LOCAL GOVERNMENT NSW

RECYCLED MATERIALS IN ROADS AND PAVEMENTS
A TECHNICAL REVIEW

August 2020

WASTE TRANSFORMATION RESEARCH HUB, SCHOOL OF CHEMICAL AND BIOMOLECULAR ENGINEERING

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Acknowledgements

This document has been prepared by the Waste Transformation Research Hub for Local Government NSW (LGNSW). It has been carried out under the guidance of a Project Steering Group and with feedback from industry stakeholders including representatives from:

- Australian Asphalt Pavement Association (AAPA)
- Delta Electricity
- Downer Group
- Institute of Public Works Engineering Australasia (IPWEA)
- NATSPEC
- NSW Environment Protection Authority (EPA)
- Parkes Shire Council
- Roads and Maritime Services (RMS)
- Southern Sydney Regional Organisation of Councils (SSROC)
- Transport for NSW.

Executive Summary

With the support of LGNSW's Research and Innovation Fund, the Waste Transformation Research Hub (WTRH) at the University of Sydney have developed a guide (the Guide) for the use of recycled materials in roads and pavements. The Guide and this accompanying Technical Review promote good practice in the specification and application of recycled material reuse in roads and pavements and attempts to address concerns preventing the use of recycled materials by local councils.

At present, the increasing generation and disposal of waste is an important issue, having clear impacts on the sustainability of our environment, society and the economy. In 2017–18, NSW generated 21.4 million tonnes of waste (equivalent to about 30% of Australia's overall waste generation), which is expected to grow to more than 31 million tonnes over the next 20 years (NSW DPIE, 2020b).

The Guide and Technical Review focus on the treatment of waste as a valuable resource in a regenerative circular economy. One key area in society, where waste-derived resources have been and continue to be an important consideration in, is roads and pavements. The use of recycled materials in roads and pavements, a well-developed technology, has accelerated recently. With most road products now recycled also, there is potential to continue and expand circular systems of recycled material use. This approach reduces the need for depleting virgin materials, increases diversion rates and contributes to creating end markets for recycled materials, as described in the 20-year Waste Strategy being developed for NSW (NSW DPIE, 2020b).

Several waste streams of interest (glass; fly ash; plastics; rubber; reclaimed asphalt; crush rock, masonry and concrete) are described in this Technical Review, many of which have long demonstrated successful incorporation into roads and pavements. This document also presents a technology review of roads and pavements utilising these streams as well as other recycled materials. Such review highlights similar or greater product performance in comparison to those made from virgin materials. Possible factors influencing the properties of the concrete and asphalt include the amount of recycled material used, the quality of the material (due to possible contamination) and their particle sizes. Recommendations of recycled material compositions reported by various trials and studies are summarised in this Technical Review.

In terms of occupational health, safety and environment risks related to the use of recycled materials in roads and pavements, some of the common concerns such as dust exposure when handling recycled crushed glass (RCG), toxicity of raw materials, leaching of heavy metals from fly ash (FA) and microplastics from recycled plastics are addressed by analysing results in previously published literature.

A collection of relevant codes, standards, industry guides and research papers are provided as practical guidelines in ensuring the quality of supplied recycled materials as well as strategies to evaluate and monitor the quality of the final product with respect to common indicators including mechanical properties, durability, workability, and leachability.

Furthermore, an increasing number of studies and trials have demonstrated the incorporation of recycled materials into roads and pavements, using features of a circular

economy approach. Three selected case studies are discussed in this Technical Review to illustrate how such eco-pavement projects are evolving:

- University of Sydney-Delta Electricity Project (Small scale pavement for footpaths) for light load
- Downer asphalt trials (Large scale application) for heavy vehicle load
- City of Sydney-UNSW Geopolymer road trial.

These chosen case studies highlight the effective incorporation of various recycled materials into asphalt and concrete. Their reported results demonstrate suitable performance for their different respective applications.

The shift to a circular economy requires systemic changes in society and in the way business operates. The Guide and Technical Review recognise transitioning to a circular economy is an important phase, and that the inclusion of recycled materials into roads and pavements makes a significant contribution in this transition. This growing circular solution, despite its multi-faceted complexities, will create new circular business in NSW impacting positively on the future of waste in NSW. Local councils have the opportunity to utilise such recycled materials in their roads and pavements, through the application of the principle of "designing out waste" and maximising material resource value while in use (Ellen MacArthur Foundation, 2013). In doing so, Councils will contribute to various United Nation Sustainable Development Goals and align with the principles of the 2018 National Waste Policy. The Guide and Technical Review attempt to harmonise the approach across councils, to amplify the opportunity to establish regenerative business for roads and pavements, in a way that best benefits the sustainability of the environment, society and the economy.

Background

The Waste Transformation Research Hub (WTRH) at the University of Sydney (USYD) aims to build research capacity in transformative waste research and innovations and provides research and consulting services to various industry sectors, making improvements in process efficiencies and material recoveries. Local Government NSW (LGNSW) is the peak industry association that represents the interests of NSW general and special purpose councils.

LGNSW approached the WTRH at USYD to develop a guide (the Guide) for the use of recycled materials in roads and pavements. This is in response to the issue of a reported risk aversion by many council engineers to the adoption of recycled materials in roads and pavements, stemming from concerns about compliance with EPA requirements, health and safety risks to employees and cost to councils.

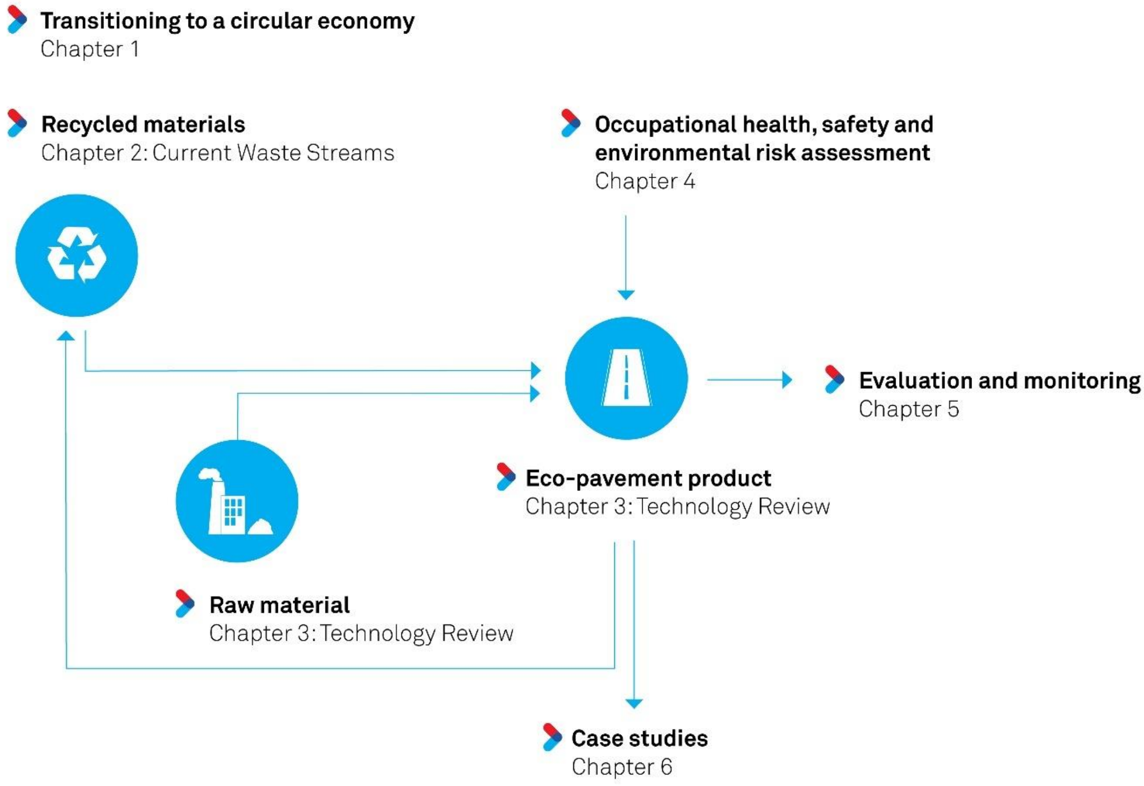
As part of the project, the WTRH has engaged with various groups including the NSW Environment Protection Authority (EPA), NATSPEC, Australian Asphalt Pavement Association (AAPA), and Southern Sydney Regional Organisation of Councils (SSROC) to keep informed of the latest developments on waste and circular economy, including regulations and standards. These aspects are considered in combination with scientific research literature to develop the Guide that can be used by council engineers with the aim to increase confidence within councils in adopting recyclable content in roads and pavements.

Scope of the Technical Review

The aim of the Guide and Technical Review is to promote national uniformity and good practice in the specification and application of recycled material reuse in roads and pavements. The requirements in these documents are applicable to engineering projects for local roads and pavements carried out by local councils. This Technical Review document comprises of six chapters revolving around the use of recycled materials in roads and pavements:

- Chapter 1: An overview of the circular economy
- Chapter 2: Current relevant waste streams
- Chapter 3: A review of the technology
- Chapter 4: Occupational Health, Safety and Environment Risk Assessment
- Chapter 5: Evaluation and monitoring
- Chapter 6: Case Studies.

An overview of these chapters is provided below:



Flowchart illustrating the structure of this Technical Review

An overview of the Circular economy

The circular economy is a systemic shift from the linear economy and applies across market products broadly, including the use of recycled materials in construction products such as 'green' concrete used in eco-pavements. The circular economy accounts for material flow and circulations, but not in the commonly understood recycling approach. Rather, the circular economy accounts for material reuse extended across long periods and for multiple lifetimes or purposes. The circularity of a product or material is measured using material circularity indices formulated around longevity and utility. These indices are presented and explained in this review.

Current relevant waste streams

This section reviews the available waste streams in selected NSW council areas to give an insight as to what waste-derived resources are available in council areas that are usable in the preparation and manufacture of construction products. The aim is not to carry out a comprehensive waste survey but rather provide data/details of relevant streams (quantity estimates and types) provided by councils. The public perception of using waste materials in pavement/roads is also covered in this section.

A review of the technology

The technology and processes for the treatment and blending of the raw materials are reviewed in this section. This Technical Review, reinforces the perspective of the reuse of waste-derived resources, taking into consideration the synergetic interaction between different wastes and their role as strength enhancing additives. The current research published in pavement-related technical journals, has reported the positive impact of using additives such as slag, lime and fly ash with other recycled materials. In the technology review, the positive influence of strength enhancing agents on the recycled waste final product is compared and the mixing formula found by latest research in this area are reported.

Occupational health, safety and environment risk assessment

There are several occupational health, safety and environment (OHSE) issues relating to the use of recycled materials in roads/pavements. This section aims to address these concerns by looking at the relevant literature and published data investigating the occupational health and safety and life cycle environmental impacts related to the use of recycled crushed glass (RCG), recycled concrete aggregates (RCA), fly ash (FA), crumb rubber and recycled plastics in road construction.

Evaluation and monitoring

This section covers the supply of recycled waste materials for use in roads/pavements and strategies to evaluate the quality of the final product. The recycled waste materials are industry by-products which have uncontrollable qualities among different suppliers. It is imperative for an engineer to be satisfied that the specification is suitable for their local conditions. The designer should use the guidelines provided by this Technical Review to classify the waste material and to ensure that inherent material characteristics are appropriate for the intended purposes.

Materials must be supplied from stockpiles that have been tested and shown to conform to specified requirements before their use in construction work. Certified stockpiles must be created for each material class to prevent segregation or mixing with other materials and must be clearly signposted with unique identification numbers.

There are numerous potential applications for recycled waste materials in pavement engineering construction. The standard test methods are listed in this section of the Technical Review. These can be used for monitoring and evaluation of the waste material final product.

Case studies

Recent eco-pavement projects are reviewed to illustrate the successful implementation of several waste streams in roads/pavements. The potential economic and environmental impacts of using the recycled waste materials are addressed. For example, a project co-funded by Delta Electricity and USYD on “upcycling of fly ash”, a combination of non-recyclable glass, fly ash and carbon dioxide (in carbonated solid form) are used in pavements, and will ‘pave’ the way for wider application of this recipe across USYD’s campuses and Delta Electricity’s site.

Introduction

At present, the increasing generation and disposal of waste is an important societal issue. The reliance on landfills in NSW highlights this issue from an environmental perspective. This is because landfills can result in various forms of emissions including leachate and greenhouse gas emissions (NSW EPA, 2016). NSW landfills are also expected to reach capacity in the next 10-15 years (NSW DPIE, 2020b). Waste also has economic and social relevance, such as impacts on human health, sanitation and employment. In 2017–18, NSW generated 21.4 million tonnes of waste, which is expected to grow to more than 31 million tonnes over the next 20 years (NSW DPIE, 2020b). With additional pressures placed by China's waste importation ban and national waste export bans, due to high contamination rates, it is essential that there is a resilient and sustainable system of waste management in NSW.

Waste is a valuable resource. One key area in society, where waste-derived resources have been and continue to be an important consideration in, is roads and pavements. Specifically, through the use of recycled materials in roads and pavements, which is not a new technology. With most road products now also being recycled, there is potential to continue and expand circular systems of recycled material use. The rationale for the use of recycled materials aligns with the 20-year Waste Strategy being developed for NSW, as it relates to the three objectives of sustainability, reliability and affordability (NSW DPIE, 2020b). In particular, *Direction 4: Create end markets* is of key relevance to the focus of the Guide and Technical Review, where efforts to develop a consistent approach to the use of recycled materials in roads and pavements can increase the market demand for these materials. This includes making the most of our plastic resources, as highlighted in the NSW Plastic Plan discussion paper (NSW DPIE, 2020a).

Furthermore, benefits of utilising recycled materials in roads and pavements include increasing the diversion of waste from landfill; improving recycling through increasing the application of recycled materials (Arvanitoyannis, 2013); and reducing the need for virgin materials for roads and pavements. The use of recycled materials reduces imported materials, thus lowering supply-chain related GHG emission and stimulating domestic industry. In terms of waste reduction, there is also the potential to increase the service life of roads and pavements and minimise their maintenance, through intensive effort focused on design in incorporating recycled materials (Austroads, 2009, AAPA). Numerous studies and trials investigating the use of recycled materials in concrete and asphalt in literature have demonstrated the role of research in discovering enhanced properties. Thus, there is rising confidence in the technology, which continues to be optimised to increase waste utilisation, whilst ensuring adequate performance.

However, the sources of the standards and specifications are complex in NSW. In the construction industry, the National Construction Code, Australian Standards, RMS specification and NATSPEC specification all play important roles as the resource of technical references. In addition, to comply with the relevant legislations governing material reuse is a crucial step in incorporating the recycled materials into roads and pavements. The recovery of resources from waste to be used as fill materials must be approved by EPA through Resource Recovery Orders and Exemptions to ensure such a practice is beneficial and poses minimal risk of harm to the environment or human health (NSW EPA, 2017a). A collection of current specifications and regulations will be of great help to the local council engineers.

Despite this described solution, the implementation of a circular economy model is also a current challenge, specifically for roads and pavements. It requires a whole system approach from various fields. When considering a 'designing out' waste strategy, it is important to consider other environmental aspects in the circulation of materials. These considerations include the greenhouse gas emissions impacts of material transportation from the source of waste generation to the processing site, to the location of road and pavement construction, then after which it can be ideally reprocessed into new roads and pavements. Another challenge stated by LGNSW is addressing perceptions of recycled material performance being inferior compared to virgin products (The Senate Environment and Communications References Committee, 2018).

Therefore, in a step towards addressing these current challenges, this project set out to develop a guide for the use of recycled materials in roads and pavements, using a circular economy approach. In doing so, it attempts to address the concerns preventing the use of recycled materials by local councils and thus promote national uniformity and good practice in the specification and application of material reuse in roads and pavements.

1. Circular economy

Transitioning to a circular economy

A circular economy is characterised as being restorative or regenerative, involving a redesign of the future through consideration of the entire value chain such as the product design and logistics (Ellen MacArthur Foundation, 2013). Effectively, the circular economy eliminates waste, pollution and contaminants by design. Products in a circular economy are kept in use while the economy prospers based on shifted business models that extend value of materials through repurposing and reuse.

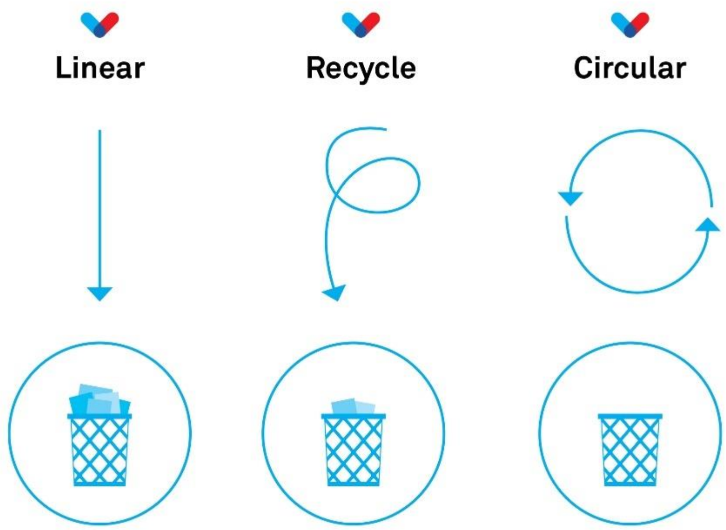


Figure 1.1 Depiction of a linear, recycling and circular economy

(image source: https://lowwastewellness.com/lifestyle/2018/9/6/a-circular-mindset-in-a-linear-economy)

A circular economy also contributes to Australia's engagement in the United Nation's Sustainable Development Goals (SDGs) (Commonwealth of Australia, 2018). Specifically, it relates to SDG 12 on Responsible Consumption and Production, as production and consumption are transformed as part of a circular economy. However, with the systemic transformation, this also positively contributes to achieving several other SDGs, including SDG 7 on clean energy, 8 on work and economic growth, 11 on sustainable cities and communities, 13 on climate action, 14 on oceans, and 15 on life on land (United Nations, World Economic Forum, 2018).

Furthermore, a circular economy rejects the typical “take-make-dispose” linear economy approach and goes beyond improving recycling (UK GBC, 2019). The limits of linear consumption highlight the need to transition to a circular economy. These include the unsustainable depletion of our available natural resources, higher price levels and greater volatility in markets, which demonstrate how a consumption-based linear economy system has resulted in negative effects and losses throughout the value chain (Ellen MacArthur Foundation, 2013).

In contrast to a linear economy, a circular one is based on the principles of “designing out” waste and pollution; keeping products and materials in use by distinguishing between consumable and durable (i.e. biological and technical) components of a product; and regenerating natural systems, fuelled by renewable energy to increase system resilience (Ellen MacArthur Foundation, 2013, UK GBC, 2019). It is designed to maximise resource value while in use, which can then be recovered and regenerated for further use (The Senate Environment and Communications References Committee, 2018). The concept of a circular economy has been developed from multiple schools of thought, including regenerative design, performance economy, cradle to cradle design, industrial ecology and biomimicry, where nature is considered as a model, measure and mentor (Ellen MacArthur Foundation, 2013).

In addition to the environmental sustainability of a circular economy, there are also advantages from the economic and social spheres. Transitioning to a circular economy will provide economic opportunity through material cost savings, mitigation of price volatility and new avenues of profit through reverse value cycles (Ellen MacArthur Foundation, 2013). Furthermore, it will increase employment prospects, with the Waste Management Association of Australia (WMAA, now known as the Waste Management and Resource Recovery (WMRR) Association) stating that “for every 10,000 tonnes of waste recycled, 9.2 jobs are created” (The Senate Environment and Communications References Committee, 2018).

An example of a circular economy approach is a “lease” model, where products such as washing machines are offered as a service under a leased contract (Ellen MacArthur Foundation, 2013). Car rentals are also an example of this, which reduce the impacts associated with the purchase of many cars. Possible setbacks include an increase in the total cost of ownership, with newer models offering better features; as well as gaining consumers, when a purchase currently seems “easier” compared to the financing involved in contracts (Ellen MacArthur Foundation, 2013). Thus, there are still challenges to be addressed for the lease model to provide an effective alternative business model using a circular economy approach.

Circular Economy does not happen overnight – it is a transition

Transitioning to a circular economy is a key challenge. Several reasons have been described to explain why a circular economy is still not a reality. One reason is that the cost of recycling is more expensive compared to landfill disposal, making it a “market failure” (Ritchie, 2019), although there are instances of recycled road products such as reclaimed asphalt pavement (RAP) with lower processing costs compared to landfill charges (AAPA). To establish a circular economy, several things need to occur, including supporting research into the design of long-lasting products, the development of domestic markets through the sustainable procurement of recycled content, as well as making waste regulation a ‘level playing field’ (The Senate Environment and Communications References Committee, 2018).

Making the circular economy a reality, requires a systemic change in current operating models. Innovation and cooperation are required from all areas such as the recycling industry, the manufacturer, the user, the government and industry bodies and so on. It needs investment in infrastructure, market development and integration of legislation, policy and programs from all levels of government (The Senate Environment and Communications References Committee, 2018). Most importantly, it requires leadership that understands the importance of the transition to the circular economy and commitment to pull together all these areas just mentioned. In doing so, circular economy transition pathways achieve sustainability goals for the environment, society and the economy, for the long-term.

Circular Economy in NSW

According to the 2018 National Waste Policy, “at the broadest level, a circular economy aims to change the patterns of natural resource use in the economy in order to achieve sustainable growth by slowing, narrowing or closing material loops” (Commonwealth of Australia, 2018).

The concept of a circular economy has gained international interest, with an increasing number of countries implementing aspects of this model. In Australia, the NSW Government has also adopted a circular economy approach, as highlighted by “Too Good to Waste”, a discussion paper on a circular economy approach for NSW (NSW EPA, Oct 2018), as well as the NSW Circular Economy Policy Statement paper (NSW EPA, Feb 2019). These documents will help guide NSW Government decision making in the transition to a circular economy, through outlining circular economy principles unique to the context of NSW (NSW EPA, Feb 2019). The circular economy life cycle presented in the NSW EPA Discussion paper, is shown in Figure 1.2 (NSW EPA, Oct 2018).

Figure 1.2 The circular economy life cycle (image source: Too Good to waste discussion paper, pg. 15 (NSW EPA, Oct 2018))

Various local councils in NSW have incorporated a circular economy approach to their sustainability plans and policy. For example, the City of Sydney has included the idea of circular economy into its Waste Strategy and Action Plan 2017-2030, to ensure that as part of their target objectives, waste materials can be reused (City of Sydney, 2017). Lake Macquarie City Council have further used circular economy principles for recycling of construction and demolition waste. One of their strategies to avoid and reduce waste generation and reuse waste, is supporting industrial ecology initiatives across the Hunter region, where relevant to their council's business interests (Lake Macquarie City Council, 2015). Parkes Shire Council is teaming up with NSW Government to set up NSW's first of several Special Activation Precincts (SAPs) to activate business and industry in regional areas (NSW Government, 2019). These SAPs are being developed to incorporate circular economy principles in their design (Abbas, 2019). To lead the use of a circular economy as an eco-industrial park, the Parkes SAP is setting goals for the efficient management of environmental factors such as waste, energy, water, mobility, climate resilience and emissions (NSW Government, 2019).

The circular economy is not “Recycling’

A common misconception is that the circular economy is equivalent to recycling. There are however clear differences between the two models. The “designing out” waste aspect of the circular economy can be contrasted to recycling, where significant amounts of embedded energy and labour are lost through recycling (Ellen MacArthur Foundation, 2013). As shown by the depiction in Figure 1.1, recycling converts waste into a reusable form, but still ultimately produces waste when it cannot be further recycled. In contrast to recycling, the circular economy keeps materials in circulation and thus avoids the generation of waste.

Furthermore, unlike the circular economy, recycling processes often reduce material utility to its lowest ‘nutrient’ level, as part of long or “loose” cycles (Ellen MacArthur Foundation, 2013). Keeping resources in use as part of the circular economy demonstrates an approach with greater foresight, as it considers material quality at all stages, including how it will be circulated from the beginning design stage.

Various indicators have been developed to measure the effectiveness of transitioning from a linear to circular economy (Ellen MacArthur Foundation and Granta Design, 2015). A simplified distinction between quantitative estimates of recycling and circular economy are as shown:

Recycling	= recycling rate or diversion rate (diversion from landfill)
Circular Economy	= Circularity index (is a function of several variables including mainly longevity and utility)

The main indicator developed by the Ellen MacArthur Foundation is the Material Circularity Indicator (MCI), which measures how restorative the material flows of a product and a company are (Ellen MacArthur Foundation and Granta Design, 2015). These are early days for the use of circular economy indicators such as MCI. The methodology for calculating these indicators requires project-specific data, features such as recycling factored into the calculation as well as whole sector averaging. Nevertheless, such efforts are emerging, for example, the normalisation of MCI data against economic factors was recently highlighted by a study, demonstrating varying circular economy conformity of products (Tashkeel and Abbas, 2019). Another study investigating the sustainability of reclaimed asphalt as a resource for road pavement management through a circular economic model is a useful example (Mantalovas and Di Mino, 2019). The cycle of stages for reclaimed asphalt from manufacture, to use, to end of life and dismantling, then transport, processing and recycling, were considered. Estimates of a Product Material Circularity Index were made to compare the surface, binder and base course, where their findings demonstrated the need to optimise factors such as its utility function relating to its mechanical resistance, as well as mix and equipment design, and recycling techniques.

Transitioning to the circular economy through the use of recycled materials into roads and pavements

Implementing a circular economy approach to roads and pavements is a more complex one, as it cannot be simply “leased” as a service. It involves challenges such as asset ownership, where some level of responsibility needs to be placed on the initial producer of the road or pavement, so that all aspects of its service life are considered and not just by the end owner

(US FHWA, 2015). However, a circular economy approach still offers the potential to adopt features of its model (Figure 1.3). A circular economy approach is especially necessary for roads and pavements due to decreasing landfill capacity, the intensive consumption of raw materials, as well as the environmental effects on the air, soil and water (Mantalovas and Di Mino, 2019).

Incorporating recycled materials into roads and pavements relates to several aspects of the five principles described in the 2018 National Waste Policy, underpinning waste management, recycling and resource recovery in a circular economy (Commonwealth of Australia, 2018). Firstly, as part of avoiding waste, the sustainable design of road and pavement products with enhanced properties can enable greater material recovery for input into new roads. Research into material and product design is critical for this to come to practical fruition. Additionally, recycled material incorporation into roads and pavements increases the use of recycled material and builds demand and market for recycled products (principle 3). These aspects work in cooperation with the other principles such as improvements in recycled material quality, which would enhance road and pavement performance.

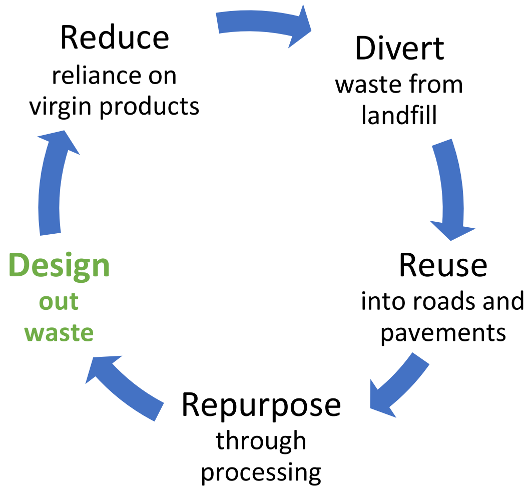


Figure 10.3 Material flow cycle for roads and pavements

In a report providing circular economy guidance for construction clients, aspects such as design for optimisation and adaptability and utilisation of recycled content were highlighted, with useful solutions provided for perceived challenges (UK GBC, 2019). These features can also be applied to road and pavements, in terms of their design, performance and life cycle. Related studies have also highlighted that greater utilisation of reclaimed asphalt is dependent on mixture design and its properties, which impact scale up considerations from the laboratory to the pavement (Mantalovas and Di Mino, 2019).

Therefore, applying a circular economy approach to roads and pavements is a relatively new but feasible one. Logistics, technology, material recycling and reuse, education and manufacture are some aspects that can be considered in the use of recycled material in roads and pavements. Through improved performance and material circularity of these assets using a circular economy approach, there is increasing opportunity to establish regenerative systems of road and pavement use.

2. Current Waste Streams

This chapter provides an overview of the current waste situation in NSW and highlights particular waste materials that are of interest for incorporation into roads and pavements, using a circular economy approach.

Data quality

Most data used in this chapter is sourced from the Australian National Waste Report 2018 (Pickin et al., 2018) and NSW Waste Avoidance and Resource Recovery (WARR) Strategy Progress Report 2017-18 (NSW EPA, 2019b). Waste data values, including tonnages of waste generated or recycled, were taken from these reports or database files. Other data sources and methods of calculation are noted, where used.

Whilst the presented data aims to be as accurate as possible, it is noted that they also carry the assumptions of the data reports used. This includes some data of waste streams being incomplete or estimates; and that few waste streams are not fully separate. Most data used is taken from publicly available sources.

Overview of Waste

Waste in New South Wales

Moving towards a circular economy model, firstly requires an understanding of the current waste situation, including availability of waste materials; data trends; as well as the flow and fate of waste.

Data trends from 2007 to 2017 show a steady increase in the generation of core waste, in NSW and Australia (Figure 2.1). Within this period, NSW on average, generated 17.6Mt annually, making up about 34% of Australia's total core waste generated each year. Thus, this large proportion, reflects the potential to shape the future of Australia's waste, by targeting waste in NSW.

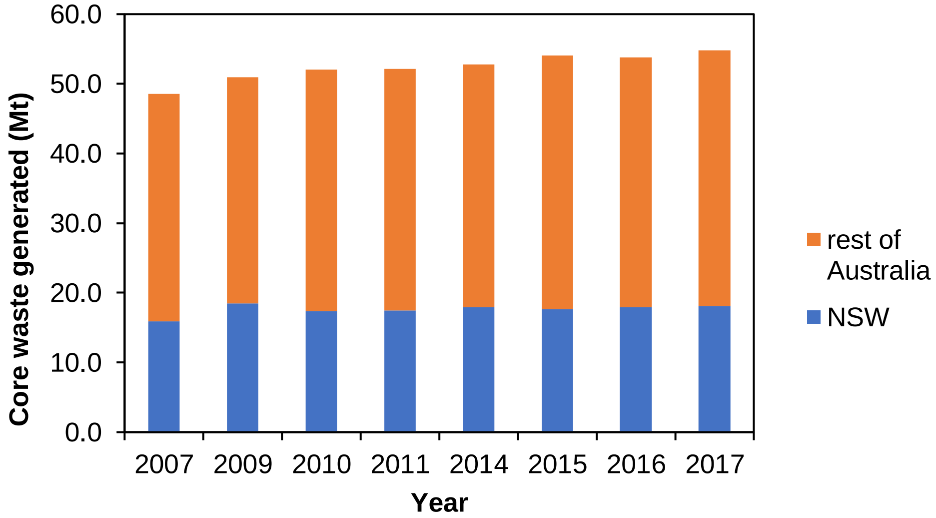


Figure 2.1 Generation of core waste in NSW in relation to rest of Australia from 2007 to 2017

(data source: National Waste Report 2018, p.93)

According to the NSW EPA waste hierarchy, the ideal would be to avoid waste generation in the first place, then secondly to decrease waste generation (NSW EPA, 2017b). However, at present, despite increased waste management efforts, there is still a steady trend, with no clear reduction of waste over time (Figure 2.1 above). This suggests effects such as increasing populations and material demand, but also reflects the need to utilise and target the waste streams, currently present. A closer analysis of these streams will be discussed below to demonstrate key waste materials of interest in this Technical Review.

Core waste generated in NSW can be analysed using its three component main waste streams: municipal solid waste (MSW), commercial and industrial waste (C&I), and construction and demolition waste (C&D). As shown in

Figure 2.2, C&D waste stream is consistently the greatest contributor to the mass of waste generated in NSW. C&D waste includes building and demolition waste, asphalt waste and excavated natural material (WARR, 2017-18). On average, the MSW and C&I streams both generated 4.3Mt of waste annually. Thus, the three streams, and in particular the C&D stream will be key areas of focus for this Technical Review.

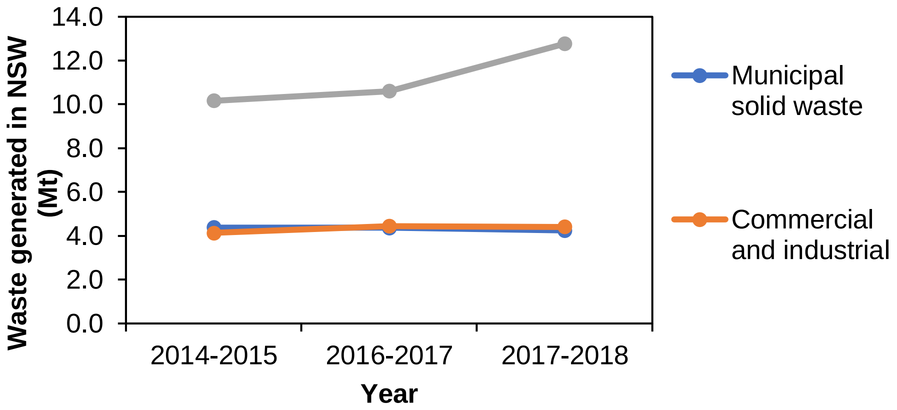


Figure 2.2 Waste generated, by waste stream from 2014-15 to 2017-18

(data source: WARR Progress Report p.16)

Fate of Waste

The fate of waste in NSW can be depicted by the flow diagram below (Figure 2.3). Whilst in reality there are many complex variations of the system, this simple depiction will be used as the basis of understanding material flow. Core waste generated, as used in the previous two figures, has two possible main outcomes: to be recycled or disposed. This will determine the availability of waste materials for incorporation into roads and pavements.

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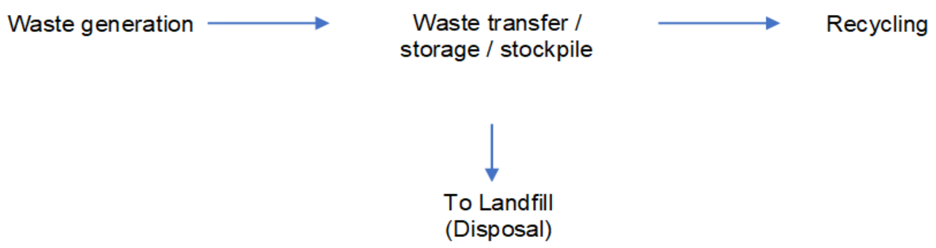

Figure 2.3 Flow diagram of the fate of waste and material flow

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significant amounts end up being disposed or recycled (Figure 2.4 below). From the *National Waste Report 2018* data, 60% of core waste generated is recycled. These recycling rates may appear to be quite high, but remain steady, showing no significant increase over the data period. Furthermore, on average 6 Mt of waste continues to be disposed of annually. This highlights that there is still greater opportunity for waste materials to be utilised in a circular economy.

In both outcomes of the fate of waste, there are possible areas to be addressed. For example, greater segregation of waste material through advanced technology, has been proposed as means to enable greater resource recovery. For the focus of this project on roads and pavements, recycled material use will target both a reduction in waste disposal and also optimisation of waste recycling. The next section will narrow down to the materials of interest, to achieve these outcomes.

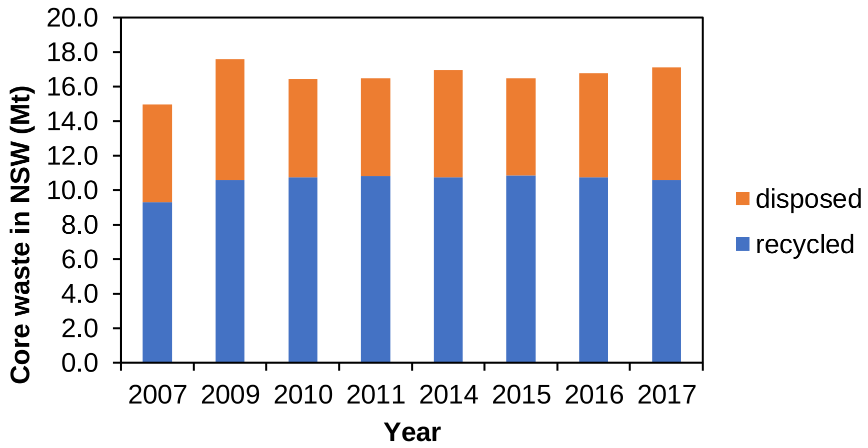


Figure 2.4 Disposal and recycling of core waste in NSW from 2007 to 2017

(data source: National Waste Report 2018, p.93, 95)

Waste Streams of Interest

In this Technical Review, the chosen waste streams of interest for incorporation in roads and pavements are:

- Glass
- Fly Ash
- Plastics

- Rubber
- Reclaimed Asphalt
- Crushed Rock, Masonry and Concrete.

These waste streams have been chosen due to their technical properties, which make them suitable for their incorporation into roads and pavements. As described earlier, the use of recycled material is not a new technology. It has been supported by an increasing number of successful roads, trials, case studies, as well as widely accepted sets of specifications by RMS and Austroads. To adopt the use of these materials in roads and pavements, using a circular economy model, will be important.

In a report by NATSPEC (NATSPEC, 2019c), NSW councils demonstrated the greatest number of responses to a survey on recycled materials for roadworks, compared to other Australian states. The type of recycled material used by the most number of councils in the survey was Reclaimed Asphalt Pavement (RAP), followed by crushed concrete, crushed glass, crumb rubber and so on. Thus, there is increasing council interest in using recycled materials in roads and pavements, which could suggest public perception is improving.

For each waste stream of interest, the amounts disposed and recycled in 2016-17 in NSW are shown in Figure 2.5 below. Collectively, excluding fly ash, these waste streams of interest make up almost 50% of the total core waste disposed in NSW in 2017-18, showing the significance of these streams. Masonry materials in the figure, include asphalt, bricks, concrete, rubble, plasterboard and cement sheeting. These are combined as data for each material is not available. Key details of each stream will be discussed below, with further technical details of the use of these recycled materials into roads and pavements discussed in Chapter 3: *Technology Review*.

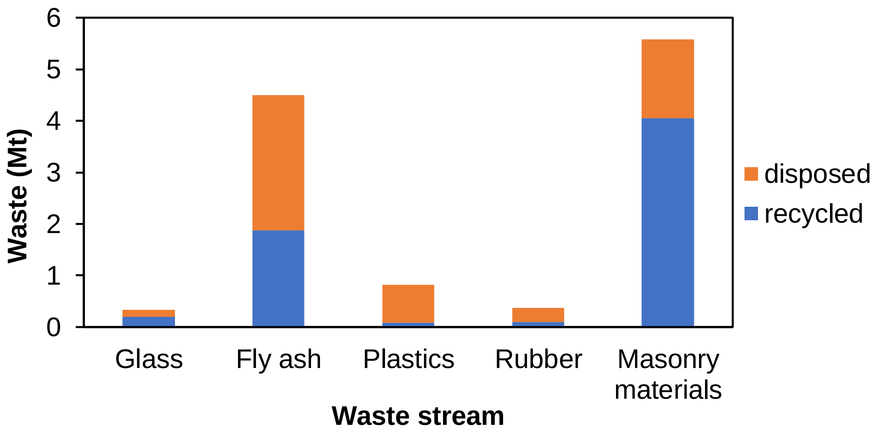


Figure 2.5 Waste disposed and recycled in NSW in 2016-17 (data source: national-waste-report-2018-data)

Glass

Glass is an important material, which continues to be used as construction material and as a packaging medium. Glass is not biodegradable, contributing to waste stockpiles if not efficiently recycled.

In Australia, glass recovery rates in 2014-15 were 56% according to National Waste Report 2016 (Figure 2.6). In 2015-16, Australian Packaging Covenant Organisation (APCO)

National Recycling and Recovery Survey stated a 43% recovery rate (DoEE, 2018). In 2017-18, the Australian glass packaging recovery rate was 46% (APCO, 2019). As a state, NSW in 2017-18, had recycling recovery rates of 44% for glass (APCO, 2019). Despite the data showing that the recovery rate is slowly improving over time, there is potential for greater recovery through the use of recycled glass in more roads and pavements.

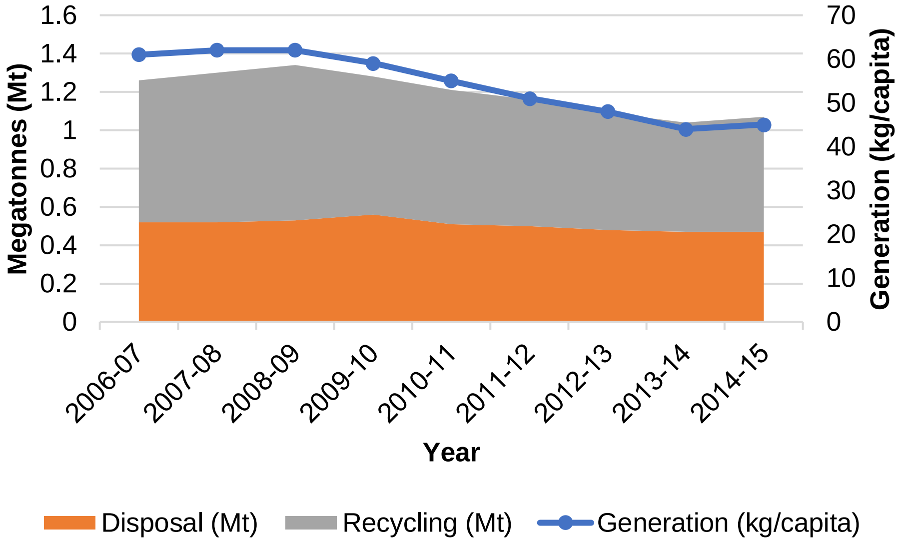


Figure 2.6 Glass waste generation and fate, Australia 2006-07 to 2014-15 (National Waste Report 2016, pg24)

Glass is currently collected as part of the comingled waste kerbside collection from households, commercial locations, or container deposit depots. It is then taken to Material Recovery Facilities (MRFs) to be sorted. As a result of mixing and compaction with other waste, there is often cross-contamination and reduction in material quality (DoEE, 2018).

The feasibility of using glass as a cement replacement in concrete has been demonstrated by various studies. Due to its high silica content, allowing it to function as a pozzolanic material, it is able to react with Portlandite in hydrated cement, forming C-S-H bonds, increasing the strength and durability of the concrete (Ling et al., 2013).

According to a review of crushed waste glass (CWG) in construction materials, there are still barriers preventing widespread use in concrete and asphalt applications (Mohajerani et al., 2017). These include alkali-silica reaction (ASR) expansions within the concrete, which limit the amount that can be replaced with glass.

Other studies investigating the use of recycled waste as a fine aggregate replacement in cementitious materials, found that glass sand increased mixture workability and bleeding, whilst decreasing density and mechanical strength. Despite these effects, glass was also found to increase chemical and fire resistance. These challenges and benefits highlight the potential for further optimisation of waste glass incorporation into roads and pavements.

There are many types and variations of glass, such as colour, particle size and degree of contamination. These variations may affect its suitability for reuse in roads and pavements, making it difficult to apply a single approach. However, there are still opportunities for reuse as low-order mixed glass, when colour is not considered an issue, being crushed down to form aggregate with uniform particle size (typically 4-5mm for recycled glass sand).

Fly ash

Fly ash is defined as a “solid material extracted from the flue gases of a boiler fired with pulverised coal” (ADAA, 2009). Due to the continued dependence on the use of coal as an energy source in Australia, the generation of fly ash as a product is currently unavoidable. Furthermore, the resulting treatment and disposal of fly ash is of environmental concern, as ash dams for example, negatively impact aquatic ecosystems. Thus, harnessing the use of fly ash as a resource, in an environmentally sustainable way, is essential. The incorporation of waste fly ash into roads and pavements, presents us with a means of achieving this.

In addition to reducing the consequences of fly ash disposal, fly ash has several properties which make it useful for incorporation. In the Australian Standard, AS3582.1, the two grades of fly ash are Normal Grade and Special Grade, which are classified based on properties such as fineness, loss on ignition, moisture content and SO_3 content (ADAA, 2009). In general, fly ash exhibits properties of pozzolans, due to the presence of SiO_2 and Al_2O_3 in amorphous form, making them able to react with calcium hydroxide at room temperature (1991).

However, the properties of coal are affected by the type of coal and conditions of the coal-fired power plant combustion (Adriano et al., 1980). Coal categorised as class F is a bituminous coal, mainly composed of silica and alumina and of a light to mid-grey colour, with irregularly spherical particles. Class F ash is useful as a cementitious material, due to its pozzolanic properties (Heidrich, 2002). Class C ash is fly ash that is a by-product of lignite coal (brown coal) combustion and is characterised by having greater lime content (15-30% lime compared to less than 7% in class F ash) (Fisher et al., 1978). It is also a pozzolanic and cementitious material. Depending on the type of coal and fly ash, the property of dry compacted voids (DCV) could present a risk to the performance of the mastic in the asphalt. Thus, fly ash may only be used to supplement the use of crushed virgin aggregates and RAP as fillers with hydrated lime for adhesive properties (AAPA).

According to the *National Waste Report 2018*, Australia generated 12.3Mt of ash in 2016-17. Around 57% (7Mt) of ash was disposed on-site and about 43% (5.3Mt) was recycled into products like concrete. Thus, there is growing potential to recycle more fly ash through the incorporation of fly ash into concrete roads and pavements. Trends in ash generation reflect the changes in coal-fired power generation, such as the 14% drop in ash generation from 2006 to 2016, due to the decline in coal energy. As a waste stream, ash is mostly managed outside the main waste management system. This highlights the input required from both industry and government, in order to effectively utilise fly ash from the source of generation, to the location of road and pavement construction.

Plastics

Plastics, as defined in the *Australian Plastics Recycling Survey Report 2017-18,* are synthetic or semi-synthetic, mouldable material, typically organic polymers of high molecular mass and mostly derived from petrochemicals

(O'Farrell, 2019). There are seven main types of plastic: 1 Polyethylene terephthalate (PET); 2 High density polyethylene (HPDE); 3 Polyvinyl chloride (PVC); 4 Low density polyethylene (LDPE); 5 Polypropylene (PP); 6 Polystyrene (PS); and 7 Other plastics. Examples of plastics include film packaging and soft plastics.

In 2016-17, Australia generated 2.5Mt of plastic waste, from which 12% was recycled, 87% sent to landfill and 1% to a waste to energy facility (Pickin et al., 2018). In NSW, plastic recycling rates are low, only recycling 11% of total plastic waste generated in 2016-17 (Figure 2.5 above). Single use shopping bag bans are not implemented across all stores in NSW (National Waste Report, Table 6 pg40), making it a possible factor, keeping plastic generation steady (Figure 2.7).

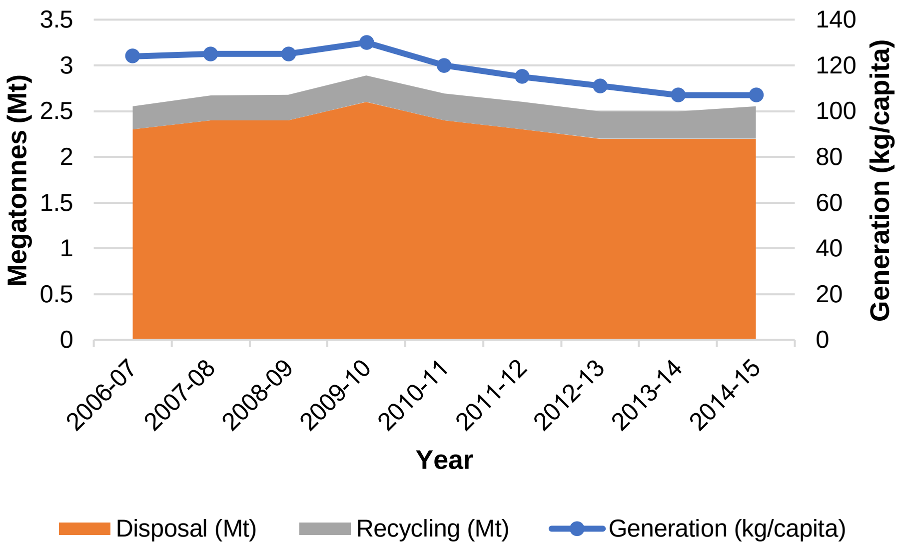


Figure 2.7 Plastic waste generation and fate, Australia 2006-07 to 2014-15 (National Waste Report 2016, pg24)

Plastics are hard to degrade, having high melting and decomposition temperatures, as well as high resistance to UV radiation. This presents a key environmental issue but opportunity, as these properties make it suitable for incorporation into roads and pavements.

Studies testing the use of plastics have demonstrated improvement in deformation and fracture resistance as well as an increase in structural contribution of the asphalt, with the addition of waste plastic (White and Reid, 2018).

However, these studies have also demonstrated the importance of properties such as low melt-temperature of plastics, which will determine its use, through its digestion into the asphalt. Plastics with melt-temperatures higher than the typical bituminous binder and asphalt, would be used as an asphalt mixture or aggregate extender (White and Reid, 2018).

Current concerns of waste plastic use in roads and pavements are mainly regarding the microplastics issue, due to its leachability into waterways. Trial studies have explained that both soft and hard plastics additive melts as part of the 5% bituminous binder in asphalt, making it unable to be released into the environment (Sustainability Victoria, 2018b, Redland City Council trial (Crick, 2019)).

Rubber

There are many types of waste rubber, but for the focus of inclusion in roads and pavements, rubber in this Technical Review will focus on tyre rubber, as demonstrated by various scientific trials. Tyres have properties such as resistance to mould and sunlight, as well as being non-toxic and elastic. These characteristics made rubber tyres advantageous for on-road life purposes such as for vehicles, however, has consequently led to storage and disposal issues, following consumer product use (Lo Presti, 2013). The incorporation of rubber tyres into roads and pavements offer an alternative solution to utilise these properties, which has been undertaken for many years.

In Australia, there is approximately 450,000 tonnes of tyre waste, with only 10,000 tonnes used in bitumen surfacing (Tyre Stewardship Australia). In the National Waste Report 2018, tyres are reported as hazardous wastes, due to the fire hazard they pose as well as being a “controlled waste”. It is also noted that significant stockpiles of tyres have been abandoned or inadequately managed in recent years (Pickin et al., 2018).

In NSW, approximately 20% of waste tyres were recycled in 2016-17 (recycled over sum of recycled and disposed). Tyres have also been included in product stewardship programs, specifically the Tyre Stewardship Scheme, an industry run initiative, since 2014, with an estimated quantity of about 45,000T recycled.

Rubber is a waste stream of interest due to the enhanced properties it provides to roads and pavements. The addition of rubber into concrete has been found to increase ductility and impact resistance. Rubberised concrete is suitable in applications subject to dynamic loading, such as concrete pavements with moving vehicles or people. Properties such as size and distribution of rubber particles and aggregate type are important as they affect the compressive strength and workability of the concrete (Moustafa and ElGawady, 2015).

An example of current technology is Recycled Tyre Rubber Modified Bitumens (RTR-MBs), which is used in the “wet-process” and have been demonstrated to enhance road pavement performance (Lo Presti, 2013). Crumbed rubber are also well tested products, which act as polymer modified binders (Tyre Stewardship Australia). These allow greater reflection cracking resistance in aged or cracked pavements, due to a thicker bituminous membrane (Austroads, 2009).

Reclaimed Asphalt

Asphalt is the most reused construction material in the world (AAPA, 2018). It is potentially 100% recyclable, depending on factors such as the quality and age of the asphalt road. Asphalt pavements are typically composed of around 5% bitumen and 95% aggregate. The section of interest is the top layer, known as the wearing course, which is removed and replaced every 10-15 years.

Thus, the stage of asphalt road replacement or resurfacing offers the opportunity to both extract material that can be reused as well as construct roads with higher or ideally complete waste replacement, when other waste materials are used in combination. This asphalt is referred to as Reclaimed Asphalt Pavement (RAP). It is defined as asphalt that was previously used as an engineering material and must not contain a detectable quantity of coal tar or asbestos (RMS, 2015). Recycled asphalt content in these mixes usually ranges between 10-15%. Recycled asphalt is mainly used in the base course and road base layers and to a lesser extent in the wearing course layer (DSEWPaC, 2012). However, the wearing course layer generally takes more of the RAP due to its larger thickness compared with base course.

Data on asphalt is limited, as it is often reported as part of masonry materials. As noted in the *Waste in NSW* section above, the C&D stream is a major contributor to core waste generation in Australia and the use of RAP is a major product of recycled C&D waste. As the incorporation of reclaimed asphalt into roads has become standard practice for many years, there is potential to utilise more of this waste as a recycled material. They have also incorporated other waste materials such as waste print toner.

Studies have also described the significance of certain properties of asphalt. For example, as RAP particles are temperature sensitive, their cohesive properties are affected by preparation temperature (Jayakody et al., 2019). Viscosity can be used as an indicator of RAP performance, which influences stiffness, wheel tracking rate and overall road fatigue life (Austroads, 2015b).

A key aspect of reclaimed asphalt use is the process technology required to restore the asphalt to a usable state. This involves stockpiling, crushing, testing and recycling at the production plant (Austroads, 2015b). Interestingly, the associated processing costs and energy use are less than that those for the use of virgin materials. The financial incentive along with the environmental benefit from using waste materials and reducing the unsustainable extraction and consumption of virgin materials present an opportunity to move towards a true circular economy.

Further details of the technology will be explained in the next chapter, *Technology review*.

Crushed rock, Masonry and Concrete

Like reclaimed asphalt, the waste stream of crushed rock, masonry and concrete, are generated as part of C&D wastes. The incorporation of these recycled materials as a substitute for aggregate in roads and pavements would significantly reduce the large amounts of waste disposed from the C&D stream. As crushed rock, masonry and concrete products are typically construction waste materials, they are more readily able to be recycled and incorporated into roads and pavements.

In Australia, 17.1 Mt of masonry material waste was generated in 2016-17 (*National Waste Report 2018* (Pickin et al., 2018)). From this generated waste, 12.3Mt was recycled. This trend was similar for NSW, where approximately 70% of waste masonry material was recycled. Although these recovery rates appear high, this waste stream does however, by mass still contribute significant amounts of waste to landfill. For example, about 1.5Mt of waste masonry material was disposed of in 2016-17.

An important aspect of concrete reprocessing is the incentive to avoid weight-based disposal charges where high landfill fees are present (DSEWPaC, 2012). However, mixed loads of demolition waste containing crushed rock, masonry and concrete, are often sent directly to landfill due to the difficulty of material separation (Pickin et al., 2018). Thus, improvements to crushing technology, as well as collection and segregation of demolition wastes can further optimise recovery rates, to be used in the development of roads and pavements.

The use of crushed concrete in applications such as low-grade roads and in pavement sub-bases are key growing markets for this waste stream. These masonry products offer a substitute for virgin crushed rock, decreasing the use of raw material. It was found that recycled crushed concrete increased the overall product volume, in comparison to crushed quarry rock of the same weight (DSEWPaC, 2012). Additionally, due to the cement present in recycled concrete, the aggregate forms a more stable hardstand compared to virgin aggregate (Pickin et al., 2018). TfNSW/RMS allow 100% crushed concrete and a maximum of 20% crushed brick to be blended to be used as road base aggregates (2019b).

Possible concerns of waste crushed rock, masonry and concrete include asbestos contamination risks, which need to be identified and handled following appropriate specifications (Pickin et al., 2018). As waste materials of masonry and concrete contain varying compositions of constituent components, properties such as cement content and aggregate size will affect the overall quality of the road or pavement. Thus, specifications of material properties will be required to ensure optimal recycling into roads and pavements, without compromise of performance.

Geographical Distribution of waste streams in NSW

The location of both the source of waste material generation and the area of road and pavement construction are important to note as the distribution of materials contribute to the efficiency of waste utilisation. Limiting the transport distance between locations, by using waste in closer proximity to the source, will reduce environmental impacts such as greenhouse gas emissions and reduce transport costs. It is recognised that these distances will be further apart in a rural context for example. Distributing waste transfer stations can provide increased access to recycled materials and reduce transport. Going a step further, the in-situ recycling of existing road material with a strengthening agent, provides a sustainable solution with environmental benefit and cost savings from avoiding the transport of old material away and the import of new material. Considering these various aspects, will optimise the circularity of recycled material use in roads and pavements.

Examples of roads and pavements using recycled materials

Several examples of roads and pavements where these waste materials have been trialled, are shown in Table 2.1. Details of specific case studies will be further discussed in Chapter 6.

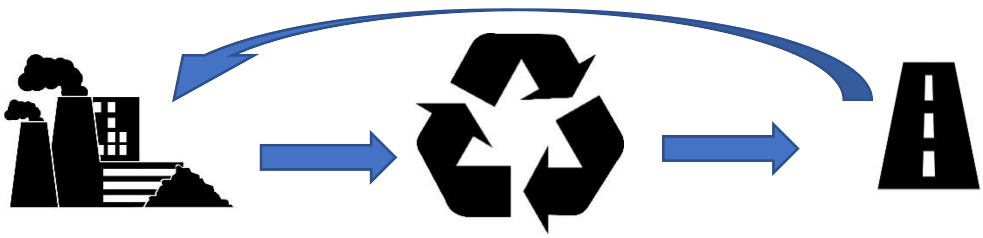
Table 2.1 Examples of roads and pavements using recycled materials

Waste stream	Trial location	Details	Organisation (s)	Reference
Plastic, Glass	Engadine, Sydney NSW	Asphalt road using recycled soft plastics, glass and toner, recycled asphalt	Downer, Sutherland Shire Council, Close the loop, RED Group and Plastic police.	(Waste Management Review, 2018)
Rubber (crumbed)	Mitcham, SA	Approximately 850 used tyres were recycled in trial asphalt resurfacing		Tyre Stewardship Australia Annual Report 2018-19, p.10
Recovered Plastics (soft), Glass (fines)	VIC	Concrete footpath met standard requirements without compromise of mechanical properties	Swinbourne University of Technology, Polytrade Recycling	(Sustainability Victoria, 2018a)
Crushed Rock, Masonry, Concrete	Gilmore Ave, Western Australia	Recycled Concrete Aggregate (RCA)	Waste Stream Management, in partnership with Town of Kwinana and Marin Roads WA	(Newman et al., 2012)

3. Technology Review

This chapter will review the technology of roads and pavements containing recycled materials. Various sources have been referenced in this chapter including journal articles, government publications and reports from relevant organisations such as Austroads and NATSPEC.

The first section, *Raw Material* will focus on the recycling, treatment and mixing processes involved in using raw waste-derived materials. Then, the next section, *Primary Product*, will highlight details of utilising various combinations of recycled materials in roads and pavements. The areas of technology reviewed in this chapter are depicted in the figure below, with sections listed for reference. By reviewing the technology, concerns of recycled material performance compared to virgin products, can be addressed.



RAW MATERIAL — Recycling, treatment, mixing

Recycled Material

PRIMARY PRODUCT — Road & pavement applications (asphalt/concrete)

RAW MATERIAL	PRIMARY PRODUCT
• Waste Recycling • Raw Material Treatment • Raw Material Mixing Process	• Using fly ash in concrete as replacement of cement • Using fly ash in asphalt as replacement of common filler • Rubber concrete • Concrete with recycled glass • Concrete with recycled plastic waste • Asphalt with recycled rubber • Asphalt with recycled glass • Using waste plastic in road construction • Alternative materials as binder in asphalt • Other recycled materials • Interaction between wastes • Recommendations of recycled material compositions made by various trials and studies

Raw material

In this section, aspects of the recycle of waste, raw material treatment and the mixing process, are discussed. A review of these technologies highlights the importance of raw material in the overall circular economy model, as well as the new business opportunities they present. This is because the general recycling of raw materials is often insufficient to generate products with a quality suitable for direct incorporation into roads and pavements. Further treatment and processing are required, such as to remove contaminant residues or crush material to specified particle size distributions. Thus, with consideration of these challenges as well as the need to minimise waste transport, there is the potential for businesses to evolve waste transfer stations that can offer these capabilities. These will enable waste to be aggregated and processed in preparation for various uses such as road and pavement construction in locations closer to end use.

Recycling

To appreciate the circulation of waste within a circular economy model, it is important to first understand the current waste recycling technologies. Recycling refers to the collection, sorting, processing and conversion of waste into raw materials which can be used in the production of new products (National Waste Report, 2018, (Pickin et al., 2018)). It forms an integral component within the overall flow of waste, as waste enters from source streams at one end and then discharges material at the other, to markets such as packaging industries. Thus, the net quantity and quality of recycled product is dependent on the effectiveness of the recycling technology. Furthermore, recycling falls into the second priority of the waste hierarchy, following waste avoidance and reduction. Yet, it is still a key aspect of waste management, in order to utilise the volumes of waste present, which currently cannot be avoided from being generated.

As described in Arvanitoyannis, 2013, the effectiveness of recycling is influenced by aspects such as packaging and product design (that should be designed for recycling); material contamination; management operations (e.g. distribution channels); legislation; consumer education; and technological advances (Arvanitoyannis, 2013). Thus, the various aspects of influence, highlight the importance of a circular economy approach for utilising recycled materials in roads and pavements. Also, from an economic perspective, the cost of recycling can be summarised as the cost of collection and sorting; minus the cost of landfill avoided and minus the revenue of the recycled material sold (Arvanitoyannis, 2013). These are also important considerations for the raw material resources required for the road and pavements.

The options for recycling plastics, which can be described for recycling waste in general (WWF-Australia, 2019), include:

- *Kerbside recycling* – Recycled waste is collected by contractors or council then taken to Material Recovery Facilities (MRF). At MRFs, the waste is sorted and compacted.
- *Container deposit schemes* – At collection points with systems such as reverse vending machines, consumers return eligible bottles (such as plastic and beer bottles), in return for 10c a bottle.

- *Collect and return to store* – Materials like soft plastics waste are brought by consumers into supermarkets, where they are collected by companies such as REDcycle, and sold mainly to Replas.
- *Commercial and industrial* – This is similar to kerbside recycling, however with larger volumes of recycled waste collected.

Current concerns with material recycling include the high levels of contamination present in co-mingled municipal waste, and the lack of technical capacity for MRFs to sort these (DoEE, 2018). This results in reduced quality and quantity of recycled materials, not meeting export standards and being sent to landfill, as well limiting the opportunity for further recycling into products such as roads and pavements.

There are also additional details for recycling certain raw material streams. For example, plastics collected from municipal kerbside collections are sorted from co-mingled recycled materials at MRFs, into either a single, mixed-plastics grade, or often into three grades: PET, HDPE, and other residual mixed plastics (DoEE, 2018). Sorting waste plastic by type is generally undertaken by hand sorting. However, complex technology and better sorting infrastructure can improve the quality of material recovery (DoEE, 2018). Additionally, for glass, the different colours present a challenge when it is collected and crushed with other co-mingled wastes, as it becomes difficult to separate and recover, with different chemical compositions and quality grades (Lachance-Tremblay et al., 2016). Generally, in Sydney, glass collected from kerbside recycling is recycled back into glass packaging, but is however of a lower quality due to the co-mingled system of collection (DoEE, 2018). A depiction of the recycling process for glass is shown in Figure 3.1 (Arvanitoyannis, 2013).

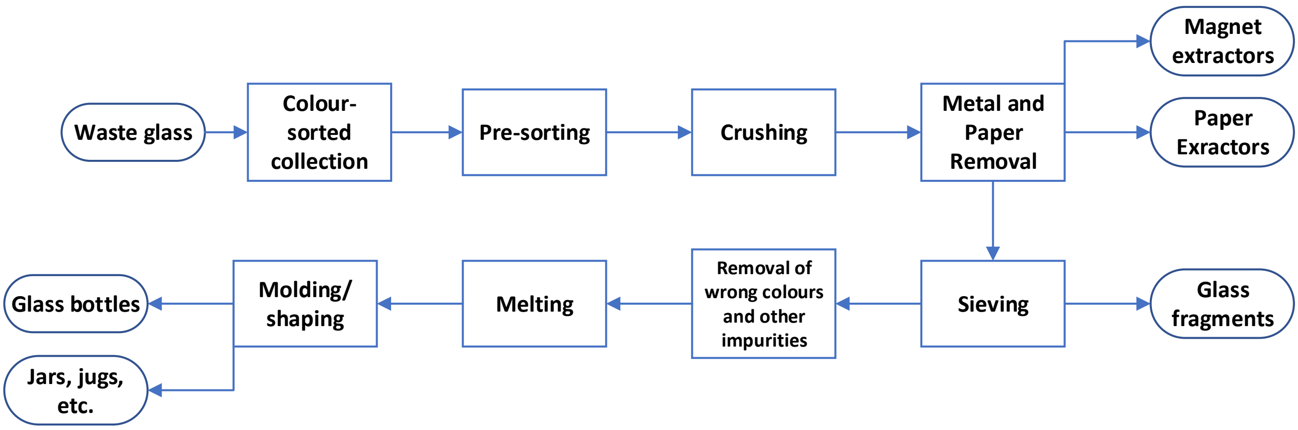


Figure 3.1 Recycling process of glass (source: Arvanitoyannis, 2013)

Additional aspects to be considered in recycling, include the transportation of waste and the resulting generation of greenhouse gas emissions. For example, reducing transport between the source (location of waste generation) and the location of road and pavement development, would enhance sustainability efforts. Waste export bans have also influenced recycling, placing greater restrictions and thus incentives to increase recycling technology.

As part of COAG's waste export bans, from July 2020, glass waste will be banned for export, followed by mixed waste plastics banned from the following year (July 2021) and all whole tyres in December 2021. Ban on single resin/polymer plastics will be effective from July

2022, and ban on the export of mixed and unsorted paper and cardboard from July 2024. All bans will be in effect by 1 July 2024 (Department of Agriculture; Water and the Environment).

Raw material treatment

The treatment technology of raw materials can be broadly categorised as either thermal or non-thermal. Thermal treatment includes pyrolysis, incineration technologies, whilst non-thermal types include landfill and mechanical processing. There are also other alternative waste treatment technologies such as biological treatment using composting and anaerobic digestion. However, for the purpose of the Technical Review, only treatment technologies relevant for road and pavement applications, will be covered in this section.

Thermal treatment

- Incineration

Incineration is an alternative raw material treatment of growing interest as a waste to energy technology. It involves the thermal destruction of waste using combustion to convert waste into carbon dioxide and water with residues such as sulfur and ash also produced (Arvanitoyannis, 2013). Incineration technology reduces the amount of waste disposed by about 70% in mass and 90% in volume (2019a).

The incineration process requires a system of units, including the main combustion chamber or furnace, where waste enters and is preheated with air. Incineration temperatures range between 750°C to 1000°C. The product streams of the incineration process can be simplified as either residues and gases which need to be treated using equipment such as precipitators, filters and scrubbers; or the steam stream, which can be recovered as energy from the heat of combustion in a waste heat boiler (2019a). It is also noted that the incineration by-product is suitable for use as an aggregate substitute in road construction, due to its granular nature and dense characteristics (2019a).

Incineration of typical Australian waste compositions would generate about half the rate of greenhouse gas emissions that bituminous coal would, per unit power generated (Pickin et al., 2018). From an economic perspective, the cost effectiveness of incineration with energy recovery has been shown in highly populated areas. Issues relating to incineration, which limit the use of the technology, include fire and explosion risks, pollution of groundwater and air, contamination and disposal of potentially hazardous residues (Arvanitoyannis, 2013).

Furthermore, there are often varying views in the discussion of implementing waste to energy technologies (The Senate Environment and Communications References Committee, 2018). For example, incineration can be seen as a favourable means to deal with waste especially in response to waste export bans. However, another opinion is that the amount of materials recycled are potentially decreased, due to dependence on waste to energy technology and agreements. There are also concerns about the generated emissions, which contributes to the overall regard of incineration as a final resort but above landfill in the waste hierarchy (Pickin et al., 2018).

LOCAL GOVERNMENT NSW

- Pyrolysis

Pyrolysis technology involves the thermochemical decomposition of waste in an oxygen free atmosphere, with temperatures usually ranging between 300°C and 650°C (2019a). This treatment technology is useful for converting wastes, such as plastic into oils, fuel, combustible gas and heavy residues (Arvanitoyannis, 2013). In general, the three types of pyrolysis processes are conventional (slow), fast or flash, which varying in their operating temperature ranges, heating rates, particle sizes and solid residence times (2019a).

Several advantages of pyrolysis technology have been described (2019a), including:

- Significant reduction in waste volume (50-90%)
- Production of fuels from waste that can be stored and transported
- Use of renewable energy sources such as municipal solid waste
- Lower capital cost compared to incineration
- Self-sustaining process, once initiated.

Non-thermal treatment

- Landfill

The Environmental Guidelines for Solid waste landfills, defines a landfill as an engineered, in-ground facility for the safe and secure disposal of society's wastes (NSW EPA, 2016). Landfilling is the disposal, compression and embankment fill of waste at suitable sites (Arvanitoyannis, 2013). Six classes of waste are defined in the *Protection of the Environment Operations Act 1997,* which is of relevance for landfill disposal in NSW. These are general solid waste (putrescible); general solid waste (non-putrescible); restricted solid waste; special waste; hazardous waste; and liquid waste. According to the 2018 National Waste Report, 21.7 Mt of waste ended up in landfill in 2016-17, making up 40% of the 54 Mt of core waste generated (Pickin et al., 2018). Thus, landfill is currently a major waste treatment technology.

Concerns of landfill waste treatment include potential pollution in the form of leachate, stormwater runoff, landfill gas, odour, dust, noise and litter (NSW EPA, 2016), as well as possible infection (2019a). Also, a challenge of landfill is the suitability of site location, where waste often needs to be transported far from the source of generation to be disposed, due to high land prices. Another challenge is encroachment and the need for buffer zones around landfills, for the safe management of the site and protection of the residents (The Senate Environment and Communications References Committee, 2018). These aspects of landfill technology continue to pose increasing challenges to environmental sustainability. Yet, a beneficial aspect of landfill is energy recovery through ways such as the collection of methane gas from organic waste breakdown in large landfills (Pickin et al., 2018).

Furthermore, minimum standards for general and restricted solid waste landfills in NSW are outlined in the Solid waste landfill guidelines (NSW EPA, 2016). These standards highlight features such as landfill site design, construction and operation, in order to minimise impact to the environment, human health and amenity. Also described is the aspect of extracting and reusing resources from waste, where possible. Incorporating recycled materials into road and pavements, will contribute to this, increasing waste diversion rates.

- Mechanical processing

Mechanical processing is often used as a means of recycling, where waste materials are processed into a reusable form. In general, it involves processes such as cutting, shredding, screening and magnetic separation of ferrous metals (Havukainen et al., 2017). Specifically for plastic packaging, mechanical processes could also include compression, extrusion, intrusion, injection moulding and regranulation (Arvanitoyannis, 2013).

For example, mechanical treatment is necessary to remove contamination and process the waste glass to a suitable particle quality and size, as depicted in Figure 3.1. Optical sorting technology increases glass separation, and thus the amount of glass that can be recycled into roads and pavements. Mechanical processing is often required to crush glass into cullet form, which is then sieved into streams by particle size for various uses. Milling would also be required to process glass into glass powder, which can be used as a partial cement replacement in concrete (Ling et al., 2013).

In a study assessing the environmental impact of a waste treatment technology system, the production of refuse-derived fuels from mechanical treatment is highlighted. It is described that the use of these fuels with incineration technology, has a lower global warming impact compared to co-incineration (Havukainen et al., 2017).

However, currently, practical challenges of mechanical recycling include the high cost of equipment for collection and separation, as well as the lack of a substantial and reliable market for recycled materials due to limited applications (Arvanitoyannis, 2013). Again, the incorporation of recycled materials into roads and pavements can help to address this issue by increasing utilisation of recycled materials.

Raw material mixing process

There are several typical mixing processes used in the production of concrete or asphalt roads and pavements. Mixing plays in important role in the performance of the final product as it influences properties of the mix such as workability and rheology (Ferraris, 2001).

In general, for asphalt, there are two main processes of mixing – either the dry or wet process. In the dry process, waste materials such as plastic modifiers are added directly to hot aggregate before the binder, which is then mixed altogether. On the other hand, the wet process involves the addition of the waste material to the binder, which is then mixed with the aggregate (Austroads, 2019b). Mixing of stored asphalt is also needed, where it is heated regularly to maintain fluidity (Newman et al., 2012).

For concrete, the method of incorporation can be summarised into three periods – firstly loading, followed by mixing then finally the discharge period (Ferraris, 2001). Within the loading period, dry materials such as cement are firstly introduced. The order of material addition is often important to note. Then, once water is added in the loading period, wet mixing occurs, for a set mixing time so that it prevents overworking the mix whilst ensuring homogeneity.

For the incorporation of recycled materials into asphalt and concrete mixes, there are additional considerations to ensure they are efficiently incorporated. The type of mixing process depends on the application and the form of material replacement. For example, recycled material can be used in concrete as a replacement of either aggregate or cement, which would determine how it is added to the mix. For asphalt bitumen substitution, the amount replaced determines its use in asphalt and thus method of incorporation (Aziz et al., 2015). These are:

- Direct alternative (75-100% bitumen replacement)
- Bitumen extender (10-75% bitumen replacement)
- Bitumen modifier (<10% bitumen replacement).

Bitumen can be modified with additives above 10%, where it is possible for example to modify a virgin binder to a grade higher. Furthermore, mixing conditions such as mixing duration and temperature vary depending on aspects such as the amount and the nature of the recycled material incorporated, as well as the climate and site conditions. Thus, there are often a range of parameters that vary by case. For the use of manufactured products, specifications and instructions of mixing are often provided as a guide. Further details of mixing with reference to standards are provided in Chapter 5: *Evaluation and Monitoring*.

In literature, additional details for the mixing of certain raw materials have been discussed. For example, in a study investigating the incorporation of plastic polymers into asphalt, several factors are described to influence the mixing process, including (Kalantar et al., 2012):

- Nature of the polymer
- Physical form
- Nature and grade of bitumen
- Type of mixing equipment – high shear or low shear
- Time-temperature profile during mixing.

To summarise the findings of this study, these parameters relate to both the waste material (e.g. plastic type, molecular weight, size, chemical composition) and bitumen (e.g. composition, viscosity). For example, polymers with lower molecular weight would require less mixing time. The type of mixing can also differ, where for high shear mixing, polymer particles are reduced in size to improve their dispersion within the bitumen; while low shear mixing is limited to swelling and dissolving the bitumen with polymer at a fixed temperature. High shear mixing can take place at increased temperatures to dissolve the polymer into the bitumen thereby achieving a homogenous mix. The ideal is a mixing process at low temperatures for the shortest time to reduce any thermal effects on the polymer (Kalantar et al., 2012).

Other means of recycled material use in roads

In addition to using recycled materials in full road construction, other ways recycled materials can be used in roads and pavements include in:

Spray seals

- Most common form consists of a single layer of bitumen that is sprayed as a hot liquid, which is covered by a single layer of crushed aggregate (Austroads, 2019a).
- The seal prevents loss of wearing course material through water infiltration or other action.
- Example of recycled material used – Crumb rubber

  - As part of the polymer modified binder
  - Mixes with up to 20% of crumb rubber by mass of bitumen binder can be used in sprayed sealing work (Austroads, 2019b, Aziz et al., 2015)
  - Rubberised sprayed bitumen surfaces are already in heavy use mainly in urban regional and rural scenarios where road surfaces are subject to heavy, screwing loads.

Maintenance/ Management of roads

- Heavy patch or full width rehabilitation
  - involving the mechanical removal of existing material and laying of new mixes (with recycled materials).
- In-situ recycling
  - A strengthening agent (often lime) is added to the surface, where a mixer continuously lifts the existing pavement, pulverizes it, incorporates lime with water and lays the material
  - Large cost savings from not needing to take away the material and import new material.

Primary product

For the development of concrete and asphalt products using recycled materials, factors such as the compatibility of material properties, components and amount of replacement (e.g. aggregate, filler) are considered. Further guidance for specifying recycled materials for road works using AUS-SPEC, is provided in Technote GEN 028 (NATSPEC, 2019b). Recipes used in literature and their reported performance are provided in this section. Details of the tests used to evaluate performance, based on various standards, will be discussed in *Chapter 5: Evaluation and Monitoring*. By understanding the fundamental technology used, the sustainability of roads and pavements can be improved.

Using fly ash in concrete as replacement of cement

Concrete technology incorporating fly ash as replacement of cement has several environmental and economic advantages. From an environmental viewpoint, the consequences of ash disposal, including contamination of aquatic ecosystems can be reduced. Economically, fly ash, which is a waste product of coal-fired power generation, can often be utilised without additional cost, thus reducing construction costs (Woszuk et al., 2019). In terms of application, it diversifies fly ash utilisation, offering a sustainable and advantageous solution to the current generation of fly ash in Australia.

Yet, for effective application of concrete incorporating fly ash, there are several considerations to note, which vary by case. For example, variations in the type and source of fly ash could alter properties such as fly ash reactivity, which affects the hydration and strength development of concrete (1991). Also, greater free lime content in fly ash results in early setting and high compressive strength (Kaewmanee et al., 2013). Generally, there may be possible concerns of the environmental contamination of fly ash. However, when incorporated into concrete, it is described that fly ash chemically reacts with cement and minimises any leaching effect (Ahmaruzzaman, 2010).

Furthermore, several studies have investigated the incorporation of fly ash into concrete, demonstrating enhanced properties in terms of strength and performance. In a study utilising Class F fly ash, microstructural morphology investigation showed improvements in binder matrix density, due to the pozzolanic properties of fly ash (Saha, 2018). In another study, utilising high volumes of Class F fly ash reduced the heat and degree of hydration, bleeding and segregation, but increased workability and setting time (Rashad, 2015).

Another important factor often described by various studies is the effect of fly ash content and in particular, replacing too much of the cement with fly ash. For example, drying shrinkage and concrete porosity decreased with increasing fly ash content (Saha, 2018). Also, mechanical strength and abrasion decreased with greater fly ash content (Rashad, 2015). To address these effects, the use of additives is recommended for their synergistic properties. See the section, *Interaction of Wastes*, for additional details.

Additionally, a growing area of research is into geopolymer concrete utilising fly ash, which enables greater utilisation of fly ash, as a sustainable alternative to Portland cement. Further details of geopolymer utilising fly ash will be covered in Chapter 6: *Case Studies.*

Using fly ash in asphalt as replacement of common filler

Fly ash has been used in asphalt since the 1980's and continuously over the years, although not as the main filler (AAPA). Yet, the viability of using fly ash as an alternative replacement of common filler in asphalt, has been demonstrated by several studies, showing enhanced properties. Due to the pozzolanic properties of fly ash, properties such as strength are often investigated.

The use of fly ash as common filler plays an important role in asphalt, since the interlocking of the aggregate and cohesiveness of the binder, determine properties of stability, stiffness and wearing properties (Tapkın, 2008). In general, mineral fillers are finely divided mineral matter, with examples such as rock dust, Portland cement, hydrated lime, fly ash and waste glass. The mineral filler can potentially affect the hot-mix asphalt by (Tapkın, 2008):

- Stiffening the asphalt
- Extending the asphalt cement
- Altering the moisture resistance and ageing characteristics of the mix
- Affecting the workability and compaction characteristics of the mix.

Furthermore, properties of asphalt with fly ash as a replacement of common filler include having better mixture flow and higher rut resistance compared to a control mixture without fly ash (Mirković et al., 2019). In an investigation by Mistry and Roy on the effect of using fly ash as alternative filler in hot mix asphalt, properties of higher stability values and generally less deformation (higher rut resistance) compared to conventional mixes, were described (Mistry and Roy, 2016). These investigations highlight the use of technology such as scanning electron microscopy to fly ash and bitumen interaction, as well as fatigue tests to determine rheological properties (Tapkın, 2008).

There are, however, some factors which have been described to affect the properties of asphalt with fly ash. One of these, is the type of fly ash such as either Class F or Class C fly ash, which influences the bulk density and air voids of the mineral, due to different compositions and properties such as affinity to bitumen. This was demonstrated in a study by Woszuk, where air voids ranged from 1.2 to 1.6% for Class F fly ash samples, compared to values of 1.3 to 2.8% for Class C samples (Woszuk et al., 2019). In this example, despite this difference, samples of both classes met the required standards. In addition to the type of fly ash, another factor is the amount of fly ash used to replace the common filler in asphalt. For example, using fly ash with extremely high DCV at replacement levels above 2% has negative impacts on the binder properties compromising the rutting resistance. Furthermore, both the type and content of fly ash affect properties such as the water sensitivity of mixtures and resistance to deformation (Mirković et al., 2019). Thus, these factors are key considerations due to the effect on the quality and durability of the asphalt produced.

Overall, the benefits of asphalt utilising fly ash are often described both from an economic and environmental perspective. As fly ash is a waste product generated from coal-fired power plants, it can often be obtained, without the cost of conventional fillers. In addition to fly ash, another recycled component to note is baghouse fines, which are generated and also reused in asphalt.

Also, a recommendation made by a study was the use of fly ash in asphalt as a filler in warmer climates, since the stiffening effect is greater at higher temperatures (Mirković et al., 2019). However, the small extent of this effect may not always guarantee performance in hot climates.

Rubber concrete

Rubber concrete technology has increasingly been demonstrated as an environmentally beneficial solution for rubber waste. Rubber is often used as a substitute of aggregates in concrete pavements. For the method of incorporation, a dry mixing technique is typically used, where the rubber is added to the concrete mixture, as an aggregate would be (Mohammadi et al., 2014).

Rubber concrete technology has several characteristics showing both the advantages of rubber incorporation as well as possible challenges to address. As reported by Mohammadi et al. (2014), some beneficial characteristics which result from the incorporation of rubber into concrete, include:

- High toughness
- Ductility
- Fire resistance
- Resistance against cracking
- Better sound insulation.

Rubber concrete also improves durability for cyclic efforts and noise level generated, giving it acoustic benefits (Pacheco-Torres et al., 2018). However, reported disadvantages of rubber concrete technology include the reduction of concrete strength. Homogeneity issues, affecting load transfer capabilities have also been highlighted. This is due to the weaker bond between rubber particles and cement, compared to typical aggregates (Pacheco-Torres et al., 2018). Furthermore, due to the lower density of rubber, the density of the rubber concrete product is also reduced.

Factors influencing properties of rubber concrete include the size, shape, surface texture of rubber particles. A study by Li, found that concrete samples had greater compressive strength, split tensile strength and modulus of elasticity when rubber fibres were used compared to chips (Li et al., 2004). Another factor affecting the product is the proportion of rubber particles in the concrete (Pacheco-Torres et al., 2018). From this study, the recommendation is to not exceed a rubber composition of 20%, so that mechanical properties would not be reduced.

Concrete with recycled glass

Recycled glass is used in concrete as either a coarse grade replacement of natural aggregate or fine grade cement replacement. Several properties of concrete with recycled glass have been described by literature. These include enhancing the fluidity of fresh concrete and reducing the water absorption and drying shrinkage of concrete due to the impermeable properties of glass (Ling et al., 2013). Durability of the concrete is also improved because of the high resistance of glass to abrasion and acid. The addition of crushed waste glass (CWG) to concrete has also demonstrated overall improvement in compressive strength, flexural strength and modulus of elasticity (Mohajerani et al., 2017).

Despite these improved properties of concrete with recycled glass, an often-highlighted concern for this product, is the Alkali Silica Reaction (ASR). Due to the high silica content of glass, a reaction can occur with the alkaline cement to cause expansion in the cement (Ling et al., 2013). This expansion results in other structural effects such as cracking and reduced compressive strength. However, its effect may depend on the type of mixing, with dry-mixing reported to have a less critical effect than wet-mixed concrete (Ling et al., 2013). Thus, to help mitigate ASR expansion, it is recommended to use a dry mix method, in combination with annealing concrete (Mohajerani et al., 2017).

In addition to the mixing method, other solutions to reduce ASR effects, involve either mechanical or chemical treatment. In terms of mechanical treatment, it has been described by several studies that decreasing particle size of glass or using fibres in concrete can mitigate the ASR (Jamshidi et al., 2016). Chemical treatment has also demonstrated to reduce the ASR expansions in concrete with CWG, through the addition of additives, such as fly ash, silica fume, metakaolin or ground granulated blast furnace slag (GGBS), finely ground powdered glass, steel fibre, polypropylene fibre or lithium compounds (Mohajerani et al., 2017). More specifically, a study by Rashad, 2014, described that the ASR expansions can be reduced by the inclusion of 10–30% metakaolin, 20–50% fly ash, 50–60% slag, 10% steel fibre, 1–2% $Ni2CO3$, 1% $LiNO3$ with a suitable amount of fibres (Rashad, 2014).

There are several factors that have been highlighted by various studies to affect the properties of concrete with recycled glass. These include:

- *Glass color* (e.g. green (emerald), brown (amber), clear)

  For example, a study found that the temperatures generated during the hydration of concrete, were highest for concrete with green cullet, followed by clear, then brown (Poutos et al., 2008).

- *Particle size*

  Decreasing particle size, increases compressive strength and decreases the ASR reaction (Jamshidi et al., 2016). Some reported that to prevent ASR expansion, a particle size of 0.3mm is necessary (Rashad, 2014).

- *Glass content*

  Generally, with increasing glass content, it was found that workability and bleeding increased, whilst density and mechanical strength decreased (Rashad, 2014).

- *Form of glass* – powder, fine aggregate, coarse aggregate

  An investigation found that 30% glass powder could be used as a cement or aggregate replacement in concrete without any damaging effects in the long-term (Shayan and Xu, 2004). Also, for concrete with 32 MPa strength grade requirement, up to 50% of both course and fine aggregates could be replaced. Another study concluded that utilising glass, the optimum replacement of cement is 10% as a powder; and of fine aggregates is 20% (Mohajerani et al., 2017). An alternative form of glass also mentioned is foamed waste glass, which can also be used in concrete as an aggregate and can replace up to 15% of fine aggregates and 40% of coarse aggregates (Mohajerani et al., 2017).

Concrete with recycled plastic waste

Currently, most plastic wastes are sent to landfill or in certain countries are being incinerated, which contributes to toxic pollution (Li et al., 2001). Increasing the use of waste-derived plastics in concrete will reduce these negative environmental consequences. Recycled plastics are generally incorporated into concrete as plastic aggregates or fibres, where plastics maintain their chemical properties due to mechanical recycling of waste plastic. Both flexible and rigid plastic products can be used in footpath construction (Sustainability Victoria, 2018a).

Studies in literature have investigated various properties of concrete incorporating plastics, including how it compares to typical concrete without plastics, or how virgin plastics compare to recycled plastics in terms of performance. The addition of plastic fibres in concrete have been described to improve flexural strength of the concrete, as well as improve ductility (Sharma and Bansal, 2016). Furthermore, macro plastic fibres help to control plastic shrinkage cracking, despite a decrease in the workability of fresh concrete. Macro plastic fibre reinforced concrete shows excellent post-cracking performance and high energy absorption capacity, making it suitable for pavement applications (Yin et al., 2015).

However, it is noted that these properties are dependent on different factors such as the amount of waste-derived plastic. For example, as more waste plastic is added, compressive strength of the concrete product decreases (Sharma and Bansal, 2016). It was reported that concrete containing 10-50% recycled plastic, had compressive strength measures ranging between 48 and 19MPa, which was a 34-67% reduction in strength compared to typical concrete without plastic (Siddique et al., 2008).

Another factor affecting the properties of concrete with recycled plastic waste is the form and type of plastic. For example, in shredded form, the incorporation of waste plastic bags, showed improved abrasion resistance in the concrete, however decreased flow ability and hardened concrete properties (Jain et al., 2018). Also, in another study, polypropylene fibre showed enhanced impact resistance in the concrete (Siddique et al., 2008). Thus, the choice of plastic form and type are important considerations as they influence the morphology and the structural properties of the concrete product.

Also, in order to enhance the strength of concrete, a study by Sharma and Bansal, described the need to add admixtures and reactive materials such as iron slag, silica fume and metakaolin into the mix (Sharma and Bansal, 2016). The amount added will depend on the strength of the concrete required, and details in accordance with product specifications. In a trial utilising recovered plastics and glass fine in concrete footpaths, it was noted that the amount of additives should be limited to 10% of any combination of recovered plastics and/or glass fines (Sustainability Victoria, 2018a).

Asphalt with recycled rubber

Rubber, specifically in the form of scrap tyres, is typically used in asphalt as an additive, either as an aggregate or modifier (Newman et al., 2012). It is usually in used a granulated form, known as crumb rubber modifier (CRM). Crumb rubber modified binders have been produced by industry for many years. For the method of incorporation, rubber is used in hot mix asphalt, using either the wet or dry process. In the wet process, Rubber Modified Bitumen (RMB) is produced, from using a blended and partially reacted CRM, which is then used a binder. The majority of RMB cases since 1960s have shown to enhance road performance (Lo Presti, 2013). The alternative is the dry process, in which CRM is added to the aggregate of the hot mix, where some CRM reacts with the asphalt bitumen and larger particles replace part of the mineral aggregates.

For asphalt rubber binder, three stages of interaction have been described (Jensen and Abdelrahman, 2006):

1. an early stage – happens straight after mixing crumb rubber with bitumen;
2. an intermediate storage stage – the binder is held at elevated temperatures for up to a few hours before mixing with aggregate;
3. an extended (storage) stage – bitumen-rubber blends are stored for extended periods before aggregate mixing.

Issues related to asphalt with recycled rubber include high temperatures causing crumb rubber to melt, whilst cutting tyres to crumb is also quite energy intensive (Newman et al., 2012). Another challenge is the high viscosity of rubberised bitumen (Mohammadi et al., 2014). These issues may limit application, depending on the conditions of the asphalt location. However, it is suggested that using warm mix asphalt additive can reduce the production temperatures and improve the performance of asphalt rubber mixtures (Oliveira et al., 2013, Pereira et al., 2018).

Furthermore, there are enhanced properties of using rubber in asphalt. For example, rubberised bitumen binders were described in a study to demonstrate the following properties (Mashaan and Karim, 2014):

- improved bitumen resistance to rutting due to high viscosity and softening point;
- improved bitumen resistance to surface-initiated cracks and reduction of fatigue cracking;
- reduction of temperature susceptibility and improved durability as well as;
- reduction in road pavement maintenance costs.

There are, however, several factors to note, which have been shown to influence these properties of rubber asphalt. One of these is the size of the rubber particles, which affects the consistency during mixing and the quality of the primary product formed. This was demonstrated by an investigation, showing that adding ultrafine rubber particles into asphalt bituminous binder, is the most effective means of avoiding trunk-crack formation (Kaplan and Chekunaev, 2014).

In addition to rubber size, another study highlighted the importance of crumb rubber content, rubber texture and the chemistry of bitumen binder (Mashaan and Karim, 2014). Furthermore, the digestion process of asphalt (bitumen) and rubber is influenced by factors such as rubber content, rubber gradations, blending conditions (temperature and time), binder viscosity, binder source (Shen et al., 2009). Thus, whilst this product has been used for many years, it is important these factors are also considered, as conditions vary depending on the site.

Asphalt with recycled glass

Recycled glass in asphalt technology has been increasingly used in road applications. It has been used in wearing course applications and as an aggregate for road base and binder course (Newman et al., 2012). Asphalt with recycled glass has increased utilisation of mixed colour crushed glass, which has lower value than single colour (NSW EPA, 2012).

The properties of recycled glass asphalt can be categorised under its structural performance or durability (Jamshidi et al., 2016). In terms of its structural performance, it is noted that the bitumen should be less susceptible to temperature rutting, in order to perform well (Kumar and Garg, 2011). Additionally, another structural property is fatigue. Studies on asphalt with recycled glass have shown that at relatively low and intermediate temperatures, the asphalt displays equal or greater fatigue performance.

Furthermore, regarding the durability of the asphalt, the properties of ageing and moisture sensitivity showed promising performance. Another aspect of durability is the permeability, where bleeding can occur due to the hydrophobic glass having a lower binder absorption compared with natural aggregate (Jamshidi et al., 2016). Thus, whilst these properties generally enhance the performance of the asphalt, it is important that they are monitored on a case by case basis.

There are some concerns related to the use of recycled glass in asphalt including the stripping and potential leaching into the environment. Glass used in wearing course asphalt presents the risk of reduced adhesion and potential unravelling. By adding anti-stripping agent or hydrated lime, the stripping of asphalt mixtures containing Crushed Waste Glass (CWG) can be mitigated (Mohajerani et al., 2017). Some liquid adhesion agents may be required to reduce the loss of glass through ravelling. This will also improve the water stability of the glass asphalt. Furthermore, it is described that leaching of contaminants from CWG in road applications have generally been negligible (Mohajerani et al., 2017).

Particle size is an important factor to consider in glass asphalt technology. The size of the glass particles will determine the form and amount of glass that can be replaced. It has been described that long and flat particles contribute to stripping, due to the larger surface area that can erode with water. Thus, as a solution, it is advised to crush glass to a size less than 4.75mm, in order to have similar characteristics to sand (GHD, 2008). In addition to size, it is also noted that properties such as glass colour and contamination in the form of residues also impact on asphalt performance. These often limit the quality and extent of incorporation of glass into roads. The amount of recycled glass used in the asphalt is also important to consider in the design, as the recommended limit may be exceeded when it is recycled and processed again in the future. Other recommendations made by studies on asphalt with recycled glass, have been summarised in Table 3.3.

Using waste plastic in road construction

In Australia, both unmodified bitumen and Polymer Modified Bitumen (PMB) are used as the binder in asphalt mixtures for road construction. PMB involves the addition of polymers, and other additives in order to improve properties such as resistance to high temperature deformation (White and Reid, 2018). Thus, the incorporation of polymers such as plastic have been increasingly used in road construction applications. Australia retains a system of PMB grades based on properties of production which indicate the type and percentage of polymer (White, 2017).

Plastics are classified into seven different types, which are identified by code. Each category has different properties which make it suitable for different applications. For details of these and their applications, refer to Figure 2.1 and Table 2.1 of the report by Austroads (Austroads, 2019b). The use of waste-derived plastic in road construction has also gained industry attention. An example product in road construction is Plastiphalt, which incorporates recycled materials such as soft plastics and glass. Companies such Downer, Close the Loop and RED Group have collaborated together in numerous road trials in Australia. Various asphalt processing plants have been developed by Downer, such as at Rosehill, NSW. More details of these asphalt trials are provided in Chapter 6: Case Studies.

Properties

The use of plastic polymers in asphalt have showed improved engineering properties of thermal cracking, stripping, rutting resistance, temperature susceptibility, fatigue damage and stability to withstand traffic demand (Kalantar et al., 2012). Also, testing of bitumen rheology using dynamic shear rheometers, indicated that small amounts of polymer modifier will improve these properties (Kumar and Garg, 2011). Additional properties that result from the addition of recycled plastic to asphalt, are the reduction in air voids, decrease of bitumen bleeding and improved workability, with improvement in Marshall properties (Tiwari and Rao, 2017). It is noted that the enhancement of certain properties, may be at the expense of other properties.

Possible Concerns

Despite the increasing use of PMB, one concern may be whether recycled plastics are comparable in performance to virgin polymers used in PMB. It is described that properties of a conventional binder can be enhanced by the addition of recycled plastic, but may not match a PMB. Yet, there have been studies describing recycled polymers to show similar outcomes in enhancing road performance as compared to virgin polymers (Kalantar et al., 2012). Thus, continued research is required to optimise recycled plastic use and ensure consistency. Several trials have also used recycled plastic waste in asphalt including a trial which incorporated plastic crate waste as a warm mix asphalt wax additive in Vancouver (White and Reid, 2018, Ridden, 2012). Another concern related to plastic use is leachability. However, Tiwari and Rao, in their study, revealed that waste plastic is safe and sustainable for road construction, due to its chemical binding properties (Tiwari and Rao, 2017).

Factors influencing properties of plastic asphalt

- Method of incorporation

Waste plastic is used in road construction as a bitumen modifier and often in the top layer coat of flexible pavement (Gawande et al., 2012). In a report by *Austroads*, it is described that waste plastic can be used as partial aggregate replacement in bituminous mixes, and as binder extender without significant effect on the asphalt mix properties (Austroads, 2019b). Plastic polymers are incorporated using either the dry process, where polymers are added directly to the mixing chamber during the blending of the aggregate and binder; or the wet process, where polymers are added to the binder, prior to mixing with the aggregate (Austroads, 2019b). There are advantages and disadvantages of both methods.

For example, the wet process can be used for many types, sizes and shapes of waste material like plastic, but also has the disadvantage that greater mechanical energy and cooling is required (Gawande et al., 2012). In wet mixing, the polymer is added to the binder so that it is either digested and dispersed throughout the binder, or swells and is dispersed, with agitation useful during storage. On the other hand, the dry process has advantages such as doubling the binding and surface property of aggregates; and making it possible to use more than 15% of waste plastic compared to 8% from the wet process. Thus, the method of incorporation continues to be evaluated by recent studies (Gawande et al., 2012, Kalantar et al., 2012, White and Reid, 2018).

- Type of plastic polymer

There are many types of plastic, which can be incorporated into road asphalt mixtures, such as LDPE. The type determines features such as the time and temperature of mixing. It is noted however, that not all recycled plastics are suitable for incorporation into asphalt bitumen, including PVC which can produce dangerous chloride emissions at high temperatures (Austroads, 2019b). Some plastics may melt but aren't compatible in the bitumen and will separate on storage (AAPA). Also, PET plastics are not extensively considered, since bottles are already reused as part of existing recycling technologies, like the NSW Container Deposit Scheme (CDS). Details of several different plastic types are described in a review by (Kalantar et al., 2012). These are summarised in Table 3.1.

Table 3.1 Details of polymers used to modify bitumen (Kalantar et al., 2012)

Polymer	Advantages	Disadvantages	Uses
Polyethylene (PE)	- High temperature resistance - Aging resistance - High modulus - Low cost	- Hard to disperse in bitumen - High polymer content required to achieve better properties	- Industrial Uses - Few road applications

Polymer	Advantages	Disadvantages	Uses
Polypropylene (PP)	- Widens plasticity range and improves binder's load resistance	- Separation problems	- Isotactic PP is not commercially applied
Polyvinyl Chloride (PVC)	- Lower cracking PVC disposal	- Acts mostly as a filler - Dangerous chloride emissions at high temperatures (Austroads, 2019b)	- Not commercially applied
Styrene – butadiene block copolymer (SBS)	- Higher flexibility at low temperatures - Strength and very good elasticity - Increase in rutting resistance	- High cost - Higher viscosity at layout temperatures	- Paving and roofing - Road applications (AAPA)
Styrene – isoprene block copolymer (SIS)	- Higher aging resistance - Better asphalt-aggregate adhesivity		

Reported Values

Several recommendations have been made by trials investigating the effect of plastic waste addition. In a study by Tiwari and Rao, it is demonstrated that the stability value of the bituminous mix can be improved through the addition of 8% of the LDPE and HDPE plastic waste. As a result, toughness increases, improving the service life of roads and the ability to withstand heavy traffic (Tiwari and Rao, 2017). However, it is noted that factors such as fatigue characteristics and microplastic generation were not reported in the study. In another study, recycled waste plastic in shredded and pellet form, replaced 6% of the binder volume, using a dry mixing process (White and Reid, 2018).

Alternative materials as binder in asphalt

According to an unpublished literature review on Alternatives to Bitumen As a Binder in Asphalt by Waste Transformation Research Hub of The University of Sydney, bitumen is consumed in a large scale considering the large road infrastructure of most countries. For instance, approximately 44,000 kg of bitumen are used in the construction of 1 km of road (Vila-Cortavitarte et al., 2018). Hence, there has been great interest in the search for alternative binders for road pavements in recent years. Using a performance-based design concept, research groups have studied many different materials while searching for a sustainable binder, including recycled tyre rubber, recycled polystyrene, waste motor oil, swine manure, various sources of lignin, waste cooking oil, polyurethane, polyethylene, phenolic resins, soy fatty acids and others. Among these alternative materials to bitumen, the recycled tyre rubber is the only material commonly employed in asphalt mixtures (Lo Presti, 2013). Studies to use rubber in bitumen started as early as the 1950s in Australia. Considering the technology of using rubber in bitumen is well-developed, it is suggested that local council engineers use recycled tyre rubber in asphalt as their first trial.

Other recycled materials

This section covers the technology of roads and pavements incorporating several other recycled materials. Key details are summarised here from various sources for reclaimed asphalt (White and Reid, 2018, Austroads, 2015b, Austroads, 2009); waste toner (Austroads, 2019b, Sharp et al., 2017); and Incinerator Bottom Ash (Ahmed and Khalid, 2011, Santarem et al., 2019, Li et al., 2012).

Reclaimed asphalt

- Most common form of incorporation is into Reclaimed Asphalt Pavement (RAP)
- Use of RAP regarded as standard practice by many road agencies
- At production plants, reclaimed asphalt is often stockpiled, crushed, tested and recycled back into new asphalt.
- Sometimes incorporated in combination with other recycled materials such as crushed glass, waste printer toner, incinerator waste, etc., with the impact of such additives assessed and managed during the mix design process.

Amount and quality of RAP processing (Austroads, 2009)

- 15 – 20% RAP addition has minimal impact on asphalt mix characteristics
- For use of 20% to 40% RAP, a bitumen grade that is one grade softer may be used, to adjust for the stiffness of the aged binder in the RAP. However, this depends on the RAP being used.
- For greater proportions (>30%) of RAP, it is recommended to crush, screen and separate by size for uniformity. This again depends on the RAP.
- Due to limitations of factors such as heat capacity and hydrocarbon emissions, about 40% to 50% RAP is generally considered the practical limit for RAP content in hot mix asphalt. This depends on the type of asphalt plant, as High Recycling Technology (HRT) plants can manage 80% RAP for example.

Waste Toner

- Application: asphalt
- Components used: waste toner and toner residue
- Showed improved field performance compared to conventional control mix (11% modulus decrease, 30% fatigue life increase, 50% cracking reduction) (Sharp et al., 2017).

Other Considerations

- Amount of toner-modified binder used
    - Increased amounts of toner led to stiffening of binder and greater susceptibly to low-temperature cracking.
- Poor storage ability
    - Toner is an additive added to the dry process and not via the wet process, for this reason
    - To ensure a homogenous mix, agitation is required before mixing with aggregate as well as a minimum of 60-90 minutes of blending beforehand.

LOCAL GOVERNMENT NSW

Example - TonerPave product developed by Close the Loop and Downer

- Main ingredient: toner powder (including plastics like styrene acrylate, styrene butadiene and polyester, with small amounts of minerals, pigments, wax, iron oxide and silica)
- Low melting temperature property reduces energy needed to heat mix; can be readily incorporated with binder in asphalt plants
- Based on carbon modelling, the product was described to lower emissions by about 23% compared to typical products used by Vic Roads.

Coal-fired Bottom Ash NSW

- Known as Incinerator Bottom Ash (IBA)
- According to the National Waste Report 2018, Bottom ash is defined as the ash produced by burning coal or other materials that remains in the furnace or incinerator.
- A material stream from the emerging waste to energy sector
- Generated from burning Municipal Solid Waste (MSW), where IBA makes up about 80% of the ash produced.
- Application: in blended cement (concrete) and bituminous mixes (asphalt)
- Form of replacement: as base material of road pavement or aggregate fill material.

Some outcomes described by several studies include (Ahmed and Khalid, 2011):

- Bottom ash having similar Unconfined Compressive Strength to compacted fine-grain soils
- IBA blends showing suitable performance, with 30 and 50% IBA blends having greater resilient modulus values compared to limestone control blends
- Enzyme treatment helping to improve chemical bonding, increasing resistance to weathering.

Factors affecting bottom ash incorporation (Santarem et al., 2019)

- Grain size distribution
- Incombustible coal content
- Mineralogy of deposit
- Possibility of the presence of heavy metals.

Interaction between wastes

The technology associated with the interaction between wastes is an important consideration in order to maximise recycled material utilisation, whilst ensuring strength and performance are not compromised. Recently, there has been numerous studies on the interaction of different wastes when used as supplementary cementitious materials. For example, the blending of steel slag and fly ash together with $CaCO_3$, has shown a synergistic improvement in the properties of the formed cementitious material (Qi et al., 2016, De Weerdt et al., 2011). Various blends of slag, fly ash and hydrated lime are also commonly used in the stabilisation field. De Weerdt et al. (2011) observed a significant increase in the mechanical strength of cement mortars produced by mixing 5% limestone powder ($CaCO_3$) and 30% fly ash with Portland cement. It is reported that $CaCO_3$ can react with tricalcium aluminate (C_3A) of the Portland cement to form a more stable single-carbon hydrated calcium aluminate ($Ca_4Al_2O_6 \cdot CO_3 \cdot 11H_2O$). Whereas, in an ordinary Portland cement without limestone powder, the C_3A will react with the calcium sulphate to form ettringite ($C_3A{\cdot}3CaSO_4{\cdot}32H_2O$). Upon depletion of the sulphates, the remaining C_3A will react with the ettringite to form less stable monosulphate ($C_3A{\cdot}CaSO_4{\cdot}12H_2O$) (Lothenbach et al., 2008). The use of fly ash amplifies the mentioned effect of $CaCO_3$ in formation of monocarbonate due to the additional alumina present in fly ash resulting in an increase in the compressive strength. Jo et al. (2015) exploited this idea to produce a synthetic cementitious material using $CaCO_3$ infused with silica fume and hydrated alumina in a hydrothermal method instead of the high-temperature clinkering process.

However, to understand the true interactions between various components in these new complex mixtures and make informed design decisions about the type and mixing ratio of recycled materials remains a challenge. There is ongoing research by Waste Transformation Research Hub at University of Sydney that fundamentally studies the relationship between the atomic-scale interactions and the long-term performance and stability of cementitious materials formed from different wastes, such as fly ash, recycled crushed glass, rice husk, sludge and CO_2 sequestered and locked as waste carbonates.

Regional/ Rural Road Applications

Unlike metro roads in urban areas which are constructed from asphalt and concrete, the majority of regional and rural roads are constructed with flexible pavements and either sealed with a sprayed bitumen or left unsealed. In Australia, sprayed seal is the predominant surfacing type in rural areas. Sprayed seals account for around 70% of the total length of all surfaced roads. In urban areas, asphalt and concrete surfaces predominate due to their structural strength, durability, improved resistance to surface stresses and lower maintenance (Austroads, 2019a).

This is important to note, by total carrying value, regional/rural roads make up a significantly greater length of the roads in NSW, compared to metro roads. Hence, there is a great opportunity to extend the use of recycled materials in regional and rural road applications. Most of the material utilised in regional/rural road application is natural gravel and engineering crushed gravel for the base and wearing course of the road, with the bitumen seal applied by spray. Thus, in these circumstances, recycled materials such as rubber and masonry materials can be used. Rubberised sprayed bitumen surfaces are already in heavy use mainly in urban regional and rural scenarios, where road surfaces are subject to heavy, screwing loads. By utilising recycled materials in ways unique to the material composition and structure of regional/rural roads, there is a large opportunity to promote the use of such bitumen and the ability to use recycled rubber as the main component.

From a circular economy context, a key aspect of recycled material use in regional/rural council roads is the distance between material source and the location of road construction. Currently, regional and rural engineers can obtain engineered material within 30-50kms in most cases and sprayed bitumen and asphalt in only a selected number of locations across regional NSW. Thus, these circumstances impact the cost and sustainability of the approach, due to factors such as transport, carbon emissions, labour and time.

Another aspect that may be a barrier to uptake of recycled materials is its cost in comparison to conventional material. This also contributes to the question of viability, where in the NATSPEC survey report (NATSPEC, 2019c), small rural councils described how they “do not have volumes of recyclables to justify the cost of preparation of road making material". Thus, there are several areas still to address to increase use of recycled material technology in regional/rural roads. For example, greater distribution of recycled material sites, such as waste transfer stations may improve this, as well as utilising forms of road management such as in-situ recycling which avoids the need to transport existing materials away and new materials in.

Table 3.2 lists the relevant specifications (Industry Guides) that can be applied to the construction of regional/rural roads.

Table 3.2 Specifications (Industry Guides) relevant to regional/rural road applications

Publisher	Specification/Industry Guide
NATSPEC	0053 – Rural pavement design – sealed
	0054 – Rural pavement design – unsealed
Austroad	AGPT04K-18 Guide to Pavement Technology Part 4K: Selection and Design of Sprayed Seals
	AGPT06-09 Guide to Pavement Technology Part 6: Unsealed Pavements

Recommendations of Recycled Material Compositions made by various trials and studies

Table 3.4. It is noted that this list is not exhaustive and should be considered on a case by case basis.

The document, *AUS-SPEC Case studies and Technical information*, provides further information and detailed examples demonstrating use of AUS-SPEC documents (NATSPEC and IPWEA, 2019). Also, *TECHnote GEN028* published by NATSPEC lists relevant references that can be used by local councils. The objective of *GEN028* is to assist local road authorities in implementing the use of recycled materials by including it in their policies, construction specifications and approval processes. The AUS-SPEC Design Worksection includes the use of recycled materials as a "template" to encourage designers to recommend these materials at the design stage. Councils with access to NATSPEC specifications can use the suggested references for their projects.

Table 3.3 Recommendations from various trials and studies for single material replacements

Primary product		Replacement Form	Replacement (%)	Performance parameter	Reference
Recycled material	Application type				
Fly ash	Concrete	Mineral addition in Portland cement	Less than 5%		(ADAA, 2009)
Fly ash	Asphalt	Filler	Less than 2%	Depends on fly ash type and	(AAPA)

Primary product		Replacement Form	Replacement (%)	Performance parameter	Reference
Recycled material	**Application type**				
				factors e.g. DCV	
Rubber	Concrete	Rubber content	No greater than 20%	Mechanical properties	(Pacheco-Torres et al., 2018)
Glass	Concrete	Crushed glass • Fine aggregate	20%		(Mohajerani et al., 2017)
			15% of fines in concrete mix; Road base: 10%		(2019b)
		Glass powder • Cement	10%	Compressive strength (literature review)	(Mohajerani et al., 2017)
			30%		(Shayan and Xu, 2004)
		Foamed waste glass • Fine aggregates • Coarse aggregates	15% 40%		(Mohajerani et al., 2017)
Rubber	Asphalt	Crumb rubber • bitumen binder	20%		(Austroads, 2019b)
Glass	Asphalt	Glass (2.36mm max size)	10%	Optimum based on properties tests	(Abu Salem et al., 2017)
		Recycled Crushed Glass	2.5% Wearing Course, 10% base and subbase layers in asphalt		(2019b)
		Crushed waste glass • aggregate	15% max	Durability and performance	(Mohajerani et al., 2017)
		Crushed waste glass (<4.75mm size)	30%		(Mohajerani et al., 2017)

Primary product		Replacement Form	Replacement (%)	Performance parameter	Reference
Recycled material	**Application type**				
		• rock in subbase			
Plastic	Asphalt	LDPE and HDPE • bitumen	8%	Stability, toughness, but fatigue and microplastics were not tested	(Tiwari and Rao, 2017)
		Plastic (shredded, pellet form) • binder volume	6%	Dry mixing process	(White and Reid, 2018)
Reclaimed Asphalt Pavement		Wearing course	Max 20% RAP		(2019b)
		Base and subbase layers	Max 40% RAP (Typically 5 to 30% used)		(2019b)

Table 3.4 Recommendations made by various trials and studies for incorporating a combination of recycled materials

Recycled material					Application	Overall performance* (+/n/-)	Reference
Fly Ash	**Glass**	**Rubber**	**Plastic**	**Other**			
	✓		✓		concrete footpath	n (meets compressive strength requirements)	(Sustainability Victoria, 2018a)
	✓ (20%)			✓ (Recycled concrete aggregate or waste rock)	pavement	N (met sub-base criteria)	(Arulrajah et al., 2014)
✓	✓			✓ (carbon dioxide)	concrete pavement	+ (exceeded standard strength requirement)	Usyd-Delta project (see Chapter 6: Case Studies)

* reported performance result based on noted criteria (+ = positive/ n = no difference/ - = negative)

4. Occupational Health, Safety and Environment Risk Assessment

There are concerns raised by various stakeholder regarding the occupational health, safety and environment (OHSE) issues relating to the use of recycled wastes in roads/pavements. This section aims to address these concerns including health issues due to exposure to dust when handling recycled crushed glass (RCG), abrasive characteristics of crushed glass, toxicity of raw materials, leaching of heavy metals from fly ash (FA) and recycled concrete aggregates (RCA), and issues related to microplastics when using recycled plastics in road construction.

Occupational health and safety impacts

Recycled crushed glass (RCG)

In the research conducted by AusTox and commissioned by Packaging Stewardship Forum (PSF) of the Australian Food and Grocery Council (AFGC) (Winder, 2011), abrasiveness and respiratory hazards were highlighted as the main OHSE issues related to the use of recovered crushed glass (RCG) in civil construction applications. It is believed that the crystalline silica present in the dusts generated by RCG has carcinogenic potential imposing safety hazards for workers. The abrasive nature of crushed glass is also perceived to cause skin or even eye injuries during the handling.

In a safety analysis study conducted by Shin and Sonntag (1994), the concentration of crystalline silica in the glass dust was found to be less than one percent categorising it as just a nuisance according to US Occupational Safety and Health Administration (1910.1000). They also reported that the dust concentration of air samples taken during compaction test of crushed glass was less than 0.5 mg/m^3 which was well below the permissible exposure limit of 10.0 mg/m^3. The silica present in glass is mainly amorphous with no carcinogenic properties as opposed to its crystalline form typically present in silica sand. It was concluded that RCG is in fact much safer that sand as it contains less respirable crystalline silica (Winder, 2011). Similar statements were also made in the trial conducted by Sydney Water using recycled glass as pipe embedment material (Department of Environment and Climate Change NSW, 2007). According to this report which was published by Department of Environment and Climate Change NSW, the subcontractors at the Greystaynes site reported less dust generated from glass cullet compared with other materials onsite. Hosing down the

RCG stockpiles and supplying the crushed glass moist were recommended as effective strategies in suppressing the dust to minimise the occupational health and safety issues.

With regards to abrasiveness, it was reported that crushed glass particles below 19 mm impose no greater skin cut hazards than other typical construction aggregates and undoubtedly less hazards compared to larger glass fragments from crushed glass bottles, drinking glasses and plate glass. Glass particles less than 6 mm can be considered as completely benign. However, taking protective measures commonly used for other natural crushed aggregates as well as those specified in the Material Safety Data Sheets (MSDS) of crushed glass is highly recommended (Department of Environment and Climate Change NSW, 2007, Shin and Sonntag, 1994, Winder, 2011).

Shin and Sonntag (1994) analysed the environmental impact of using RCG as concrete aggregate by evaluating the organic and inorganic chemicals present in RCG, the long-term leachability of contaminants and in particular leachable lead. Their study revealed low concentration of lead in the leachate and limited organic compounds mainly plastic debris at levels below the harmful thresholds and similar to the levels commonly found in natural soils.

Fly ash (FA) and recycled concrete aggregates (RCA)

Toxicity risks arising from the potential leaching of the heavy metals such as Cd, Pb, As, and Hg present in fly ash (FA) and recycled concrete aggregates (RCA) are the main concerns associated with the use of these materials in construction applications. It should be noted that however, toxicity concerns are not limited only to recycled materials as it also extends to the traditional raw materials such as Ordinary Portland cement (OPC) and natural aggregates (NA). In a literature review by Kurda et al. (2018), the toxicity and environmental risks of concretes made from conventional (OPC and NA) and non-conventional (FA and RCA) construction materials were compared. Ecotoxicology which involves leaching tests, chemical characterisation, and toxicity tests on living organisms was referred as the main risk assessment methodology.

In general, toxicity characteristic leaching procedure (TCLP) studies on cement mortars from NA and RCA from construction and demolition waste (C&D) revealed that these samples do not release detectable concentrations of heavy metals when properly cured (Barbudo et al., 2012, Hillier et al., 1999, Kurda et al., 2018). However, Hillier et al. (1999) observed detectable concentrations of Vanadium (V) released from poorly cured concrete samples.

In case of FA, the TCLP results showed high concentrations of heavy metals releasing from raw FA. However, locking the FA in a well-cured concrete proved to be effective in significantly decreasing the heavy metal's concentration in the leachates below the threshold levels defined by Environmental Protection Agency (EPA) drinking water standard. This has been attributed to the ability of hydrated cement in encapsulating and stabilizing the heavy metals within the cement matrix (Shirazi and Marandi, 2012, Siong and Cheong, 2003, Kurda et al., 2018).

Recycled plastics

In a technical report published by Austroads (Austroads, 2019b), the chemical additives used during the plastic manufacturing were suggested as the main cause of OHSE concerns related to the use of recycled plastics in in road construction. Royer et al. (2018) reported the release of toxic emissions such as carbon monoxide, formaldehyde, and toluene from heating the plastics during the melting process. However, a recent study by White (2019) revealed no difference in the fumes generated from normal bitumen and those from recycled plastics creating a need for more conclusive research in this area. Austroads (AUSTROADS 2019b) (Chin and Damen, October 2019) concluded that the fuming issue is not specific to recycled plastics as it also applies to other additives such as crumb rubber and further research is needed to ensure worker safety.

Recycled plastics can break down to microparticles known as microplastics with significant environment impacts especially on marine ecosystem (Royer et al., 2018, Eriksen et al., 2018). However, similar to the positive results of emission study, White (2019) found no hazardous chemicals leaching out from bituminous binders with and without recycled plastics suggesting no environmental and occupational risks associated with the use of recycled plastics in road construction.

In a recent soft-plastic asphalt road trial commissioned by Downer, Close The Loop and RED Group with partnership with Hume City Council in Melbourne, recycled plastic bags and packaging and printer toner were used as waste plastic source. The Fact Sheet published by Sustainability Victoria (July 2018) ruled out the possibility of any environmental risk associated with the release of microplastics. It was stated that melting the soft plastics and mixing it with the bituminous binder would prevent the plastics to leach out as microplastics. The Sutherland Shire used the same approach in their Plastiphalt and stated that melting the plastics into the bitumen may stop microplastics release to the environment but risks cannot be dismissed completely. Austroads (AUSTROADS 2019b) (Chin and Damen, October 2019) concluded that using plastics in roads in Australia and New Zealand is a relatively new development with limited field testing so until extensive research and long-term environmental impact assessments have been conducted, such projects should be approached with precautionary measures.

Life Cycle Environmental impacts

There has been numerous studies using life cycle assessment (LCA) methodology to investigate the eco-profile of roads constructed with recycled materials (Farina et al., 2017, Chiu et al., 2008, Kurda et al., 2018, Praticò et al., 2020). Recently, Praticò et al. (2020) used a 'cradle-to-grave' LCA to evaluate the energy and environmental performance of different bituminous mixtures containing reclaimed asphalt pavements (RAP), crumb rubber, and waste plastics. They also included the impact of two different technologies such as hot mix asphalt and warm mix asphalt in their LCA study. Different scenarios of pavement production, transportation, construction, maintenance and end-of-life of road pavements were analysed and compared to a reference case using common paving materials. They concluded that material production stage contributes the most to the overall impacts. In addition, lower energy and environmental impacts were observed when using warm mix asphalts and recycled materials in bituminous mixtures with the smallest impacts found for the scenario using 45% RAP.

The LCA results for the scenario in which the friction course was made using neat bitumen, 10% waste plastics (WP) and 10% crumb rubber (CR) showed a significant decrease in all the LCA indicators compared to those of base scenario. For example, the HT-ce (Human toxicity, cancer effects [CTUh]) and Ftox (Freshwater ecotoxicity [kg Sb_{eq}]) index for the recycled scenario were 1.66×10^{-6} and 2.95×10^{2} per Functional Unit (FU, 1 m^2 of road pavement) compared to 5.89×10^{-6} and 4.21×10^{2} for the common asphalt, respectively.

Farina et al. (2017) applied the same LCA methodology for asphalt roads mixed with CR and RAP using two mixing methods, i.e. "dry" and "wet" processes. The LCA indicators in terms of gross energy requirement (GER, MJ/ton) and global warming potential (GWP, $kgCO_2$/ton) showed significant benefits for rubberized bituminous produced by wet technology in comparison with the base scenario using common paving materials. They also found that using only RAP did not have a significant impact in improving the LCA indicators. It should be noted that in wet process, crumb rubber is used as an asphalt binder modifier, whereas in dry process, granulated CR acts merely as the fine aggregate.

Kurda et al. (2018) reviewed the LCA studies reported in the literature to evaluate the environmental impact (EI) and toxicity of partially replacing cement with RCA, FA in comparison with NA in concrete. The EI indicators used in this study were Abiotic depletion potential (ADP), global warming potential (GWP), ozone depletion potential (ODP), and acidification potential (AP) to name a few. They concluded that incorporation of recycled aggregates reduces the EI and cost of concrete with the highest CO_2 emissions reduction found for FA compared to RCA. It also reduces the landfill space and need for quarrying the virgin materials. In terms of toxicity, leaching of heavy metals from FA decrease when incorporated in concrete.

In light of the aforementioned benefit of adding FA in concrete in reducing the CO_2 emission, Ebrahimi et al. (2017) took a step further and used carbonated fly ash (CFA) as partial replacement of cement. Such an approach was suggested to be an effective strategy in not only reducing the fuel and raw material consumption during cement production but also utilizing the CO_2 sequestered in the form of carbonates during the mineral CO_2 sequestration process. The viability of large-scale implementation of CFA scenario was evaluated by scale-up calculation for a real-scale power plant and Portland cement production in Australia in comparison with the business as usual (BAU) scenario as shown in Figure 4.1.

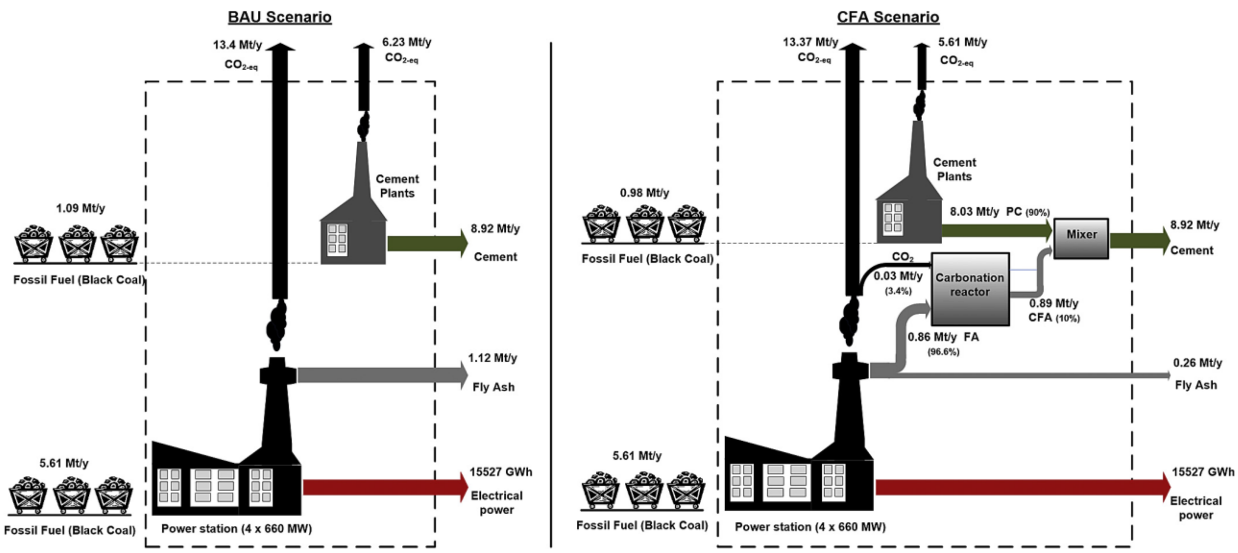


Figure 4.1. A comparison between business as usual (BAU) scenario (left) and 10% partial replacement of cement with CFA scenario (right). (Reprinted from Ebrahimi et al. (2017) with permission from Elsevier)

As can be seen from the figure, the 10% CFA stream (0.89 Mt/y) requires 0.86 Mt of FA (approximately 76.7% of the FA waste) and 0.03 $MtCO_2$-eq per annum resulting in a slight decline in the total emissions from the power station. However, the integration of power plant and cement industry would have a significant impact by saving the Bituminous coal (0.11 Mt/y), reducing the FA waste (0.86 Mt/y, equivalent to 55.4 kgFA/GWh) and reducing the CO_2 emission by 0.65 $MtCO_2$-eq, an equivalent of 72.9 $kgCO_2$-eq/tcement and 41.9 $kgCO_2$-eq/GWh.

Risk assessment and control

AusTox (Winder, 2011) created a risk assessment and control table for the use of RCG in civil construction applications (Figure 4.2). Winder (2011) also created a MSDS for the RCG (Figure 4.3) based on the requirements of the Safe Work Australia *National Code of Practice for Preparation of a Safety Data Sheet*. Such an approach should be used for other recycled materials using information provided by their MSDS during the initial stages of the project.

AusTox CCS Pty Ltd
OHSE Risk Assessment:
Use of Recovered Crushed Glass in Civil Construction Applications

Appendix 1: Risk Assessment and Control Table

Hazard	Effects	Severity of harm	Likelihood of occurrence	Initial risk	Existing controls	Final level of Risk	Risk Decision	Additional Controls
This risk assessment is for using and handling RCG in road base construction. For the purposes of this risk assessment, RCG is crushed, recycled glass to a particle size of 3 mm or less.								
Dust, inhalation	**Short term:** nose and airways irritation, aggravation of asthma	Temporary injury	Possible	Low	Wherever possible, avoid exposure to dust. Work in well ventilated areas. Use wet methods to suppress any airborne dust. Where dust levels are high, wear a P2 respirator.	Low	Acceptable (use OHSE controls)	
	Long term: asthma, bronchitis, respiratory disease	Life threatening	Rare	Medium		Low	Acceptable (use OHSE controls)	
Silica, inhalation	**Short term:** nose and airways irritation, aggravation of asthma	Temporary injury	Possible	Low		Low	Acceptable (use OHSE controls)	
	Long term: asthma, bronchitis, respiratory disease, silicosis, lung cancer	Life threatening	Rare	Medium		Low	Acceptable (use OHSE controls)	No smoking on site
Dust, eye contact	Eye irritation from contact with dust	Temporary injury	Possible	Low	As for "dust, inhalation", **Plus** Wherever possible, avoid eye contact. Where eye contact possible, wear eye protection (at least safety glasses).	Low	Acceptable (use OHSE controls)	Eyewash should be available
	Eye damage from contact from rubbing dust in the eye	Permanent injury	Possible	Medium-High		Medium	Acceptable (use OHSE controls)	

Figure 4.2 Risk assessment and control table for the use of RCG in civil construction applications. See (Winder, 2011) for the complete table.

LOCAL GOVERNMENT NSW

Materials Safety Data Sheet

SDS No:		Issued	?
Product Name:	**Recovered Crushed Glass (RCG)**		
Other names:	Glass Fines, Crushed glass, Glass Granulates, Glass Aggregate		

Hazard Classification: Not classified as being a Hazardous Substance according to the classification criteria of Safe Work Australia.

Section 1: Company and Product Details

Company Details:

Company Name:
Address:
Telephone: Fax:
Emergency contact: Mobile:

Product Details:

Product Name:	RCG
Product Use:	Crushed recycled glass for use in construction of road base or trench backfill.

Section 2: Identification of Hazards

Hazard Classification:

Hazardous Substance:	No classification
Dangerous Goods:	No classification
Poisons Schedule:	No schedule

Health Effects:

Precautionary Note:	While this material does not meet hazard classification criteria, It is still considered that exposure to this dust may be irritating and it is recommended that wherever possible, exposure be avoided, or where this is not possible, recommended respiratory eye and skin protection be used, as indicated in Section 8.
Inhaled:	Inhalation of dusts may cause irritation of the airways of the nose, throat and respiratory system Repeated inhalation may add to the serious health effects caused by smoking tobacco.

Figure 4.3 Material Safety Data Sheet (MSDS) for RCG. See (Winder, 2011) for the complete table.

5. Evaluation and Monitoring

This section covers the provision of reusable waste substances for application to roads as well as strategies to evaluate the quality of the final product. The recycled waste materials are industry by-products which have uncontrollable conditions among different suppliers. It is imperative for an engineer to have satisfaction with the specification appropriate for the regional practicalities. The designer may use the guidelines provided by the Guide and Technical Review to classify the waste material and to make sure that the features of intrinsic substances are fit for purposes. However, these documents are not mandatory for all stakeholders of the local councils.

It is required that substances are provided from stock proved to comply with the specifications before using in construction work. Verified stocks are required to be made available for every single category of substance to avoid separation or blending with other substances and shall be prominently marked.

The applications for reusable waste substances in road building are diversified. This Technical Review is an inexhaustive collection of the codes, standards, industry guides and research papers. Further information on utilising recycled materials can be obtained from material suppliers, IPWEA (NSW) Roads & Transport Directorate, NATSPEC and experienced council engineers.

Mapping regulations

Hierarchy of construction guidelines and regulations

Under Australia legislative framework, the hierarchy of construction guidelines and regulations are divided into five levels, as shown in Figure 5.1. The mandatory documents are listed in the following:

- Act –by Parliament (also known as statutes). For example, the Environmental Planning & Assessment Act 1979 (NSW, 1980) and Roads Act 1993 (NSW, 2019) are mandatory documents among NSW statewide.
- Regulations –by the Governor in Council. For example, the Environmental Planning and Assessment Regulation 2000 (NSW, 2001) is a mandatory regulation in NSW.
- The National Construction Code (Board, 2019) is a mandatory performance-based national-wide used standards. The NCC is referenced in both the Act and the Regulation.
- Australian Standard abbreviated as AS. Only the Australian Standards referenced in an Act or a Regulation or the Code are mandatory in the construction practice.
- Enforceable guidelines –only become mandatory if cited by the Code.
- Other specifications and standards. Although some international standards are not mandatory in Australia, they may be used as the supplementary standards by some organisations. For example, the ASTM D4843 (ASTM, 2009) has been used for wetting and drying test method. A similar case concerns the specifications published by Austroads, which is the peak organisation of Australasian road transport and traffic agencies. Some designers used them as standards. However, in the Austroads AGRD01-15 (Austroads, 2015a), it states “Each member organisation will determine whether any other documents, including its own supplementary guidelines, take precedence over Austroads Guides.”, which means it is not a mandatory document. Most

of RMS design reference documents, e.g. D&C R71 (RMS, 2018b), are either guidelines or supplements to current standards which are voluntary standards.

- Industry guide: the industry guide (NATSPEC, 2019a) is not mandatory among the Australian Legislation Framework. However, it still plays an important role in the construction industry. Take the AUS-SPEC specification (NATSPEC, 2019a) system for example, it provides an essential technical resource for local government infrastructure work. It complies to the legislative requirements, NCC and cites the relevant AS Standards and the Austroads Guides. The industry guide can be very helpful for all stakeholders in the construction industry.

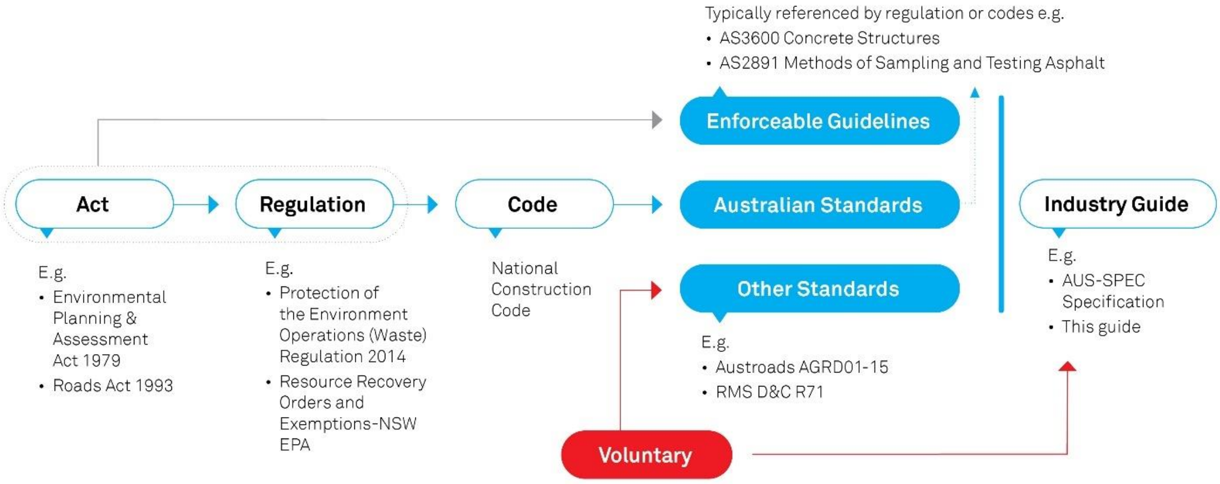


Figure 5.1 Hierarchy of constructional legislation – primary NSW

Circular waste material reuse

Reusing waste in the construction industry can reduce waste sent to landfill, which is the most common form of waste disposal. The successful applications of reusing waste in construction include but are not limited to cement stabilised waste, recycled coarse aggregate, recycled glass aggregate and reclaimed asphalt. The use of waste can save both the virgin material and the landfill. The construction material using waste material has been widely known as the eco-friendly construction material.

A concept map of eco-friendly construction material is shown in Figure 5.2. The loop of reused constructional material minimises the input of virgin material and output of waste material. The loop starts with step A which is the input of waste material including municipal solid waste, commercial and industrial waste and construction and demolition waste. After the raw material quality control (step B) and final product quality control (steps C & D), the eco-friendly material can be used in the construction work. During the duration of using, the consumer or the regulatory authority must continuously evaluate the eco-pavement or eco-building (step E). When the consumer or the regulatory authority finds the eco-pavement or eco-building is no longer suitable for use, the eco-pavement or eco-building will be demolished (step F) and recycled into the next loop.

In order to safely promote the application of using waste in construction, the quality of eco-friendly material should be not inferior to the traditional material. In this chapter, the quality control and long-term monitoring methods of reusing waste material are proposed in Figure 5.2. The waste material reusing has been divided into six stages. To be accepted by the market, most of the test methods are from Australia Standard and industry guideline.

For the local council, steps A, B and F are important because the local council is mainly responsible for the recycling and supply of waste materials to the market; for materials suppliers and builders, B, C and D are the most important stages, especially stage D which control the strength, stiffness and other material properties of the final product; for consumers, stages D and E are more important because they are more concerned about the performance of the material and when the material will lose its functionality.

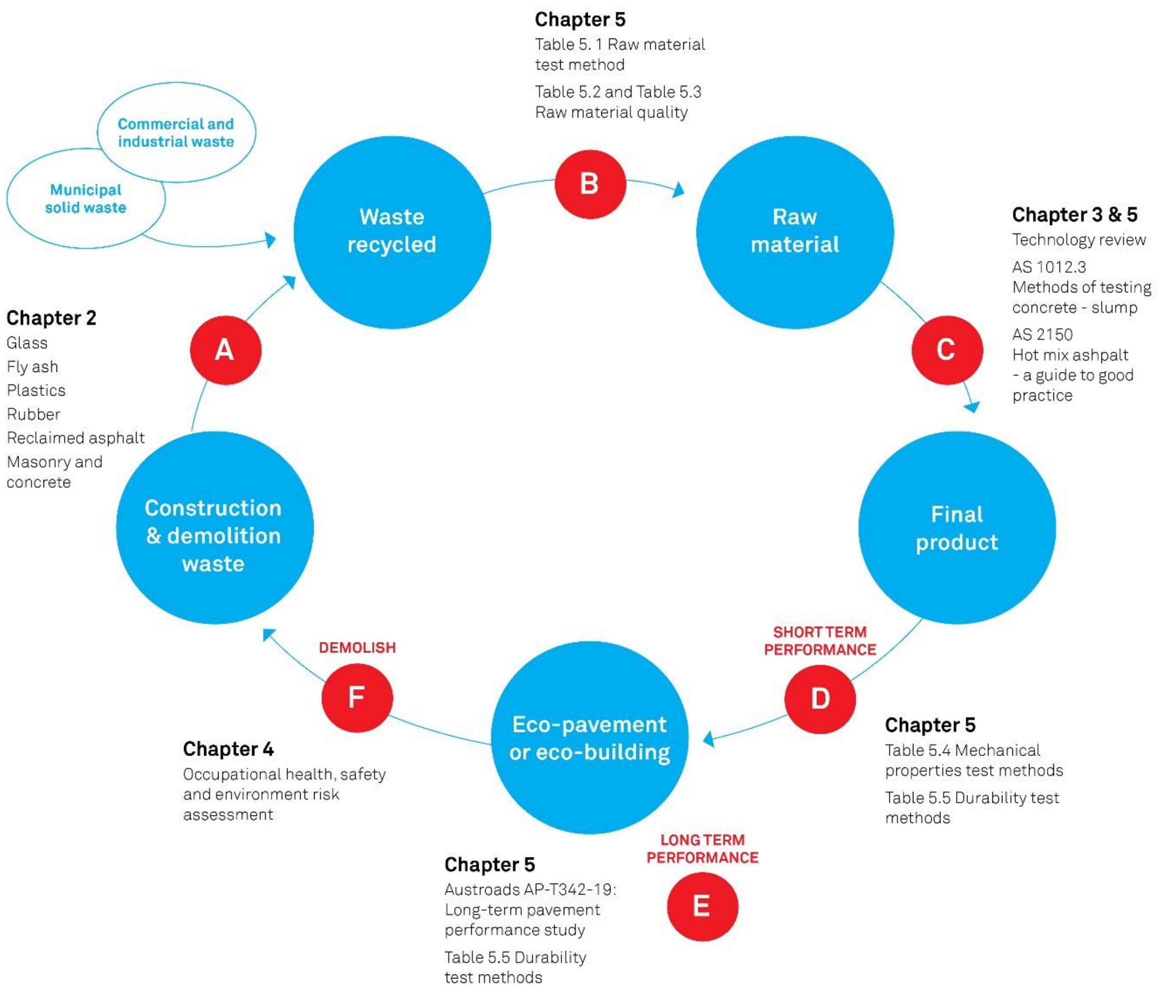


Figure 5.2 Loop of reused construction materials

Supply of raw material

Raw material classes

NSW government has targeted to increase the use of secondary resources since 2003. Increasing the demand for recycled concrete, reclaimed asphalt and recycled rubber will make a significant contribution to achieve this goal. The recycled glass aggregate, reclaimed asphalt, recycled rubber and recycled masonry or concrete can be used as raw material for construction industry. However, Australian standards or building codes focus less on recycled materials than on virgin materials. If the quality of the recycled materials is consistently controlled, most of the recycled materials could be used as the raw material in the construction industry.

The raw material test standards have been listed in Table 5.1. To consistently control the raw material property, each raw material class must conform to the properties outlined in the following table. The hazardous material, i.e. asbestos, was widely used in building before the ban at 2003. Specialised resources are needed if the material recycled from the demolished buildings could have an amount of asbestos. For the glass recycled from bottles, organic or sugar impurities could be found if the glass is not properly washed. Both the grading curve and water absorption of recycled fine aggregates are important, as both can affect the mechanical properties of the concrete.

Table 5.1 Raw material test method

Test method	Standard
Sampling and testing aggregates	AS 1141-1974 Methods for sampling and testing aggregates
Water absorption and apparent particle density	AS 1012.21-1999 (R2014) Methods of testing concrete determination of water absorption and apparent volume of permeable voids in hardened concrete
Particle density of fine aggregate	AS 1141.5-2000 (R2016) Methods for sampling and testing aggregates Particle density and water absorption of fine aggregate
Particle density and water absorption of coarse aggregate	AS 1141.6.2-1996 (R2016) Methods for sampling and testing of aggregates Particle density and water absorption of coarse aggregate - Pycnometer method
Grading of aggregates	AS 1141.11.1-2009 Methods for sampling and testing aggregates Particle size distribution - Sieving method
Organic impurities	AS 1141.34:2018 Methods for sampling and testing aggregates Organic impurities other than sugar
Sugar impurities	AS 1141.35-2007 Methods for sampling and testing aggregates Sugar
Fine particle size distribution	AS 1141.19:2018 Methods for sampling and testing aggregates Fine particle size distribution in road materials by sieving and decantation
Particle distribution of road aggregates by washing	RMS Test method T201 Particle distribution of aggregates (by washing)

The recycled material will be classified into the following material types, as shown in Table 5.2. Class S, B and D are commonly used in construction by government and contractors (Savage, 2010). The road base is divided into the base course and sub-base course, and the specification of the base course is stricter than that of sub-base course. In practice, the supplier normally produces only the material for the base course, and contractor uses this material for the both base course and sub-base course.

Table 5.2 Recycled material classification (Savage, 2010)

Material	Class	Description
Road Base	Class R1	Suitable for use on roads with a traffic loading of greater than 1×10^6 equivalent standard axle (ESA*). as either basecourse or sub-base. This material has similar characteristics to RTA 3051 for dense graded basecourse.
	Class R2	Suitable for use on roads with a traffic loading of less than 1×10^6 ESA as either basecourse or sub-base. This material has similar characteristics to RTA 3051 for dense graded sub-base.
Select Fill	Class S	Material placed directly on the subgrade to improve subgrade performance. Can also be used as engineered fill to raise site levels. Material placed directly on the subgrade to improve subgrade performance. Can also be used as engineered fill to raise site levels, particularly in road embankments or beneath buildings. Engineered fill should have a California bearing ratio ** of at least 5%.
Bedding Material	Class B	Material used as support for paving blocks in pedestrian areas, carparks, shopping malls, footpaths, cycleways or on lightly trafficked accessways. A material with about a 7 mm maximum particle size used as support for paving blocks in pedestrian areas, carparks, shopping malls, footpaths, pipe bedding, cycleways or on lightly trafficked accessways.
Drainage Medium	Class D10 Class D20 Class D75	Material used as support for paving blocks in pedestrian areas, carparks, shopping malls, footpaths, cycleways or on lightly trafficked accessways. A material with about a 7 mm maximum particle size used as support for paving blocks in pedestrian areas, carparks, shopping malls, footpaths, pipe bedding, cycleways or on lightly trafficked accessways.

* The number of standard axle load repetitions of 8.2 tonne which has the same damaging effect on a pavement as the load under consideration.

** The ratio, expressed as a percentage, between a test load and an arbitrarily defined standard load. This test load is required to cause a plunger of standard dimensions to penetrate at a specified rate into a specifically prepared soil specimen.

Raw material quality

Every single category of substance is required to comply with the characteristics set out in Table 5.3 and Table 5.4. A supplier must provide test certificates from an accredited laboratory confirming that the material complies with the specification. Some small amounts of timber, metal, glass, plastic and other organic impurities are permitted. The requirement of the allowable contaminants has been shown in Table 5.3. All the recycled raw material should be free from asbestos which may be friable if disturbed and poses a threat to the health if inhaled. Metal, glass and ceramics are permitted for up to 5% because it has less effect on the strength of the material and the health of people.

Dense Graded Asphalt (DGA): Make sure the proportion of granulated glass aggregate does not exceed 10% of the total mix for mixes used in bases and no more than 2.5% for asphalt used in wearing courses.

Table 5.3 Maximum allowable contaminants of raw material (Savage, 2010)

Maximum Allowable Contaminants (% by mass)	**Material Type**						
	Road Base		**Select Fill**	**Bedding Material**	**Drainage Medium**		
	N>10^{6}ESA	**N<10^{6}ESA**					
	Class R1	**Class R2**	**Class S**	**Class B**	**Class D75**	**Class D20**	**Class D10**
Asbestos	0	0	0	0	0	0	0
Metal, glass and ceramics	3	5	5	5	5	5	5
Plaster, clay lumps and other friable materials	0.2	0.2	1	0.5	0.5	0.5	0.5
Rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter	0.1	0.2	0.2	0.5	0.5	0.5	0.5

When necessary, the provider is required to give prior, formal notice to the buyer about the percentage of reusable concrete, brick/tile, reclaimed asphalt and other related substances as provided.

The particle size distribution of raw material is an essential factor. For recycled glass used as fine aggregate in road base, the maximum nominal size should be no more than 5 mm (NATSPEC 1144 Asphalt specifications) (NATSPEC, 2019a). The standard requirements for how particle size ought to be distributed are indicated in Table 5.4, which presents the range of every single individual sieve size. The particle size distribution curve needs to show smoothness and resistance to sudden fluctuations from one side of the grading envelope to the other to prevent gap grading.

Table 5.4 Particle size distribution of raw material (Savage, 2010)

Particle Size Distribution	Material Type						
	Road Base		Select Fill	Bedding Material	Drainage Medium		
	N>106ESA	N<106ESA					
	Class R1	Class R2	Class S	Class B	Class D75	Class D20	Class D10
% Passing 100 mm			100		100		
% Passing 75 mm			95-100		80-100		
% Passing 53 mm							
% Passing 37.5 mm							
% Passing 26.5 mm	100	100				100	
% Passing 19 mm	95-100	85-100	50-85		5-10	80-100	
% Passing 13.2 mm	70-90	70-90				5-10	100
% Passing 9.5 mm	60-80	60-80	40-80	100			
% Passing 4.75 mm	40-65	40-65		80-100			0-10
% Passing 2.36 mm	35-55	35-55	35-70	50-80			
% Passing 0.425 mm	10-30	10-30		10-35			
% Passing 0.075 mm	5-15	5-15		5-20	0-5	0-5	0-5

The gradation has an effect on the physical stability and permeability of the final product. During the design of pavement, stable mix with resistance to water is fundamental to achieve the desired properties of the material. The particle size distribution result needs to be reported for every stockpile of the raw material. Any contaminants or big size recycled material that can cause gap grading should be eliminated.

Resource Recovery Framework – Orders and Exemptions

The recycled materials incorporated into roads and pavements need to strictly comply with the relevant legislations governing material reuse. The key legislative documents for the regulation of waste in NSW are the Protection of the Environment Operations Act 1997 (POEO Act) and the Protection of the Environment Operations (Waste) Regulation 2014 (Waste Regulation) (NSW EPA, 2017a).

This section provides a general overview of the aspects of these documents relevant to reuse of recycled materials from various sources (NSW EPA, 2017a, Savage, 2010). It is the responsibility of the user of the Guide and Technical Review, to always refer to the latest information provided by NSW EPA.

Firstly, a fundamental definition to note, as used in the Act and Regulation, is of 'waste', which is defined in the dictionary section of the POEO Act (see Appendix Section A of the Technical Review). In the Waste Regulation, a description of the waste which Clause 92 applies to is also provided (Appendix Section B). The materials described in this Technical Review fall into this definition of waste.

The recovery of resources from waste to be used as fill materials is encouraged by the EPA, where it is beneficial and poses minimal risk of harm to the environment or human health (NSW EPA, 2017a). As such, in some cases, the EPA has the power to give exemptions from particular regulatory requirements that would otherwise apply to the land application of a material that is produced wholly or partly from waste (NSW EPA, 2017a). Orders and exemptions are only appropriate where the re-use (NSW EPA, 2018):

- is genuine, rather than a means of waste disposal,
- is beneficial or fit-for-purpose, and
- will not cause harm to human health or the environment

Of interest for the use of recycled materials into roads and pavements by local council engineers, are the resource recovery exemptions, as they are for the consumers of the waste. The general provisions relating to exemptions are specified in Part 9, clause 91 of the Waste Regulation; and the exemptions relating to resource recovery are provided in clause 92. These clauses (91 and 92) are included in Section B of the Appendix. For the supply of the waste, details of resource recovery orders are outlined in clause 93 of the Waste Regulation.

All sampling and testing requirements included in an order and exemption must be met, for the reuse of the resource recovery waste to be lawful (NSW EPA, 2019a). It should be noted that this is in addition to the testing requirements previously mentioned for the supplied raw materials. Thus, this applies to the incorporation of recycled material into roads and pavements, where the requirements of exemption must be met for application. Several recovered waste materials that have current orders and exemptions approved for use by everyone, are provided on the EPA website:

https://www.epa.nsw.gov.au/your-environment/recycling-and-reuse/resource-recovery-framework/current-orders-and-exemption

Current orders and exemptions are provided for materials such as recovered aggregate, tyres, excavated public road material, coal ash and glass sand. As an example, the current material exemption for reclaimed asphalt pavement is provided in Section C of the Appendix, to show the typical content and structure of an exemption.

For materials that do not have a current order and exemption, but could still be incorporated into roads and pavements, it is possible to apply to the EPA for an exemption (NSW EPA, 2019a). For example, for the land application of other waste types as fill, the application process requires information such as the characterisation of the waste, quality assurance and controls, as well as specifications and standards. For more details regarding the application process for resource recovery orders and exemptions, refer to the EPA website and documents including *Guidelines for Resource Recovery Orders and Exemptions*. It is expected that these application and approvals processes may take months, and planning ahead for these approvals is warranted.

Certified stockpiles

Stocks that are verified to comply with the specifications of the standard, are classified as certified stockpiles. In the event that the stock passes certification, no more substances should be added particularly if the additional substance is untested to comply with the requirements. Certificates have to be provided verifying the conformity of each additional material.

Substances provided by proved stock will normally need no secondary verification. Nevertheless, in the case following examination and/or testing of the substance at the stockpile or at the venue of delivery suggest that the characteristics of the substance have transformed since being certified, for instance, because of separation, pollution or diminishing, halt more shipments of the substance and request more sampling and testing of the stock (RMS, 2011). The compliance or otherwise of the substance will be evaluated by considering these testing outcomes.

Every single delivery slot is required to recognise the verified stock from which the substance is provided. The shipment of unbound or altered substances to site stockpiles is required to conform to what is specified in standards. Stockpiles of unbound substances or substances to be altered can only be placed at the suggested venues.

When stockpiling material on-site, comply with the following (RMS, 2018b):

(a) Place stockpiles on firm, even, well-drained ground or over a constructed floor.
(b) Install and maintain around the stockpiles appropriate erosion and sedimentation controls.
(c) Construct stockpiles in a manner which does not result in segregation. Place the material in horizontal layers, with each new additional layer fully within the boundary of the underlying layer. Do not push the stockpile into a cone shape. The total height of stock is required to be no greater than four meters, unless otherwise specified in the design documentation.
(d) The working surface of any stock is required to be the complete surface of the stock.
(e) Keep the stock substance adequately dampened to prevent penalty and to keep dust levels down.
(f) Keep the stockpiles separated from each other and maintain them to avoid the stocked substances from blending, or contamination by external substances.
(g) With regard to sampling and testing, the stockpile may be constructed in either one of the following two ways:

    i. the stockpile is built up continuously until it is complete, and once complete, no further material is added to the stockpile, with each stockpile constituting a separate Lot; or
    ii. the stockpile is built up incrementally, and any further material added to the stockpile previously verified as conforming is considered to be a new Lot, with

the new material first tested and verified as conforming before it is added to the stockpile.

(h) Prominently and specifically identify each stockpile by signing, stating what type or quantity the substance present in the stockpile is.

Acceptance of material is on the basis of conformity of samples taken from stockpiles. Each stockpile will be regarded as one Lot for the purpose of testing for conformity.

The principal may accept material using alternative production and/or delivery methods if you can demonstrate that production and quality control procedures for verifying conformity to the specification are in place.

Substances are required to be provided from stock verified to comply with the demands of the standard before integration in roadwork. The largest scale of every single stock is required to be no greater than 4000 tonnes if opposed formally by the buyer (RMS, 2018a). Verified stock is required for every single category of substance to avoid separation or blending with other substances and shall be prominently marked with different codes to identify. Each truckload of material delivered by the Supplier should be accompanied by delivery dockets with information about the certified stockpile identification number, the Supplier's name, the tonnage of material, and a Resource Recovery Exemption Statement.

Final product

Mechanical properties

The mechanical property evaluation based on standard methods of the recycled material is reported in this section. The standards are applied for both structure and road application. The material supplier must provide the test certificate of the raw material to the purchaser. Specimens should be made and kept for future testing.

Although many different materials may be used in road construction, the general order of layers include (Savage, 2010):

- The natural subgrade, which is the lowest layer of a road and can consist of remnants that have been left from old roads or the natural soil that is unearthed for new road building.
- The sub-base, comprised of compacted gravel, stone or sand, is the first layer that the road constructor lays on the natural subgrade.
- The road base, consisting of graded mineral aggregates, is viewed as the primary operating layer of the road that ensures it to be strong and flexible. The mix can involve bitumen if loading demands are stringent.
- The base course, consisting of aggregates and bitumen, is a flattened surface base for the top layer.
- The wearing course, normally comprised of a uniformly distributed mix of aggregate and bitumen, is required to have the resistance to traffic-induced friction and offer a surface of smoothness for vehicles to drive. It needs to be applicable in various weather conditions and able of spreading water in an effective way to reduce the risk of skidding.
- A tack coat of bitumen is possibly applicable between layers to make sure they stick to each other tightly.

Different structures require specific mechanical properties. The following mechanical properties of the construction are widely used during the design, construction and maintenance process:

- The yield strength, also known as the amount of stress that a substance is capable of taking before plastically deforming.
- The ultimate strength, which is the highest stress a substance is capable of resisting while being compressed or pulled before breaking.
- The toughness, which is the extent to which the substance is capable of withstanding fracturing at the time of loading.
- The fatigue, is the weakening of a material caused by repetitive (cyclic) loading that results in the growth of cracks.
- The resilience, which is the ability to store strain energy and deflect elastically without yielding.
- The creep, also known as the ability of a material to shift gradually or suffer permanent deformation due to mechanical stresses.

When compliance is validated, the existing version of below the standards and test methods is recommended as a default option. In Table 5.5, the standard test methods for engineering properties, e.g. shrinkage, strength, viscosity, and resilient modulus, have been listed; at the same time, the test methods, e.g. soil treatment, weathering pretreatment and foreign material, recommended by Roads and Maritime Services (RMS) have also been shown. Test methods recommended by Australian Standard cover a wide area. In contrast, the RMS standards cover are more targeted for engineering application.

Table 5.5 Mechanical properties test method

Test method	Standard
Shrinkage	AS 1012.13:2015 Methods of testing concrete determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory
Unconfined compressive strength	AS 1141.51-1996 Methods for sampling and testing aggregates unconfined compressive strength of compacted materials
Methods of testing bitumen and related roadmaking products	AS 2341 Methods of testing bitumen and related roadmaking products
Viscosity by flow through vacuum capillary tubes	AS/NZS 2341.2:2015 Methods of testing bitumen and related roadmaking products
Methods of sampling and testing asphalt	Australian Standard 2891 Methods of Sampling and Testing Asphalt
Bitumen content	AS/NZS 2891.3.1:2013 Methods of sampling and testing asphalt binder content and aggregate grading - Reflux method
Resilient modulus of asphalt	AS/NZS 2891.13.1:2013 Methods of sampling and testing asphalt determination of the resilient modulus of asphalt-indirect tensile method

Test method	Standard
Methods for the preparation and testing of stabilised materials	AS 5101 Methods for the preparation and testing of stabilised materials
Cement content	AS 5101.3.3-2008 (R2017) Methods for preparation and testing of stabilized materials Cement content of cement stabilized materials
Soil treatment	AS1289 Method of Testing of Soil for Engineering Purposes
Compaction pretreatment	RTA T102 Pretreatment of Road Materials by Compaction
Road material compressive strength	RTA T151 - Determination of absorption and compressive strength of road materials stabilised or modified with bituminous materials
Road material dry compressive strength	RTA T114 Maximum Dry Compressive Strength of Road Materials
Shrinkage of road material	RTA T113 Linear shrinkage of road construction materials
Road material compressive strength	RTA T116 Determination of Unconfined Compressive Strength of Remoulded Road Materials which are Self Cementing
Foreign material for road	RTA T276 Foreign Material Content of Recycled Crushed Concrete

Workability

Workability indicates the ease with which concrete can be transported and consolidated. The asphalt mixing method was given in AS 2150-2005 Hot mix asphalt – A guide to good practice. The major factors influencing workability are binder viscosity, binder content, filler type and content, nominal size of mix, aggregate grading, aggregate shape and temperature of placing. However, there are no defined tests for workability according to a report from Australian Asphalt Pavement Association (AAPA) (AAPA, 2004).

The workability of cement-based material was normally measured by drop testing. The AS 1012.3.1:2014 Methods of testing concrete: Determination of properties related to the consistency of concrete – Slump (AS, 2014) testing is widely applied to measure the workability of concrete. If a report is made, the details below are contained:

(a) Identification of the concrete.
(b) Date of test.
(c) Measured slump in 'mm'.
(d) Lateral collapse or shear, if any.

The procedures of the concrete slump test shall be followed:

- Put the mould on a smooth surface. Hold the mould firmly during the rodding of concrete.

- Cast the concrete into the mould in three layers. Rod each layer with a round-headed rod for 25 strokes in a uniform manner to squeeze the bubbles out.
- Remove the surplus concrete after rodding the third layer of concrete so that the mould is completely filled.
- Quickly remove the mould from concrete by raising it in 3□1 s. Avoid any lateral vibration or torsional displacement on the concrete.
- Measure the difference between the height of the mould and the height of the concrete cone. The slump results shall be reported to the nearest 5 mm for slumps under 100 mm and less, or to the nearest 10 mm for slumps greater than 100 mm.

Durability

Durability refers to the capability of a physical product to remain functionalities, without extra maintenance and repair, when encountering with the challenges of normal operation over its design lifetime. The resilience of asphalt is used to evaluate the stiffness of asphalt mix which is similar to Young's modulus. The weathering effects on pavement and concrete were evaluated by RMS T103 and ASTM D4843, respectively. The freezing and thaw resistance is widely used to avoid the spalling phenomenon which is detrimental for the durability of concrete. The resilience, weathering effect resistance and freezing and thaw resistance standard test methods are shown in Table 5.6.

Table 5.6 Durability test methods

Test method	Standard
Resilience of the asphalt	AS 2891.13.1-1995 Determination of the resilient modulus of asphalt- Indirect tensile method
Artificial weathering pretreatment	RMS T103 Pretreatment of Road Materials by Artificial Weathering
Wetting and drying test	ASTM D4843 Standard Test Method for Wetting and Drying Test of Solid Wastes
Resistance to freezing and thawing	ASTM D4842 Standard Test Method for Determining the Resistance of Solid Wastes to Freezing and Thawing
Durability of cement stabilised material	RMS T133 Durability of road materials modified or stabilised by the addition of cement

Other specifications

The sources of the standards and specifications are complex in NSW. In the local council level, the National Construction Code, Australian Standards, RMS specification and NATSPEC specification are all playing important roles as the resource of technical references. The previous sections mainly focus on the Australian Standards which are national-wide. Some local council engineers in NSW may use other specifications from RMS, NATSPEC and Austroads. For the convenience of local council engineers, the

Technical Review lists some specifications which are relevant to the recycled materials in the following Table 5.7. However, it is the responsibility of the engineers to select the specification in the design stage.

Table 5.7 Other relevant specifications applied to the use of recycled materials in roads/pavements

Publisher	Specification
RMS	3153 - Reclaimed asphalt pavement material
	3154 - Granulated glass aggregate
	3204 - Preformed Joint Fillers for Concrete Road Pavements and Structures
	3252 - Polymer Modified Binder for Pavements
	3253 - Bitumen for Pavements
	3268 - Aggregate precoating agent (for polymer modified binder)
	R118 - Crumb Rubber Asphalt
NATSPEC	0053 Rural pavement design – sealed
	0054 Rural pavement design – unsealed
	0173 Environmental management
	1113 Stabilisation
	1144 ASPHALT (ROADWAYS)
	1141 Flexible pavement base and subbase
Austroads	ATS-5330-20 Supply of Geopolymer Concrete
	ATS-5380-20 Fibre Reinforced Polymer Composite Strengthening
	ATS-3110-20 Supply of Polymer Modified Binders
	AGPT-T142-20 Rubber Content of Crumb Rubber Modified Bitumen: Soxhlet Method
	AGPT Guide to pavement technology

Toxicity characteristic leaching procedure (TCLP)

The toxicity characteristic leaching test is conducted according to AS 4439.3-2019 Wastes, sediments and contaminated soils preparation of leachates - bottle leaching procedures (AS, 2019). A flow chart for the leaching procedure has been shown in Figure 5.3. The "leachates" is the substance resulting from the leaching of the aggregates can toxically affect and alter the characteristics of all the surrounding elements. The "leachant" is the solution for the leaching test (Maia et al., 2018). The leachability of waste is assessed through leaching tests of three fundamental classes, including batch, column, and static/dynamic tests. Roughly, a batch test requires agitation of waste using a leachant, a column test involves the leachant pumped vertically via a column filled with waste, while a static or dynamic test assesses dispersion and applies neither stirring or moving of leachant or waste (Beard, 2002).

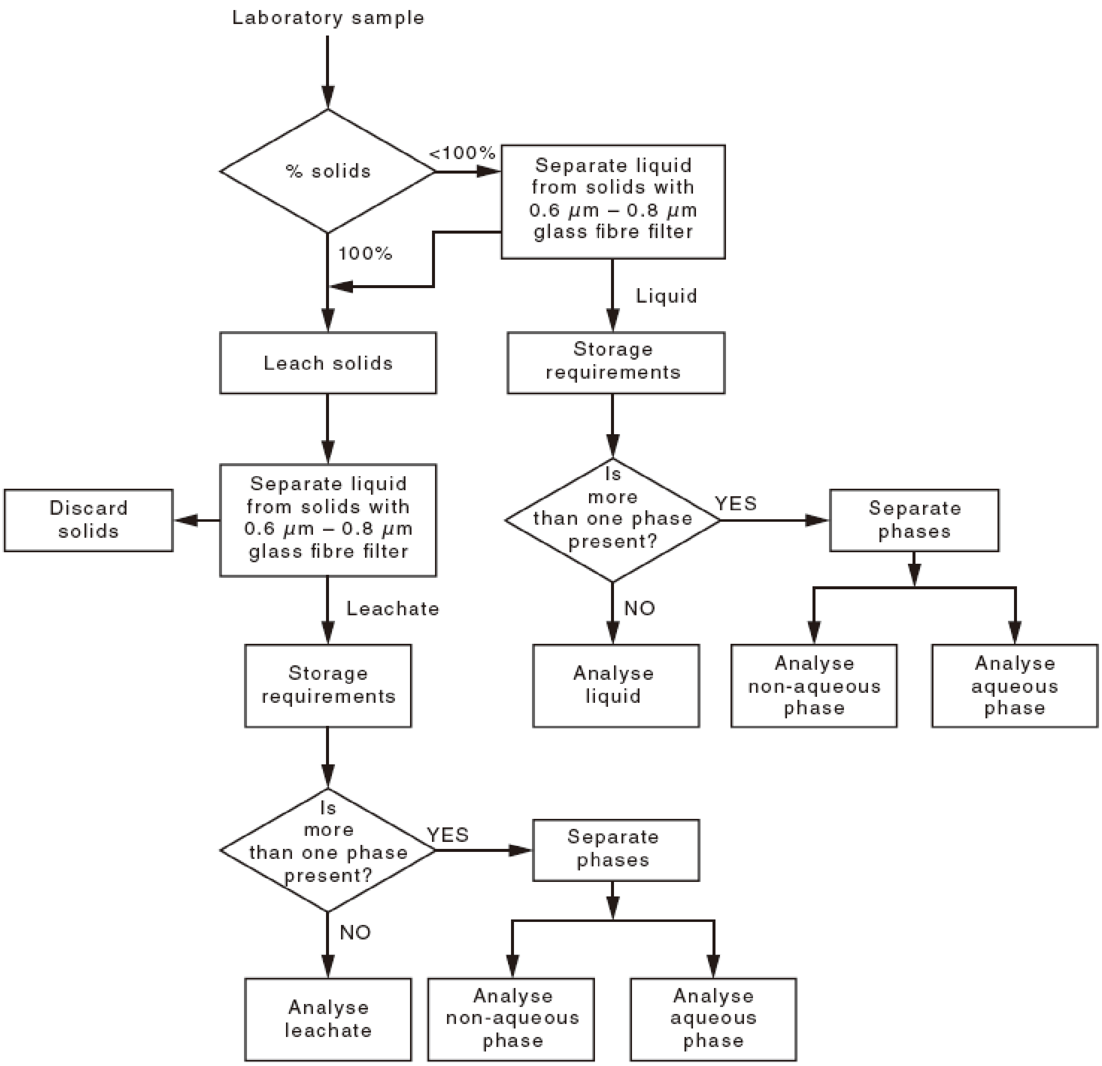


Figure 5.3 Toxicity Characteristic Leaching Procedure Flow Chart (AS, 2019)

After the above steps, the leachate from the waste is ready for analysis. If any harmful substance is detected, a related risk analysis of its concentration is required. According to a previous research (Lee et al., 2012), eleven harmful substances are considered in the designated recycled construction material. The eluted solution is produced with the liquid:solid (*L*:*S*) ratio of 10:1. The soluble content of harmful substance (mg/l) included in the specimens is analysed according to the respective harmful substance testing methods. For copper, cadmium, arsenic, lead, and chromium (VI), the inductively coupled plasma spectrometer is used; the ultraviolet–visible spectrophotometer is used for cyanide; the mercury analyser is used for mercury; gas chromatography and gas chromatography mass spectrometry were used for organic phosphorus, tetrachloroethylene (TCE), and trichloroethylene (PCE).

Table 5.8 Harmful substance acceptance (Lee et al., 2012)

Harmful substance limit in waste (mg/l)	
Copper	3
Cadmium	0.3
Mercury	0.005
Arsenic	1.5
Lead	3
Chromium (VI)	1.5
Cyanide	1
Organic phosphorus	1
Trichloroethylene	0.3
Tetrachloroethylene	0.1

Delivery

The recycled material should be transported with the conventional construction material transporting vehicles to prevent loss of material. The recycled material can be delivered into the stockpile or at the construction site. The facilities for handling and storing materials have been shown in the following (NATSPEC, 2019a):

- Aggregates: Prevent contamination and segregation. Allow for separate stockpiles of aggregates from different sources or of different sizes.
- Fillers: Keep dry and free flowing at all times. Separate fillers of different types.
- Additives, including cellulose or mineral fibres: Protect from moisture or contamination. Do not use wet materials.
- Binders: In thermostatically controlled binder tanks, each fitted with a thermometer that is located where it can be read conveniently and to allow for sampling of binders.

On delivery, the supplier should provide the material test report, stockpile identification number, supplier's information and a copy of recovered aggregate exemption record. Some samples need to be taken to perform tests for contaminants. According to the Recovered Aggregate Exemption 2014 - NSW EPA (NSW EPA, 2014), the consumer must keep the written records for six years.

Long-term pavement performance

The long-term performance of pavement on deflection, roughness, rutting and cracking are important factors for road asset management strategies. According to the long-term pavement performance data from 1994 to 2018, the pavements with different surface treatment were all affected by the deflection, roughness, rutting and cracking, more or less (Martin, 2019). In the report, the performance of the Accelerated Loading Facility (ALF) test was compared with the actual Long Term Pavement Performance (LTPP) test, having been concluded that the pavement performance predictions made from ALF pavements were generally comparable with the performance of in-service pavements.

However, no details concerning the setup of the ALF test were given in the long-term performance report (Martin, 2019). Similar ALF methods from relevant research papers can be used to predict the long-term rutting performance of new pavements. For example, Ji et al. (2013) reported the test parameters and pavement structure used in their ALF test. The ALF pavement specimen has 7 layers which are, from bottom to top, 19.3 cm cement stabilized sands, 15 cm cement stabilized sands, 15 cm cement stabilized sands, 0.7 cm seal coat, 6 cm asphalt, 5 cm asphalt and 4 cm asphalt. The ALF pavement specimen should be properly compacted to avoid the separation between layers. The width and length of the ALF pavement specimen are 3 m and 20 m, respectively. The temperature is kept at 45 ℃ constantly during the experiment. The axle load applied on the ALF pavement sample is controlled at 160 kN (Ji et al., 2013).

The ALF test method has been successfully used by some local councils in Australia for the pavement test. However, the ALF test method is labour-intensive and time-consuming, and it can only be used to evaluate the performance of pavement in a small segment of the pavement which can only provide preliminary and rough condition surveys. The test method for a large area is needed to evaluate the long-term performance of the road network.

The comprehensive pavement condition assessment of the road network is essential to evaluate its long-term performance. Conventional data collecting methods, including weigh-in-motion and stress-strain sensors, are widely used in the current road system. The weigh-in-motion devices are designed to capture the vehicle weights as vehicles drive over a measurement site. The stress-strain sensors are used to measure the deformation of the pavement under certain vehicle weight. In addition to the old methods, new techniques have also been used in recent years. Previous researchers proposed new methods to investigate the condition of potholes and rutting, which cause serious harm to road safety. Wang et al., (2015) proposed a real-time pothole detection method based on mobile sensing techniques. According to their results from the pothole patrol system, the proposed method can precisely detect potholes without false-positives, and the accuracy of the proposed approach is 100%.

As for the rutting test, several conventional loaded wheel testers have been developed and used in Europe and in the United States. These include: 1) the Hamburg wheel tracking device; 2) the French rutting tester; 3) the Nottingham rutting tester; 4) the Georgia loaded wheel tester (Xiao et al., 2007). The point-based bar systems were used to measure the depth of the rutting area at 3 or 5 measuring points. Tsai and Wu (2013) developed a system called emerging 3D line-laser-imaging system for rutting measurements . A sensing vehicle was used to acquire high-resolution transverse profile of the rutting area with more than 4,000 measuring points. This mobile device is reported to improve the accuracy and reliability of rutting measurement with lower cost in a comprehensive environment.

6. Case Studies

Details of the use of recycled materials in various road and pavement projects have been documented as case studies, which provide a reference for conducting projects at your local council. In addition to these examples, smaller scale trials both in the laboratory and field, investigate new formulations to continue optimising and enhancing the efficiency and success of these road technologies.

For this Technical Review, three case studies have been selected. It is recognised that circumstances vary from council to council, which may be outside the scope of the chosen projects. For example, councils may differ in their type of roads (e.g. regional/rural or metro roads); and the source of recycled material they have access to (e.g. local or external supply), which affect factors such as procurement and cost. Thus, it is important to consider these features unique to one’s local council and the nature of their roads, when using case studies as reference.

Examples of recycled material case studies in public work projects including regional council projects are provided by IPWEA (NSW) Roads and Transport Directorate in the *Specification for Supply of Recycled Material for Pavements, Earthworks and Drainage 2010* (Savage, 2010). Specifically, case studies demonstrating the use of recycled glass can be found at https://www.roadsdirectorate.org.au/glass-recycling-information. These include examples from various local councils across Australia and provide details of aspects such as costing in their projects. Case studies from both references highlight considerable cost savings from using recycled material in their roads compared to virgin material.

A Selection of Recent projects

In this section, three recent projects have been chosen to demonstrate the use of recycled materials into road and pavements, using a circular economy approach. These three projects are:

- USYD-Delta Project (Small scale pavement for footpaths) for light load
- Asphalt trials by Downer (Large scale application) for heavy vehicle load
- City of Sydney-UNSW Geopolymer road trial

CASE STUDY 1: USYD-Delta Project (Small scale pavement for footpaths) for light load

Project Background

Title: Upcycling of power plant fly ash into low-carbon engineered eco-pavements

Date: August 2018 to present

Organisation

Waste Transformation Research Hub at the University of Sydney (authors of the guide), in partnership with Delta Electricity (provision of fly ash)

Application: Small scale concrete pavement for footpaths (light load)

Location: The University of Sydney (Camperdown/Darlington campus)

Recycled Materials used:

Carbonated fly ash, mixed Ground Waste Glass (GWG)

Objectives

- To utilise fly ash and waste glass as replacements of cement and fine aggregate, and optimise compositions to maximise waste incorporation whilst maintaining adequate strength
- To develop eco-pavements suitable for foot traffic.

Design Requirements

- Having a minimum concrete design strength of 20MPa at 28 days (AS 2870);
- Having concrete with ability to flow under its weight and adequately fill the formwork;
- Utilising fly ash and waste glass in the replacement of OPC and other aggregate material;
- Utilising carbon dioxide as carbonated material to further reduce carbon footprint
- No leaching of cement stabilised waste.

Outcomes

Material Characterisation

- X-Ray Fluorescence (XRF) values
    - Portland Cement: calcium oxide (64%) and silicate (20%)
    - Fly Ash: silicate (58%) and aluminate (26%)
    - GWG: silicate (70%) and calcium oxide (11%)

Laboratory Product Testing

Ultimate Compressive Strength: The final product with fly ash replacing up to 60% portland cement exceeded minimum strength criteria (i.e. greater than 20MPa at 28 days). A photograph of a concrete sample with recycled materials, after 7 days compressive strength testing, is shown below (Figure 6.1a).

Pavement trial

In order to use the laboratory product as a pavement trial, considerations of scale up were made by accounting for material quantities and environmental performance. The proposed location of the pavement trial on campus at the University of Sydney is shown in Figure 6.1b.

a)

b)

Figure 6.1 a) Photograph of a eco-concrete sample, after 7 days compressive strength testing (left); b) Proposed location of pavement trial on campus at the University of Sydney (right)

CASE STUDY 2: Asphalt trials by Downer (Large scale application) for heavy vehicle load

Project background

Partner Organisations: Downer, Close the Loop, RED Group

Date: May 2018 to present

Examples of trials – Partner Councils and Locations (separate projects)**:**

- Hume City Council, VIC – Rayfield Avenue, Craigieburn, north of Melbourne
- Sutherland Shire Council, NSW – Engadine, Sydney
- Randwick Council, NSW – selected roads in Randwick and Maroubra.

Application: Asphalt roads, Heavy vehicle loads

Objectives (of Research & Development):

- Minimise reliance on natural resources and virgin materials
- Reduce carbon emissions
- Reduce the amount of waste material being disposed to landfill.

Recycled materials used:

- Reconophalt: TonerPlas (soft plastics, waste toner), waste glass, Reclaimed Asphalt Pavement (RAP), crumb rubber from tyres, coarse aggregate and sand from street sweepings
- Plastiphalt: soft plastic, glass.

Detritus processing facility location (NSW): Rosehill

Soft plastics asphalt plant location (NSW): Lake Macquarie

Outcomes of the trial

Waste incorporation: One kilometre of road (two lanes) paved with Reconophalt can contain 500,000 plastic bag and packaging equivalents, 165,000 glass bottle equivalents and toner from 12,000 used printer cartridges.

Product composition of Reconophalt (available): 20 to 30% RAP, 2.5 to 10% Crushed recycled glass and TonerPlas

Performance testing

- Improves fatigue (up to 65% has been shown) and rut resistance
- Superior deformation resistance for heavy vehicle loads
- Lasts 15% longer than standard asphalt
- Capable of withstanding 20% increased traffic loading.

Results from the first Reconophalt trial in Engadine, Sydney are shown in Table 6.1 (Downer, 2018).

Cost evaluation: Reconophalt costs 2-5% more than standard asphalt, due to costs of production and transportation, but is still 25% cheaper than PMB-modified asphalt, according to Downer (Austroads, 2019b).

Most of the information described in this case study was obtained from a report by Downer (Downer, 2018).

Table 6.1 Performance testing results from Reconophalt trial in Sydney (Downer, 2018).

Parameter	"Reconophalt" Plant mix (30% RAP, 5% Glass, 5.9% Binder, 0.75% Additive)	"Reconophalt" Lab mix (30% RAP, 5% Glass, 5.9% Binder, 0.75% Additive)	NSW (Control) (30% RAP, 5% Glass, 5.9% Binder)	RMS AC10H Specification	VicRoads AC10H Specification
Resilient Modulus @ 25°C (MPa)	Tested	4780	3606	N/A	2500-5500
Wheel Tracking Depth @ 60°C mm)	2.0	1.3	Not tested	N/A	<11
Fatigue Life @ 20°C (Kcycles)	567 (preliminary result)	552	Not tested	N/A	>140
Moisture Sensitivity – Tensile Strength Ratio (%)	Not tested	84	Not tested	≥80	>80

Parameter	"Reconophalt" Plant mix (30% RAP, 5% Glass, 5.9% Binder, 0.75% Additive)	"Reconophalt" Lab mix (30% RAP, 5% Glass, 5.9% Binder, 0.75% Additive)	NSW (Control) (30% RAP, 5% Glass, 5.9% Binder)	RMS AC10H Specification	VicRoads AC10H Specification
Particle Loss, Unconditioned (%)	10	Not tested	Not tested	N/A	N/A
Air Voids @ 80 / 120 Cycles (%)	N/A	4.7 / 4.5	5.5 / N/A	3.0 – 6.0	N/A

CASE STUDY 3: City of Sydney-UNSW Geopolymer road trial utilising fly ash Geopolymer concrete

Fly ash Geopolymer concrete is an alternative material, which uses waste products such as fly ash to make alkali-activated cements. This significantly reduces the carbon emissions generated compared to concrete made from Portland cement, due to avoiding processes of high temperature breakdown (Newman et al., 2012). An image of a concrete sample mixed with fly ash aggregate is shown in Figure 6.2. The case study selected is a trial conducted in Sydney (City of Sydney, 2019, UNSW Media, 2019, Foster and Parvez, 2019).

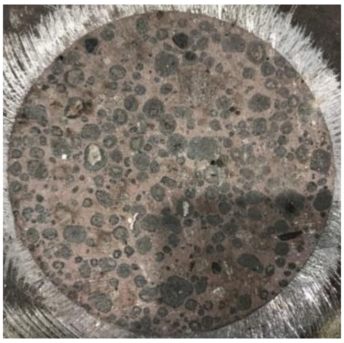


Figure 6.2 Concrete sample mixed with fly ash aggregate

Project background

Title: World-first green roads trial

Date: June 2019

Council and Industry Organisation(s) involved: City of Sydney, UNSW, Industry partner Craig Heidrich (executive director Australian (Iron and Steel) Association and Ash Development Association)

Application: concrete pavement for vehicle road

Objectives: To obtain trial results to create industry guidelines for geopolymer concrete

Recycled materials used: fly ash, blast furnace slag with geopolymer concrete

Details of Trial

Location: section of Wyndham Street, Alexandria, Sydney (see Figure 6.3).

Dimensions: 30m x 3m (15m geopolymer concrete and 15m traditional concrete to compare performance)

Testing

- Road in-situ (using Schmidt hammer): compressive strength of 15-20 MPa at 24 hours, also no cracking
- For cylinder and prism samples collected from site
    - compressive strength (28 days): 41 MPa
    - indirect tensile strength: 3.9 MPa.

Figure 6.3 Road trial of Geopolymer with fly ash in Alexandria, Sydney (City of Sydney, 2019)

Other details

- Geopolymer mixed produced by Wagner
- Open to traffic 36 hours after casting
- Monitoring will be carried out for five years, through the use of nine resistance strain and vibration strain gauge sensors placed under the concrete.

Appendix

Appendix A: Definition of waste

In the Protection of the Environment Operations (POEO) Act 1997 No 156, the dictionary definition of waste is stated, as below.

Waste includes —

(a) any substance (whether solid, liquid or gaseous) that is discharged, emitted or deposited in the environment in such volume, constituency or manner as to cause an alteration in the environment, or
(b) any discarded, rejected, unwanted, surplus or abandoned substance, or
(c) any otherwise discarded, rejected, unwanted, surplus or abandoned substance intended for sale or for recycling, processing, recovery or purification by a separate operation from that which produced the substance, or
(d) any processed, recycled, re-used or recovered substance produced wholly or partly from waste that is applied to land, or used as fuel, but only in the circumstances prescribed by the regulations, or
(e) any substance prescribed by the regulations to be waste.

A substance is not precluded from being waste for the purposes of this Act merely because it is or may be processed, recycled, re-used or recovered.

Appendix B – Resource Recovery Exemption

The general provisions relating to exemptions are provided in the Protection of the Environment Operations (Waste) Regulation 2014 – Part 9, which states:

Clause 91 General provisions relating to exemptions (cf clause 51 of 2005 Reg)

1. The EPA may, if authorised to do so by another provision of this Regulation, grant an exemption under this clause from specified provisions of the Act or this Regulation.
2. The EPA may grant an exemption to any person or class of persons.
3. Without limiting subclause (2), any exemption may be granted to any person or class of persons by reference to—

    (a) any premises or class of premises, or
    (b) any area or class of areas, or
    (c) any activity or class of activities, or
    (d) any other matter or thing or class of matters or things.

4. The EPA may grant an exemption—

    a) on its own initiative, or
    b) on the application of a person to whom the exemption applies, or
    c) on the application of a person belonging to a class of persons to which the exemption applies, or
    d) in the case of an exemption authorised to be granted by clause 92—on the application of a person who—
        i) supplies, or intends to supply, waste to a person to whom the exemption applies, or

ii) supplies, or intends to supply, waste to a person belonging to a class of persons to which the exemption applies, or
iii) supplies, or intends to supply, waste to a person or class of persons for resupply to another person to whom the exemption applies, or
iv) supplies, or intends to supply, waste to a person or class of persons for resupply to another person belonging to a class of persons to which the exemption applies.

5. An application under this clause must—
   a) be in the approved form, and
   b) be accompanied by the fee (if any) that the EPA determines, and
   c) be accompanied by any information, documents or evidence that the EPA requires for the purposes of determining whether the exemption should be granted.
6. An exemption granted under this clause is effected as follows—
   (a) in the case of an exemption granted to specified persons only—by notice published in the Gazette or by written notice given to those persons,
   (b) in any other case—by notice published in the Gazette.
7. An exemption granted under this clause takes effect—
   (a) on the date on which the notice is published or given in accordance with this clause, or
   (b) if a later date is specified in the notice—the later date.
8. An exemption granted under this clause may be unconditional or may be subject to conditions specified in the notice.
9. The EPA may vary or revoke an exemption granted under this clause by a further notice published or given in accordance with this clause.

Clause 92 Exemptions relating to resource recovery *(cf clauses 46 and 51A of 2005 Reg)*

1. This clause applies to the following waste—
   (a) waste (including any processed, recycled, re-used or recovered substance that is produced wholly or partly from waste) that is applied, or is intended to be applied, to land as follows—
      i. by spraying, spreading or depositing it on the land,
      ii. by ploughing, injecting or mixing it into the land,
      iii. by filling, raising, reclaiming or contouring the land,
   (b) waste (including any processed, recycled, re-used or recovered substance that is produced wholly or partly from waste) that is used, or is intended to be used, as a fuel,
   (c) waste used, or intended to be used, in connection with a process of thermal treatment.
2. The EPA may grant an exemption under clause 91 from any one or more of the following provisions, in relation to an activity or class of activities relating to waste to which this clause applies—

(a) the provisions of sections 47–49 and 88 of the Act,
(b) the provisions of Schedule 1 to the Act, either in total or as they apply to a particular type of activity,
(c) the provisions of Part 4 and clauses 109, 110 and 114 of this Regulation.

3. Without limiting subclause (2), the EPA may also grant an exemption under clause 91 from section 142A of the Act, in relation to the application to land (as referred to in subclause (1)(a)) of waste that is produced wholly or partly from restricted solid waste or waste tyres.
4. However, the EPA may not grant an exemption in relation to land pollution within the meaning of paragraph (a) of the definition of land pollution in the Dictionary to the Act.

Appendix C – Example of a Resource Recovery Order and Exemption – Reclaimed Asphalt Pavement

Resource Recovery Order under Part 9, Clause 93 of the Protection of the Environment Operations (Waste) Regulation 2014

The reclaimed asphalt pavement order 2014

Introduction

This order, issued by the Environment Protection Authority (EPA) under clause 93 of the Protection of the Environment Operations (Waste) Regulation 2014 (Waste Regulation), imposes the requirements that must be met by suppliers of reclaimed asphalt pavement to which 'the reclaimed asphalt pavement exemption 2014' applies. The requirements in this order apply in relation to the supply of reclaimed asphalt pavement for application to land for road maintenance activities, being use as a road base and sub base, applied as a surface layer on road shoulders and unsealed roads, and use as an engineering fill. The requirements in this order also apply to the supply of reclaimed asphalt pavement for use as an alternative raw material in the manufacture of asphalt.

1. Waste to which this order applies

1.1 This order applies to reclaimed asphalt pavement. In this order, reclaimed asphalt pavement means an asphalt matrix which was previously used as an engineering material and which must not contain a detectable quantity of coal tar or asbestos.

2. Persons to whom this order applies

2.1. The requirements in this order apply, as relevant, to any person who supplies reclaimed asphalt pavement that has been generated, processed or recovered by the person.

2.2. This order does not apply to the supply of reclaimed asphalt pavement to a consumer for land application or in connection with a process involving thermal treatment at a premises for which the consumer holds a licence under the POEO Act that authorises the carrying out of the scheduled activities on the premises under clause 39 'waste disposal (application to land)' or clause 40 'waste disposal (thermal treatment)' of Schedule 1 of the POEO Act.

3. Duration

3.1. This order commences on 24 November 2014 and is valid until revoked by the EPA by notice published in the Government Gazette.

4. Processor requirements

The EPA imposes the following requirements on any processor who supplies reclaimed asphalt pavement.

General requirements

4.1. The processor must implement procedures to minimise the potential to receive or process reclaimed asphalt pavement containing asbestos. These procedures must be formally documented and the records of compliance must be kept for a period of six years.

4.2. The processor must implement procedures to minimise the potential to receive or process reclaimed asphalt pavement in which the asphalt matrix contains detectable quantities of coal tar. These procedures must be formally documented and the records of compliance must be kept for a period of six years.

Notification

4.3. On or before each transaction, the processor must provide the following to each person to whom the processor supplies the reclaimed asphalt pavement:

- a written statement of compliance certifying that all the requirements set out in this order have been met;
- a copy of the reclaimed asphalt pavement exemption, or a link to the EPA website where the reclaimed asphalt pavement exemption can be found; and
- a copy of the reclaimed asphalt pavement order, or a link to the EPA website where the reclaimed asphalt pavement order can be found.

Record keeping and reporting

4.4. The processor must keep a written record of the following for a period of six years:

- the quantity of any reclaimed asphalt pavement supplied; and
- the name and address of each person to whom the processor supplied the reclaimed asphalt pavement, or the registration details of the vehicle used to transport the reclaimed asphalt pavement.

5. Definitions

In this order:

application or apply to land means applying to land by:

- spraying, spreading or depositing on the land; or
- ploughing, injecting or mixing into the land; or
- filling, raising, reclaiming or contouring the land.

asphalt matrix means the solid material typically comprising of sand, aggregates and similar materials bound together with bituminous and/or other similar binders.

coal tar means the by-product of the thermal processing of coal and means material that has or reasonably is suspected to have present volatile organic contaminants, such as phenols, as well as other toxic materials such as polycyclic aromatic hydrocarbons (PAHs).

consumer means:

- a person who applies, or intends to apply, reclaimed asphalt pavement to land; and
- a person who uses, or intends to use, reclaimed asphalt pavement in connection with a process involving thermal treatment.

detectable quantity of coal tar means the coal tar deemed to be present in an asphalt matrix when it gives a positive red colour result when tested using RTA Test Method T542.

processor means a person who processes, mixes, blends, or otherwise incorporates reclaimed asphalt pavement into a material in its final form for supply to a consumer.

transaction means:

- in the case of a one-off supply, the supply of a batch, truckload or stockpile of reclaimed asphalt pavement waste that is not repeated.
- in the case where the supplier has an arrangement with the recipient for more than one supply of reclaimed asphalt pavement waste the first supply of reclaimed asphalt pavement waste as required under the arrangement.

Notes

The EPA may amend or revoke this order at any time. It is the responsibility of each of the generator and processor to ensure it complies with all relevant requirements of the most current order. The current version of this order will be available on www.epa.nsw.gov.au

In gazetting or otherwise issuing this order, the EPA is not in any way endorsing the supply or use of this substance or guaranteeing that the substance will confer benefit.

The conditions set out in this order are designed to minimise the risk of potential harm to the environment, human health or agriculture, although neither this order nor the accompanying exemption guarantee that the environment, human health or agriculture will not be harmed.

Any person or entity which supplies reclaimed asphalt pavement should assess whether the material is fit for the purpose the material is proposed to be used for, and whether this use may cause harm. The supplier may need to seek expert engineering or technical advice.

Regardless of any exemption or order provided by the EPA, the person who causes or permits the application of the substance to land must ensure that the action is lawful and consistent with any other legislative requirements including, if applicable, any development consent(s) for managing operations on the site(s).

The supply of reclaimed asphalt pavement remains subject to other relevant environmental regulations in the POEO Act and Waste Regulation. For example, a person who pollutes land (s. 142A) or water (s. 120), or causes air pollution through the emission of odours (s. 126), or does not meet the special requirements for asbestos waste (Part 7 of the Waste Regulation), regardless of this order, is guilty of an offence and subject to prosecution.

This order does not alter the requirements of any other relevant legislation that must be met in supplying this material, including for example, the need to prepare a Safety Data Sheet.

Failure to comply with the conditions of this order constitutes an offence under clause 93 of the Waste Regulation.

Resource Recovery Exemption under Part 9, Clauses 91 and 92 of the Protection of the Environment Operations (Waste) Regulation 2014

The reclaimed asphalt pavement exemption 2014

Introduction

This exemption:

- is issued by the Environment Protection Authority (EPA) under clauses 91 and 92 of the Protection of the Environment Operations (Waste) Regulation 2014 (Waste Regulation); and
- exempts a consumer of reclaimed asphalt pavement from certain requirements under the *Protection of the Environment Operations Act 1997* (POEO Act) and the Waste Regulation in relation to the application of that waste to land or in connection with a process of thermal treatment, provided the consumer complies with the conditions of this exemption.

This exemption should be read in conjunction with 'the reclaimed asphalt pavement order 2014'.

1. Waste to which this exemption applies

1.1. This exemption applies to reclaimed asphalt pavement that is, or is intended to be:

1.1.1. applied to land for road related activities including road construction or road maintenance activities being:

(a) use as a road base and sub base,
(b) applied as a surface layer on road shoulders and unsealed roads, and
(c) use as an engineering fill material.

1.1.2. used as an alternative input into thermal processes for non-energy recovery purposes in the manufacture of asphalt.

1.2. Reclaimed asphalt pavement means an asphalt matrix which was previously used as an engineering material and which must not contain a detectable quantity of coal tar or asbestos.

2. Persons to whom this exemption applies

2.1. This exemption applies to any person who applies, or intends to apply, reclaimed asphalt pavement to land and any person who uses, or intends to use, reclaimed asphalt pavement in connection with a process of thermal treatment as set out in 1.1.

3. Duration

3.1. This exemption commences on 24 November 2014 and is valid until revoked by the EPA by notice published in the Government Gazette.

4.`Premises to which this exemption applies

4.1. This exemption applies to the premises at which the consumer's actual or intended application of reclaimed asphalt pavement is carried out.

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5. Revocation

5.1. 'The reclaimed asphalt pavement exemption 2012' which commenced on 16 January 2012 is revoked from 24 November 2014.

6. Exemption

6.1. Subject to the conditions of this exemption, the EPA exempts each consumer from the following provisions of the POEO Act and the Waste Regulation in relation to the consumer's actual or intended application of reclaimed asphalt pavement to land or use in connection with a process of thermal treatment at the premises:

- section 48 of the POEO Act in respect of the scheduled activities described in clauses 39, 40 and 42 of Schedule 1 of the POEO Act;
- Part 4 of the Waste Regulation;
- section 88 of the POEO Act; and
- clause 109 and 110 of the Waste Regulation. 6.2. The exemption does not apply in circumstances where reclaimed asphalt pavement is received at the premises for which the consumer holds a licence under the POEO Act that authorises the carrying out of the scheduled activities on the premises under clause 39 'waste disposal (application to land)' or clause 40 'waste disposal (thermal treatment)' of Schedule 1 of the POEO Act.

7. Conditions of exemption

The exemption is subject to the following conditions:
7.1. The reclaimed asphalt pavement can only be: 7.1.1. applied to land for road related activities including road construction or road maintenance activities being:

(a) use as a road base and sub base,
(b) applied as a surface layer on road shoulders and unsealed roads, and
(c) use as an engineering fill material 7.1.2. used as an alternative input into thermal processes for non-energy recovery purposes in the manufacture of asphalt.

7.2. The consumer must ensure that any application of reclaimed asphalt pavement to land or any use of reclaimed asphalt pavement in connection with a process of thermal treatment must occur within a reasonable period of time after its receipt.

8. Definitions

In this exemption:

application or apply to land means applying to land by:

- spraying, spreading or depositing on the land; or
- ploughing, injecting or mixing into the land; or
- filling, raising, reclaiming or contouring the land.

asphalt matrix means the solid material typically comprising of sand, aggregates and similar materials bound together with bituminous and/or other similar binders.

coal tar means the by-product of the thermal processing of coal and means material that has or reasonably is suspected to have present volatile organic contaminants, such as phenols, as well as other toxic materials such as polycyclic aromatic hydrocarbons (PAHs).

consumer means:

- a person who applies, or intends to apply, reclaimed asphalt pavement to land; and
- a person who uses, or intends to use, reclaimed asphalt pavement in connection with a process involving thermal treatment.

detectable quantity of coal tar means the coal tar deemed to be present in an asphalt matrix when it gives a positive red colour result when tested using RTA Test Method T542.

Notes

The EPA may amend or revoke this exemption at any time. It is the responsibility of the consumer to ensure they comply with all relevant requirements of the most current exemption. The current version of this exemption will be available on www.epa.nsw.gov.au

In gazetting this exemption, the EPA is not in any way endorsing the use of this substance or guaranteeing that the substance will confer benefit.

The conditions set out in this exemption are designed to minimise the risk of potential harm to the environment, human health or agriculture, although neither this exemption nor the accompanying order guarantee that the environment, human health or agriculture will not be harmed.

The consumer should assess whether or not the reclaimed asphalt pavement is fit for the purpose the material is proposed to be used for, and whether this use will cause harm. The consumer may need to seek expert engineering or technical advice.

Regardless of any exemption provided by the EPA, the person who causes or permits the application of the substance to land must ensure that the action is lawful and consistent with any other legislative requirements including, if applicable, any development consent(s) for managing operations on the site.

The receipt of reclaimed asphalt pavement remains subject to other relevant environmental regulations in the POEO Act and Waste Regulation. For example, a person who pollutes land (s. 142A) or water (s. 120), or causes air pollution through the emission of odours (s. 126), or does not meet the special requirements for asbestos waste (Part 7 of the Waste Regulation), regardless of having an exemption, is guilty of an offence and subject to prosecution.

This exemption does not alter the requirements of any other relevant legislation that must be met in utilising this material, including for example, the need to prepare a Safety Data Sheet (SDS).

Failure to comply with the conditions of this exemption constitutes an offence under clause 91 of the Waste Regulation.

LOCAL GOVERNMENT NSW

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LIST OF ABBREVIATIONS

AAPA	Australian Asphalt Pavement Association
ASR	Alkali Silica Reaction
APCO	Australian Packaging Covenant Organisation
CFA	Carbonated Fly Ash
CRM	Crumb Rubber Modifier
C-S-H	Calcium Silicate Hydrate
CWG	Crushed Waste Glass
C&D	Construction and Demolition
C&I	Commercial and Industrial
CR	Crumb Rubber
DCV	Dry Compacted Voids
EI	Environmental Impact
EPA	Environment Protection Authority
FA	Fly Ash
HDPE	High density polyethylene
IBA	Incinerator Bottom Ash
LCA	Life Cycle Assessment
LDPE	Low density polyethylene
MRF	Materials Recovery Facility
MSDS	Material Safety Data Sheet
MSW	Municipal Solid Waste
NA	Natural Aggregates
OHSE	Occupational Health, Safety and Environment
OPC	Ordinary Portland Cement
PET	Polyethylene terephthalate
PMB	Polymer Modifier Bitumen
PVC	Polyvinyl Chloride
RAP	Reclaimed Asphalt Pavement
RCG	Recycled Crushed Glass
RCA	Recycled Concrete Aggregates
RMB	Rubber Modified Bitumen

RMS	Roads & Maritime Services
SAP	Special Activation Precinct
TCLP	Toxic Characteristic Leaching Procedure
TfNSW	Transport for New South Wales
WWF	World Wide Fund for Nature