three routine and two periodic maintenances as compared to 4 routine and 3 periodic maintenances for the base case over the period of 40 years (Table A.1). Figure 4.5 shows the contribution of different emissions sources to the production of CR. Fewer maintenance interventions decrease the overall GHG emissions of CR-DGA. Figure 4.5 shows that the highest emission saving is from maintenance materials (embodied) followed by maintenance processes and maintenance materials manufacturing. One kg CR has 0.169 kg CO_2-eq of embodied emissions as compared to 0.384 kg CO_2-eq for 1 kg of bitumen production. CR-DGA (1 wt.% CR) requires less binder (4.5 wt.%) as compared to conventional DGA which constitutes up to 5 wt.% binders. Therefore, reducing the usage of material with

[9] In the wet method, the binder is first blended with the CR at a specific temperature and then mixed with hot aggregates. Generally, the mixing temperature for the wet method is in the range of 160 – 180 °C.

higher emissions (binder) by adding material with lower emissions (CR) significantly reduces the overall emissions. Figure 4.6 shows that material emissions for CR-DGA were reduced by 2.5% while maintenance emissions were reduced by 3.86% when compared to conventional DGA.

Figure 4.5: Contribution analysis of pavement containing CR compared with conventional pavement (base case)

Figure 4.6: Percentage change in life cycle GHG emissions from CR-DGA as compared to conventional DGA



Alternative case 3 (RP-DGA) vs base case

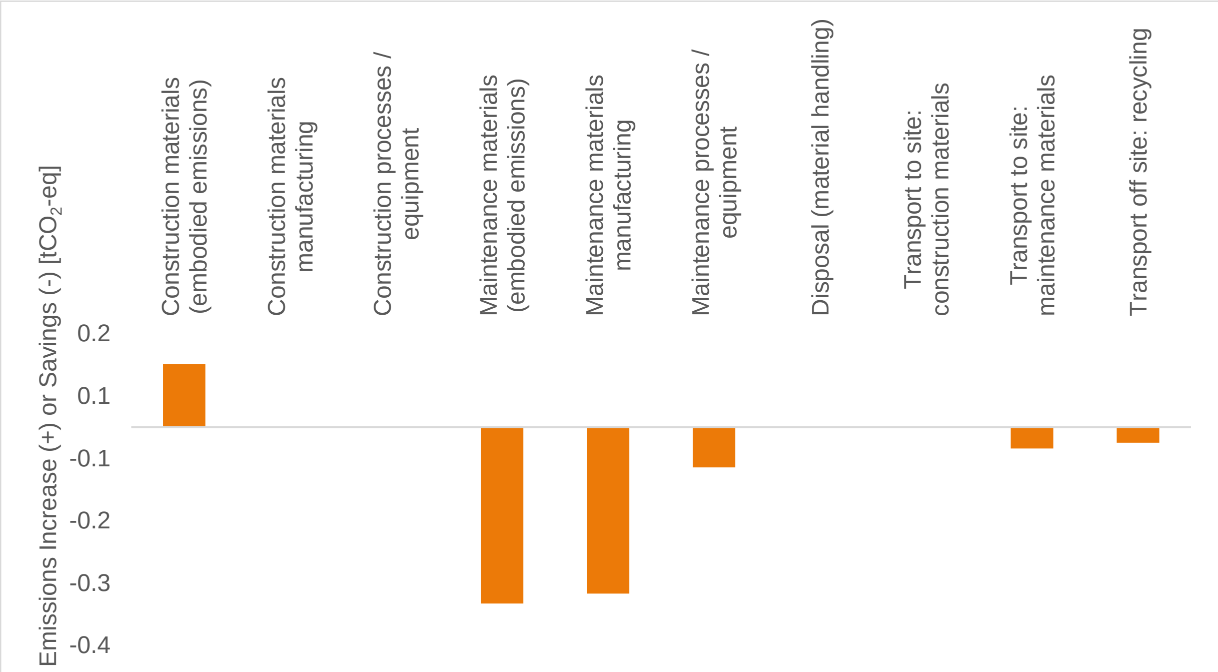
RP (0.5 wt.% of asphalt) was added into the wearing course as a binder modifier or enhancer through the hybrid method[10]. RP was assumed to be polyethylene recovered from mixed plastics. Polymers (plastics) are added to asphalt to improve its durability and long-term performance therefore it was assumed that RP requires two periodic maintenance treatments as compared to three for the base case over the 40 year assessment period. The overall GHG emission of RP-DGA decreased to 53.8 tCO_2-eq as compared to 54.4 tCO_2-eq for the conventional DGA. This is due to the higher emissions savings linked to the maintenance activities (Figure 4.7. Both RP and CR are added into asphalt for the same purpose which is to modify binder properties. However, RP-DGA has higher overall emissions (53.8 tCO_2-eq) as compared to CR-DGA (53 tCO_2-eq) for two reasons:

1. The RP (polyethylene) sorting process produces 0.237 $kgCO_2$-eq per kg of plastic whereas the CR sorting process accounts for 0.169 $kgCO_2$-eq/kg of material
2. The RP added is 0.5 wt.% of asphalt as compared to 1 wt.% CR in asphalt.

These two reasons have a combined effect on overall maintenance, construction and transportation emissions. Figure 4.8 shows that the material emissions from RP-DGA are only 0.73% less than the conventional DGA whereas the major reduction is from maintenance and transport accounting for 2.23% and 2.0% respectively.

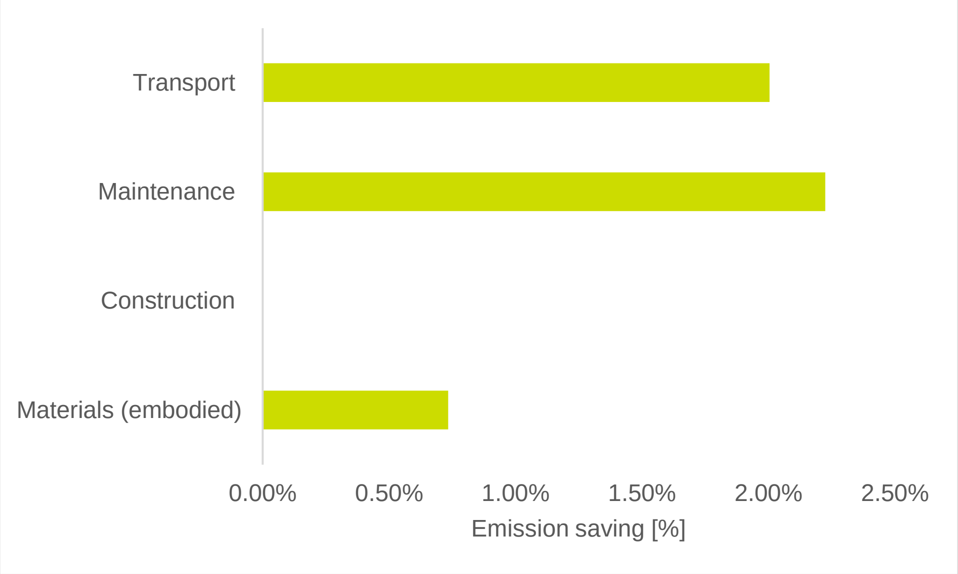
The recovery process of RP is sourced from the international Ecoinvent library which calculates emissions based on Europe's average electricity consumption for plastic recycling. Therefore, reported GHG emission and other enviropoints for RP are indicative and estimated values.

Figure 4.7: Contribution analysis of pavement containing RP compared with conventional pavement (base case)



[10] For the hybrid process, the aggregates are heated first then the recycled plastic and bitumen are added to the hot aggregates. Plastic creates a thin layer covering the aggregates and then is mixed with a binder. The final performance of the asphalt mixture depends on the degree of interaction between plastic and bitumen.

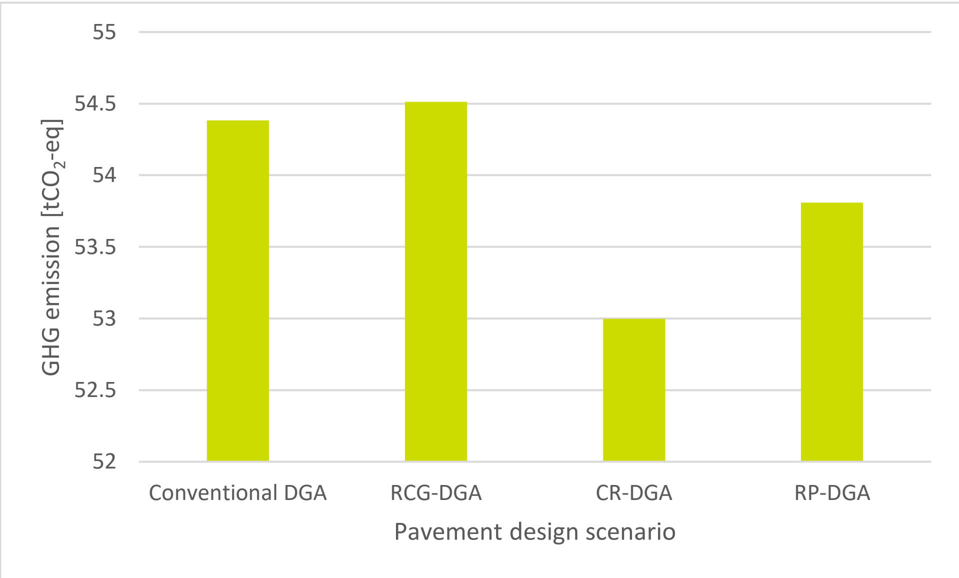
Figure 4.8: Percentage change in life cycle GHG emissions from RP-DGA as compared to conventional DGA



5. Conclusion

The purpose of this report was to investigate the environmental impacts of using recycled materials as a raw material for the construction of a road. This study covers the life cycle assessment of three pavements incorporating recycled materials i.e., RCG, CR and RP compared with a base case conventional DGA. The scope of the report covers the materials, construction, maintenance and rehabilitation emissions of roads containing recycled material in their wearing course.
Figure 5.1 represents the GHG emissions of the base case conventional asphalt and the three alternative cases. Overall lifecycle GHG differences are minor (ranging from 53 tCO2-eq to 54.5 tCO2-eq) across the four designs. Material emissions account for the highest GHG emissions for all alternative and base cases. Maintenance activities are the second highest source of GHG emissions, including materials manufacturing and maintenance processes emissions.

Figure 5.1: GHG emissions of base case vs recycled materials alternatives



The modelling showed the lifecycle GHG emissions of the conventional DGA (54.5 tCO_2-eq) over the 40-year assessment period. The comparative analysis shows that CR-DGA (1 wt.% CR) has the lowest GHG emissions (53 tCO_2-eq) among the alternative cases. The GHG emissions reductions are mainly attributable to the enhanced durability and reduced need for maintenance treatments over the pavement's lifecycle. Additionally, CR has lower embodied emissions compared to the bitumen it partially replaces. RP-DGA (0.5 wt.% RP) has higher lifecycle GHG emissions (53.8 tCO_2-eq) than CR-DGA due to its low RP content in bitumen and higher embodied emissions of RP in comparison to CR.

RCG-DGA (5 wt.% RCG) has slightly higher emissions (54.5 tCO_2-eq) than conventional DGA (54.5 tCO_2-eq) because RCG has higher embodied emissions than the aggregate it partially replaces.

The lifecycle GHG modelling is based on the national lifecycle inventory data, which may differ across jurisdictions and production facilities. Further, there is an opportunity to reduce the embodied emissions of pavement materials by improving efficiencies of materials processing facilities, transitioning to renewable energy resources for the extraction of materials and decreasing materials haulage emissions. Advancements in materials production and recovery processes can decrease emissions significantly in a shorter time.

As the overall lifecycle GHG differences across the four designs are minor (ranging from 53 tCO_2-eq to 54.5 tCO_2-eq), local government pavement engineers and asset managers should also consider local project parameters, such as transportation distances from the material supply to the project location, and any plant, product or process specific attributes that may vary from the national averages and affect the embodied emissions of pavement materials other lifecycle processes.

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ISO standards

ISO 14040:2006, *Environmental management — Life cycle assessment — Principles and framework*

Eurpeon standards

EN 15804:2012, *Environmental product declarations - Core rules for the product category of construction products*

Appendix A Supplementary Data

A.1 Maintenance Type and Frequency Chart

Table A.1: Maintenance frequencies of base case and alternative cases over the assessment period of 40 years.

Year	Base case-conventional DGA	RCG-DGA	CR-DGA	RP-DGA
5	Routine	Routine		
6				Routine
7			Routine	
8				
9				
10	Periodic (patch)	Periodic (patch)		
11				
12				Periodic (patch)
13				
14			Periodic (patch)	
15	Routine	Routine		
16				
17				
18				Routine
19				
20	Periodic (resurface)	Periodic (resurface)		
21			Routine	
22				
23				
24				Periodic (resurface)
25	Routine	Routine		
26				
27				
28			Periodic (resurface)	
29				
30	Periodic (patch)	Periodic (patch)		Routine
31				
32				
33				
34				
35	Routine	Routine	Routine	
36				Routine
37				
38				
39				

Year	Base case-conventional DGA	RCG-DGA	CR-DGA	RP-DGA
40	Rehab	Rehab	Rehab	Rehab
Summary	4 routine; 3 periodic; 1 rehab	4 routine; 3 periodic; 1 rehab	3 routine; 2 periodic; 1 rehab	4 routine; 2 periodic; 1 rehab

A.2 Quantified Environmental Impacts

Table A.2: Quantified environmental impacts (impact categories) of RCG, CR and RP

Impact category/Indicator	Unit	RCG	CR	RP
Global warming (GHG)	kg CO_2-eq	0.013	0.169	0.237
Ozone depletion	kg CFC-11-eq	5.38E-10	1.28E-10	1.55E-08
Acidification	kg mol H+	2.12E-05	7.6E-05	0.0003999
Eutrophication	kg PO4-eq	6.80E-06	2.15E-05	8.004E-05
Photochemical oxidation	kg NMVOC-eq	1.46E-05	1.91E-05	4.503E-05
Abiotic depletion (minerals)	kg Sb eq	2.30E-09	3.66E-10	6.13E-07
Abiotic depletion (fossil fuels)	MJ	0.074	2.708	1.367

A.3 Tree Diagram for Recycled Material

Figure A.1: GHG [kg CO_2-eq] flow within the system to produce 1 kg of RCG

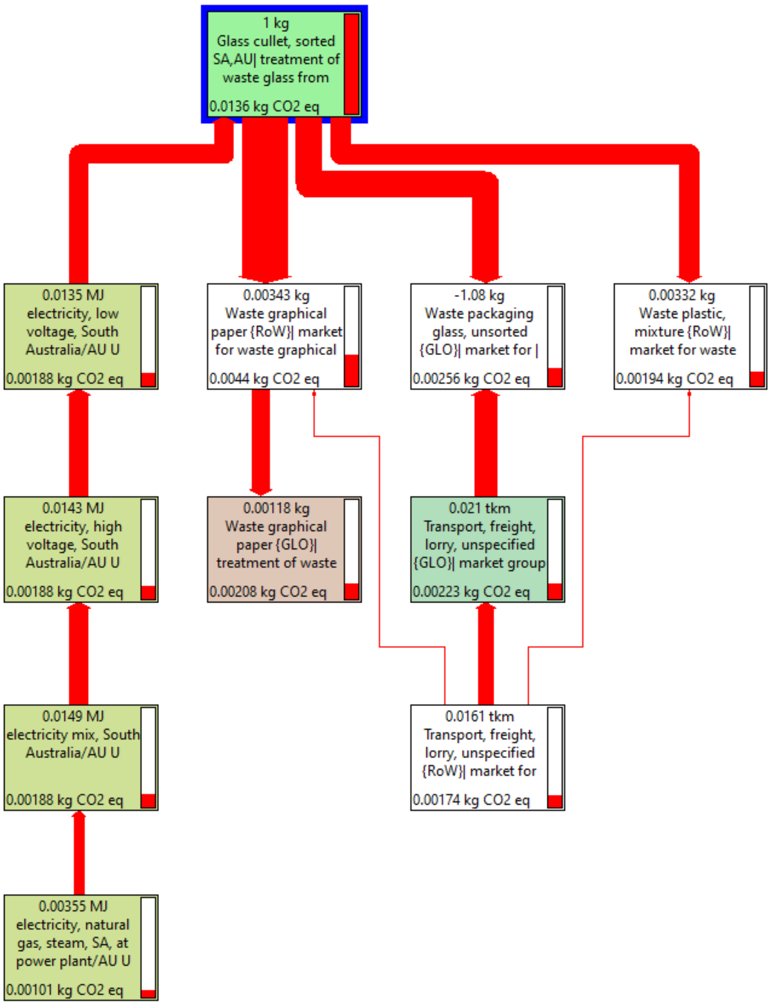


Figure A.2: GHG [kg CO_2-eq] flow within the system to produce 1 kg of CR

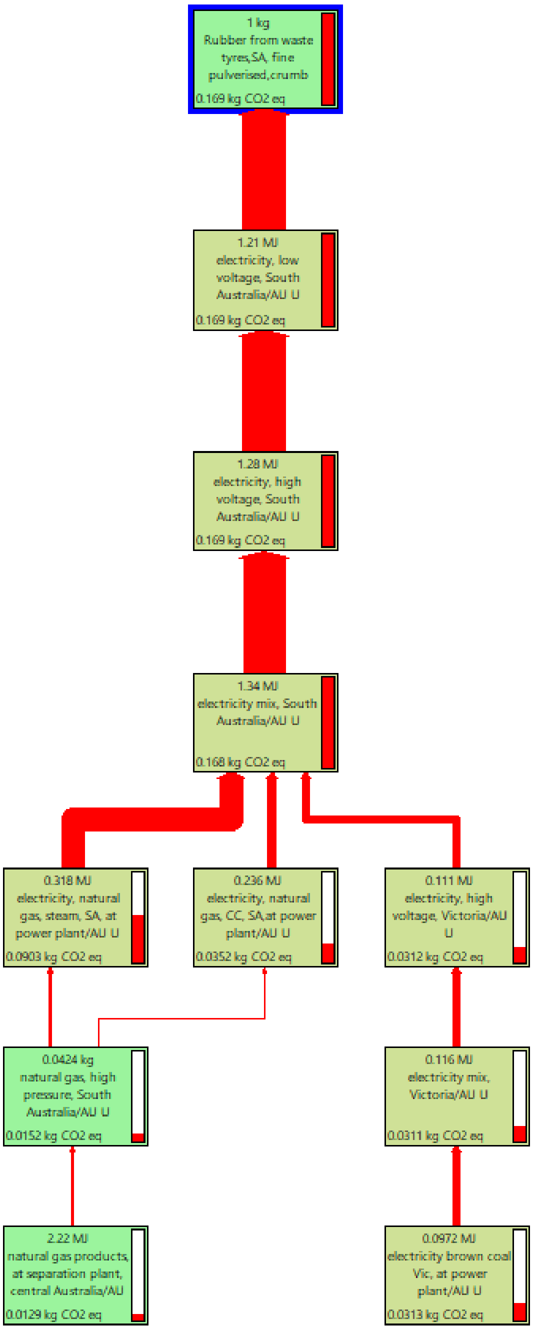
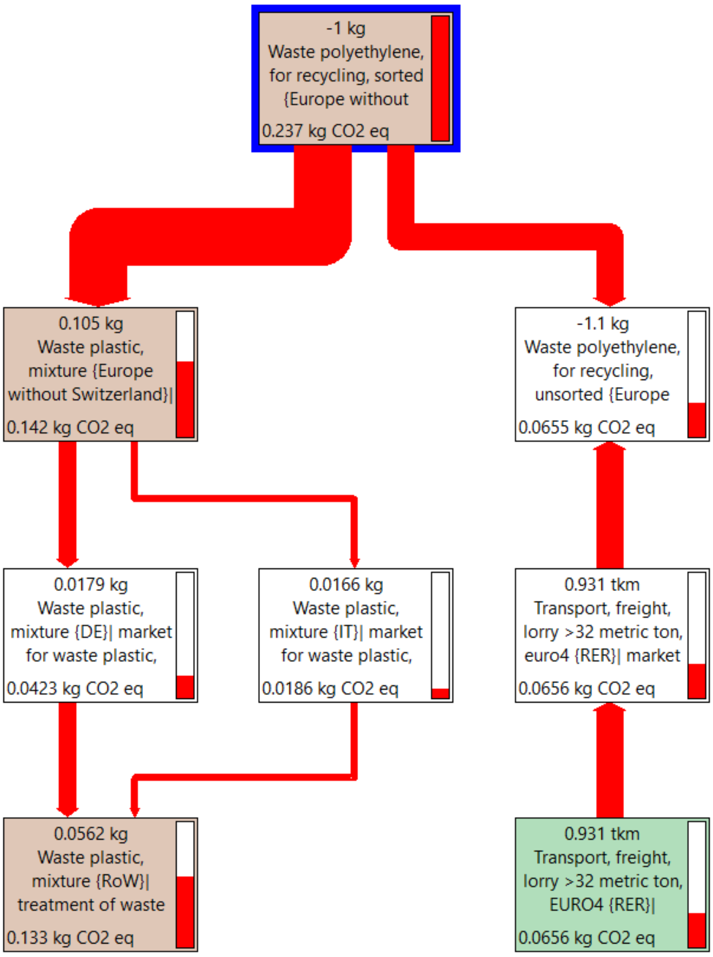


Figure A.3: GHG [kg CO_2-eq] flow within the system to produce 1 kg of RP



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