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Best Practice Expert Advice on the Use of Recycled Materials in Road and Rail Infrastructure: Part B Sustainability Impacts Report

Prepared for:
Commonwealth Sustainable Procurement Advocacy and Resource Centre (C-SPARC), Department of Agriculture, Water and the Environment

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Final Report

Executive Summary

This report (*Part B: Sustainability Impacts Report)* is the second of two *Best Practice Expert Advice on the Use of Recycled Materials in Infrastructure* reports. Combined, these reports support the Australian Government's delivery of the *National Waste Policy Action Plan 2019* objective to increase the use of recycled content in road and rail infrastructure and inform government procurement requirements.

This report reviews, assesses and reports on the environmental, economic and social impacts of using recycled materials in major infrastructure projects across the road and rail industries in Australia. The analysis focusses on the environmental impacts and provides summarised knowledge on the economic (quantified and non-quantified costs and benefits) and social implications of using recycled materials in road and rail infrastructure.

The following materials are considered:

1. Crushed Concrete and Brick
2. Recycled Crushed Glass (RCG)
3. Reclaimed Asphalt Pavement (RAP)
4. Crumb Rubber
5. Ground Granulated Blast Furnace Slag (GGBFS)
6. Fly Ash
7. Bottom Ash
8. Recycled Solid Organics
9. Recycled Ballast
10. Recycled Plastics.

This report also extends the information provided in *Part A*, by detailing barriers to the increased adoption of recycled materials and key recommendations to address these barriers.

Part A provided a review of **government policies and actions** that support the transition to a circular economy through the use of recycled materials in road and rail infrastructure. It also provided a **technical examination** of the application and uses of recycled materials; emerging opportunities; comparative performance to virgin materials; market maturity; supply; and estimated recycled content potential.

Key Findings

Environmental impacts

Significant environmental benefits (i.e. reductions in negative environmental impacts) can be expected for the majority of recycled material applications in road and rail infrastructure.

Greenhouse gas (GHG) emission reductions range from 47% to as high as 98% and overall environmental improvements between 59% to 99% measured as reductions in Enviropoint score. On the environmental impact measures, the best-performing recycled materials were:

- the use of RAP in surface and base layers as a replacement for asphalt made with virgin aggregates and binders (98% fewer GHG emissions and 99% lower Enviropoint score)
- the use of fly ash as a replacement for hydrated lime and cement in stabilised asphalts and concrete pavements (98% fewer GHG emissions and 98% lower Enviropoint score).

Economic impacts

Economic benefits (i.e. material cost savings) can be expected for the majority of recycled material applications in road and rail infrastructure. Cost savings range from 2% to 83%, where the most cost-effective recycled material is RAP. Notably, bottom ash presently does not have a market value, so the material costs is assumed to be zero.

Wider adoption of recycled materials in infrastructure projects is also expected to generate additional employment opportunities in Australia. Specifically, it will create more jobs in the recycling industry to meet the higher demand for recycled material while lowering the labour demand in the waste disposal sector.

Social impacts

The social impacts of using recycled materials may be positive, like new employment opportunities, or negative, like generation of dust and odours generated during the recycling process. The positive social impacts include community and civic pride in using recycled products, and intergenerational equity through contributing to the preservation of natural resources for future generations. There can also be some health and environmental benefits, such as reducing tyre stockpiles (a major fire and vermin hazard), greenhouse gas emissions and quarry blast noise.

As research in this space continues to progress, so will a clearer idea of any health risks and their mitigation strategies. Research to date has already shown that crumb rubber modified asphalt poses no greater emissions threat than regular asphalt, and that the respirable crystalline silica of recycled glass sand is less than that of regular beach sand. Such findings continue to enable more recycled materials to be used and highlight the appropriate safety strategies needed.

Barriers

The key barriers limiting the adoption and use of recycled materials in road and rail infrastructure include:

- *Awareness*: A general lack of awareness as to which applications recycled materials can be used in or allowable limits within specifications.
- *Prescriptive specifications*: Specifications that prescribe which materials to use, rather than focussing on their performance outcomes, can restrict use.
- *Availability of materials*: Logistically difficult and uneconomical collection and recycling of waste in regional areas.
- *Procurement*: Current procurement policies facilitate the use of recycled materials as opposed to *optimising* the use of recycled materials.
- *Perceived inferior performance*: There is a lack of confidence in the use of recycled materials because of this perception.
- *Perceived health, safety and environmental concerns*: Concerns include the environmental impacts, such as those of heavy metals and micro plastics, as well as health and safety considerations for workers and the community.
- *Costs*: Novel applications and technologies are often more expensive than traditional ones, mainly due to research and development costs.

Opportunities and recommendations

- Increasing industry awareness and confidence via knowledge sharing and collaboration.
- Filling in data and evidence gaps via further research using life cycle assessment for emerging materials and applications.
- Continuing the development of performance-based or performance-related specifications and encouraging consistent product evaluation and certification schemes.
- Improving sustainability procurement via incentives and customising policy with project-specific requirements.
- Addressing WHS concerns via evidence-based research, demonstration trials and development of PPE-use standards.
- Creating more opportunities for the cost reduction of recycled material use via encouraging low-energy recycling and processing facilities and supporting the market and supply chain development.

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ARRB – YOUR NATIONAL TRANSPORT RESEARCH ORGANISATION

ABN 68 004 620 651
National Transport Research Centre and Head Office: 80a Turner St, Port Melbourne, 3207 VIC, Australia
With offices in Brisbane, Sydney, Adelaide, Perth.
arrb.com.au

Glossary

Term	Definition
Abiotic depletion	Abiotic depletion refers to the exhaustion of non-living resources like peat, minerals, fossil fuels, and clay.
Acidification	Acidification is an environmental problem caused by acidified rivers, streams, oceans and soil due to anthropogenic air pollutants such as sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x). Acidification increases adverse impacts on aquatic and terrestrial animals and plants by disturbing the food web.
Creep	Long-term deformation of material under a constant load, which occurs as a result of rearrangement of material particles.
EN 15804	EN 15804 is the EPD standard for the sustainability of construction works and services. This standard harmonises the structure for EPDs in the construction sector, making the information transparent and comparable.
Environmental Product Declaration	Environmental Product Declaration (EPD) is a document which presents the environmental impacts of a product. EPDs are a formal and internationally recognised way to present these impacts.
Enviropoint indicator values	Enviropoint indicator values are scores calculated based on the Enviropoint methodology. Enviropoint is a composite measure of seven environmental outcomes developed by Infrastructure Sustainability Council. It is a measure of infrastructure sustainability performance in the IS rating scheme. Lower Envriopoint values indicate fewer negative environmental impacts and are therefore desirable.
Eutrophication	Eutrophication refers to the enrichment of a body of water, partially or in full, with nutrients and minerals like phosphorous and nitrogen.
Fossil fuels	Fossil fuels, which include natural gas, heavy oils, oil shales, petroleum, tar sands, coal, and bitumen, contain carbon and were formed by a geologic process acting on the remains of organic matter produced by photosynthesis.
Global warming	Global warming refers to the long-term increase in the Earth's temperature from the pre-industrial era as a result of human activity.
Global warming potential	Global warming potential is the heat absorbed by the greenhouse gases in the atmosphere. This was developed as a measure of comparison of the global warming impacts of different gasses.
Life Cycle Assessment	Life Cycle Assessment (LCA) is the factual analysis of a product's entire life cycle in terms of sustainability. Every part of a product's life cycle – extraction of materials from the environment, the production of the product, the use phase and its disposal – can have an impact on the environment in many ways. Life cycle studies can be performed for various scopes: cradle to gate (raw materials until factory gate), gate to gate (only focussing on the manufacturing processes) or cradle to grave (raw materials until disposal).
Ozone layer depletion	Ozone layer depletion is the gradual thinning of the ozone layer caused by human activity that results in the release of certain chemical compounds.
Photochemical oxidation	Photochemical oxidation is a mixture of pollutants that are formed when nitrogen oxides and volatile organic compounds (VOCs) react to sunlight, creating a brown haze above cities. Also known as smog.
Processed solid organic waste	A pasteurised material from a processing site that does not include liquid organic waste, digestate from anaerobic digestion, or vermicast. In addition, it does not contain any chemical contaminant concentrations or non-organic physical contaminants exceeding the upper limits for that chemical contaminant parameters.
Recycled organics	A general term, used by industry, for products that are recycled from organic waste. This includes compost, soil conditioners, mulch and other products that can be applied to the land, for landscaping or soil treatment.
Triple Bottom Line	An accounting framework that incorporates three dimensions of performance: social, environmental and financial.

List of Abbreviations

Abbreviation	Term
ACRI	Australasian Centre for Rail Innovation
AfPA	Australian Flexible Pavement Association
ARRB	Australian Road Research Board
ARTI	Australia Transport Index
CO_2	Carbon Dioxide
CFC	Chlorofluorocarbon
C_2H_4	Ethylene
C-SPARC	Commonwealth Sustainable Procurement Advocacy and Resource Centre
DAWE	Department of Agriculture, Water and the Environment (Commonwealth)
EPD	Environmental Product Declarations
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDPE	High-density Polyethylene
ISC	Infrastructure Sustainability Council
LCA	Life Cycle Assessment
LDPE	Low-density Polyethylene
NIS	National Interest Services
PO_4	Phosphate
PPE	Personal Protective Equipment
RAP	Reclaimed Asphalt Pavement
RCG	Recycled Crushed Glass
SDS	Safety Data Sheet
SWMS	Safe Working Method Statement
Sb	Antimony
SO_2	Sulfur Dioxide
WES	Workplace Exposure Standards
WHS	Work Health and Safety

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1. Introduction

1.1 Background

National roads and railways form the backbone of the transport network in Australia. Over the next 10-years, $120 billion is being invested in infrastructure projects under the Australian Government's Infrastructure Investment Program. The infrastructure pipeline is driving substantial road and rail investment as well as unlocking the economic potential of many regions. Further, state and territory governments are in the midst of an unprecedented infrastructure investment program with a major focus on road and rail infrastructure.

While the investments will deliver economic and social benefits, the construction of road and rail infrastructure is resource intensive, requiring significant amounts of natural raw and engineered materials. The extraction, transportation and production of these materials produces waste, consumes energy and emits greenhouse gases. Significant benefits can be realised by using recycled materials and selecting materials that can be reused or recycled at the end of their useful lives as infrastructure assets are eventually upgraded or decommissioned. Australian governments have highlighted the importance of recycled content in road and rail projects in the *National Waste Policy Action Plan 2019.* Incorporating recycled products such as recycled glass, crumbed rubber, reclaimed asphalt pavement, recycled concrete aggregate, recycled plastics and fly ash can achieve significant benefits affecting the triple bottom line of infrastructure projects. State and territory governments have established waste reduction, recycling and circular economy policies that are supported by sustainable procurement requirements to drive the use of recycled materials in funded projects.

The increasing use of recycled materials in infrastructure projects is also being driven by industry with leadership from the Infrastructure Sustainability Council, its members, and other private businesses that are aiming to reduce their environmental impacts. Similarly, waste-generating and waste-management businesses are increasingly exploring opportunities to make better use of their collected and stockpiled materials and industrial by-products.

Lastly, there is a strong driver from within the Australian community to do better in reusing and recycling household and industrial waste, creating a circular economy and reducing the country's environmental footprint.

Recycled materials have a proven ability to play a strong role as alternatives to traditional materials – which are often depleting and increasingly costly – in road and rail infrastructure construction and maintenance. In some cases, recycled materials can be used in combination to improve the properties of traditional materials. Recycled materials also make use of undervalued waste streams, giving a waste product a second life and keeping it out of landfill.

Recycled materials have been used in roads and associated infrastructure for a long time as a cost-effective way to reduce waste and emissions to deliver safe, sustainable and reliable road and rail infrastructure. In recent years, demand for recycled products and industry capability to process and use the products has grown significantly – the beginnings of a major shift in the way road and rail infrastructure are built.

State transport agencies and local governments have been gradually introducing recycled materials into road construction to reduce economic and environmental costs. Meanwhile, recycled materials are also starting to make their way into rail infrastructure projects.

The incorporation of recycled materials in the construction, rehabilitation, and maintenance of roads and rail infrastructure, can provide comparative benefits including:

- reducing the amount of waste sent to landfill
- reducing illegal dumping and littering

- reducing the greenhouse gas (GHG) emissions generated by the production of new materials and the disposal of waste materials
- reducing our reliance on non-renewable and imported resources
- developing a circular economy in which materials are continually re-used in their highest and best usage
- creating new and enhancing existing markets and creating new jobs
- reducing whole of life infrastructure costs
- improving asset durability and performance.

However, the use of recycled materials as business-as-usual materials is progressing slowly. This is due to the lack of awareness and education, lack of experience and confidence in using recycled materials; the disconnection of market demand and supply; variable specifications and guidelines; and the lack of consistent and scientific evidence to report on longer-term performance and sustainability benefits.

This project delivers best practice expert advice on the environmental, economic and social impacts of using recycled materials in major land transport infrastructure projects across Australia. It also details barriers to the increased adoption of recycled materials and opportunities to address these barriers.

1.1.1 Project Partners

This research is funded by the Australian Government's Department of Agriculture, Water and the Environment and managed by the Commonwealth Sustainable Procurement Advocacy and Resource Centre within the Department. The research and best practice advice is provided by the Australian Road Research Board (ARRB).

The **Commonwealth Sustainable Procurement Advocacy and Resource Centre** (C-SPARC) is supporting the transition to a circular economy by generating demand for recycled content and promoting sustainable procurement.

C-SPARC works between government and industry to facilitate opportunities to significantly increase the use of recycled content in line with target four of the *National Waste Policy Action Plan 2019*. C-SPARC runs an education and advocacy program to help Australian Government agencies to embed sustainable procurement practices in their purchases. C-SPARC is also working with industry partners to identify the potential to optimise the use of recycled content in infrastructure.

The Australian Road Research Board

ARRB is a source of independent, expert transport knowledge, advising key decision makers on our nation's most important transport challenges. ARRB's collective knowledge gained over more than 60 years includes significant research in sustainable, innovative and creative solutions on low-carbon options for recycled and recovered materials in road, rail and transport infrastructure.

ARRB has a long history working with Austroads and state road agencies in developing value-added applied knowledge including state-specific fact sheets, specifications and guidelines to address the engineering properties and environmental suitability issues. Recently, ARRB has increasingly been sharing knowledge and expertise with local governments and with the rail industry.

ARRB's work covers a broad range of recycled materials, applications, assessments, trials and implementation guidance for states and territories across Australia. It also actively delivers assessment methodologies, frameworks and tools to help asset managers understand and quantify the impacts associated with the applications of recycled materials. Along the journey, ARRB has identified sustainability benefits including reduced greenhouse gas emissions, captured value from waste materials, improved asset durability and lowered costs from feasible recycled materials.

1.2 Purpose of the Project

The purpose of this report is to provide the Australian Government with robust, evidence-based knowledge for policy setting and informing major infrastructure procurements that aim to enhance the uptake of recycled materials in these infrastructure projects. It also provides the resource recovery sector and the transport industry with new information to build confidence in the benefits of using recycled content in road and rail infrastructure, which will ultimately drive market adoption and improved sustainability outcomes.

This report supports the findings presented in Part A of *Best Practice Expert Advice on the Use of Recycled Materials in Infrastructure* (Section 1.4 provides an overview of Part A's key findings and recycled material specifications).

The project supports the Australian Government's commitment under the *National Waste Policy Action Plan 2019* to significantly increase the use of recycled content, prioritising road and rail.

1.3 Scope of this Report

This report provides best practice expert advice on the environmental, economic and social impacts of using recycled materials in road and rail infrastructure projects across Australia.

The following recycled materials are assessed:

1. Crushed Concrete and Brick
2. Recycled Crushed Glass (RCG)
3. Reclaimed Asphalt Pavement (RAP)
4. Crumb Rubber
5. Ground Granulated Blast Furnace Slag (GGBFS)
6. Fly Ash
7. Bottom Ash
8. Recycled Solid Organics
9. Recycled Ballast
10. Recycled Plastics.

The analysis presented focusses on the environmental impacts and provides summary knowledge on the economic (quantified and non-quantified costs and benefits) and social implications of using recycled materials in road and rail infrastructure.

It also details barriers to the increased adoption of recycled materials and opportunities to address these barriers.

1.4 Key Findings from Part A Report

Part A of the *Best Practice Expert Advice on the Use of Recycled Materials in Infrastructure* project provided a review of **government policies and actions** that support the transition to a circular economy through the use of recycled materials in road and rail infrastructure. It also provides a **technical examination** of the application and uses of recycled materials; emerging opportunities; comparative performance to virgin materials; market maturity; supply; and estimated recycled content potential.

1.4.1 Key Findings

The *2018 National Waste Policy: Less waste, more resources* provides the national framework for waste and resource recovery in Australia and has been endorsed by all levels of government.

As purchasers and managers of major road and rail infrastructure, governments drive market demand through their purchasing decisions. All jurisdictions have procurement guidance that supports value-for-money purchasing that delivers on environmental, social and economic goals. Most jurisdictions have sustainable or green procurement policies or guidance that refer to purchasing considerations around the desirability of using recycled materials, recyclability and reuse of purchased products together with waste reduction. Few jurisdictions, however, have set mandatory, minimum or desirable requirements for use of recycled material for road and rail infrastructure projects, presenting an opportunity for stronger procurement directions.

In this setting, industry and local and state governments have been gradually increasing their use of recycled material in road and rail infrastructure projects, and there is keen interest across industry and government to improve sustainability outcomes. Industry confidence is variable, according to how well each material's use is established. For example, newer opportunities such as recycled plastics in pavement or rail sleepers are emerging compared to the use of crumb rubber in sprayed seals, which has been done with confidence on a national basis for decades.

Some of the key barriers to the growing use of recycled materials in infrastructure include a lack of awareness and education; a disconnection between market demand and supply; a need for more enabling specifications, standards and guidelines; and lastly, a lack of evidence to guide long-term performance outcomes and sustainability benefits.

The *Part A* report showed that there is a range of recycled materials widely used and ample opportunity to increase the recycled material content and/or increase the frequency of use. Emerging recycled material technologies present a significant opportunity for increased uptake. Improved awareness and education in how these materials are used, supported by policy and procurement drivers, new and improved specifications and more modern recycling facilities with increased capacity, can contribute to increasing the use of recycled materials, improving sustainability outcomes and a more circular economy.

1.4.2 Best Practice Recycled Materials in Specifications

Part A presented a detailed analysis of 10 mature and emerging recycled materials and their applications in road and rail infrastructure. The analysis noted the different state and territory standards and specifications that regulate the safe and effective use of recycled materials in different road and rail applications. The analysis showed that state and territory specifications are diverse and varied.

Table 1.1 provides a subset of all possible applications that were identified in *Part A* report and the highest allowable content limits as permitted by the leading state and territory specifications. The subset of applications used for the sustainability assessments focusses on the best practice applications based on the degree of research, testing and trials and the maturity of their use in real-world applications. The full range of replacement opportunities can be found in *Part A* report for individual recycled materials. Information contained in Table 1.1 is used as the basis for quantifying replacement potential.

Table 1.1: Replacement potential by recycled materials

Recycled material	Infrastructure type	Application	Virgin material	Content limit	Source
Crushed concrete	Road	Aggregates in granular subbase layer	Crushed rock	100%(1)	Savage (2010), MRTS35-2017 VicRoads (2017)
Crushed brick	Road	Aggregates in granular subbase layer	Crushed rock	20%(1)	VicRoads (2017)

Recycled material	Infrastructure type	Application	Virgin material	Content limit	Source
RCG	Road	Aggregates in granular base layer	Crushed aggregate[3]	10%[1]	VicRoads (2017), Specification D&C 3051:2020) and IPWEA & WALGA (2019)
		Aggregates in granular subbase layer	Crushed aggregate[3]	50%[1]	VicRoads (2017), IPWEA & WALGA (2019)
		Aggregates in asphalt base layer	Crushed aggregate[3]	10%[1]	MRTS35-2017, Specification D&C 3051:2020
		Aggregates in asphalt surface layer	Crushed aggregate[3]	5%[1]	VicRoads (2017)
		Aggregates in drainage layer	Crushed aggregate[3]	100%[1]	Austroads (2022a)
	General	Bedding and backfill material in trench layer	Crushed aggregate[3]	100%[1]	MRTS35-2017
		Fill for embankment	Crushed aggregate[3]	20%[1]	Specification 302:2020
RAP	Road	Asphalt in surface layer	Asphalt	20%[1]	Specification D&C R116:2021
		Asphalt in base layer	Asphalt	40%[1]	QA Specification R117:2020
Crumb rubber	Road	Spray seal	Bitumen	20%[2]	QA Specification R118:2020, QA Specification 3252:2020
		Binder in asphalt mixture	Bitumen	20%[2]	Austroads (2021a)
Fly ash	Road	Cementitious stabiliser in the subgrade layer	Hydrated lime	5%[1]	Yaghoubi et al. (2019)
		Cementitious stabiliser in base layer	Cement	40%[2]	Specification D&C 3211:2020, MRTS40-2018
		Cementitious material in concrete pavement	Cement	20%[2]	Section 520:2018
GGBFS	Road	Cementitious material in concrete pavement	Cement	50%[2]	Information from Specification D&C 3211:2020 amended based on expert advice.
		Cementitious stabiliser in base layer	Cement	70%[2]	Austroads (2019a)
	General	Cementitious material in concrete structures	Cement	70%[2]	Specification D&C 3211:2020
Bottom ash	Road	Aggregates in granular subbase (unbound pavement)	Crushed rock	10%[1]	Specification D&C 3051:2020
Recycled ballast	Rail	Ballast	Ballast	100%[1]	Jia et al. (2019)
Recycled solid organics	General	Landscaping mulch	Mulch	100%	ARRB (unpublished) for the Department of Transport, Victoria
Recycled plastics	Roads	Binder in asphalt	Bitumen	6%[2]	Current (unpublished) NACOE/ WARRIP research
	Rail	Sleepers	Timber sleeper	100%[1]	Integrated Recycling (2022)
	General	Noise walls	Virgin HDPE plastics	75%[1]	Macken et al. (2021)
	General	Plastic pipes	Virgin HDPE plastics	100%[1]	ARRB (unpublished) for the Department of Transport, Victoria

1. As a percentage of total mass of the infrastructure unit.
2. As a percentage of the mass of the applicable material component per application.
3. 5 mm crushed aggregates.

2. Sustainability Assessment

In simple conceptual terms, recycled materials are used in road and rail infrastructure to replace or substitute virgin materials. In many applications, road and rail infrastructure containing recycled materials are recyclable at the end of their 'second life', contributing to the circular outcomes. By using fewer virgin materials, there is less waste and significant potential to realise environmental, economic and social benefits from using recycled materials.

In practice, the use of recycled materials and extent of substitution in road and rail infrastructure applications is complex and governed by different specifications, controls and performance expectations (as explained in *Part A*). Recycled materials are also diverse in terms of the processing and manufacturing requirements that enable their use in appropriate applications and to meet specified performance requirements. As such, the sustainability impacts are not straightforward.

Acknowledging the complexities, there are many potential environmental, economic and social benefits from using recycled materials that justify the efforts governments and industry are making to increasingly adopt them in road and rail infrastructure. Some of these benefits include:

- reducing the amount of waste sent to landfill
- reducing illegal dumping and littering
- reducing the GHG emissions generated by the production of new materials and the disposal of waste materials
- reducing reliance on non-renewable and imported resources
- developing a circular economy in which materials are continually re-used in their highest and best usage
- reducing short- and long-term costs – short-term costs refer to material procurement cost and waste disposal cost; long-term costs refer to ongoing maintenance and operational costs as well as climate change costs and the depletion of natural resources
- potentially improving asset durability and performance.

Noting the potential benefits, this analysis also considers the potential negative impacts, or adverse outcomes, of using recycled materials. These can include:

- higher GHG emissions generated in the processing of recycled materials
- higher costs compared with virgin materials
- health and environmental impacts of recycled materials (adverse outcomes), e.g. tyre fuming, micro-plastics.

This report provides a best practice quantification and qualitative assessment of the positive and adverse environmental, economic and social impacts of using recycled materials in road and rail infrastructure. It will also help quantify the potential benefits that can be achieved with best practice recycled material applications and specifications.

The analysis provided will help to overcome lack of knowledge and misconceptions about the impact of using recycled materials (as outlined in Section 3) that can reduce confidence and inhibit adoption.

2.1 Assessment Methodology

The sustainability impact assessment method focusses on:

1. quantifying the replacement potential of recycled materials
2. quantifying and comparing the environmental impacts and resource consumption of using recycled materials compared with virgin materials
3. quantifying the economic impacts of using recycled materials
4. providing qualitative assessment of the social impacts and concerns of using recycled materials.

2.1.1 Quantifying the Replacement Potential

The magnitude of sustainability impacts of recycled materials use is determined by uptake. Quantifying the potential of recycled materials to replace virgin materials as a percentage of total materials provides a basis for determining the sustainability impacts in specific road and rail applications.

Quantifying the replacement potential involves:

1. **Identify best practice replacement opportunities** by filtering the long list of replacement opportunities (as detailed in *Part A* and summarised in Table 1.1) considering their: research and testing rigor; maturity of applications; performance confidence; and applicability. Identifying the best practice replacement opportunities focusses the impact assessment on where there is confidence in the materials and applications and generally better data to support the impact assessment.
2. **Identify a best practice replacement rate** by adopting the upper limit (the potential) of the replacement opportunity that is supported by relevant Australian standards and specifications. Replacement rates for the same recycled material may vary from application to application and are expressed in terms of percentages of material mass that correspond to specific infrastructure use cases. Identifying a best practice replacement rate allows impact assessment results to be based on the greatest potential use of recycled materials.
3. **Quantify the replacement potential** by calculating and comparing the masses of the replaceable virgin materials and the recycled materials. This comparison recognises the differences in the densities of different material to achieve a consistent material replacement volume.

The quantified replacement material potential is measured on an infrastructure unit basis (e.g. per lane km of road carriageway, or km of rail track) to provide a consistent basis for the sustainability impact analysis. It also allows for a simplified parameter for estimating replacement potential at larger scales, such as at the project or network levels.

2.1.2 Environmental Impacts

Environmental impacts are assessed by comparing a range of indicator values that reflect the environmental consequences of using virgin and recycled materials in infrastructure applications. The environmental indicators can be grouped into two broad categories of environmental consequences: environmental impact and the resource consumption impact.

Environmental impact indicators

Environmental impact is caused by the emission of environmental pollutants and the depletion of non-renewable resources during the production (extraction and manufacturing processes) of infrastructure materials. Environmental impacts are quantified using the following indicators:

- the emission of CO_2-equivalent gasses that lead to *global warming*
- the emission of CFC-11-equivalent gasses that lead to *ozone layer depletion*
- the emission of SO_2-equivalent gasses that lead to *acidification*
- the emission of PO_4-equivalent gasses that lead to *eutrophication*
- the emission of C_2H_4-equivalent gasses that lead to *photochemical oxidation*
- the consumption of Sb-equivalent that leads to *abiotic depletion in minerals*
- the consumption of energy that leads to *abiotic depletion in fossil fuel*.

The indicators above are the standard environmental indicators used in Environmental Product Declarations (EPDs) and are also used as inputs for calculating Enviropoint – a single composite indicator recommended by the Infrastructure Sustainability Council (ISC) as a comprehensive measure of the environmental impact of infrastructure materials and processes. To obtain this measure, component indicators are normalised, weighted and summed following the methodology provided by ISC.

The value of environmental impact indicators is calculated as the product of material-specific impact factors and the mass of the materials used in an infrastructure application. Impact factors measure the intensity of environmental impacts due to the production of a unit (1 kg) of material.

ARRB modelled the impact factors using the SimaPro Life Cycle Assessment (LCA) software following the EN15804 standard (for EPDs). The modelling assumes all processes for producing virgin and recycled materials source energy from a nationally representative energy grid. This assumption implies that any difference in the environmental footprint between the use of different materials is caused only by the type of material production processes and the quantity of material produced. Modelled impact factors can be found in Appendix A.

For each replacement application, indicator values are calculated based on the virgin and recycled material masses. To account for the environmental benefit of avoided landfill due to recycling, environmental indicator values for landfill are calculated based on the mass of recycled material in each application. These indicator values are then added to the indicator values for virgin materials to reflect their higher environmental cost than recycled materials (which would have resulted in the avoidance of landfill).

As most road and rail infrastructure materials are generally inert (i.e. they do not decompose), the disposal impacts are based on only the processes of landfilling inert waste (e.g. separation of wastes and on-site processes), rather than the decomposition process of buried waste. Aside from solid organics, the recycled materials investigated in this report are predominately inert in nature and produce negligible environmental emissions once landfilled.

Environmental impact indicator values are calculated based on the methodology described in Section 2.2.2.

Resource consumption indicators

Valuable natural resources are consumed in the process of producing infrastructure materials. The resulting environment impact can be significant, as the resource demand by infrastructure projects can be large and unsustainable in the long term. To assess the environmental impact of utilising recycled materials in infrastructure projects, the magnitude of the following resource inputs for producing virgin and recycled materials for each replacement application is estimated:

- electricity use
- water use
- natural gas use
- diesel use.

The value of resource consumption indicators is calculated as the product of material-specific consumption factors for each resource type and the mass of the materials. Consumption factors measure the rate of consumption associated with the production of a unit (1 kg) of material. ARRB modelled the consumption factors using the SimaPro LCA software. As with the environmental impact indicators, the modelling assumes all processes for producing virgin and recycled materials source energy from a nationally representative energy grid. This assumption implies any difference in the environmental footprint between the use of different materials is caused only by the type of material production processes and the quantity of material produced. Modelled consumption factors can be found in Table A.2 in Appendix A.

For each replacement application, indicator values measuring resource consumption are calculated based on the virgin and recycled material masses. To account for the resource conservation benefit of avoided landfill due to recycling, resource consumption indicator values for landfill are calculated based on the mass of recycled material in each application. These indicator values are then added to the indicator values for virgin materials to reflect their higher level of resource consumption than recycled materials (which would have resulted in the avoidance of landfill).

Resource consumption indicator values are calculated based on the methodology described in Section 2.2.2.

2.1.3 Economic Impacts

Economic impacts are assessed by comparing the material costs and the impact on employment opportunities of using virgin and recycled materials in infrastructure applications.

Impact of material costs

The economic impact of material costs is assessed by comparing the costs of virgin and recycled materials used in the same infrastructure application. Haulage costs of materials are project-specific and depend on the distance between material processing locations and the project site. Assessing the impact of haulage cost of materials is not practical at the application-level. Nonetheless, it is important to note the haulage costs can have a significant impact on the overall economic outcomes of a material and should be included in the material option analysis of specific infrastructure projects.

Material costs are estimated by multiplying the unit cost (cost per kg) of a material by its estimated mass quantity used in an application for its specified unit value.

ARRB obtained unit material costs from a range of sources including unit costs published in research papers, on supplier websites, in news media, and through direct communication with material suppliers and relevant government agencies. ARRB has reviewed the sourced cost data carefully and ensured that adopted unit material costs are appropriate for the type of infrastructure project and the typical scale of usage under each application.

Organisations that have been contacted directly for material cost information include:

- Repurpose It – a supplier of recycled material for infrastructure applications.
- Tyre Stewardship Australia – a national industry-based organisation for promoting the development of markets for end-of-life tyres.
- Independent Cement and Lime Group – a supplier of cement, lime and other pavement materials, with operations in Victoria and New South Wales.
- Sacyr Environment Services – an international company that specialises in treating and resourcing waste materials and has operations in Victoria.

ARRB notes that the unit costs of materials can vary significantly over time, geography and by suppliers. Unit costs presented in in Table 2.6 are point-in-time estimated cost values reflecting current market conditions (supply and demand) of individual material products.

Future costs are subject to change as underlying market conditions change. Such changes may include greater processing capacity, introduction of new technology and processes and greater demand with improved uptake.

Importantly, the magnitude of the economic impact will depend on the relative price differences between virgin and recycled materials for each application. The direction of future change in economic impact will therefore depend on the relative change in the cost of substitutable materials.

Economic impact on material costs is provided in Section 2.2.3.

Impact on employment opportunities

Increased use of recycled materials in infrastructure will lead to an increase in employment opportunities in the recycling sector. The impact on employment is assessed for each infrastructure application based on the employment potential in the recycling and disposal industries and the estimated replacement potential for each application.

The employment potential for the recycling industry is provided by Deloitte's *Access Economics* (2009) which states that for every 10,000 tonnes of waste that is recycled, 9.2 jobs are created. This compares with the creation of 2.8 jobs if the same amount of waste was sent to landfill. Economic impact on employment opportunities is provided in Section 2.2.3.

2.1.4 Social Impacts

ARRB has done extensive research into the use of recycled materials in road and rail infrastructure for Austroads, Australian state and territory road agencies and private organisations. Where relevant, social impact information has been sourced from these previous project reports and expert opinion. Additional materials were also sourced through a desktop review of literature obtained through the ARRB M.G. Lay Library, the Australia Transport Index (ATRI) Database, the Rail Knowledge Bank, and other information resources managed through the National Interest Services (NIS).

2.2 Assessment Results

2.2.1 Quantified Replacement Potential

Table 2.1 presents the replacement potential for individual recycled materials. The *Mass Content of Virgin Material* column shows the mass of virgin materials that may be replaced with recycled material in a unit of infrastructure based on the replacement percentage in the *Content Limit* column in Table 1.1. *Mass Content of Recycled Material* column shows the mass of recycled materials that can replace the corresponding volume of virgin materials in a unit of infrastructure. Differences in mass are due to different material densities that deliver the same volume in the infrastructure.

Table 2.1: Replacement potential by recycled materials

Recycled material	Infrastructure type	Infrastructure unit	Virgin material	Mass content of virgin material (kg)	Mass content of recycled material (kg)
Crushed concrete	Road	lane-km of granular subbase	Crushed rock	1,207,500	1,050,000
Crushed brick	Road	lane-km of granular subbase	Crushed rock	278,250	229,859
RCG	Road	lane-km of granular base	Crushed aggregate	185,500	182,000
		lane-km of granular subbase	Crushed aggregate	695,625	682,500
		lane-km of asphalt base	Crushed aggregate	175,000	171,698
		lane-km of asphalt surface	Crushed aggregate	21,875	21,462
		lane-km of drainage layer	Crushed aggregate	927,500	910,000
	General	km of trench (0.5 m-wide)	Crushed aggregate	1,325,000	1,300,000
		km of embarkment (7 m-wide)	Crushed aggregate	8,268,000	8,112,000
RAP	Road	lane-km of asphalt surface	Virgin asphalt	87,500	87,500
		lane-km of asphalt base	Virgin asphalt	175,000	175,000
Crumb rubber	Road	lane-km of surface (as spray seal)	Bitumen	1,082	1,208
		lane-km of asphalt pavement (as binder)	Bitumen	35,000	39,078
Fly ash	Road	lane-km of asphalt subgrade (as stabiliser)	Hydrated lime	24,150	26,250
		lane-km of asphalt base (as stabiliser)	Cement	14,000	10,938
		lane-km of concrete pavement	Cement	71,400	55,781

Recycled material	Infrastructure type	Infrastructure unit	Virgin material	Mass content of virgin material (kg)	Mass content of recycled material (kg)
GGBFS	Road	lane-km of concrete pavement	Cement	178,500	178,500
		lane-km of asphalt base (as stabiliser)	Cement	24,500	24,500
	General	100 m^3 of structural concrete	Cement	28,560	28,560
Bottom ash	Road	lane-km of granular subbase	Crushed rock	120,750	131,250
Recycled ballast	Rail	track-km of railway ballast	Virgin ballast	2,940,000	2,940,000
Recycled solid organics	General	1 tonne of landscaping mulch	Mulch	1,000	1,000
Recycled plastics	Roads	lane-km of asphalt surface (as binder)	Bitumen	1,313	1,172
	Rail	track-km of railway sleepers	Timber	52,880	64,000
	General	km of noise wall (3 m height)	Virgin HDPE plastics	103,500	103,500
	General	kg of pipes	Virgin HDPE plastics	1,000	1,000

Table 2.1 shows that significant quantities of recycled materials can be used as substitutes for virgin materials, especially in structural applications such as granular and asphalt pavement layers, embankments and rail ballast.

2.2.2 Environmental Impacts

Environmental impact indicators

Table 2.2 presents the assessment results for environmental impact indicators for global warming measured in GHG (tCO_2-e) emissions and Enviropoints. This table shows the percentage change in environmental impacts due to the replacement of virgin materials with recycled materials. Full details of the environmental impact indicators that contribute to the calculation of Enviropoints can be found in Appendix A.

Table 2.2: Environmental impact indicators (before accounting for avoided landfill impact)

Recycled material	Infrastructure type	Infrastructure unit	Global warming ($kg\ CO_2$ eq)	Enviropoint
Crushed concrete	Road	lane-km of granular subbase	−50%	−59%
Crushed brick	Road	lane-km of granular subbase	−53%	−61%
RCG	Road	lane-km of granular base	127%	82%
		lane-km of granular subbase	127%	82%
		lane-km of asphalt base	127%	82%
		lane-km of asphalt surface	127%	82%
		lane-km of drainage layer	127%	82%
	General	km of trench (0.5 m-wide)	127%	82%
		km of embarkment (7 m-wide)	127%	82%
RAP	Road	lane-km of asphalt surface	−98%	−99%
		lane-km of asphalt base	−98%	−99%
Crumb rubber	Road	lane-km of surface (as spray seal)	−47%	−80%
		lane-km of asphalt pavement (as binder)	−47%	−80%
Fly ash	Road	lane-km of asphalt subgrade (as stabiliser)	−98%	−98%
		lane-km of asphalt base (as stabiliser)	−98%	−98%
		lane-km of concrete pavement	−98%	−98%
GGBFS	Road	lane-km of concrete pavement	−73%	−62%
		lane-km of asphalt base (as stabiliser)	−73%	−62%
	General	100 m^3 of structural concrete	−73%	−62%
Bottom ash	Road	lane-km of granular subbase	44%	19%
Recycled ballast	Rail(1)	track-km of railway ballast	–	–
Recycled solid organics	General(1)	1 tonne of landscaping mulch	–	–
Recycled plastics	Roads	lane-km of asphalt surface (as binder)	−65%	−86%
	Rail(1)	track-km of railway sleepers	-	-
	General	km of noise wall (3 m height)	−90%	−93%
	General	kg of pipes	−90%	−93%

1. Estimation not available due to the lack of information to generate required impact.

Table 2.3 presents assessment results that also account for the environmental benefits of avoiding landfill by utilising recycling materials. Positive values indicate worsening environmental outcomes after material replacement and dash symbols (‘–‘) denote values that cannot be estimated due to information gaps.

Table 2.3: Environmental impact indicators (after accounting for avoided landfill impact)

Recycled material	Infrastructure type	Infrastructure unit	Global warming (kg CO_2 eq)	Enviropoint
Crushed concrete	Road	lane-km of granular subbase	−67%	−71%
Crushed brick	Road	lane-km of granular subbase	−68%	−72%
RCG	Road	lane-km of granular base	43%	23%
		lane-km of granular subbase	43%	23%
		lane-km of asphalt base	43%	23%
		lane-km of asphalt surface	43%	23%
		lane-km of drainage layer	43%	23%
	General	km of trench (0.5 m-wide)	43%	23%
		km of embarkment (7 m-wide)	43%	23%
RAP	Road	lane-km of asphalt surface	−98%	−99%
		lane-km of asphalt base	−98%	−99%
Crumb rubber	Road	lane-km of surface (as spray seal)	−48%	−80%
		lane-km of asphalt pavement (as binder)	−48%	−80%
Fly ash	Road	lane-km of asphalt subgrade (as stabiliser)	−98%	−98%
		lane-km of asphalt base (as stabiliser)	−98%	−98%
		lane-km of concrete pavement	−98%	−98%
GGBFS	Road	lane-km of concrete pavement	−74%	−63%
		lane-km of asphalt base (as stabiliser)	−74%	−63%
	General	100 m^3 of structural concrete	−74%	−63%
Bottom ash	Road	lane-km of granular subbase	−13%	−23%
Recycled ballast	Rail[(1)]	track-km of railway ballast	–	–
Recycled solid organics	General[(1)]	1 tonne of landscaping mulch	–	–
Recycled plastics	Roads	lane-km of asphalt surface (as binder)	−65%	−86%
	Rail[(1)]	track-km of railway sleepers	-	-
	General	km of noise wall (3 m height)	−90%	−93%
	General	kg of pipes	−90%	−93%

1. Estimation not available due to the lack of information to generate required impact factor.

Resource consumption indicators

Table 2.4 presents the assessment results for resource consumption indicators. This table shows the percentage change in resources consumed for material production due to their replacement with recycled materials. Positive values indicate a worsening of environmental outcomes after material replacement.

Table 2.4: Resource consumption indicators (before accounting for avoided landfill impact)

Recycled material	Infrastructure type	Infrastructure unit	Electricity use (kWh)	Water use (m^3 eq)	Natural gas use (GJ)	Diesel use (MJ)
Crushed concrete	Road	lane-km of granular subbase	−91%	−100%	−98%	105%
Crushed brick	Road	lane-km of granular subbase	−91%	−100%	−98%	94%
RCG	Road	lane-km of granular base	−63%	−80%	−93%	−99%
		lane-km of granular subbase	−63%	−80%	−93%	−99%
		lane-km of asphalt base	−63%	−80%	−93%	−99%
		lane-km of asphalt surface	−63%	−80%	−93%	−99%
		lane-km of drainage layer	−63%	−80%	−93%	−99%
	General	km of trench (0.5 m-wide)	−63%	−80%	−93%	−99%
		km of embarkment (7 m-wide)	−63%	−80%	−93%	−99%
RAP	Road	lane-km of asphalt surface	−100%	−100%	−100%	−63%
		lane-km of asphalt base	−100%	−100%	−100%	−63%
Crumb rubber	Road	lane-km of surface (as spray seal)	300%	−77%	213%	−92%
		lane-km of asphalt pavement (as binder)	300%	−77%	213%	−92%
Fly ash	Road	lane-km of asphalt subgrade (as stabiliser)	−99%	−100%	−99%	87%
		lane-km of asphalt base (as stabiliser)	−100%	−99%	−100%	−56%
		lane-km of concrete pavement	−100%	−99%	−100%	−56%
GGBFS	Road	lane-km of concrete pavement	−16%	−54%	−11%	−75%
		lane-km of asphalt base (as stabiliser)	−16%	−54%	−11%	−75%
	General	100 m^3 of structural concrete	−16%	−54%	−11%	−75%
Bottom ash	Road(1)	lane-km of granular subbase	–	–	–	–
Recycled ballast	Rail(1)	track-km of railway ballast	–	–	–	–
Recycled solid organics	General(1)	1 tonne of landscaping mulch	–	–	–	–
Recycled plastics	Roads(1)	lane-km of asphalt surface (as binder)	–	–	–	–
	Rail(1)	track-km of railway sleepers	–	–	–	–
	General(1)	km of noise wall (3 m height)	–	–	–	–
	General(1)	kg of pipes	–	–	–	–

1. Estimation not available due to the lack of information to generate the required consumption factors.

Table 2.5 presents assessment results that also account for the resource conservation benefits of avoiding landfill as a result of utilising recycling materials. Positive values indicate a worsening of environmental outcomes after material replacement.

Table 2.5: Resource consumption indicators (after accounting for avoided landfill impact)

Recycled material	Infrastructure type	Infrastructure unit	Electricity use (kWh)	Water use (m^3 eq)	Natural gas use (GJ)	Diesel use (MJ)
Crushed concrete	Road	lane-km of granular subbase	−91%	−100%	−98%	−39%
Crushed brick	Road	lane-km of granular subbase	−92%	−100%	−98%	−40%
RCG	Road	lane-km of granular base	−66%	−80%	−93%	−100%
		lane-km of granular subbase	−66%	−80%	−93%	−100%
		lane-km of asphalt base	−66%	−80%	−93%	−100%
		lane-km of asphalt surface	−66%	−80%	−93%	−100%
		lane-km of drainage layer	−66%	−80%	−93%	−100%
	General	km of trench (0.5 m-wide)	−66%	−80%	−93%	−100%
		km of embarkment (7 m-wide)	−66%	−80%	−93%	−100%
RAP	Road	lane-km of asphalt surface	−100%	−100%	−100%	−85%
		lane-km of asphalt base	−100%	−100%	−100%	−85%
Crumb rubber	Road	lane-km of surface (as spray seal)	295%	−77%	210%	−93%
		lane-km of asphalt pavement (as binder)	295%	−77%	210%	−93%
Fly ash	Road	lane-km of asphalt subgrade (as stabiliser)	−99%	−100%	−99%	−29%
		lane-km of asphalt base (as stabiliser)	−100%	−99%	−100%	−60%
		lane-km of concrete pavement	−100%	−99%	−100%	−60%
GGBFS	Road	lane-km of concrete pavement	−17%	−54%	−11%	−78%
		lane-km of asphalt base (as stabiliser)	−17%	−54%	−11%	−78%
	General	100 m^3 of structural concrete	−17%	−54%	−11%	−78%
Bottom ash	Road(1)	lane-km of granular subbase	–	–	–	–
Recycled ballast	Rail(1)	track-km of railway ballast	–	–	–	–
Recycled solid organics	General(1)	1 tonne of landscaping mulch	–	–	–	–
Recycled plastics	Roads(1)	lane-km of asphalt surface (as binder)	–	–	–	–
	Rail(1)	track-km of railway sleepers	–	–	–	–
	General(1)	km of noise wall (3 m height)	–	–	–	–
	General(1)	kg of pipes	–	–	–	–

1. Estimation not available due to the lack of information to generate the required consumption factors.

2.2.3 Economic Impacts

Impact on material cost

Table 2.6 presents the assessment results for economic impact of material costs. This table shows virgin and recycled material cost estimates on an infrastructure unit basis and the percentage change in material cost due to the material replacement. Positive values indicate higher material cost due to material replacement.

Table 2.6: Economic impacts of material replacement

Recycled material	Infrastructure type	Infrastructure unit	Virgin material cost	Recycled material cost	Change in cost
Crushed concrete	Road	lane-km of granular subbase	$30,188	$16,800	−44%
Crushed brick	Road	lane-km of granular subbase	$6,956	$5,976	−14%
RCG	Road	lane-km of granular base	$3,710	$3,640	−2%
		lane-km of granular subbase	$13,913	$13,650	−2%
		lane-km of asphalt base	$3,500	$3,434	−2%
		lane-km of asphalt surface	$438	$429	−2%
		lane-km of drainage layer	$18,550	$18,200	−2%
	General	km of trench (0.5 m-wide)	$26,500	$26,000	−2%
		km of embarkment (7 m-wide)	$165,360	$162,240	−2%
RAP	Road	lane-km of asphalt surface	$10,500	$1,750	−83%
		lane-km of asphalt base	$21,000	$3,500	−83%
Crumb rubber	Road	lane-km of surface (as spray seal)	$1,352	$725	−46%
		lane-km of asphalt pavement (as binder)	$43,750	$23,447	−46%
Fly ash	Road	lane-km of asphalt subgrade (as stabiliser)	$7,221	$4,463	−38%
		lane-km of asphalt base (as stabiliser)	$3,080	$1,859	−40%
		lane-km of concrete pavement	$15,708	$9,483	−40%
GGBFS	Road	lane-km of concrete pavement	$39,270	$28,560	−27%
		lane-km of asphalt base (as stabiliser)	$5,390	$3,920	−27%
	General	100 m^3 of structural concrete	$6,283	$4,570	−27%
Bottom ash	Road	lane-km of granular subbase	$3,019	$0 (approx. free)	−100%
Recycled ballast	Rail	track-km of railway ballast	$194,775	$222,600	14%
Recycled solid organics	General	1 tonne of landscaping mulch	$68[(1)]	$20	−71%
Recycled plastics	Roads	lane-km of asphalt surface (as binder)	$1,641	$586	−64%
	Rail	track-km of railway sleepers	$135,000	$240,000	78%
	General	km of noise wall (3 m height)	$150,075	$72,450	−52%
	General	kg of pipes	$1,450	$700	−52%

1. Converted from published price in cubic metre based assuming density of mulch is 1.5 tonne per cubic metre.

Results in Table 2.6 are based on the indicative unit material cost (per kg material cost) presented in Table 2.7 and Table 2.8.

The unit costs of materials vary considerably over time, locations and by suppliers. As such it is difficult to obtain a nation-wide cost average or a historical cost average. Table 2.7 and Table 2.8 provides indicative unit cost for recycled and virgin materials indicating the sources of the data estimates.

Table 2.7: Unit cost of recycled materials

Materials	Unit cost	Source type	Source
Crushed concrete	$16 per tonne	Academic journal	Imteaz et al.(2021)
Crushed brick	$26 per tonne	Published cost by supplier	Moreton Bay Recycling (2019)
RCG	$20 per tonne	Conversation with supplier	RepurposeIT
RAP	$0(1)	Conversation with supplier	RepurposeIT
Crumb rubber	$600 per tonne	Conversation with industry body	Tyre Stewardship Australia
Fly ash	$170 per tonne	Conversation with supplier	Independent Cement & Lime Group
GGBFS	$160 per tonne	Conversation with supplier	Independent Cement & Lime Group
Bottom ash	$0(2)	Conversation with supplier	Independent Cement & Lime Group
Recycled ballast	$40 per tonne	Conversation with supplier	RepurposeIT
Recycled solid organics	$20 per tonne	Conversation with supplier	Sacyr Environment Services
Recycled plastics (LDPE)	$500 per tonne(3)	Published cost by public agency	Sustainability Victoria (2021)
Recycled plastics (HDPE)	$700 per tonne(3)	Published cost by public agency	Sustainability Victoria (2021)
Recycled plastics (Duratrack sleepers)	$160 per sleeper(4)	ARRB estimate based on public information	Integrated Recycling

1. RAP is not currently sold in the market as it is recycled on-site where it is sourced.
2. Bottom ash is currently considered to have no resell value.
3. Price subject to significant variation overtime. Presented price is based on latest reported price from Sustainability Victoria.
4. Based on narrow gauge track sleeper.

Table 2.8: Unit cost of virgin materials

Materials	Unit cost	Source type	Source
Crushed rock	$25 per tonne	ARRB estimate	AfPA members
Crushed aggregate	$20 per tonne	ARRB estimate	AfPA members
Asphalt	$120 per tonne	ARRB estimate	AfPA members
Bitumen	$1,250 per tonne	ARRB estimate	ARRB estimate. Benchmarked against ABS monthly average cost data for bitumen.
Hydrated Lime	$299 per tonne	Conversation with supplier	Independent Cement & Lime Group
Cement	$220 per tonne(1)	ARRB estimate	ARRB
Ballast	$35(2)	ARRB estimate	ACRI
Landscaping mulch	$102 per m^3	Published cost by supplier	SoilWorx (n.d.)
Timber sleeper	$90 per sleeper or $135,000 per km of railway tracks(3)	Published cost by supplier	Statewide Sleepers (2022)
HDPE plastics	$1,450 per tonne(4)	Published cost by public agency	Sustainability Victoria (2021)

1. Estimate based on general purpose cement.
2. ARRB estimate based on large-scale purchase for railway projects.
3. Assumes 1,500 sleepers per km of railway track.
4. Price subject to significant variation overtime. Presented price is based on latest reported price from Sustainability Victoria.

Impact on employment opportunities

Table 2.9 presents the assessment results for economic impact on employment opportunities in the recycling and waste sectors. This table shows the number of full-time jobs created in the recycling sector, the number of full-time jobs diverted from disposal and landfill industry and the net change in full time jobs due to material replacements. Employment figures in Table 2.9 do not include jobs in transport and construction sectors.

Table 2.9: **Economic impacts of employment opportunities**

Recycled material	Infrastructure type	Infrastructure unit	New recycling jobs created	Disposal and landfill jobs diverted	Net change in jobs
Crushed concrete	Road	lane-km of granular subbase	0.67	0.29	0.38
Crushed brick	Road	lane-km of granular subbase	0.15	0.06	0.08
RCG	Road	lane-km of granular base	0.12	0.05	0.07
		lane-km of granular subbase	0.44	0.19	0.25
		lane-km of asphalt base	0.11	0.05	0.06
		lane-km of asphalt surface	0.01	0.01	0.01
		lane-km of drainage layer	0.58	0.25	0.33
	General	km of trench (0.5 m-wide)	0.83	0.36	0.47
		km of embarkment (7 m-wide)	5.19	2.27	2.92
RAP	Road	lane-km of asphalt surface	0.06	0.02	0.03
		lane-km of asphalt base	0.11	0.05	0.06
Crumb rubber	Road	lane-km of surface (as spray seal)	0.00	0.00	0.00
		lane-km of asphalt pavement (as binder)	0.03	0.01	0.01
Fly ash	Road	lane-km of asphalt subgrade (as stabiliser)	0.02	0.01	0.01
		lane-km of asphalt base (as stabiliser)	0.01	0.00	0.00
		lane-km of concrete pavement	0.04	0.02	0.02
GGBFS	Road	lane-km of concrete pavement	0.11	0.05	0.06
		lane-km of asphalt base (as stabiliser)	0.02	0.01	0.01
	General	100 m^3 of structural concrete	0.02	0.01	0.01
Bottom ash	Road	lane-km of granular subbase	0.08	0.04	0.05
Recycled ballast	General	track-km of railway ballast	0.001	0.0003	0.0004
Recycled solid organics	General	1 tonne of landscaping mulch	3.56	1.56	2.00
Recycled plastics	Road	lane-km of asphalt surface (as binder)	0.00	0.00	0.00
	Rail	track-km of railway sleepers	0.04	0.02	0.02
	General	km of noise wall (3 m height)	0.07	0.03	0.04
	General	kg of pipes	0.00	0.00	0.00

1. Jobs creation estimates are based on 9.2 jobs direct Full Time Equivalent employment per 10,000 tonnes of recycled material and 2.8 jobs for landfill disposal.

2.2.4 Social Impacts

The *2018 National Waste Policy* aims to eliminate waste and improve economic, social and environmental outcomes. This policy direction highlights the importance of considering the social impacts of using recycled materials. The policy includes several strategies that relate to the social impacts of using recycled materials in road and rail infrastructure, specifically in terms of community involvement and civic pride; health and safety; and supporting growth of a circular economy. These include:

- Strategy 3 – Knowledge sharing, education and behaviour change: Implement coordinated knowledge sharing and education initiatives, focussed on the waste hierarchy and the circular economy, that address the needs of governments, businesses and individuals, and encourages the redesign, reuse, repair, resource recovery, recycling and reprocessing of products.
- Strategy 5 – A common approach: Implement a common approach towards waste policy and regulation, particularly in relation to national opportunities to support development of markets for recycling.
- Strategy 6 – Improving access: Identify and improve regional, remote and Indigenous communities' ability to access, influence and participate in a circular economy.

- Strategy 9 – Sustainable procurement by business and individuals: Businesses and individuals in Australia take environmental issues into account when purchasing or manufacturing goods and services and promote domestic demand for recycled materials and products containing recycled content.
- Strategy 11 – Sound management of chemicals and hazardous waste: Manage and regulate chemicals and wastes throughout their life cycle to minimise environmental and human health impacts and meet Australia's national and international obligations.

Figure 2.1 provides a summary of the positive and negative social implications of using recycled materials in road and rail infrastructure.

Figure 2.1: Positive and negative social implications of using recycled materials in road and rail infrastructure

Positive

Creation of a Circular Economy: Supporting the goals of the 2018 National Waste Policy.

Employment Opportunities: Creating employment opportunities in both the materials supply/recycled sector and in the road construction and maintenance sectors.

Reduced landfilling and waste stockpiles: These can pose hazards such as fire, verim, odour, leaching and land use issues.

Waste managed locally in Australia: Enables a great oversight of practices, ensuring worker safety and environmental requirements are adhered to. Local supply chain enables an ability to manage modern slavery requirements.

Intergenerational Equity: Reducing the degradeadtion of the natural resource base for future generations.

Community Support: Creating a sense of civic pride and satisfaction in the community, felt through participation in recycling.

Negative

Health Impacts[1]: Possible health impacts to road and rail construction workers due to their exposure to recycled materials, such as end-of-life tyres.

Pollution: Causing noise, air and odour pollution from collection and reprocessing facilities, leading to impacts on the community.

Contaminants[2]: Entering the environment, such as microplastics, heavy metals, asbestos or other leachates.

Risk to re-recyclability: Possible reduced ability of a material to be recycled again at end-of-life.

Economic Costs: Possible up front costs to set up recycling infrastructure, capacity and building markets, which may need to come through community funding. This may increase tax rates etc.

1. Note that several health concerns have been investigated in comparison to virgin or conventional materials, and shown to pose no greater or less risk, for example, crumb rubber asphalt and recycled glass. See Negative social impacts for more information.
2. Some materials have been shown to have similar or lesser risk of contaminants than their virgin counterparts, such as microplastics. Further research is required in this space; however, a focus for many research projects is to understand and mitigate these potential risks. Refer to Negative social impacts and Workplace health and safety for further discussion.

Positive social impacts

Employment opportunities stands as one of the strongest social positive outcomes to using recycled materials in road and rail infrastructure and in the construction and maintenance sectors. Deloitte Access Economics found that 9.2 jobs are created for every 10,000 tonnes of waste that is recycled. This is in contrast with the 2.8 jobs that are created around sending waste to landfill (Deloitte Access Economics 2009). Australia can better support its economy, protect the health of our communities, reduce environmental impacts by harnessing the value of material typically disposed of and return them to productive use (Department of Agriculture, Water and Environment 2018).

For rural communities, the use of non-standard granular and marginal materials, which are readily available within those areas, could also stimulate employment growth. Non-standard granular and marginal materials are materials that do not comply with standard specifications, however, are known to successfully perform as granular base and subbase in select roads. These materials are often considered in rural communities as more sustainable and economical options, as they can be sourced locally and therefore do not require significant haulage distance (Austroads 2018a).

Further, there are several Energy from Waste facilities proposed for rural towns, which would create jobs for the community. The resulting bottom ash, from the proposed facilities, constitutes a possible material for reuse in road infrastructure that may develop a market in future (Gurrie et al. 2020).

Community support is another major positive outcome for social impacts when implementing sustainable road infrastructure. Civic pride is a type of gratification where communities are brought together to make their residents and ratepayers feel a sense of pride in living in that area or city (Marchi & Bay 2016). If the community can participate in sustainable activities that drive local circular economy outcomes, such as recycling, their sense of pride, involvement and co-operation will increase. An example of civic pride being initiated through implementing recyclable materials is in the City of Mitcham, a local government in South Australia. This council has begun creating new roads using recycled aggregates sourced from the area's yellow bins, as well as crumb rubber and recycled glass, in conjunction with a number of contractors (City of Mitcham n.d.). These projects increase the pride of the community through demonstrating that recycling materials back into community assets can have positive outcomes, including directly contributing towards job generation and a more sustainable local government area.

In addition to the civic pride associated with recycling of consumables such as plastic and glass, recycling of organic material, particularly on-site (e.g. through composting), can also have a positive impact as it can reduce the frequency of waste collection and associated costs for the community (Department of Health 2019).

Managing waste locally also enables greater oversight of working conditions and environmental practices, ensuring our waste processing fits within our national policies for workers' rights, safety and environmental constraints. Exporting waste and transferring that burden of processing elsewhere, removes Australia's ability to monitor activities around our own waste streams, with some reports indicating unsafe and unethical working conditions in many foreign waste processing streams (Retamal et al. 2019).

Improvements in this space are underway, for example, TSA has developed a Modern Slavery Impact Statement that highlights two main risks: workers' rights in Australian tyre collection and recycling facilities, and labour risks in foreign processing destinations (Tyre Stewardship Australia 2021). TSA requires all their accredited recyclers to complete an annual Employee Entitlements Declaration and has developed a Foreign End Market Verification Program that aims to mitigate these risks in cases where Australian tyres are being processed overseas. Risks of modern slavery and measures to address these concerns should continue to be considered in the Australian recycling industry, and localised processing of materials allows greater oversight.

Using recycled materials support **intergenerational equity** by improving natural resource preservation and security. The Brundtland Report described equal access to resources across generations as one of sustainability's most critical factors is to ensure that future generations' wellbeing is not compromised (Brundtland Commission 1987). Improved and sustained resource access can be achieved through markets which view waste as a valuable commodity. For example, crushed concrete and crushed brick, recycled crushed glass and bottom ash may be used as partial virgin aggregate and sand replacement and RAP can be used as a partial replacement for virgin aggregates and bitumen in road construction. The intergenerational benefits of using recycled materials includes:

- preservation of natural resources such as virgin rock and crude oil
- reduced quarrying costs
- reduced amenity and biodiversity costs

- landfill diversion (Austroads 2018b)
- reduced energy consumption when compared to quarrying (Arup and ARRB 2021)
- decreased greenhouse gas emissions (Austroads 2018b).

If society continues to transition into a circular economy through harnessing recyclable materials, it will ensure that natural resources are extracted less frequently, reduce the carbon footprint, enable resources to be more readily available and allow for intergenerational security. This supports the goals of the *2018 National Waste Policy*.

Negative social impacts

Economic costs can, in some cases, have an impact on the feasibility of using recycled materials in pavement applications. Some recycled materials can have higher upfront costs to use, especially when in early use or development stages. Material costs, however, are variable and dependent on location, type of recycled material and its availability in any given region. For example, Sustainability Victoria (2015) undertook a market study and found that cost competitiveness was directly related to haulage distances. Where recycled materials are available within a close proximity (e.g. less than 45 km), the recycled materials were found to be cost competitive with quarry materials, however further haulage distances resulted in increased costs. Furthermore, **economic costs** associated with the development of new local recycling and processing facilities may need to come through community funding.

The market maturity of materials can also impact cost competitiveness, as novel materials are less likely to be available; more costly due to cleaning, shredding or other processing requirements; and may require different construction practices that can impact on training, technology and plant requirements. Crumb rubber asphalt products, for example, can be more expensive due to a higher amount of binder required. There may also be greater upfront costs to use a less common product *(Infrastructure Magazine* 2018). On the other hand, using materials such as fly ash as a stabilising medium for base courses, partially replacing lime and other virgin fine aggregates, has the potential to reduce road construction costs (Cooper 2014). Costs may however be offset by improved durability of the pavement design, something that asset owners need to consider when investigating the potential use of recycled products (*Infrastructure Magazine* 2018).

While technological advancements are making the way for safer implementation and use of recycled materials in road pavements, certain materials still exist that are associated with being harmful to **human health** and contributing towards **pollution**, either during the construction phase to workers or after the construction phase to the community. Specific risks, such as microplastic generation with the use of recycled plastics, need to be researched further to provide definitive knowledge regarding the impact these materials may have for future generations.

Noise and odour pollution are prominent factors in the collection and reprocessing of recycled materials, including those that may be used in road applications. Prolonged exposure to loud noises can be observed in the recovery and recycling industry, including when operating noisy plant, for operators in enclosed spaces with machinery and other similar activities. Serious injury can be a risk, especially if appropriate hearing protection is not worn (SafeWork NSW n.d.). Odour pollution poses a nuisance to society and under heat or during processing, recycled materials such as crumb rubber, recycled plastics, recycled glass and RAP can omit odours that people find offensive. Odour may be mitigated through washing certain materials, such as glass and plastics, or with appropriate personal protective equipment (PPE).

Certain reported health concerns, however, have been proven to be misconceptions. For example, crumb rubber modified asphalt has been perceived to have negative impact on human health due to potential fuming of the product. In 2020, a Victorian study (Department of Transport 2020) tested construction worker exposure to volatile organic compounds, polycyclic aromatic hydrocarbons, suspended particles, benzothiazoles and bitumen fumes for both crumb rubber asphalt and conventional asphalt. Air emissions, exposures and health questionnaires were carried out. It was found that for both types of asphalt, all airborne particulates, compounds and fumes were below Australian SafeWork emission standards, producing no evidence that crumb rubber asphalt provided the greater risk to human health. Additionally, mild symptoms reported from the construction team were equivalent to those during construction of conventional asphalt mixes. Another example is the common misconception that the use of recycled crushed glass increases exposure to respirable crystalline silica (which can cause inflammation in the lungs if inhaled). However, it has been found that recycled crushed glass contains less respirable silica than regular beach sand (Winder 2011). As technology advances and further research is performed, it is becoming more feasible to utilise recycled materials with reduced concerns for health implications.

Lastly, there is the potential for **issues of re-recyclability** to arise with use of recycled materials. That is there are concerns about whether adding recycled materials impacts the ability for end-of-life assets to be recycled. Re-recyclability needs to be factored into evaluations of potential recycled materials products. It is identified that further research is required in this space, as it is critical to ensure that including recycled materials does not hinder reuse of materials in future. Some examples of research to date include an investigation in Western Australia to determine whether the inclusion of crumb rubber in asphalt would limit the ability of the asphalt to be used as RAP. Preliminary findings identified that high levels of crumb rubber made extraction of RAP slightly more challenging, however overall, it was determined that crumb rubber modified asphalt was still able to be extracted and used as RAP, using the same technology for extraction of non-modified asphalt (Rice & Harrison 2021).

Workplace health and safety

This section of the report provides a brief overview of the legislation and regulations considered relevant to the use of recycled materials to be used in road and rail infrastructure for workplace health and safety (WHS), as community safety is a key element of social sustainability. In addition, this section provides specific WHS concerns for the 10 key recycled materials considered in this project.

Safe Work Australia

In 2011, Safe Work Australia implemented a single set of WHS laws across Australia, developed as a single point of reference known as the *model laws*. However, Safe Work Australia do not enforce or regulate these. For the model WHS laws to become legally binding, the Commonwealth, states and territories must implement them separately as their own laws (Safe Work Australia n.d.) The model WHS laws include:

- the model WHS Act
- the model WHS Regulations
- model Codes of Practice.

WHS Legislation is triggered for all components of road and rail infrastructure design, construction, maintenance, operations, and decommissioning. As WHS legislation is relevant for all materials, it needs to be considered when implementing the use of recycled materials across road and rail infrastructure projects.

Safety Data Sheets

A Safety Data Sheet (SDS) is a document that provides information to users on the risks associated with certain products. This is an important document for recycled materials, as it clearly outlines any risks associated with using that material.

The development of this document is a legal requirement under WHS legislation. In addition, under WHS legislation, there is a requirement for workplaces to have copies of the relevant SDSs onsite and to ensure that the SDSs are current. The purpose of an SDS is to ensure that all workers who handle materials or chemicals have the hazard information they need to safely use, handle, store and dispose of them (VelocityEHS 2022).

Safe Work Australia (n.d.b) outline that an SDS must provide information on:

- hazards of the chemical/material and how to handle it safely, including storage and disposal
- physical and chemical properties of the chemical/material, as well as potential health and emergency response measures
- environmental effects of the chemical/material.

The responsibilities for SDS implementation are defined by the states and jurisdictions who implement the model WHS laws.

Workplace Exposure Standards

Workplace Exposure Standards (WES) for airborne contaminants are available on the Safe Work Australia website (Safe Work Australia 2019). If the relevant recycled materials are perceived to create airborne contaminants, the WES needs to be complied with and is required under jurisdictional Work Health and Safety (WHS) laws.

Concerns for specific materials

Table 2.10 outlines the WHS considerations for the use of the 10 recycled materials considered in this project, including both benefits and risks, where any have been identified.

Table 2.10: WHS considerations for recycled materials

Recycled materials	WHS consideration
Crushed concrete and crushed brick	• Building demolition waste may contain asbestos which can have significant health impacts to the exposed worker if not identified. Relevant handling advice on PPE has been developed and should be strictly followed (Western Australia Department of Water and Environmental Regulation 2021). • Potential contaminants in materials, such as asbestos from construction and demolition waste.
RCG	• Abrasion caused during handling of glass particles – anecdotal claims have been made by construction workers of recycled glass fines causing abrasions to skin. This can be avoided by wearing appropriate PPE, reducing the size of the particles to 5 mm and using appropriate crushing techniques such as a hammer mill which has also been shown to produce rounder particle shapes that will reduce risk of cuts (Winder 2011). • Silicosis and lung damage – silica in glass is mainly amorphous and not seen as a concern to human health. RCG can also contain crystalline silica, however environmental analysis has shown that crystalline silica does not typically exceed 1% which is also less than what is in natural sand (Latter 2020). Personal protective equipment (PPE) should be utilised when handling RCG to prevent exposure to the proportion of crystalline silica. • Dust inhalation – glass dust can cause skin, ear and eye irritation which can be minimised by wearing PPE. A trial conducted in NSW concluded that dust generated by recycled glass fines is no more harmful than generation of dust from virgin sand (DECC 2007). Dust suppression measures can be taken, such as wet storage and handling, to prevent airborne dust particles as well as ensure no sediment run off into drains. • Odours from unwashed glass fines have been noted by construction workers. Washing of glass to reduce odour as well as the use of odour suppressants can mitigate this effect. • Recycled glass can contain harmful materials and/or contamination. Certified suppliers (i.e. Environmental Standard ISO 14001 certification, ISO 9001 Quality Management) can ensure recycled glass meets quality and safety standards (Ecologiq 2021).
RAP	• Potential for RAP to contain asphalt that is made from carcinogenic materials such as tar or contaminants such wire, pipes and other debris. • Aggregates in RAP could be high in crystalline silica content that could pose an inhalation issue when processing the RAP. • Safety measures such as PPE, following a RAP management plan including classification of the RAP material is recommended.
Crumb rubber	• Disposed tyres going to landfill, or illegally dumped, can: be a source of health concern, cause fires in stockpiles that can release toxic gases; and provide breeding habitats for pests (Department of Environment 2014; cited in Denneman et al. 2015). Recycling tyres into crumb rubber provides the opportunity to reduce these outcomes. • Landfilling tyres affects the amenity of a region due to the visual, noise, odour and litter impacts of the disposal facility (Denneman et al. 2015). • Crumb rubber modified asphalt pavement may offer reduced road noise (Denneman et al. 2015). • The use of crumb rubber in asphalt and sprayed sealing has been associated with odours from fuming of crumb rubber at high temperatures and may have negative health impacts to the material manufacturers and construction workers due to their close proximity and exposure to the material. Emissions monitoring has been undertaken on construction projects as well as independently by asphalt manufacturers and has showed that all bitumen fume levels (i.e. those that contained crumb rubber and those without) were all below the SafeWork Australia time-weight average workplace exposure standard for bitumen fume of 5 mg/m^3.
GGBFS	• Risk of potential heavy metal contents.

Recycled materials	WHS consideration
	• GGBFS is ground to a fine powder, therefore inhalation of fines if not wearing correct PPE could be an issue.
Fly ash	• Potential contaminants in materials.
Bottom ash	• Potential contaminants in materials, such as heavy metals. • Leaching of heavy metals may pose a significant environmental impact affecting groundwater resources. • Possible health risks, including skin or respiratory irritation, and possible carcinogenic impacts (Agency for Toxic Substances and Disease Registry 2018).
Recycled ballast	• Reduce quarry blast noise. • Recycled ballast may contain contaminants that could enter the environment and eco-system through water run-off if not properly managed. Recycled ballast should go through appropriate washing processes to ensure contaminants are removed and they meet relevant specification.
Recycled solid organics	• There will be improved local amenity such as reduced vermin and odour at waste collection sites (Department of Health 2019). • Organic matter can be used to provide natural nutrients to soil, removing the need for chemical fertilisers. This in turn will improve the health of the food supply (Grow Ensemble 2021). • Possible risks with organics processing can be include manual handling, fire, biological hazards (pathogens, microbes, fungi and bio-aerosols), and odour (Sustainability Victoria 2018).
Recycled plastics	• Health effects to the workers due to the generation of fumes and emissions during the reprocessing of plastics have been identified as risks and are currently under investigation (Austroads 2021b)[1]. • Presence of chemicals, additives and contaminants and generation of microplastics are a key issue for recycled plastics and there is potential for exposure to workers, environment and community. Migration of contaminants or microplastics into the aquatic environment and migration via surface water runoff, leaching and airborne particles and deposition are areas of concern[2].

1. Note there is existing risk, such as fuming, odours, burns etc., when placing conventional bitumen or virgin polymer modified bitumen. These risks are typically mitigated by PPE, advances in plant technology and additives that enable placement of bituminous products at lower temperatures etc. (Roads and Maritime Services 2017). These workplace practices will also be relevant to mitigating risk associated with the use of recycled plastic products.
2. Austroads (2022b) compared microplastic generation from recycled plastic modified asphalt and virgin polymer modified asphalt, determining that overall, the risk of microplastics from recycled plastic was similar to or lower than its virgin counterpart.

3. Barriers and Opportunities for Adoption

3.1 General Barriers and Opportunities

Identifying barriers to the use of recycled materials in the construction and maintenance of road and rail infrastructure is crucial to promoting their uptake. Some apply to all recycled materials, including:

- *Awareness*: There is a general lack of awareness from the construction industry as to which applications recycled materials can be used in and around what level of incorporation is allowed within specifications. This will lead to less demand for recycled materials, causing suppliers to leave their capacity undeveloped. Key to improving awareness within industry is adequate dissemination of new knowledge and results from trials of new products, such as through technical notes, webinars and presentations.
- *Prescriptive specifications*: Specifications that prescribe which materials to use, rather than focussing on their performance outcomes, can restrict their use. Development of performance-based specifications that do not preclude the use of recycled materials, as long as they meet requirements and clear guidelines on where recycled materials can be used (e.g. technical notes), can help overcome this barrier.
- *Availability of materials*: Logistically difficult and uneconomical collection and recycling of waste in regional areas is a barrier. Accessing recycled material sources, if there are none processed locally, could be economically unviable or unsustainable. There is also the risk that availability is limited by restricted local waste generation, which will lead to the importation of material that is less sustainable and less economically viable. The sustainability of using recycled materials needs to be considered: reducing material transportation and using local materials, where suitable, should be practiced.
- *Procurement*: Current procurement policies facilitate the use of recycled materials as opposed to *optimising* the use of recycled materials. Using Approach to Market documents that clarify the desirability of sustainability outcomes and the use of recycled materials as criteria in value for money assessments is preferrable to setting minimum requirements or targets. This flexible, project-by-project procurement approach allows contractors to liaise with recycled materials suppliers and determine if adequate supplies of the necessary products are available. Additionally, state and territory transport agencies, such as Transport for New South Wales and Queensland Department of Transport and Main Road, can work with industry to build the capability to supply and construct infrastructure with recycled materials, and with government partners to increase industry confidence.
- *Perceived inferior performance*: There is a lack of confidence in the use of recycled materials as a result of this perception. Conducting research on the use of recycled materials to ensure equivalent if not better performance than traditional materials, dissemination of the findings and new knowledge (through presentations, webinars and public forums), and developing specifications on the use of recycled materials, will help overcome this barrier. The development of test methodologies that streamline the assessment of new recycled materials and provide confidence in their incorporation will also be of value.
- *Perceived health, safety and environmental concerns*: Concerns include the environmental impacts, such as leaching of heavy metals, as well as health and safety considerations for workers and the community. Measures to remove this barrier include sufficient research and demonstration trials, including monitoring emissions and leaching, using appropriate PPE, and developing appropriate standards, specifications and Safe Working Method Statements (SWMS).
- *Costs*: Novel applications and technologies are often more expensive than traditional ones, mainly due to research and development costs. Initial investment by government bodies on research and demonstration trials can help overcome this barrier. Once the market for a material is mature, the costs are usually reduced. This may not be true for all recycled materials though, and a whole life costing or emissions analysis can demonstrate the benefits of utilising the recycled materials options.

3.2 Material-Specific Barriers, Risks and Opportunities

In addition to the general barriers, each material can have its own challenges. Table 3.1 presents the barriers specific to each recycled material in the construction of road and rail infrastructure. Mitigation measures are also proposed to manage each specific risk.

Table 3.1: Barriers specific to the use of recycled materials in the construction of road and rail infrastructure

Recycled material	Barrier	Risk	Mitigation
Crushed concrete and crushed brick	Environmental	High pH value of crushed concrete	• Avoid using crushed concrete in surface layers without a suitable surfacing • Avoid using crushed concrete as drainage in areas less than 30 m to waterways • Using wetted crushed concrete
	Performance	Physical contaminations, such as plastics, glass, and metals, can impact the performance	• Procurement from a certified supplier
		CC can re-cement leading to cracking potential, especially if used as a granular base	• Incorporation in lower layers such as subbase with granular base over the top • Blending with other materials such as crushed brick and RCG
		Crushed brick not being employed as a 100% replacement of virgin materials	• Blending with other materials, especially with crushed concrete as crushed brick can be used as a plasticity enhancer for say a high plasticity material
	OH&S	Dust	• Using relevant PPE (e.g. mask)
RCG	Environmental concerns	Contaminated RCG	• Procurement from a certified supplier • Requesting an environmental compliance certificate • Requesting an SDS
	OH&S	RCG larger than 5 mm may cause abrasion due to particles with potential sharp edges	• Using appropriate PPE when handling • Machine placement
		Dust	• Applying dust suppression measures • Keeping RCG moist • Using relevant PPE (e.g. mask)
	Fit-for-purpose RCG	Sourcing feedstock of RCG types with suitable characteristics for use in infrastructure applications	• Procurement from a certified supplier • Requesting the RCG characteristics report/data (e.g. particle size distribution and SDS) from supplier
RAP	Performance	Presence of unknown materials within RAP, such as other recycled materials or debris, that may impact performance when used in asphalt	• Procurement from a certified supplier • Good stockpile management and professional handling of this resource product • Additional research to determine if reuse of RAP containing recycled materials is feasible
		There has been concerns over long term creep of RAP when used in granular applications, especially in elevated temperatures and under higher load bearing applications such as within/under high embankments	• Conducting research to understand the behaviour of and measures required to decrease and/or eliminate potential creep • Blending RAP with other recycled materials including fly ash (stabilisation) • Using rejuvenators
Crumb rubber	OH&S	Unpleasant fumes	• Using appropriate PPE
	Performance	Crumb rubber/bitumen segregation and degradation	• Pre-treatment of crumb rubber with function specific catalysts
	Procurement	High supply costs of crumb rubber modified bitumen or asphalt compared to conventional asphalt	• Overall performance and service life of high-quality crumb rubber modified bitumen or asphalt can mitigate those costs
		Only a few facilities capable of producing high-quality crumb rubber currently exist	• Investing in processing and manufacturing infrastructure supported by government

Recycled material	Barrier	Risk	Mitigation
GGBFS	Performance	There are concerns over stiffness and initiation of cracks if used as the only binder (100% binder)	• Blending with other cementitious and/or bituminous binders such as fly ash
	OH&S	Dust	• Using relevant PPE (e.g. mask)
Fly ash	Performance	Setting time of binder containing only fly ash (100% fly ash as binder) can be long, depending on the type of soil to be stabilised	• Blending with other cementitious binders such as GGBFS
	OH&S	Dust	• Using relevant PPE (e.g. mask)
Bottom ash	Performance	Lack of uncertainty on the performance of bottom ash due to not being commonly used	• Establishing feasibility and field trials to understand various engineering properties and performances based on applications
	Fit-for-purpose bottom ash	The chemical, physical and mechanical properties of bottom ash could vary depending on the source of feedstock, i.e. coal vs waste and type of coal/waste	• Procurement from a certified supplier • Requesting the RCG characteristics report/data (e.g. particle size distribution and SDS) from supplier
	Potential risks to the environment and human health	Potential for leaching of heavy metals and existence of contaminations	• Investigating the leachability and total contamination concentration of bottom ash from different sources • Developing environmental testing frameworks
Ballast	Performance	Degraded ballast can have an impact on the performance	• Blending recycled ballast with fresh ballast or other granular materials • Screening and washing can deliver a like for like end product
Recycled solid organics	Lack of appropriate specifications	Current specifications for landscaping and revegetation do not include recycled organics. In addition, the current standards and guidelines developed for recycled organics are designed for the use of these materials in agriculture and urban amenities. As such, the level of contamination is very tight compared to that required for road and rail applications	• Developing specification(s) and guidelines for the use of recycled organics specific to transport infrastructure applications, such as landscaping and temporary erosion control

Recycled material	Barrier	Risk	Mitigation
Recycled plastics	Lack of solid understanding of engineering performance	There are a variety of waste plastics and a variety of applications in which recycled plastics can be used	• Conducting research studies and demonstration trials, data collection and evaluation program • For each type of plastic and related application, focussing on end material/product performance, not input material characteristics
	Potential risks to the environment and human health	Uncertainty on the potential risks, including leaching of chemicals, generation of microplastics and fumes emitted during the manufacturing process and during road construction	• Establishing a risk-based approach for assessing work, health, safety, and environmental implications of incorporating recycled plastics
	Market factors	Feedstock availability, quality, volumes, and price	• Investing in processing and manufacturing infrastructure supported by government • Government agencies can introduce incentives that encourage and promote the use of recycled plastics in transport infrastructure • Tender applications can be prioritised from contractors that utilise recycled plastic products

3.3 Opportunities to Enhance Adoption

By reviewing the barriers, risks and proposed mitigation measures as discussed in this section, a significant number of opportunities are also identified to enhance the uptake of recycled materials in infrastructure projects.

Improve industry awareness and confidence

- Continue and enhance industry engagement via training and knowledge-sharing activities and improve awareness amongst suppliers and their customers.
- Work with industry to build the capability to supply and construct infrastructure with recycled materials, and with government partners to increase industry confidence.

Fill in data and evidence gap via further research

- Address life cycle inventory data (i.e. environmental inputs and outputs associated with a product or service) gaps that are used to assess environmental impacts, especially for emerging recycled materials such as bottom ash.
- Undertake representative life cycle assessments and life cycle cost analysis for emerging applications.
- Prioritise replacement materials that demonstrate significant environmental, economic and social benefits. Note: further research is needed to enable comprehensive sustainability assessments where quantifiable data is lacking and/or where trade-offs between impact categories occur. For example, a recycled material application that presents positive environmental and social benefits but has adverse economic impacts.
- Continue and encourage research on performance, lab testing and field trials of the recycled materials to ensure equivalent, if not better, performance than traditional materials.

Specifications and assessment methods

- Develop performance-based specifications that do not preclude the use of recycled materials, as long as they meet requirements and clear guidelines on where recycled materials can be used (e.g. technical notes).
- Develop specifications and test methodologies that streamline the assessment of new recycled materials and provide confidence in their incorporation.
- Encourage the establishment of consistent novel product evaluation and certificate schemes.

Address WHS concerns

- Conduct more sufficient research and demonstration trials including monitoring emissions, leaching and using appropriate PPE.

- Develop appropriate standards, specifications and Safe Working Method Statements (SWMS) for the use of PPE.

Encourage sustainability procurement

- Consider incentives, including seed investment on research and demonstration trials to support understanding and awareness of emerging materials and improve the cost-competitiveness of higher cost recycled materials.
- Consider policies that do not set minimum requirements or targets for the use of recycled materials, allowing instead for a project-by-project approach wherein contractors can liaise with recycled materials suppliers and determine if adequate supplies of the necessary products are available, could overcome this barrier.

Cost reduction

- Support low energy waste processing and recycling facilities, including the use of renewable energy sources to lower the embodied energy of recycled materials.
- Connect demand and supply via government market analysis, information sharing and policy promotion.

4. Conclusions

Significant quantities of recycled materials can be used as substitutes for virgin materials, especially in structural applications such as granular and asphalt pavement layers, embankments and rail ballast. The quantities of material use determine the extent of the sustainability impacts.

4.1 Environmental Impacts

Significant environmental benefits (i.e. reductions in negative environmental impacts) can be expected for the majority of recycled material applications in road and rail infrastructure.

GHG emission reductions range from 47% to as high as 98% and overall environmental benefits (i.e. lower Enviropoint indicator values) range from 59% to 99%. On the environmental impact measures, the best performing recycled materials were:

- The use of RAP in surface and base layers as a replacement for asphalt made with virgin aggregates and binders (98% fewer GHG emissions and 99% lower Enviropoint score).
- The use of fly ash as a replacement for hydrated lime and cement in stabilised asphalts and concrete pavements (98% fewer GHG emissions and 98% lower Enviropoint score).

Conversely, the use of recycled crushed glass and bottom ash provided adverse environmental impacts compared with their virgin material equivalents across all infrastructure applications assessed. However, it is to be considered that many virgin material sources are finite, and thus there is a need to consider the positive effect of using recycled materials within that context.

There was a lack of data for recycled solid organics, recycled ballast and rail sleepers that prevented quantifiable environment impact assessments. Further research and life cycle modelling is still required.

Accounting for avoided landfill impact further enhanced the environmental benefits, or minimised the adverse impacts, of recycled materials over virgin materials across all materials and applications. The significance of this reduction varies across applications as it depends on the relative contribution of impacts due to material production and landfill activities to the total environmental impact. Considering landfill impacts, the overall environmental impacts of using bottom ash as an aggregate in a granular subbase improved to the extent that it became positive.

For resource consumption, similar patterns are observed. The use of recycled materials generally lowers the intensity of resource consumption except for specific applications of fly ash and recycled plastics.

As noted in *Part A*, recycling processes vary significantly depending on the waste stream. The more complex processes needed to transform materials into recycled material and products suitable for infrastructure drive higher resource consumption. For example, the manufacturing of crumb rubber from end-of-life tyres is highly energy intensive. Similarly, processing waste plastics can use a lot of water to wash the feedstock material.

Environmental impacts and resource consumption are based on the extraction and production of the materials only. Replacing virgin materials with recycled materials may also change material performance and subsequently change the requirements for, and environmental impacts of preservation (maintenance) activities. A Life Cycle Assessment is needed to account for the environmental impacts due to changed infrastructure performance, as well as material transport, which can be significantly different from some materials. Specifically, life cycle impact assessment needs comparative data that reflect the material performance of both virgin and recycled materials under comparable conditions. Such data can be collected from dedicated field trials or laboratory studies.

4.2 Economic Impacts

Economic benefits (i.e. material cost savings) can be expected for the majority of recycled material applications in road and rail infrastructure. Cost savings range from 2% to 83%, where the most cost-effective recycled material is RAP. Notably, bottom ash presently does not have a market value so the material costs is assumed to be zero (compared with $25/tonne for crushed rock, its virgin material equivalent). Conversely, the use of crushed brick as pavement aggregates and recycled ballast are the only exceptions in which the replacement results in higher material cost.

Material cost estimates are highly uncertain as costs vary significantly over geography, time, suppliers, market maturity and for quality. Additionally, cost will change as new facilities, technologies and processes are developed and implemented. Results should be viewed as indicative, rather than comprehensive. Material cost impacts are based on the initial construction material demand. Whole-of-life material costs are likely to differ after accounting for material demand from maintenance activities over the assets' life cycle. Comparative performance data for each application are needed to establish the life cycle material cost impacts. Such data can be collected from dedicated field trials or laboratory studies.

Wider adoption of recycling materials in infrastructure projects is also expected to generate additional employment opportunities in Australia. Specifically, it will create more jobs in the recycling industry to meet the higher demand of recycled material while lowering the labour demand in the waste disposal sector. Research shows that employment opportunities increased by adopting greater quantities of recycled materials, with 9.2 jobs created for every 10,000 tonnes of recycled waste, compared with only 2.8 for sending waste to landfill.

4.3 Social Impacts

The review of the social impacts of using recycled materials focussed on environmental justice, human health, resource security and education, among other social factors. The social impacts of using recycled materials may be positive or negative. The key positive social impacts include community and civic pride in using recycled products, and intergenerational equity through contributing to the preservation of natural resources for future generations. There can also be some health and environmental benefits, such as reducing tyre stockpiles (a major fire and vermin hazard), greenhouse gas emissions and quarry blast noise.

Negative social impacts mainly include a possible economic cost factor, as the use of novel material types can have higher upfront costs, require additional steps to process, or use different equipment to place. Minor community disruptions can include an unpleasant odour or noise impacts during materials processing.

A specific focus was applied to WHS implications, with some risks identified, such as abrasions from recycled crushed glass, or potential contaminants in construction and demolition waste, fly ash or bottom ash. These risks can be mitigated with the appropriate use of personal protective equipment (PPE).

Research and trials using recycled materials in construction often apply a public health lens, for example, by testing for contaminants, or undertaking emissions monitoring during construction. As research in this space continues to progress, so will a clearer idea of any health risks and their mitigation strategies. Research to date has already shown that crumb rubber modified asphalt poses no greater emissions threat than regular asphalt, and that the respirable crystalline silica of recycled glass sand is less than that of regular beach sand. Such findings continue to enable more recycled materials to be used and highlight the appropriate safety strategies needed.

4.4 Barriers and Opportunities for Adoption

This report also analyses the barriers to the adoption of recycled materials and identifies potential opportunities to increase uptake.

The key barriers limiting the adoption and use of recycled materials in road and rail infrastructure include:

- *Awareness*: A general lack of awareness as to which applications recycled materials can be used in or allowable limits within specifications.
- *Prescriptive specifications*: Specifications that prescribe which materials to use, rather than focussing on their performance outcomes, can restrict use.
- *Availability of materials*: Logistically difficult and uneconomical collection and recycling of waste in regional areas.
- *Procurement*: Current procurement policies facilitate the use of recycled materials as opposed to *optimising* the use of recycled materials.
- *Perceived inferior performance*: There is a lack of confidence in the use of recycled materials because of this perception.
- *Perceived health, safety and environmental concerns*: Concerns include the environmental impacts, such as leaching of heavy metals, as well as health and safety considerations for workers and the community.
- *Costs*: Novel applications and technologies are often more expensive than traditional ones, mainly due to research and development costs.

Key opportunities to address these barriers include:

- increasing industry awareness and confidence via knowledge sharing and collaboration
- filling in data and evidence gaps via further research using life cycle assessment for emerging materials and applications
- continuing the development of performance-based or performance-related specifications and encouraging consistent product evaluation and certification schemes
- improving sustainability procurement via incentives and customising policy with project-specific requirements
- addressing WHS concerns via evidence-based research, demonstration trials and development of PPE-use standards
- creating more opportunities for the cost reduction of recycled material use via encouraging low-energy recycling and processing facilities,and supporting the market and supply chain development.

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Appendix A Sustainability Impact Assessment Data

A.1 Environmental Impact Factors and Resource Consumption Factors

Table A.1: Factors for quantifying environmental impacts (per kg of material)

Material	Global warming (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4 eq)	Photochemical oxidation (kg C_2H_4 eq)	Abiotic depletion – minerals (kg Sb eq)	Abiotic depletion fossil fuels (MJ)
Recycled materials							
Crushed concrete and brick	0.003689	3.60383E-10	6.79634E-06	1.03676E-06	7.97766E-07	8.97882E-10	0.048976
RCG	0.014938	5.39371E-10	2.49061E-05	7.78677E-06	1.45996E-05	2.30179E-09	0.080086
RAP	0.000788	1.01639E-10	1.52484E-06	1.95834E-07	2.01529E-07	9.53191E-13	0.010933
Crumb rubber	0.285184	2.4692E-10	0.000400332	0.000109037	1.07849E-05	4.14323E-10	3.228933
GGBFS	0.176593	8.06839E-09	0.001631464	0.000159522	9.23876E-05	9.40943E-10	2.479877
Fly ash	0.013720	1.70497E-09	4.50088E-05	8.37513E-06	8.9617E-06	1.5942E-11	0.182943
Bottom ash	0.008552	4.51E-10	1.87E-05	4.06E-06	2.53E-06	5.07E-12	0.104048
Recycled ballast[1]	–	–	–	–	–	–	–
Recycled solid organics	0.038173	1.7515E-09	0.001146276	0.000259091	9.65235E-06	5.25484E-09	0.121075
Recycled plastics	0.237107	1.55028E-08	0.000399936	8.00452E-05	4.50368E-05	6.1362E-07	1.367071
Virgin materials							
Crushed rock	0.006469	6.57878E-10	3.1588E-05	4.86855E-06	3.42653E-06	1.30568E-08	0.099979
Crushed aggregate	0.006469	6.57878E-10	3.1588E-05	4.86855E-06	3.42653E-06	1.30568E-08	0.099979
Asphalt	0.036400	3.67052E-08	0.00011541	1.93529E-05	7.45966E-05	1.24374E-08	2.536526
Bitumen	0.605092	7.21605E-07	0.001708019	0.000294556	0.001426828	6.68761E-10	48.830933
Hydrated lime	0.770159	5.14367E-08	0.000683016	8.47028E-05	0.000236809	3.37582E-09	4.007249
Cement	0.663473	3.15E-09	0.001328	0.000269	6.09E-05	9.73E-10	3.616291

Material	Global warming (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4 eq)	Photochemical oxidation (kg C_2H_4 eq)	Abiotic depletion – minerals (kg Sb eq)	Abiotic depletion fossil fuels (MJ)
Timber sleeper[1]	–	–	–	–	–	–	–
HDPE	2.383836	7.94182E-08	0.002675017	0.000576172	0.000830951	6.69E-09	88.897602
Landfill							
Landfill of inert materials	0.003868	4.12E-10	7.12E-06	1.05E-06	8.40E-07	3.98E-12	0.051945
Enviropoint factors							
Weighting factors	0.475	0.100	0.075	0.075	0.075	0.100	0.100
Normalisation factors	0.014	2683.354	2.549	3.846	16.550	2908.488	0.002

1. Missing factors are due to information gaps in the production process.

Source: Modelled by ARRB with SimaPro software and Infrastructure Sustainability Council.

Table A.2: Factors for calculating resource consumption (per kg of material)

Material	Electricity use (kWh)	Water use (m3 eq)	Natural gas use (Gj)	Diesel use (Kg)
Recycled material				
Crushed concrete and brick	0.001195177	1.49846E-05	1.54074E-06	0.000799097
RCG	0.004122249	0.001999505	4.56096E-06	4.22829E-06
RAP	2.44873E-05	6.69805E-07	4.27888E-08	0.00022594
Crumb rubber	0.369367881	0.000712971	0.00040907	0.00040256
GGBFS	0.064715139	0.00032974	0.000998578	0.001704811
Fly ash	0.000379035	1.08224E-05	4.84934E-07	0.003790242
Bottom ash[1]	–	–	–	–
Recycled ballast[1]				
Recycled solid organics[1]	–	–	–	–
Recycled plastics[1]	–	–	–	–
Virgin material				
Crushed rock	0.010978321	0.00981515	6.68283E-05	0.000339623
Crushed aggregate	0.010978321	0.00981515	6.68283E-05	0.000339623
Asphalt	0.005161106	0.03852707	7.30133E-06	0.000286262

Material	Electricity use (kWh)	Water use (m3 eq)	Natural gas use (Gj)	Diesel use (Kg)
Bitumen	0.103222113	0.003413395	0.000146027	0.005725241
Hydrated lime	0.070042231	0.60430266	9.41E-05	0.002197787
Cement	0.076963	0.000715	0.00112	0.006756
Timber sleeper(1)	–	–	–	–
HDPE	0.203034037	0.000939136	0.082212369	0.026389066
Landfill				
Landfill of inert materials	0.000978585	4.02E-06	1.15E-06	0.000916

1. Missing factors are due to information gaps in the production process.

Source: ARRB analysis.

A.2 Estimated Levels of Environmental Impact

Table A.3: Environmental impacts of producing virgin materials

Recycled material	Infrastructure unit	Virgin materials	Global warming (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4 eq)	Photochemical oxidation (kg C_2H_4 eq)	Abiotic depletion minerals (kg Sb eq)	Abiotic depletion fossil fuels (MJ)
Crushed concrete	lane-km of granular subbase	Crushed rock	7,811.18	0.00	38.14	5.88	4.14	0.02	120,724.13
Crushed brick	lane-km of granular subbase	Crushed rock	1,799.97	0.00	8.79	1.35	0.95	0.00	27,819.04
RCG	lane-km of granular base	Crushed aggregate	1,199.98	0.00	5.86	0.90	0.64	0.00	18,546.03
	lane-km of granular subbase	Crushed aggregate	4,499.92	0.00	21.97	3.39	2.38	0.01	69,547.60
	lane-km of asphalt base	Crushed aggregate	1,132.05	0.00	5.53	0.85	0.60	0.00	17,496.25
	lane-km of asphalt surface	Crushed aggregate	141.51	0.00	0.69	0.11	0.07	0.00	2,187.03
	lane-km of drainage layer	Crushed aggregate	5,999.89	0.00	29.30	4.52	3.18	0.01	92,730.13
	km of trench (0.5 m-wide)	Crushed aggregate	8,571.27	0.00	41.85	6.45	4.54	0.02	132,471.61

Recycled material	Infrastructure unit	Virgin materials	Global warming (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4 eq)	Photochemical oxidation (kg C_2H_4 eq)	Abiotic depletion minerals (kg Sb eq)	Abiotic depletion fossil fuels (MJ)
	km of embarkment (7 m-wide)	Crushed aggregate	53,484.74	0.01	261.17	40.25	28.33	0.11	826,622.85
RAP	lane-km of asphalt surface	Asphalt	1,799.97	0.00	8.79	1.35	0.95	0.00	27,819.04
	lane-km of asphalt base	Asphalt	1,199.98	0.00	5.86	0.90	0.64	0.00	18,546.03
Crumb rubber	lane-km of surface (as spray seal)	Bitumen	4,499.92	0.00	21.97	3.39	2.38	0.01	69,547.60
	lane-km of asphalt pavement (as binder)	Bitumen	1,132.05	0.00	5.53	0.85	0.60	0.00	17,496.25
Fly ash	lane-km of asphalt subgrade (as stabiliser)	Hydrated lime	141.51	0.00	0.69	0.11	0.07	0.00	2,187.03
	lane-km of asphalt base (as stabiliser)	Cement	5,999.89	0.00	29.30	4.52	3.18	0.01	92,730.13
	lane-km of concrete pavement	Cement	8,571.27	0.00	41.85	6.45	4.54	0.02	132,471.61
GGBFS	lane-km of concrete pavement	Cement	118,429.93	0.00	237.05	48.02	10.87	0.00	645,507.94
	lane-km of asphalt base (as stabiliser)	Cement	16,255.09	0.00	32.54	6.59	1.49	0.00	88,599.13
	100 m^3 of structural concrete	Crushed rock	18,948.79	0.00	37.93	7.68	1.74	0.00	103,281.27
Bottom ash	lane-km of granular subbase	Crushed rock	781.12	0.00	3.81	0.59	0.41	0.00	12,072.41
Recycled ballast	track-km of railway ballast	Crushed aggregate	35,999.34	0.00	175.79	27.09	19.07	0.07	556,380.77
Recycled solid organics	1 tonne of landscaping mulch	Mulch(1)	–	–	–	–	–	–	–
Recycled plastics	lane-km of asphalt surface (as binder)	Crushed aggregate	794.18	0.00	2.24	0.39	1.87	0.00	64,090.60
	track-km of railway sleepers	Crushed aggregate	-69,094,452.03	0.21	17,810.47	4,924.60	28,567.79	0.43	23,397,964.82
	km of noise wall (3 m height)	Crushed aggregate	246,727.03	0.01	276.86	59.63	86.00	0.00	9,200,901.79
	kg of pipes	Crushed aggregate	2,383.84	0.00	2.68	0.58	0.83	0.00	88,897.60

1. Missing factors are due to information gaps in the production process.

Table A.4: Environmental impacts of producing recycled materials

Recycled material	Infrastructure unit	Virgin materials	Global warming (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4 eq)	Photochemical oxidation (kg C_2H_4 eq)	Abiotic depletion minerals (kg Sb eq)	Abiotic depletion fossil fuels (MJ)
Crushed concrete	lane-km of granular subbase	Crushed rock	3,873.85	0.00	7.14	1.09	0.84	0.00	51,425.14
Crushed brick	lane-km of granular subbase	Crushed rock	848.04	0.00	1.56	0.24	0.18	0.00	11,257.63
RCG	lane-km of granular base	Crushed aggregate	2,718.73	0.00	4.53	1.42	2.66	0.00	14,575.72
	lane-km of granular subbase	Crushed aggregate	10,195.25	0.00	17.00	5.31	9.96	0.00	54,658.93
	lane-km of asphalt base	Crushed aggregate	2,564.84	0.00	4.28	1.34	2.51	0.00	13,750.68
	lane-km of asphalt surface	Crushed aggregate	320.61	0.00	0.53	0.17	0.31	0.00	1,718.83
	lane-km of drainage layer	Crushed aggregate	13,593.67	0.00	22.66	7.09	13.29	0.00	72,878.58
	km of trench (0.5 m-wide)	Crushed aggregate	19,419.53	0.00	32.38	10.12	18.98	0.00	104,112.26
	km of embarkment (7 m-wide)	Crushed aggregate	121,177.87	0.00	202.04	63.17	118.43	0.02	649,660.48
RAP	lane-km of asphalt surface	Asphalt	68.92	0.00	0.13	0.02	0.02	0.00	956.65
	lane-km of asphalt base	Asphalt	137.85	0.00	0.27	0.03	0.04	0.00	1,913.30
Crumb rubber	lane-km of surface (as spray seal)	Bitumen	344.36	0.00	0.48	0.13	0.01	0.00	3,898.94
	lane-km of asphalt pavement (as binder)	Bitumen	11,144.33	0.00	15.64	4.26	0.42	0.00	126,179.19

Recycled material	Infrastructure unit	Virgin materials	Global warming (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4 eq)	Photochemical oxidation (kg C_2H_4 eq)	Abiotic depletion minerals (kg Sb eq)	Abiotic depletion fossil fuels (MJ)
Fly ash	lane-km of asphalt subgrade (as stabiliser)	Hydrated lime	360.14	0.00	1.18	0.22	0.24	0.00	4,802.25
	lane-km of asphalt base (as stabiliser)	Cement	150.06	0.00	0.49	0.09	0.10	0.00	2,000.94
	lane-km of concrete pavement	Cement	765.29	0.00	2.51	0.47	0.50	0.00	10,204.77
GGBFS	lane-km of concrete pavement	Cement	31,521.85	0.00	291.22	28.47	16.49	0.00	442,657.99
	lane-km of asphalt base (as stabiliser)	Cement	4,326.53	0.00	39.97	3.91	2.26	0.00	60,756.98
	100 m^3 of structural concrete	Crushed rock	5,043.50	0.00	46.59	4.56	2.64	0.00	70,825.28
Bottom ash	lane-km of granular subbase	Crushed rock	1,122.42	0.00	2.46	0.53	0.33	0.00	13,656.25
Recycled ballast	track-km of railway ballast	Crushed aggregate(1)	-	-	-	-	-	-	-
Recycled solid organics	1 tonne of landscaping mulch	Mulch	-	-	-	-	-	-	-
Recycled plastics	lane-km of asphalt surface (as binder)	Crushed aggregate	0.47	0.09	0.05	0.00	1,602.66	0.47	0.09
	track-km of railway sleepers	Crushed aggregate	25.60	5.12	2.88	0.04	7,492.57	25.60	5.12
	km of noise wall (3 m height)	Crushed aggregate	41.39	8.28	4.66	0.06	141,491.90	41.39	8.28
	kg of pipes	Crushed aggregate	0.40	0.08	0.05	0.00	1,367.07	0.40	0.08

[1]Missing factors are due to information gaps in the production process.

A.3 Infrastructure Application Design Parameters

Table A.5: Infrastructure application design parameters

Infrastructure type	Infrastructure specification	Depth (m)	Width (m)	Length (m)
Road	Asphalt surface layer	0.05	3.5	1,000
	Asphalt base layer	0.2	3.5	1,000
	Granular base	0.2	3.5	1,000
	Granular subbase	0.15	3.5	1,000
	Subgrade layer	0.3	3.5	1,000
	Spray seal	0.0015	3.5	1,000
	Drainage layer	0.1	3.5	1,000
	Concrete pavement	0.25	3.5	1,000
Rail	Ballast	0.3	7	1,000
	Sleepers	0.13	0.23	1,067
General	Trench	1	0.5	1,000
	Embankment	2	Top:2 Bottom: 7	1,000
	Concrete structures	1	10	10
	Noise walls	0.04 (2 x 2 cm thick walls with a hollow interior)	3	1,000
	Landscaping	–	–	–
	Plastic pipes	–	–	–

CONTACT US

Dr Clarissa Han
National Business Group Leader
Sustainability and Material Performance
E: Clarissa.Yihan@arrb.com.au

Brook Hall
Principal Transport Economist
Sustainability and Material Performance
E: Brook.Hall@arrb.com.au

ARRB.COM.AU