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Development of a Specification for Recycled Crushed Glass as a Sand Aggregate Replacement

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Abstract

This report presents the technical basis for the development of the Austroads technical specification and guideline for the use of recycled glass in bedding, backfilling material, concrete, road drainage, embankment fill, and landscaping applications.

Austroads is supporting government initiatives aimed at increasing the use of recycled aggregate from waste glass into transport infrastructure and road assets by promoting harmonised practice and specifications amongst road agencies, state and territory governments and local governments.

A review of current practice showed that existing specifications from Australasia and internationally showed a reasonable level of consistency. Material property data available indicates that good-quality recycled crushed glass sand generally exhibits similar characteristic to natural sand.

Potential work health and safety and environmental concerns are discussed. The short- and long-term risks can be managed by the mitigation strategies developed for Australasia and already in place.

Finally, an Austroads technical specification for recycled crushed glass sand to be used in bedding, backfilling material, concrete, drainage, embankment fill, and landscaping applications was developed including requirements for the source and quality of the crushed glass, grading and geotechnical properties as well as chemical evaluation.

Keywords

Recycled crushed glass, bedding material, backfilling material, drainage material, embankment fill, landscaping, concrete, specifications

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Summary

In 2019, the Council of Australian Governments (COAG) noted the need for Australia to take greater responsibility for the nation's waste. It agreed to deliver an export ban on certain types of waste plastics, paper, tyres, and glass. With the first step for the export ban having commenced in January 2021, the export of whole or broken unprocessed glass items, including both packaging and flat sheet glass, was prohibited. In light of this, Austroads commissioned Project APT6311, *Use of Crushed Glass in Road Infrastructure*. The aim of the project, which is to be delivered by the end of 2021, is to facilitate the development of a practicable end-market for recycled crushed glass (RCG) in the transport sector, thereby helping to reduce the amount of glass going to landfill. This was to be achieved by the development of an Austroads technical specification for the use of crushed glass in bedding sand, concrete, drainage medium, embankment fill, and landscaping applications. The specification, which is based on existing national and international best practices, proposes harmonised requirements for the use of RCG across Australia and New Zealand.

A comprehensive review of national and international literature addressing the physical and chemical properties of RCG and the material requirements, and specifications for various road infrastructure applications in which this recycled glass may be utilised, was undertaken. In summary, RCG should be clean, hard and durable, and free from contamination. Depending on the application, RCG may be used as a direct substitute for natural granular material or as a portion of the aggregate for blending (i.e. in embankment applications), or as fine aggregate in concrete applications. Although the specified RCG requirements for a specific application or RCG properties may vary between different reviewed national and international literature, some general consistencies were identified.

Work Health and Safety (WHS) and potential environmental risk analysis from past studies demonstrated that hazards associated with the use of RCG material, in terms of the health and safety of workers and the general public, is low. The processing of the waste glass can produce a consistent and sufficiently clean source of RCG aggregate that is unlikely to leach and have a negative impact on the environment when used in geotechnical and pavement road infrastructure applications (i.e. when it complies with recommended requirements and specifications).

Overall, there was a reasonable level of consistency between the specifications for the use of RCG as a granular material that were reviewed. This formed the basis for the development of an Austroads Technical Specification and guidelines for the use of crushed glass in bedding sand, drainage medium, embankment fill, landscaping and concrete applications.

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1. Introduction

1.1 Background

In 2019, the former Council of Australian Governments (COAG) noted the need for Australia to take greater responsibility for the nation's waste. It agreed to deliver an export ban on certain types of waste plastics, paper, tyres, and glass. In addition, the action also aimed to drive innovation, create jobs, and provide environmental benefits. The Commonwealth *Recycling and Waste Reduction Bill 2020* (introduced to Parliament on 27 August 2020) is the current legislative tool that will establish a framework to regulate the export of waste materials, in line with the COAG agreement.

Through consultation with the industry, the first step for the export ban commenced in January 2021, prohibiting the export of whole or broken unprocessed glass items, including both packaging and flat sheet glass. Large-scale actions are being rolled out across the country to capture and tackle glass waste, including activities such as Victoria's introduction of kerbside bins specifically for glass, and the introduction of Container Deposit Schemes (CDSs) across those jurisdictions without existing robust systems in place.

Driven by the COAG export ban, new and robust end-markets need to be developed for recycled glass, to improve the current recycling rate of 50–60%. Where glass is of high quality, the ideal practice is to recycle it back to glass products. However, for glass that does not meet requirements for this recycling process, there is a need to identify and/or develop alternative recycling avenues. One such avenue for recycling glass is transport infrastructure projects, with a preference for construction and civil works applications, particularly in the road space.

The two key opportunities in this area, outlined in the COAG waste export ban response strategy (Council of Australian Governments 2020), are:

- *All-governments opportunity*: increase the use of recycled glass content in civil works and infrastructure projects to stimulate a demand for glass that cannot be remanufactured into glass packaging.
- *State and territory and Commonwealth government opportunity*: develop and align specifications for the use of recycled glass in a range of construction applications.

Given these opportunities, the Transport and Infrastructure Council (TIC) Ministers endorsed Austroads to commence a program of work to support the repurposing of waste materials into transport infrastructure projects. Specifically, the program's outputs were set to facilitate the use of crushed glass in road construction through the development of appropriate national guidelines and technical specifications.

1.2 Purpose

The objective of project APT6311 was to develop guidelines and Austroads technical specifications that consolidate the available information on the use of recycled crushed glass (RCG) in road infrastructure. This included assessing its use as a direct bedding sand replacement, drainage medium, embankment fill, landscaping applications and concrete. These outputs are intended to support infrastructure owners as resources for understanding, promoting, and helping implement the sustainable and fit-for-purpose use of RCG in their road infrastructure assets. Harmonised national specifications for recycled glass materials will also provide contractors, the recycling industry, and potential future waste glass processing facilities, with the technical requirements surrounding the different applications.

1.3 Project Scope

This project examined some existing alternative uses for RCG in transport infrastructure. The focus of this project involved the applications defined in Table 1.1.

Table 1.1: RCG application types

Application type	Examples of application replacement	Exclusions
Bedding sand and backfill	• Pipe laying bases • Backfilling around pipes • Paver beds • Electrical conduit surround • Under concrete slabs	
Drainage medium	• Subsurface drain filter materials • Permeable fill at structures • Drainage blankets • Water sensitive urban design (WSUD) filter media	Bedding and backfill of drainage pipes (covered in bedding sand)
Embankment fill	• Embankment fill • As foamed glass lightweight fill in embankment fill	Permeable fill at structures (covered under drainage medium)
Landscaping	• Rock mulch blends for garden beds • Sand paths	• Decorative aggregates for exposed aggregate concrete • Concrete pavers
Concrete	• Concrete pavements • Kerb and channel • Maintenance strips • Footpaths • Shared paths • Traffic island infill (non-trafficable) • Footings and plinths for: – sign support structures – lighting columns – traffic signals	• Structural concrete – abutments – piles – reinforced concrete beams – retained earth wall panels • Precast pipes and culverts • Drainage pits • Lintels and lids • Structural footings • Headwalls and wingwalls

In addressing these applications, it was important to understand the processing requirements (crushing, cleaning, screening, and even blending) for each application as a means of identifying which may be the most resource efficient and most cost-effective. It was also important to look at how the properties of the recycled glass can be tailored to meet the ideal requirements of the application. There may be opportunities to use novel techniques in recycled glass processing for utilisation in certain applications, such as recycled foamed glass for embankment fill and concrete applications. The industry as a whole would benefit from the development of improved guidelines for the processing of glass for road construction applications.

It is recognised that there is a viable application for the use of RCG as a fine aggregate replacement in asphalt; however, the development of a harmonised Austroads technical specification for the use of glass in asphalt was outside the scope of project APT6311.

For the purposes of this report, bedding sand is defined as a layer of suitable sand material (i.e. natural or man-made mineral particles ranging in size from 2 mm to 60 microns, free of appreciable quantities of clay and silt), placed on a foundation to provide uniform support for a structure (adapted from Austroads 2015).

The outputs of this project are:

- an Austroads technical report including a national and international literature review, and provision of the technical basis for a national specification on the use and requirements of crushed glass in bedding sand, concrete, drainage medium, embankment fill and landscaping applications (this document)
- an Austroads technical specification for the use of recycled glass as a granular aggregate replacement in bedding sand, drainage medium, embankment fill, landscaping, non-structural concrete and concrete pavement applications
- interim guidelines for the crushing and cleaning of recycled glass; this will be application applicable
- a public Austroads webinar for the dissemination of the work, findings, and outputs of this project.

1.4 Methodology

The technical specifications were developed based on national and international best practices, with the requirements for the use of recycled glass across Australia and New Zealand standardised and harmonised. The methodology included:

- an extensive review of current practice and specifications
- the analysis of the specification requirements across road agencies for recycled glass products and its use in bedding sand, concrete, drainage medium, embankment fill and landscaping applications.

The project did not involve laboratory testing; however, typical material characteristics identified in the literature were summarised and reviewed.

1.5 Structure of the Report

The structure of this technical report is as follows:

- Section 1 – Introduction to the literature review.
- Section 2 – Current status of glass recovery, material properties, health and safety of RCG.
- Section 3 – The development of the specification framework and requirements for granular material applications.
- Section 4 – The development of a specification framework and requirements for concrete applications.
- Section 5 – Conclusions.

2. Recycled Crushed Glass

2.1 General

2.1.1 Background

Historically, Australia has minimised the accumulation of waste glass by exporting it to international markets. As recently as 2018–19, 16 000 tonnes of glass were exported, with a value of $716 000 (Pickin & Trinh 2019). However, with a growing number of countries introducing changes to their import regulations for waste-derived materials, the viability of exporting Australia's waste is decreasing. In 2019, COAG agreed that a timetable for banning the export of certain types of waste glass (as well as waste plastic, paper and tyres) should be developed, while also building capacity for high-value recycled commodities and associated demand.

After aims for a 1 July 2020 commencement deadline for the ban (Department of Agriculture, Water and the Environment 2019) were hindered by the COVID-19 pandemic (Ley & Evans 2020a), the ban on glass export commenced on 1 January 2021. The export ban looks to drive change in the waste industry, businesses, governments and the wider community, and make Australia more responsible for its waste management. Within the export ban commitment, under the *National Waste Policy Action Plan* sits the ongoing action for the 'development of new markets for recycled products and materials' (Department of Agriculture, Water and the Environment 2019).

Overall, the development of specifications and guidelines for crushed glass in bedding sand, concrete, drainage medium, embankment fill, and landscaping applications offers a clear response to the *National Waste Policy Action Plan* and associated state and territory goals, and supports the development of a practicable end-market, thereby reducing the amount of glass going to landfill. As a result, there is a significant opportunity to increase the use of recycled materials in Australia and New Zealand by making sure the right conditions exist to confidently use these products in road infrastructure projects.

2.1.2 National Waste Policy Action Plan

In Australia, while per-person waste has decreased by 10% since 2006 and recycling rates have reached 58% (up from 50% in 2006–07), overall waste generation is increasing due to the national population growth. To help combat this increase, the Federal Government has committed investments towards the recycling industry. These investments have seen a commitment of $190 million to the new Recycling Modernisation Fund (RMF), an additional $25 million to assist in implementing the goals seen in the *National Waste Policy Action Plan* (Department of Agriculture, Water and the Environment 2019), and a further $24.6 million to improve national waste data for enhanced tracking of progress against targets (Ley & Evans 2020b).

Further to this, the 2018 *National Waste Policy* (Department of Agriculture, Water and the Environment 2018), which pairs with the aforementioned 2019 *National Waste Policy Action Plan* (which targets an overall resource recovery of 80% by 2030) (Department of Agriculture, Water and the Environment 2019), responds to current recycling challenges by providing a framework for embracing innovation and creating new opportunities to overcome these challenges.

Within the policy (Department of Agriculture, Water and the Environment 2018), the following five principles underpinning waste management, recycling, and resource recovery in a circular economy are provided:

- Avoid waste:
  - prioritise waste avoidance, encourage efficient use, reuse, and repair
  - design products so waste is minimised by making to last and/or enabling easier recovery of materials.
- Improve resource recovery:
  - improve material collection systems and processes for recycling
  - improve the quality of recycled material we produce.
- Increase the use of recycled material and build demand and markets for recycled products.
- Better manage material flows to benefit human health, the environment, and the economy.
- Improve information to support innovation, guide investment and enable informed consumer decisions.

Directly responding to these principles, the opportunity for increasing the use of recycled glass in the transport infrastructure has been identified, including the specific use of crushed glass in bedding sand, concrete, drainage medium, embankment fill and landscaping applications. The development of appropriate national guidelines and model specifications (based on national and international best practice) will support improved resource recovery, increased use of recycled materials, and management of material flows.

2.1.3 Recovery Opportunities

Approximately 57% of the 1.1 million tonnes of waste glass was recycled in Australia in 2016–17 (Pickin et al. 2018). While this is an increase over the recycling rates for the decade prior, which remained consistently between 54% to 61%, glass recycling is still below that for metal, masonry, paper and cardboard, and organics (Pickin et al. 2018). The weakness in glass recycling suggested by Pickin et al. (2018) is that, outside of recycling back into glass packaging, alternative markets for glass recycling are under-developed and under-utilised.

Presently, South Australia has the highest rate of cullet[1] used for glass bottle production as a result of their well-established CDSs, with other jurisdictions (NT, NSW, Qld and WA), following suit. In 2016–17, SA recovered 85% of glass containers through the scheme, followed by the NT with 57% (Pickin et al. 2018). Recently, Victoria has released the *Recycling Victoria: a New Economy* policy (Department of Environment, Land, Water and Planning (DELWP) 2020), whereby the state will be introducing separate glass kerbside bins and access to glass recycling services for all households by 2027, and rolling out a CDS.

Aligned with this policy, Infrastructure Victoria, in its recently released *Victoria's Draft 30-Year Infrastructure Strategy*, has made recommendations on resource recovery and accelerating the transition to a circular economy (Infrastructure Victoria 2020). According to these recommendations, an immediate increase and upgrade of waste processing infrastructure for priority materials including glass must be at the focus of efforts. For this to be effective, rigorous waste processing guidelines are required. In addition, immediate update and development of relevant standards and specifications will build confidence in using recycled materials and accelerate the market development.

The recovery of glass in New Zealand (NZ) occurs through several avenues, similar to those used in Australia. Typically, household glass items (such as bottles and jars) are collected through council-funded schemes such as drop-off centres and kerbside collections, as well as through transfer stations, recovery centres and commercial recycling collections (Wakim 2009). Other waste glass can also be diverted from landfill; however, depending on the item, some restrictions on the recovery procedure may apply (e.g. for windows, no post-consumer sources are permitted, and these can only be sourced directly from factories).

1 Crushed glass that is ready to be remelted, traditionally to form new glass products, is commonly termed 'cullet'.

2.2 Challenges

2.2.1 Availability and Demand

For the glass market, some concerns have been raised regarding the accumulation and stockpiling of waste glass. For example, the recycling company Polytrade revealed in late 2017 that they were receiving more glass waste than there was reasonable market demand for. As a result, they were forced to place hundreds of thousands of tonnes of glass in stockpiles (Meldrum-Hanna, Davies & Richards 2017). The low price of imported glass products is another factor undercutting domestic recycling potential (Meldrum-Hanna et al. 2017). To assist in mitigating the risk around supply exceeding demand, reliable end-markets, supported by consistent specifications and clear procurement processes, need to be developed.

Investigations into the potential demand for RCG in NZ showed a different context. A WasteNot Consulting report (Wakim 2009) produced for the Waikato region in NZ examined the current and potential amount of recovered glass, concrete, organics, and timber that could be used in civil work. The amount of recovered glass that was currently available was ranked as the lowest of the four materials, and the immediate potential for the uptake of more glass in the civil sector was ranked third (only above timber).

Wakim (2009) considered that this low uptake potential was a result of high reuse of recovered container glass in the region, as the Owens-Illinois owned recycling facility in nearby Auckland has the capacity to consume most of the container glass that is recovered from the surrounding region. Conversely, for the South Island, the crushing of glass and its use in road construction, or other construction purposes, has been acknowledged as viable. This is due to the significant distance, and high associated material transport costs that would be associated with sending recovered glass to Auckland for recycling back into glass products (Fulton 2008). However, WSP (2018) considered that the lack of clear and consistent demand for RCG-derived sand in civil works means that companies are hesitant to invest in glass processing plant equipment. In addition, the lack of processing plants reduces the availability of RCG-derived sand and decreases opportunities for its use to be specified, and experience with it to be gained, in projects.

Where recovered glass is unable to be recycled into containers, potential alternative uses presented by WasteNot (Wakim 2009) and the NZ-based, Glass Packaging Forum (2020) include backfill, road basecourse aggregate, concrete aggregate, water filtration and service material, and concrete foundations and footpath projects. Two-thirds of post-consumer glass in NZ can be recovered and recycled back into glass products. DB Export (2020) contend that an approximate additional 10% of glass is currently diverted from landfill and recycled for low-value purposes. The availability of recovered glass for processing into RCG sand in NZ is relatively limited.

Currently, the availability and demand of RCG is highly volatile depending on geographical location and local recycling practices.

2.2.2 Contamination

Another challenge in the glass recycling market is the impact of contamination. Fit-for-purpose use of glass fines (EPA Victoria 2019) is described as meeting the specification for its intended use, having less than 2% physical contaminants, and below the chemical contamination threshold as per *Solid Industrial Waste Hazard Categorisation and Management* (EPA Victoria 2009a).

In a summary review of the Australian recycling market, Allan (2019a) reports that losses of 30–40% are currently experienced within the Australian glass recycling market, whereby glass collected for recycling is lost through the collection, sorting, and beneficiation phases. Here, beneficiation is the process of sorting, cleaning, crushing, and sizing glass to make it either suitable to be manufactured back into glass products, or be suitable for other markets, such as transport infrastructure. With glass from sorting facilities often carrying contaminants, the resultant loss during beneficiation can be significant.

Similarly, when the glass is part of a mixed recycling collection process, it can itself be, when broken, a considerable contaminant that can impact other recycling streams such as those for paper and cardboard. CDSs and separate kerbside bins for glass are two approaches that can be used to tackle this issue (Allan 2019a). However, the impact of CDSs is dependent on a variety of factors, such as if separation of glass colours occurs (colour separated glass is of a higher value), or when the collected containers are crushed. Allan (2019a) noted that the bottles in South Australia stay intact for longer compared to other schemes, reducing the risk of contamination. Allan (2019a) also emphasised that the use of glass in road construction and similar applications offers a potential market for glass that cannot meet the quality requirements for packaging production, potentially mitigating the current and significant 30–40% losses.

Glass colour – amber (brown), green and flint (clear) – is also a substantial factor in glass recycling, with the demand for different colours varying around Australia. For example, South Australia obtains green glass from other states due to high demand from South Australia's wine industry (Allan 2019b). Given that colour profiles are unlikely to be required in transport infrastructure uses of glass product, it is beneficial to recognise that use in applications such as bedding sand has the potential to utilise colours with lower demand specific to localised markets.

The Department of Environment and Climate Change (DECC) (2007) states that appropriate processing of the recycled glass fines is critical to meet quality standards and low content of residual impurities. The process of washing and removing potential contamination to acceptable levels could be required depending on the glass feedstock. It would be beneficial for the industry to develop and provide the customer with product specifications to prove cleanliness of the glass fines.

Note: Investigation of the apparent significant differences between Australian and New Zealand volumes of losses in the glass recycling stream is beyond the scope of this review.

2.3 Engineering Properties of Recycled Crushed Glass

This section summarises notable research studies where laboratory tests were conducted to characterise recycled glass or soil-crushed glass blends. The physical and mechanical properties of recycled glass discussed in this section are those which are relevant to a material that may be used for bedding sand, drainage medium, embankment fill, landscaping, and concrete applications; and includes compaction related properties, specific gravity, permeability, California Bearing Ratio (CBR) and thermal/electrical conductivity.

2.3.1 Compaction

A relationship between the material's density and moisture content for a given material type and degree of compactive effort can be established using a compaction test from which the optimum moisture content (OMC) and the maximum dry density (MDD) for each material can be obtained.

Disfani (2011) conducted extensive laboratory tests on three different samples of recycled glass produced by the recycling industries in Victoria, Australia, with maximum particle sizes of 4.75 mm ('fine recycled glass'), 9.5 mm ('medium recycled glass'), and 19 mm ('coarse recycled glass'). According to both the Australian Soil Classification System (ASCS) and the Unified Soil Classification System (USCS), 'fine recycled glass' is classified as a 'well-graded sand-sized mixture with a small quantity of silt-sized particles, SW-SM' and 'medium recycled glass' is classified as a 'well-graded gravel-sized mixture with a small amount of silt-sized particles, GW-GM' based on ASCS. It is a different soil classification according to USCS ('well-graded sand-sized mixture with a small quantity of silt-sized particles, SW-SM').

Disfani (2011) suggested that, although 'fine and medium recycled glass' were classified as 'well-graded' materials, their compaction curves were similar to a typical poorly graded sand, which may be due to the poor capability of the glass particles to absorb and retain water. According to this study, the obtained standard MDD and OMC for the recycled glass with maximum particle sizes of 4.75 mm and 9.5 mm were 1.70 t/m^3 and 12.5%, and 1.84 t/m^3 and 9%, respectively. These parameters determined from the modified Proctor for the maximum particle sizes of 4.75 mm and 9.5 mm were 1.78 t/m^3 and 10%, and 1.99 t/m^3 and 8.8%, respectively. The findings suggested that 'fine and medium recycled glass' showed generally 10% to 15% lower MDD, but slightly higher OMC compared to the natural aggregates having the same soil classification.

Wartman, Grubb and Nasim (2004) evaluated the characteristics of crushed glass from two US suppliers. The two crushed glass samples were classified as well-graded sand with gravel (SW) according to USCS classification and AASHTO No. 10 gradation. Similar to Disfani's finding, Wartman et al. noted that whilst the compaction curve shapes for crushed glass were similar to those for natural aggregates, the curves for the crushed glass were flatter, indicating the relative insensitivity of crushed glass to the change in moisture compared to the natural aggregates. The study also found a standard MDD of 1.71/1.69 t/m^3 and a standard OMC of 12.8/13.6% for the two crushed glass sources, respectively. These parameters were obtained using the modified compaction for the two samples and were equal to 1.87/1.78 t/m^3 and 9.7/11.2%.

In another study, the Pennsylvania Department of Transportation (2001) characterised two sources of crushed glass both classified as USCS well-graded sand with gravel (SW) and AASHTO No. 10. The standard MDDs for the two sources were 1.72 and 1.79 t/m^3, and the standard OMCs were 13.2 and 11.9%. These values, determined from the modified compaction for the two samples, were equal to 1.79 and 1.88 t/m^3 and 10.8 and 10.8%, respectively.

Clean Washington Center (CWC) (1998) summarised the results of compaction tests on samples consisting of two crushed glass sizes of 1/4 in. minus (6.3 mm) and 3/4 in. minus (19 mm) (each from two sources). As well as examining the compaction of the glass products themselves, the study also examined glass mixed with other aggregates. Only the 100% glass test results are examined here.

The MDD of the crushed glass of size 6.3 mm minus was 1.67–1.68 t/m^3 and Standard OMC was 4.7–5%. The MDD and OMC determined from the Modified compaction of the two samples were 1.77–1.82 t/m^3 and 5.6–5.2%, respectively. From this, it was concluded that decreasing the glass cullet content resulted in an increase in density.

For standard compaction, there was a slight increase in the OMC when the glass cullet content was decreased. Also, generally, all the compaction curves were relatively flat with minor exceptions generally observed for non-cohesive materials.

A summary of the compaction test results from different literature is presented in Table 2.1. It should be noted that in all different references shown in Table 2.1, except in CWC (1998), the modified MDD of the crushed glass/glass cullet samples increased compared to the standard MDD, while the modified OMC was lower than the OMC determined using standard compaction.

CWC (1998) reported that the sample gradation was obtained before and after compaction using both the standard and modified methods to evaluate the possible gradation change due to the compaction procedure. The gradation test results indicated that standard Proctor compaction did not result in a gradation change. However, a change in the gradation was observed when glass cullet samples were subjected to modified compaction. It was also reported that the degree of change in gradation was mostly dependent on the size of the glass cullet samples. The increase in both the OMC and MDD under modified compaction compared to standard compaction reported in CWC (1998) may be the result of the observed particles breakage and the gradation change during the modified compaction procedure.

The Disfani (2011) data showed limited particle breakdown under modified compaction for RCG with a maximum particle size of 4.75 mm. In comparison, larger particles were more likely to break down during compaction testing. About 5% of fines was generated when the 10 mm RCG was tested, whilst there was a significant change in grading for the RCG with maximum particle 20 mm (modified Proctor compaction).

Table 2.1: Summary of compaction test results of recycled glass

Reference	Crushed glass/glass cullet gradation	Maximum dry density (t/m^3)/compaction test		Optimum moisture content (%)/ compaction test	
		Standard Proctor	*Modified Proctor*	*Standard Proctor*	*Modified Proctor*
Disfani (2011)	4.75 mm minus classified as SW-SM(1)	1.70	1.78	12.5	10
	9.5 mm minus classified as SW-SM(2)	1.84	1.99	9.0	8.8
Wartman, Grubb & Nasim (2004)	SW & AASHTO No. 10 gradation (source 1)	1.71	1.87	12.8	9.7
	SW & AASHTO No. 10 gradation (source 2)	1.69	1.78	13.6	11.2
Pennsylvania Department of Transportation (2001)	SW & AASHTO No. 10 gradation (source 1)	1.72	1.79	13.2	10.8
	SW & AASHTO No. 10 gradation (source 2)	1.79	1.88	11.9	10.8
Clean Washington Center (1998)	1/4 in. (6.3 mm) minus (sample 1)	1.67	1.77	4.7	5.6
	1/4 in. (6.3 mm) minus (sample 2)	1.68	1.82	5.0	5.2

1 *According to both ASCS and USCS.*
2 *SW-SM according to USCS, but GW-GM based on ASCS.*

2.3.2 Permeability

A hydraulic conductivity test can be carried out on soil samples to determine the coefficient of permeability (or hydraulic conductivity) which describes how quickly water will flow through the material. Disfani (2011) conducted constant head hydraulic conductivity tests and found hydraulic conductivities of 1.7×10^{-5} and 2.85×10^{-5} m/s for recycled glass with the maximum particle sizes of 4.75 mm and 9.5 mm, respectively. Both samples were classified as ‘medium’ based on the soil permeability classification. The recycled glass samples were seen to demonstrate hydraulic conductivity similar to that for natural aggregates with the same gradation.

Pennsylvania Department of Transportation (2001) and Wartman et al. (2004) evaluated the permeability of crushed glass cullet samples (classified as SW) compacted to 90% of Modified Proctor MDD density using constant head hydraulic conductivity tests. The glass cullet samples had hydraulic conductivities of 1.61×10^{-6} and 6.45×10^{-6} m/s. Similar to other studies, the results were within the typical range for natural aggregates (SW classification). Crushed glass materials are relatively free-draining and consequently can have a good performance in drainage and filtration applications.

So et al. (2015) found a permeability range of 10^{-5} to 10^{-4} m/s for 3 mm minus and 20 mm minus glass cullet samples compacted to 95% of Modified Proctor MDD. This is consistent with other studies which reported that tested glass cullet had a permeability similar to that for clean sand.

CWC (1998) reported that the permeability obtained from constant head permeability testing varied from 6.0×10^{-4} and 6.4×10^{-4} m/s to 4.4×10^{-4} and 4.8×10^{-4} m/s under varying levels of compaction (90% to 95% MDD respectively) for two sources of 100% of 1/4 in. minus (6.3 mm) glass cullet samples mm. This result suggested that the tested glass cullet was in ‘medium’ soil permeability classifications.

The hydraulic conductivities obtained by different researchers are summarised in Table 2.2.

Table 2.2: Summary of hydraulic conductivity of recycled glass

Reference	Crushed glass/glass cullet gradation	Hydraulic conductivity value/range (m/s)
Disfani (2011)	4.75 mm minus classified as SW-SM	1.7×10^{-5}
	9.5 mm minus classified as SW-SM	2.85×10^{-5}
Pennsylvania Department of Transportation (2001)	SW & AASHTO No. 10 gradation (source 1)	1.61×10^{-6}
	SW & AASHTO No. 10 gradation (source 2)	6.45×10^{-6}
Clean Washington Center (1998)	1/4 in. (6.3 mm) minus (sample 1)	6.0×10^{-4}(1)
	1/4 in. (6.3 mm) minus (sample 2)	6.4×10^{-4}(1)
So et al. (2015)	3 mm minus	$10^{-5} \times 10^{-4}$

1 *Samples compacted to 90% MDD.*

2.3.3 Specific Gravity

Specific gravity (SG) is a parameter used to determine the density-volume relationship of particles within a soil mass, i.e. only the volume of the particles themselves are considered and not the volume of voids between the particles.

Table 2.3 summarises the SG of the materials examined in the studies discussed in Section 2.3.2. The SG of the crushed recycled glass materials did not vary to any significant degree, indicating that the primary types of glass in the source products studies were very similar.

Table 2.3: Summary of specific gravity of recycled glass

Reference	Crushed glass/glass cullet gradation	Specific gravity value/range (t/m^3)
Disfani (2011)	4.75 mm minus classified as SW-SM	2.48
	9.5 mm minus classified as SW-SM	2.50
Pennsylvania Department of Transportation (2001)	SW & AASHTO No. 10 gradation (source 1)	2.48
	SW & AASHTO No. 10 gradation (source 2)	2.49
Clean Washington Center (1998)	1/4 in. (6.3 mm) minus	2.49–2.52
So et al. (2015)	3 mm minus	2.40–2.55

2.3.4 California Bearing Ratio

The California Bearing Ratio (CBR) is a common measure of material strength used in the infrastructure industry. Disfani (2011) and So et al. (2015) also undertook CBR testing, and the findings are summarised in Table 2.4. Interestingly, the So et al. (2015) study tested both the upper and lower face of the CBR specimen moulds and there was a significant difference in the measured CBR values. They postulated that the difference might be due to the migration of fines from the upper to the lower section of the specimen during the compaction process, resulting in a lower void ratio and consequent higher CBR for the lower area.

Table 2.4: CBR of recycled glass

Reference	Crushed glass/glass cullet gradation	CBR (%)
Disfani (2011)	4.75 mm minus classified as SW-SM	18–21 (standard compaction) 42–46 (modified compaction)
	9.5 mm minus classified as SW-SM	31–32 (standard compaction) 73–76 (modified compaction)
So et al. (2015)	3 mm minus	8.1–20.3 (upper face of mould) 53.7–97.6 (lower face of mould)

2.3.5 Electrical Conductivity

The electrical conductivity or resistivity (resistivity = 1/conductivity) and the pH value of the bedding material are other physical properties that may affect the corrosive attack of surrounding steel pipes or structures. The electrical resistivity and its reciprocal, the electrical conductivity, are influenced by potential mineral contamination of the RCG sand and affected by dissolved minerals such as nitrate, chloride, sulphate, and phosphate anions (negatively charged) or sodium, magnesium, calcium, iron, and aluminium cations (positively charged). Therefore, electric conductivity measurement provides an indirect means of assessing contamination of RCG material as part of an environmental impact assessment (Section 3.5.6). For instance, NSW EPA (2014a) specifies an average conductivity of lower than 1000 µS/cm (microSiemens per cm), equivalent to a resistivity greater than 1000 Ω cm.

For pipe embedment, the Water Service Association of Australia (WSAA) product specifications (WSA PS 368:2020) set tighter limits specifying electrical resistivity values greater than 1500 Ω cm and pH values in the range of 5–9 as detailed in Section 3.1. A DECC (2007) and Sydney Water trial included testing of the RCG sand used, and all samples were found to meet these requirements with electrical resistivity exceeding 2000 Ω cm and pH values in the range 7.1–8.7.

For recycled crushed glass in road material applications, Queensland Department of Transport and Main Roads (TMR) specification (MRTS36:2020) stipulates a maximum electrical conductivity of 1000 µS/cm aligned with NSW EPA (2014a) limits.

2.3.6 Thermal Conductivity – Electrical Application Only

The thermal conductivity of a material is relevant to specific bedding applications such as bedding and backfilling around conduits carrying high voltage electrical cables. Furthermore, the thermal conductivity properties of the material could lead to the need for additional fit-for-purpose requirements in addition to geotechnical requirements.

In the dry state, the thermal conductivity of RCG sand is affected by the bulk thermal conductivity of the glass (1 W/m.K[2]) and particle packing (e.g. void content and particle contacts). The thermal resistivity is highest when the sand is dry and it will decrease with increasing moisture content. Data summarised by Dhir et al. (2018) for a 6 mm RCG sand showed thermal resistivity about three to four times greater than that of intact glass for moisture contents around 6–10%. As part of their assessment, the CWC (1998) concluded that the thermal conductivity of the RCG was comparable to natural aggregate, and it could replace natural aggregate in utility trench applications where the heat transfer characteristics of the backfill are of concern. It is, therefore, reasonable to assume that RCG materials could have suitable thermal properties; however, further assessment and thermal diffusion performance requirements might be necessary on a case-by-case basis.

2 Watts per metre Kelvin, or k value.

For bedding and backfilling around conduits carrying high voltage electrical cables, thermal resistivity or thermal conductivity (Thermal Resistivity = 1/Thermal Conductivity) is specified for bedding materials. Low thermal resistivity values are intended to aid in dissipating the heat produced by the cable. A maximum thermal resistivity of the dry material up to 1.2 m.K/W is commonly specified and an assessment for different moisture contents might be required. The literature review did not provide much thermal conductivity data showing the need for further exploration. It is possible that RCG might not meet the typical requirements for underground high voltage electrical cables. Of note, Ausgrid (2020) in its network standard NS130 for underground cables up to and including 11 kV, excludes the use of recycled 'GlassSand™' and other recycled crushed glass products as bedding materials. Ausgrid standards for higher voltage cables (e.g. NS168) stipulate that beddings materials meet the requirements of NS130.

2.3.7 Summary

Table 2.5 summarises the typical range for each physical and mechanical property of RCG from the studies examined (Disfani 2011; Wartman et al. 2004; Pennsylvania Department of Transportation 2001; So et al. 2015; CWC 1998). Properties are compared with typical values for natural sand including CBR and MDD/OMC values sourced from Carter and Bentley (1991). It should be noted that this summary is limited to literature considering the specified particle size of recycled glass sand; it does not cover the properties of crushed glass with other particle size distributions.

In summary, the evaluated physical and mechanical properties of the RCG/glass cullet found in the literature were comparable to those for natural sand. The differences observed between the behaviour of crushed glass and natural sand in some cases can be attributed to different factors including, but not limited to, the grain size distribution of crushed glass (not only the maximum particle size), particle shape, chemical properties, material fabric and particle assemblage, compaction (density), and the presence of debris in the crushed glass. The method of the sample preparation for the laboratory experiments may also be a contributing factor affecting the resulting properties. All these factors should be taken into account when comparing the properties of crushed glass against natural aggregates.

Very little thermal/electrical conductivity data was found during the literature review. That which was found indicated that the thermal and electrical conductivity properties of RCG are anticipated to be relatively similar to natural sand. However, Ausgrid (2020) specifically excludes the use of recycled crushed glass products for bedding materials for electrical cables. The reasoning for the exclusion warrants further investigation.

Table 2.5: Summary of recycled crushed glass and natural sand property range

Property		Typical RCG	Typical similar-sized sand
Compaction	MDD	1.69–1.79 t/m^3 (1)	1.63–2.14 t/m^3 (2)
	OMC	12.5–13.6% (1)	21–9% (3)
Permeability		1.0 x 10^{-4} to 6.5 x 10^{-6} m/s	10^{-4} to 10^{-6} m/s
Specific gravity		2.48–2.49	2.64–2.66
CBR		18–21% (4)	10–40% (5)
Thermal conductivity(6)		Limited data	2.3–3.8 W/mK (Briaud 2013)
Electrical resistivity(6)		> 2000 Ω cm	50–2000 Ω·m (Briaud 2013) 500–1500 Ω·m (Das 2016)
pH		7.1–8.7	Varying with geology

1 *Standard compaction.*
2 *1.63–1.94 t/m^3 for poorly-graded sand (SP), and 1.78–2.14 t/m^3 for well-graded sand (SW).*
3 *21–12% for poorly-graded sand, and 16–9% for well-graded sand.*
4 *Standard compaction. Data extracted from one single study on crushed glass classified as SW-SM.*
5 *10–20% for poorly-graded sand, 15–40% for well-graded sand.*
6 *Parameters varying largely with chemical composition, density, particle packing and moisture content.*

2.4 Environmental, and Work Health and Safety Considerations

2.4.1 General

As well as engineering properties of RCG needing attention in specification development, it is also crucial to allow for the assessment of environmental and public health risks.

In 2011, AusTox, a toxicology and occupational health consultant undertook a WHS and environmental risk assessment of RCG for the Australian Food and Grocery Council (AFGC) and its Packaging Stewardship Forum (Winder 2011). The assessment included an analysis of the abrasiveness of RCG, and the exposure to dust and potential long-term health issues. A significant additional output of the AusTox work was the development of practical guidelines and control measures for the safe use of RCG. This report also included a draft generic Material Safety Data Sheet (MSDS) for RCG products.

Waste glass quality and impurity content depend on feedstock, and it is anticipated that the overall processing (screening, crushing and if required washing) of the glass will generate a consistent clean product and mitigate any potential short- and long-term risks to the general public, workers and the environment. The control measures directly related to the processing of the glass were examined in depth in this project, with the aim to provide guidelines for the processing of RCG. In this section of the document, the WHS and environmental risk considerations related to the use of RCG are discussed. Risks and control measures related to material handling, dust and leachate are considered in more detail in the following sections.

2.4.2 Handling and Abrasion Risks

In a study undertaken under the management of the CWC, Shin and Sonntag (1994) investigated 29 sources of recycled glass cullet with a range of properties and contamination levels. It concluded that crushed glass particles for glass cullet smaller than 19 mm generally present no greater skin cut or penetration hazards compared to conventional crushed construction aggregates. The RCG of smaller maximum particle size (below 6 mm) contained less than 1% of flat particles and were considered benign concerning skin cut or penetration hazard.

Overall, in working with RCG, safety measures include wearing personal protective equipment (PPE) such as protective clothing (e.g. long sleeves and pants, gloves, work boots) that can help reduce skin irritation. Utilising PPE similar to protective measures adopted for natural aggregates is also recommended by the NSW DECC (2007) to avoid any eye and/or skin damage.

The AusTox report (Winder 2011) corroborates these general conclusions however it reported potential problems of abrasion with particles greater than 5 mm which can include elongated and angular-shaped particles. For RCG crushed to smaller sizes (e.g. around 3 mm), particles are rounder in shape and present lower risk of skin injury. Control measures include standard work practices and PPE. The use of PPEs is also outlined in the EPA Victoria Fact Sheet (EPA Victoria 2019) referring to recycling glass fines as RCG particles generally passing 5 mm.

Another risk of working with RCG is inhaling the dust from the airborne particles of RCG which also poses a risk of abrasion to the eyes. These issues are discussed in the next section.

2.4.3 Dust and Airborne Contamination

Amorphous silica is relatively benign to human health, but exposure to crystalline silica needs to be appropriately managed to avoid long term health issues (e.g. silicosis and lung cancer).

The research by Shin and Sonntag (1994) discussed in Section 2.4.2 also included a safety analysis and an assessment of the crystalline silica concentrations found in the 29 sources of glass cullet examined. The concentration measured in the glass dust was below 1%. During compaction of the tested crushed glass, the dust concentration was found to be below 0.5 mg/m^3, well below the permissible limit of 10.0 mg/m^3 in the US legislation at the time of testing.

More recently, the AusTox occupational health safety and environmental risk assessment report (Winder 2011) concluded that the silica in glass is mainly amorphous and that RCG can be considered safer than natural sand as it contains less respirable crystalline silica. There may be some hazards when using and handling RCG, but they can be controlled using standard workplace practices and personal protection. This report provides clear guidance about risk management and mitigation strategies. This includes avoiding situation with high concentration of dust and handling the material in well-ventilated areas or using mechanical or exhaust ventilation. In addition, exposure can be controlled by using PPE compliant to suitable standards include clothing (e.g. overall, long sleeve clothes, work boots), dust respirator, eye protection (e.g. safety glasses, face shield or goggles), hands (skin) protection (e.g. gloves suitable for handling an abrasive material).

In 2019, EPA Victoria developed a Fact Sheet (EPA Victoria 2019) which discusses, though not in detail, issues including the impact of air emissions, dust, and odours. The Fact Sheet defined glass fines as having less than 2% of physical contaminants, such as plastics, timber, paper and cardboard and to be ‘free of residue that can produce odour’. Odour issues are therefore seen by the EPA Victoria document as being mitigated in the processing of washing the glass fines. Regarding other issues it recommends the following when using glass fines:

- Personal protective equipment (PPE) should be utilised to prevent exposure to the proportion of crystalline silica from the RCG.
- Glass dust can cause skin, ear and eye irritation, which should be controlled by the use of eye and ear protection – minimising the exposure by wearing PPE will also protect workers from any cuts or wounds.
- Training for workers should also be provided, especially for hazard and dust control programs.

Dust, whether natural material or glass dust, is less likely to be moved by wind and to suspend in the air when it is moist rather than dry. Dust suppression measures are therefore to be considered and include specifying RCG is supplied moist and stockpiles are hosed down.

Also, EPA Victoria reported that the inappropriate storage or use of glass fines may result in EPA Victoria issuing a remedial notice to remove the material and also return the environment to its previous condition (EPA Victoria 2019). Risk management of RCG storage facilities needs to consider mitigation of the fire, leachate, odour and dust risks from RCG stockpiles.

In NSW, DECC and Sydney Water trial of recycled glass fines as pipe embedment material also assessed WHS issues (DECC 2007). The study report contends that dust generated by recycled glass cullet does not contribute to silicosis or cancer. The general conclusion states that the dust generated by recycled glass fines is no more harmful than the generation of dust from virgin sand. To minimise dust exposure, it is suggested that crushed glass should be supplied moist and to wear appropriate protective equipment. As an indication, the crushed glass sand and blend used in the trial were delivered at moisture content of at least 6% to mitigate this risk.

In order to provide input to the development of TMR MRTS36:2020 specification for recycled glass aggregate, ARRB and TMR measured the variability of RCG produced in Queensland to assess the risk of silicosis relative to the amorphous and crystalline silica content as part of a National Asset Centre of Excellence (NACOE) project. As reported in Latter (2020), this included testing nine RCG samples collected from five suppliers in Queensland over a six-month period from late-2019 to mid-2020. The test results indicated that the crystalline silica content of RCG did not typically exceed 1% and that natural sand contains significantly greater proportions of crystalline silica than RCG.

The study determined that the risk of exposure to respirable crystalline silica is reduced when working with RCG compared to when working with natural and manufactured sands of the same volumes. In line with the current recommendations, Latter (2020) noted that WHS controls should still be implemented when working with RCG, manufactured sand, and/or natural sand dust.

2.4.4 Chemical Composition and Leachate Potential

Australasian studies

Chemical composition and leaching tests have an important role in providing information to support the assessment of potential environmental and human health risks associated with the use of RCG. These tests help determine the concentrations of chemical constituents which may make their way to environmental and human receptors and other physical parameters. The magnitude, rate of leaching and concentrations of the chemicals depend on site-specific conditions (e.g. geology, groundwater and surface water). Glass samples collected as part of the DECC NSW and Sydney Water recycled glass fines trial, for instance (see Appendix A.1) were tested for numerous chemical and physical contaminants including:

- a range of metals and other inorganics
- pesticides
- polycyclic aromatic hydrocarbons (PAH)
- polychlorinated biphenyls (PCB)
- volatile organic compounds (VOC)
- total petroleum hydrocarbons (TPH)
- other general organics and nutrients
- biochemical oxygen demand (BOD)
- chemical oxygen demand (COD)
- total suspended solids.

The samples were also examined for asbestos, and the pH and electrical resistivity of the glass samples were determined. The results (DECC 2007) concluded that chemical or physical contaminants were not notably identifiable in the samples, and although the presence of metals and a variety of other organic pollutants were detected, the concentrations were not at any level of concern. Rather, pollutants were well below the limits for soil investigation levels as outlined in the National Environment Protection (Assessment of Site Contamination) Measure 1999. It was noted that the main metal present was aluminium, but again the level was within the standard limit and DECC (2007) therefore concluded that it does not pose a threat to human health or the environment.

Similar testing is reported by Imteaz, Ali and Arulrajah (2012) relative to five samples, from a single Melbourne-based recycling company, of a RCG product used as an aggregate in pavement subbases. The leachate collected from the waste glass stockpiles was sampled and analysed for specific contaminants. The results were compared to EPA Victoria Guidelines and National Australian Standards (where applicable). The testing parameters included in each sample were for heavy metals, organics, conductivity, pH, chlorides, sulfates and surfactant levels. The results concluded that most of the tests revealed that contamination levels for the RCG were within the EPA Victoria Guidelines specified for manual handling. RCG was deemed to have passed as a safe and viable material for use in road and pavement construction, not posing an excessive or disproportionate threat to the environment.

Another approach to assessing contaminant presence is based on the total concentration of potential contaminants. A National Asset Centre of Excellence (NACOE) project included the chemical testing of nine RCG samples sourced from five suppliers (Latter 2020). The maximum concentration limits for chemicals and other attributes were assessed to determine if the (then proposed) limits for the TMR specification were suitable for use in pavement applications, as well as other uses such as pipe bedding, drainage medium, or concrete from an environmental perspective. This assessment was undertaken by an experienced, suitably qualified person (SQP), with appropriate waste characterisation and contaminated land experience[3]. The assessment considered maximum chemical concentrations and leachate testing on the use of up to 100% RCG. The findings from the assessment undertaken by the SQP for Latter (2020) are summarised as follows (Wright 2020):

- The characteristics of RCG are consistent with those expected for natural materials or clean fill, including gravel and sand commonly used in road applications.
- There are no issues of concern in relation to risks to human health, for any location where RCG is used in road/pavement materials or as pipe bedding materials.
- There are no issues of concern in relation to potential risks to the environment (terrestrial or aquatic) that may be adjacent to roadways and pavements where RCG is used in road and pavement materials, or pipe bedding materials.

For chemical composition, TMR adopted specifications limits (MRTS36:2020) consistent with NSW EPA (NSW EPA 2014a) as are presented in Table 2.6. It is to be noted that the selected concentration limits for the specification are equal to or more stringent than the reviewed limits from Victoria, NSW, SA and Queensland. These requirements are proposed for adoption in the Austroads technical specification framework (Section 3.5.6).

3 Under the Queensland *Environmental Protection Act 1994*, a SQP is a professional that has the necessary qualifications and experience to assess contaminated land and to ensure that risks to human health and the environment have been appropriately managed.

Table 2.6: Review of RCG specification against criteria for natural materials or clean fill

Metals	Technical specification RCG maximum concentration limits (mg/kg dry weight unless otherwise specified)		Criteria available for defining clean fil or natural materials (not considered contaminated and not of concern to health or the environment) (mg/kg)				
	Maximum average concentration for characterisation	Absolute maximum concentration	EPA Victoria – Clean fill	NSW EPA – Excavated Natural Material (ENM)		SA EPA – Waste derived fill	Queensland – suggested residual soil levels
				Maximum average	Absolute maximum		
Mercury	0.5	1	1	0.5	1	1	3
Cadmium	0.5	1.5	3	0.5	1	3	4
Lead	50	100	300	50	100	300	60
Arsenic	10	20	20	20	40	20	50
Chromium (total)	20	40	1 for Cr VI(1)	75	150	400 Cr III and 1 Cr VI(1)	50
Copper	40	120	100	100	200	60	200
Molybdenum	5	10	40	NA	NA	NA	NA
Nickel	10	20	60	30	60	60	60
Zinc	100	300	200	150	300	200	400

1 *Chromium VI is not the predominant form of chromium present in the environment and is typically present as a result of industrial processes. Organic matter in soil is expected to convert chromium VI to insoluble chromium III oxide. Chromium is most commonly present as chromium III.*

Source: Wright (2020).

Additional international studies

The report prepared for CWC targeted some environmental properties of glass cullet and its leachate characteristics (CWC 1998). The findings concluded that the chemical properties were all within safe ranges, implying they do not pose any problems to construction aggregate users. However, lead concentrations need to be tested and possibly reduced prior to including glass cullet in road base applications. CWC findings state that while lead may be present its concentrations can be variable. The variability has been attributed to the presence of wine bottle neck wraps and the varying degree of lead in different glass feedstocks.

The glass evaluation by CWC (1998) also concluded that the concentration levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), pH levels, and specific conductivity, were low, decreased over time, and were not of concern. The suspended and dissolved solids concentrations were also low and difficult to measure. Furthermore, the metal concentrations in the glass cullets were at or below metal concentrations found in areas with high background levels of granite. These concentrations were also not of concern. However, semi-volatile organic concentrations might be an area requiring attention. During the CWC Glass Feedstock Evaluation, the existence of phthalates and levels of polycyclic aromatic hydrocarbons (PAHs) were identified from the semi-volatile organic test results. The regulatory limits vary across the USA; however, the levels measured in the study were not considered to be of concern by CWC (1998). The PAH content found in the glass cullet was attributed to both phthalates and residual oil contamination attributed to plastic bottles from commingled waste glass collection.

According to the Texas Department of Transportation (Nash et al. 1995), the Texas Commission on Environmental Quality (TCEQ) had identified environmental uses of this material in roadway construction, and that laboratory testing proved that no noticeable negative environmental impacts, including leaching, were detected.

More recently, as part of a residential housing project in Tumwater, Washington trialled glass cullet as both a substitute fill material for a slab-on-grade foundation capillary break and waterline pipe zone bedding (Northwest EcoBuilding Guild 2018). The environmental management process used the Construction Inspectors Guide to Recycled Glass Aggregate by CWC (CWC 1995) to ensure that glass aggregate could be used as a substitute for natural aggregate such as sand for fill/bedding material applications. The crushed glass for the project was cleaned and freed of debris before use. Samples were collected and sent to independent environmental laboratories to test for copper and lead content. The certified lead amount was measured against the ASTM D75/D75M:2014, *Standard Practice for Sampling Aggregates*, tested using US EPA SW-846 Test Method 3010A, *Acid Digestion of Aqueous Samples and Extracts for Total Metals for Analysis by Flame Atomic Absorption Spectroscopy (FLAA) or Inductively Coupled Plasma Spectroscopy (ICP)* and SW-846 Test Method 6010D, *Inductively Coupled Plasma: Atomic Emission Spectrometry,* and concluded a total lead content level of no more than 250 ppm was considered acceptable. It is worth noting that this level of concentration is above the lead maximum average concentration limit of 50 mg/kg suggested by the NSW EPA (2014a) requirements.

2.4.5 Sustainability Benefits

Recycling waste glass as a pavement material can have significant sustainability benefits in terms of resource conservation and greenhouse gas (GHG) emission reduction. Importantly, these sustainability benefits are recognised by sustainability rating schemes such as the IS Rating Scheme implemented by the Infrastructure Sustainability Council of Australia. Specifically, in the IS Rating Scheme, the use of RCG in road infrastructure is likely to attract higher rating scores under the assessments of resource efficiency, and energy and carbon – contributing to the overall sustainability rating of the road project (Infrastructure Sustainability Council of Australia 2021).

In the following sections, sustainability impacts of incorporating RCG in road infrastructure are discussed in greater detail, with the potential benefits, existing applications and ongoing challenges with the use of RCG to achieve greater sustainability highlighted.

Resource conservation benefits

Waste glass can be employed as partial or total virgin aggregate replacement, depending on the application, facilitating a reduction in the depletion rate of natural resources. Global environmental and resource depletion issues can be mitigated through the effective utilisation of waste materials. Among waste materials, glass is the only material that can be reprocessed more than once while preserving its chemical characteristics. Therefore, the reuse of RCG in road infrastructure is an ideal avenue from a sustainability and economic viewpoint. A few of the major environmental benefits of using RCG in road infrastructure are as follows (Shi & Zheng 2007):

- reduced waste disposal costs, which are likely to rise due to the introduction of a landfill tax
- extended life of our landfill sites
- significant savings in energy and reductions in the amount of CO_2, NOx, and other air pollutants associated with the production of aggregates, cement, or material processing
- increased public awareness of the problems associated with waste management and the benefits of recycling
- offers many alternative uses for recycled glass-based products, without compromising on either cost or quality.

RCG's sustainability benefit in terms of resource conservation is already recognised by some Australian road agencies. Local Government Authorities are also using RCG on their networks to demonstrate their green credentials. For example, the Waverley Council substituted 15 tonnes of glass cullet into their road projects, of which 7.5 tonnes went into asphalt and 7.5 tonnes into concrete. In 2010, there was an estimated 75 000 tonnes of fine crushed glass available in New South Wales. If the concrete industry were to use this glass as a fine aggregate, it would save 75 000 tonnes of natural sand which typically costs $30 per tonne (Department of Agriculture, Water and the Environment 2021a). As another example, it has been reported that the Southern Sydney Regional Organisation of Councils typically use approximately 9 000 m^3 of concrete. If this concrete used 30% glass-sand as a fine aggregate replacement, then more than 2 000 tonnes of virgin sand could be replaced with glass. The use of RCG in road applications is intended to support a more sustainable society (Edge Environment 2012).

GHG emission reduction

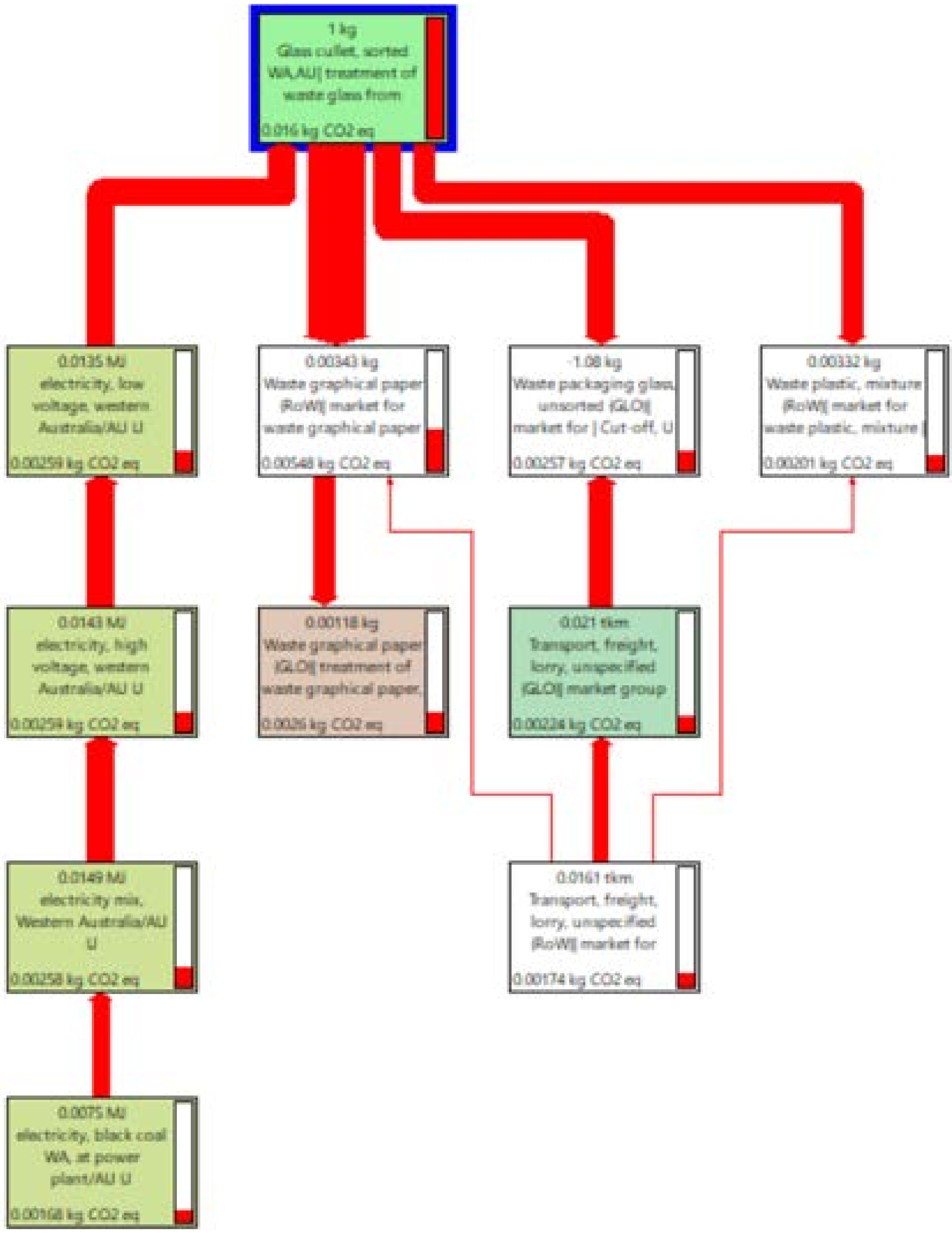
Another potential sustainability benefit of using RCG in pavement construction is its impact on mitigating climate change. Climate change refers to changes in climate patterns, including heat waves, coastal inundation due to sea level rise, disruptions to rainfall patterns and other effects (Department of Agriculture, Water and the Environment 2021b). It can have a multitude of detrimental effects on current and future generations of human and natural systems.

The general use of RCG may contribute to a reduction in the greenhouse effect of climate change by avoiding the GHG emissions associated with the landfilling of waste glass. For example, Turner, Williams and Kemp (2015) found that, when compared to virgin glass, the use of recycled glass will result in a GHG saving of 314 kg CO_{2e}/t – a 79% reduction.

Assessing the impact of RCG on GHG emissions in the context of road construction is more complicated. On one hand, emission modelling using a life-cycle analysis (LCA) tool called SimaPro has found that an equivalent mass unit of RCG has a higher embodied emission factor (16 kg CO_{2e}/t) than virgin sand (3.4 kg CO_{2e}/t). As shown in Figure 2.1 and Figure 2.2, the higher emission factor of RCG can be attributed to the vehicle emissions generated when waste glass is moved to the recycling facility and the energy use that goes into treating the waste glass. However, it should be noted that between 200 and 1600 kg of GHG generated from landfill activities is avoided by recycling a tonne of waste glass (Department of Industry, Science, Energy and Resources 2021). This upstream 'carbon credit' should therefore be considered when comparing the overall sustainability impact of using virgin sand and RCG in road construction.

There is also indirect evidence to suggest that accounting for upstream sustainability benefits is important when justifying the sustainability merit of RCG as a pavement material. Salehi et al. (2021) found that there was a mix of evidence in the existing literature on the relative life-cycle sustainability performance of RCG as a pavement material – some studies found its use translated into a reduction of life-cycle emission, whilst others found the opposite after accounting for the higher maintenance needs of road infrastructure incorporating RCG. It should be noted that these studies did not explicitly account for the 'carbon credit' of recycling waste glass obtained from avoiding upstream disposal methods such as landfill. Consequently, the overall sustainability benefits of using RCG as a pavement material for the purpose of mitigating climate change might have been understated.

Figure 2.1: Breakdown of embodied GHG emission factor of RCD



Source: ARRB analysis using SimaPro.

Figure 2.2: Breakdown of embodied GHG emission factor of virgin (natural) sand

Source: ARRB analysis using SimaPro.

3. Development of Specification for RCG as a Granular Aggregate Replacement

3.1 RCG Specifications in Other Industries

3.1.1 Early Development of RCG Specification

The current specifications for the use of RCG in Australia's transport infrastructure vary between the states and territories. However, previous research has been conducted to provide a common standard for the use of RCG as a material in specific road engineering applications. In a report, prepared for the Packaging Stewardship Forum of the Australian Food and Grocery Council, Andrews (2010) developed two specifications for the use of RCG in selected road infrastructure as follows:

- Specification 1: RCG for blending with natural unbound aggregate for various applications
  - use of RCG for blending with either naturally occurring sands or crushed fine aggregates prior to forming an RCG/natural aggregate mix (through mixing with other, coarser components) for uses in:
    - sealed road subbases or granular basecourses
    - unsealed road wearing courses
    - bedding/backfill material applications for pipes/cables and block pavers.
- Specification 2: RCG for use as fine aggregate in asphalt and concrete
  - use of RCG as a fine aggregate in asphalt and concrete mix designs when blended with either naturally occurring sands or crushed fine aggregates.

The specification of RCG for bedding/backfill applications of relevance to this review recommended by Andrews (2010) is provided in Table 3.1. This specification has been implemented by the Northern Territory Department of Infrastructure, Planning and Logistics road works specification (DIPL Specification v4.2) for bedding materials.

Table 3.1: Specification for the use of RCG in applications such as bedding/backfill

<table>
<tr><th colspan="4">Source materials</th></tr>
<tr><td colspan="4">• The material shall consist of recycled glass food and beverage containers, drinking glasses, window (or flat) glass and plain ceramic. Glass from hazardous waste containers, reinforced and laminated glass, light bulbs, fluorescent tubes and cathode-ray tubes shall not be included.
• The source shall be free of debris such as paper and cardboard, plastic, fabrics and toxins.
• The material shall be washed post crushing to remove odours, traces of original contents, soil, sugars and labels, etc.</td></tr>
<tr><th colspan="4">Blending</th></tr>
<tr><td colspan="4">RCG may be blended with natural gravels, crushed gravels and natural borrow sources. The percentage of RCG that may be incorporated into the final product can be determined from analytical computation of respective constituent particle size distributions. Final blends shall be manufactured, sampled and tested to determine compliance with the relevant target product specification viz:
• granular basecourse as defined in the relevant specifications
• granular subbase as defined in the relevant specifications
• unsealed wearing course recommendations in accordance with Austroads Pavement Technology Series Part 6: Unsealed Pavements (Austroads 2009) or other local specification
• engineering fill as defined in the relevant specifications
• natural or crushed sands for use as pipe or block paving bedding as defined in the relevant specifications.</td></tr>
<tr><th colspan="4">The manufactured RCG shall comply with the quality requirements as given below</th></tr>
<tr><th colspan="4">PRODUCTION QUALITY CONTROL</th></tr>
<tr><th>TEST</th><th>STANDARD</th><th colspan="2">REQUIREMENT</th></tr>
<tr><td rowspan="7">Particle size distribution</td><td rowspan="7">AS 1141.11</td><th>Sieve size</th><th>Per cent finer</th></tr>
<tr><td>9.5 mm</td><td>100</td></tr>
<tr><td>4.75 mm</td><td>85–100</td></tr>
<tr><td>2.36 mm</td><td>50–85</td></tr>
<tr><td>1.18 mm</td><td>20–55</td></tr>
<tr><td>0.3 mm</td><td>5–20</td></tr>
<tr><td>0.075 mm</td><td>0–10</td></tr>
<tr><td colspan="4">NOTE: Material coarser than 4.75 mm shall not have more than 1% particles with a maximum to minimum dimension of 3:1</td></tr>
<tr><td>Contaminants</td><td>Asbestos
Metal
Plaster and friable materials
Rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter</td><td colspan="2">0
0.1% by mass
2% by mass
0.2% by mass</td></tr>
<tr><td>Sampling</td><td colspan="3">Production sampling and specification compliance testing shall be carried out in accordance with the test procedures identified at a frequency of not less than one suite of tests per 1000 tonnes. Unless sampled within the plant during manufacture, RCG product shall be stacked in holding stockpiles not exceeding 1000 tonnes until such time as compliance has been determined.</td></tr>
<tr><td>Product stockpiles</td><td colspan="3">Conforming material may be stored in certified stockpiles identified as conforming to the requirements of this specification.
Certified stockpiles must be formed on firm ground that is clean, well-drained and free of all foreign material which might contaminate the material to be certified. This includes but is not limited to all forms of vegetation both dead and alive, topsoil, and material containing oils or oil deposits and remnants of previous stockpiles of dissimilar material.
Only compliant material may be added to a certified stockpile.</td></tr>
</table>

Source: Adapted from Andrews (2010).

3.1.2 The Water Services Association of Australia Specification

The Water Services Association of Australia (WSAA) has also developed a specification for RCG sand used for pipe embedment (WSA PS 368:2020). This specification has the following requirements for RCG sand:

- RCG sand shall be recovered and processed from the collection of domestic and/or commercial commingled recycled waste.
- RCG sand shall not include glass recovered from the sorting or processing of mixed municipal, commercial, and industrial waste; construction and demolition waste; cathode-ray tubes; fluorescent and incandescent lights; or other glass recovered from electrical equipment.
- RCG sand shall have a resistivity of 1500 Ω cm in accordance with AS 1289.4.4.1:2017.
- RCG sand shall have a pH ranging between 5 and 9 in accordance with AS 1289.4.3.1:1997.
- The wet strength of RCG sand shall be less than 80 kN, with a wet/dry strength variation not exceeding 20% in accordance with AS 1141.22:2019.
- RCG sand material suppliers shall have a current exemption or licence for recovery with the relevant state or territory environmental authority.

It is important to note that the WSAA specification excludes RCG sand replacement that has been sourced from ‘the sorting or processing of mixed municipal…waste’, presumably excluding kerbside collected domestic waste glass

The WSAA specification (WSA PS 368:2020) sets grading requirements for recycled glass sand for pipe embedment which are relatively consistent with the WSAA Grade A specified for compaction sand, both shown in Table 3.2. However. The WSA PS 368:2020 grading envelope is different to the grading proposed for RCG sand by Andrews (2010). Further comparison with grading requirements from current road works specifications will inform the selection of grading envelope for ‘generic RCG products’ (Section 3.4).

Table 3.2: Water Services Association of Australia grading requirement for pipe embedment

AS sieve size (mm)	Percentage passing by mass		
	Recycled glass sand	Compaction sand (WSA PS 350)	
	(WSA PS 368)	Grade A	Grade B(1)
6.7	100	100	–
4.75	85–100	95–100	100
2.36	–	85–95	90–100
1.18	65–80	65–80	85–100
0.6	50–70	50–70	70–100
0.3	30–50	30–50	50–100
0.15	5–12	5–12	0–40
0.075	3–8	3–8	0–5

1 *From table G3 of AS/NZS 2566.2:2002/Amdt 1:2013.*

3.1.3 The Metro Train Melbourne Specification

Metro Train Melbourne (MTM) has developed a recycled glass sand specification (Engineering specification L1-CHE-SPE-313:2019). The recycled glass sand may be used as a replacement of quarried sand for combined service route (CSR) installed in UPVC conduits and drainage piping.

The specification covers requirements about the source of the glass and the absence of risk to air, water and land contamination. The products shall be free of hazardous materials and shall be able to be classified as 'clean fill' in accordance with the EPA, Victoria guidelines and be provided with a Safety Data Sheet.

The specification covers the use as bedding and embedment materials (surrounding the pipe below backfill) and includes grading requirements presented in Table 3.3. Other aspects of the specification conditions can be found in Table A 1.

Table 3.3: MTM recycled glass sand grading requirement

Sieve size (mm)	Percentage passing by mass
4.75	100
2.36	75–100
0.075	0–5

1 *From Clause 9.2 of L1-CHE-SPE-313:2019.*

3.2 Chemical and Other Material Requirements

Environmental assessment and contamination limits developed in NSW provide a robust framework to the prevention of WHS and environmental risks for short and long-term impacts. Table 3.4 contains a list of chemical and other attributes that suppliers of RCG must comply with when supplying product under the NSW EPA recovered glass sand order (NSW EPA 2014a). Similar requirements were adopted in the TMR specification for recycled glass aggregate (MRTS36:2020).

Table 3.4: NSW EPA – chemical and other material requirements

Chemicals and other attributes	Maximum average concentration for characterisation (1)	Maximum average concentration for routine testing (1)	Absolute maximum concentration (1)
Mercury	0.5	Not required	1
Cadmium	0.5	0.5	1.5
Lead	50	50	100
Arsenic	10	Not required	20
Chromium (total)	20	Not required	40
Copper	40	Not required	120
Molybdenum	5	Not required	10
Nickel	10	Not required	20
Zinc	100	100	300
Total organic carbon	1.0%	Not required	2.0%
Electrical conductivity	1 dS/m	1 dS/m	2 dS/m
Metals	0.25%	0.25%	0.5%
Plaster, clay lumps and other friable materials	0.25%	0.25%	0.5%
Rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter	0.3%	0.3%	0.5%

1 *Units are in mg/kg 'dry weight' unless otherwise specified.*

Source: NSW EPA (2014a).

3.3 Overview of International Practice

A summary of the international specifications and requirements reviewed and presented in Appendix B.1 to B.10 is presented in Table 3.5. This table outlines the available information in terms of RCG application and its properties, including the maximum glass cullet/crushed glass aggregate content, maximum aggregate size, and maximum contaminant (debris) content. The key factor in the use of RCG as a replacement or supplement of natural granular soil is to ensure that the minimum requirement for each application is satisfied. It should be noted that the above-mentioned states/countries in addition to several other states or countries have specifications for the use of crushed glass in other geotechnical applications.

As detailed in previous sections, the definition of debris and its required limit varies between different specifications. For example, ceramic is permitted to be used as aggregate in Canada, while generally, it is among the prohibited items in other countries. However, non-glass materials including plastic, metal, wood, and papers are generally among the examples of debris in various specifications. Also, it should be noted that different international specifications may allow different types of aggregate grading designs for some applications, and the use of crushed glass is sometimes allowed only for specific types. It is advised that the reader refers to the provided specification for each country/state if further detailed information is required (refer to Appendix B).

Additionally, some of the international model specifications and technical requirements for the use of glass aggregate in different construction applications developed by the researchers over the last few decades as well as the selected national and international case studies for the use of RCG in bedding sand, drainage medium, embankment, fill, and landscaping applications are presented in Appendix E.

Table 3.5: International specifications for RCG as a replacement or supplement for natural granular soil

State/ country	Application	Maximum crushed glass/glass cullet content (%)	Maximum size of crushed glass/glass cullet (mm)	Maximum debris content (%)	Reference
Virginia/ USA	• Drainage medium • Embankment • Backfill[(1)]	90[(2)] for drainage medium: 100 [(3)]	9.5 (maximum 5% passing 0.075 mm sieve)	5	Virginia Department of Transportation (2020)
New York/ USA	• Embankment[(4)] backfill • Replacement for underdrain filter material (generally used in drainage systems)[(5)]	30 (for embankment)	9.5 12.7 (for underdrain filter material)	5	New York State Department of Transportation (2017)
South Carolina/ USA	• Embankment[(6)] • Fine aggregate underdrain material[(7)] • Constructing aggregate underdrains using granular filter materials[(8)]	25 (for embankment)	12.7	1	South Carolina Department of Transportation (2007)
Oregon/ USA	• Non-structural fill • Substitute for selected granular backfill[(9)]	100	12.7 & maximum 5% passing 0.075 mm sieve	10	Oregon Department of Transportation (2020) [(10)]
Washington/ USA	• Gravel backfill for drains • Backfill for sand drains • Sand drainage blanket • Gravel backfill for foundations • Gravel backfill for walls	20	9.5[(11)]	5[(11,12)]	Washington State Department of Transportation (2020)

State/ country	Application	Maximum crushed glass/glass cullet content (%)	Maximum size of crushed glass/glass cullet (mm)	Maximum debris content (%)	Reference
Alaska/USA	Embankment(4,13)	10	9.5	2	Alaska Department of Transportation and Public Facilities (2020)
Idaho/ USA	Embankment	–	9.5(11)	5(11,12)	Idaho Transportation Department (2018)
Connecticut/ USA	Embankment(14)	25	25.4	-	Connecticut Department of Transportation (2020)
Ontario/ Canada	Backfill	15(3)	13.2	1	OPSS.MUNI 1010:2013 (Rev 2017)
UK(16)	• General fill(17) • Fill to structures • Lower trench fill drainage layer to reinforced soil and anchored earth structures • Fill to reinforced soil and anchored earth structures • Starter layer	25(18)	–	–	Standards for Highways (2016)

1 *Crushed glass is permitted to be used as a crusher run aggregate for backfilling and bedding pipe applications.*
2 *For the roadway embankment application, the crushed glass must be a minimum of 2 ft inside the side slope and contain a minimum of 2 ft of soil embankment cap. Up to 90% of crushed glass can be used in the embankment area where glass is allowed to be employed.*
3 *100% crushed glass can be used for drainage application including blankets.*
4 *Glass must not be placed in contact with geotextiles, synthetic liners, geogrids, or other geosynthetic materials.*
5 *For this application, 90–100% shall pass a 9.5 mm sieve, and not more than 5% by weight shall pass a 0.075 mm.*
6 *RCG must not be used in the top 18 in. of the embankment.*
7 *RCG used as fine aggregate underdrain material shall meet the gradation requirements for aggregate No. FA-12 or FA-13.*
8 *RCG used for constructing aggregate underdrains using granular filter materials shall meet the gradation requirements of coarse aggregate No. 57.*
9 *The glass cullet needs to be placed in the trench in loose lifts of a maximum 8 in. to be compacted.*
10 *The use of reclaimed glass as a substitute for granular drainage blanket material and sand drainage blanket has been removed in this version.*
11 *Referred to the requirements of AASHTO M318 (AASHTO M318-02:2019).*
12 *No more than 5% of ceramics, china dishes, or plate glass is permitted. But any deleterious materials such as food residue, container tops, foil, wood, paper, or labels must be limited to a maximum of 1%.*
13 *RCG/soil mix shall not be placed within 4 ft from the face of the embankment slope, within 150 ft from any surface water body, and in the areas where culvert placement is needed.*
14 *Glass mix must not be placed within 5 ft from the face of the embankment slope.*
15 *A combined total of 15% of crushed glass and ceramic material.*
16 *Specification for 'Earthworks' including the national alterations of the overseeing organisations of Scotland, Wales, and Northern Ireland.*
17 *Recycled materials complying with BS EN 13242:2002+A1:2007 are permitted to be used in all these applications (for UK).*
18 *Where 'recycled aggregate except recycled asphalt' is used in this Series, it must contain a maximum of 5% of crushed glass.*

3.4 Australian and New Zealand Road Agency Specifications

The following tables summarise the material properties specified by the road agencies in Australasia based on application. These tables condense the engineering properties for bedding sand, drainage medium, embankment and landscaping applications which mostly relate to natural or quarried aggregate or sand materials.

The applications have been split into the following six categories for comparison:

- Section 3.4.1: Bedding and haunching of drainage pipes and conduits (Table 3.6 and Table 3.7).
- Section 3.4.2: Side zone and backfill of drainage pipes and conduits (Table 3.8).
- Section 3.4.3: Bedding and joint filling in segment/block paving applications (Table 3.9).
- Section 3.4.4: Bedding/filter material for drainage medium applications (Table 3.10, Table 3.11, Table 3.12 and Table 3.13).
- Section 3.4.5: Embankment fill and earthworks applications (Table 3.14, Table 3.15, Table 3.16 and Table 3.17).
- Section 3.4.6: Landscaping applications (Table 3.18).

Detailed information relating to each of the specifications, can be found in Appendix C.

3.4.1 Material Properties for Bedding and Haunching of Drainage Pipes and Conduits

Table 3.6: Summary of material properties for bedding and haunch of drainage pipes and conduits

Property	Australasia	NSW	Qld			SA
Specification reference	AS/NZS 3725:2007	TfNSW IC-QA-R11	TMR MRTS04			DIT RD-PV-S1, RD-DK-C1
Grading (% passing AS sieve) (mm)						
19	100	100	100	85–100	100	
9.5				25–55	85–100	
6.7						100
4.75						70–100
2.36	50–100	50–100	50–100	0–5	0–10	35–100
0.6	20–90	20–90	20–90			
0.425						25–70
0.3	10–60	10–60				
0.15	0–25	0–25				
0.075	0–10	0–10	0–10	0–2	0–2	8–23
Plasticity index (PI)		6 (max)				
Contaminants	Free from sticks, stones, and other deleterious material		pH 5–10(1), resistivity > 50 Ω.m(1), Chloride content < 200 mg/kg(2), Sulfate content < 1000 mg/kg(2)			
Notes			Well-graded aggregate Linear shrinkage maximum 6(4)	20 mm nominal(3) Linear shrinkage maximum 3(4)	10 mm nominal(3) Linear shrinkage maximum 3(4)	Must be crushed quarry product

1 *Applies when used to bed or backfill steel culverts.*
2 *Applies when used to bed or backfill steel culverts and resistivity is 10–50 Ω.m.*
3 *Where 10 mm or 20 mm nominal size aggregate is used, a geotextile (as per MRTS04 Clause 14.2.6) is required to surround all bedding material.*
4 *Linear shrinkage requirements are not applicable for recycled crushed glass.*

Table 3.7: Summary of material properties for bedding and haunch of drainage pipes and conduits, continued

Property	Tas	Vic		WA	ACT	NT
Specification reference	DSG 701	VicRoads 701	VicRoads 733	MRWA 404	TCCS MITS 03A	DIPL v4.2
Grading (% passing AS sieve) (mm)						
19	100	100	100	80-100	100	100
9.5						
6.7						
4.75						
2.36					50–100	50–100
0.6					20–90	20–90
0.425						
0.3					10–60	10–60
0.15					0–25	0–25
0.075	5–40	5–40	10–40		0–10	0–10
Plasticity index (PI)	20 (max)	20 (max)	2-10		6 (max)	6 (max)
Contaminants		Free from perishable matter and lumps.		Free from soluble salts, organic matter, and other deleterious matter.		
Notes	If swell ≥ 2.5%, maintain a mean moisture ratio of 92% during placement of overlying layers			Bedding shall be basecourse material, or other materials approved by the superintendent	Recycled materials in accordance with MITS 03I.	A clean granular material, RCG conforming to Specifications Section 9 (Andrews 2010) or a mixture of the two.

3.4.2 Material Properties for Side Zone and Backfill of Drainage Pipes and Conduits

Table 3.8: Summary of material properties for side zone and backfill of drainage pipes and conduits

Property	Australasia	NSW	Qld	SA	Tas	Vic		WA	ACT	NT
Specification reference	AS/NZS 3725:2007	TfNSW IC-QA-R11	TMR MRTS04	DIT RD-PV-S1, RD-EW-C2	DSG 701	VicRoads 701	VicRoads 733	MRWA 302	TCCS MITS 03A	DIPL v4.2
Sieve size (mm)	**Grading (% passing AS sieve) (mm)**									
75	100								100	
37.5			100[1], 100[2]		100	100	100	80–100		100
9.5	50–100		60–85[1], 100[2]						50–100	30–100
6.7				100						
4.75				70–100						
2.36	30–100		25–70[1], 70–100[2]	35–100				30–100	30–100	15–65
0.6	15–50								15–50	
0.425			10–40[1][2]	25–70						
0.075	0–25		3–30[1][2]	8–23	5–40	5–40	10–40	0–10	0–25	5–25
Plasticity index (PI)		2–12			20 (max)	20 (max)	5–20		2–12	2–15
Contaminants					Free from perishable matter and lumps			Maximum 1% organic matter		Free from organic matter and lumps of clay
Notes	Materials that break down when wetted shall not be used	Maximum particle dimension 53 mm	Linear shrinkage 8[1], 6[2] (max)	Must be crushed quarry product	If swell ≥ 2.5%, maintain a mean moisture ratio of 92% during placement of overlying layers			Can contain up to 20% glass cullet, linear shrinkage 1% max, CBR 12 min, CBR swell 1.5% max	Maximum particle size 50 mm	Linear shrinkage 2–6%, minimum CBR 30

1 *Applies to gravel.*
2 *Applies to loam.*

3.4.3 Material Properties for Bedding and Joint Filling in Segment/Block Paving Applications

Table 3.9: Summary of material properties for bedding and joint filling for block paving applications

Property	Australasia	NSW	Qld	SA	Tas	Vic	WA	ACT
Specification reference	Concrete Masonry Association of Australia PA02		TMR MRTS03	DIT RD-PV-S1	DSG 712	VicRoads 712	MRWA 505	TCCS MITS 07
Grading (% passing AS sieve) (mm)								
9.52	100		100		100	100		100
6.7				100				
4.75	95–100		95–100	70–100	95–100	95–100	100	95–100
2.36	80–100		80–100	35–100	80–100	80–100		80–100
1.18	50–85		50–85		50–85	50–85		50–85
0.6	25–60		25–60		25–60	25–60		25–60
0.425				25–70				
0.3	10–30		10–30		10–30	10–30		10–30
0.15	5–15		5–15		5–15	5–15		5–15
0.075	0–10		0–10	8–23	0–10	0–10	0–5	0–10
Moisture content					Maintained at uniform moisture content (1)		4–8% by mass (1)	4–8% and uniform when spread
Joint filling sand	Dry when spread, 100% passing 2.36 mm, 90–100% passing 1.18 mm, 60–90% passing 0.6 mm, 30–60% passing 0.3 mm, 15–30% passing 0.15 mm, 5–10% passing 0.075 mm		100% shall pass a 1.18 mm test sieve. Free of deleterious soluble salts or other contaminants likely to cause efflorescence or staining		Dry, free-flowing, 100% passing 1.18 mm sieve with 10–20% passing the 0.075 mm sieve.			Dry when spread, 100% passing 2.36 mm 90–100% passing 1.18 mm 60–90% passing 0.6 mm 30–60% passing 0.3 mm 15–30% passing 0.15 mm 5–10% passing 0.075 mm
Contaminants	Washed free of soluble salts or other contaminants which can cause or contribute to efflorescence		Free from soluble salts or other contaminants		Free from clay, dust, soft or flaky particles, shale, salt, alkali, organic matter, soil, or other deleterious substances		Free of organics and deleterious materials	Free of deleterious material, such as soluble salts or other contaminants which may cause efflorescence

1 *For stockpiled sand.*

3.4.4 Material Properties for Bedding/Filter Material for Drainage Medium Applications

Table 3.10: Summary of material properties for drainage medium applications

Property	NSW				Qld		
Specification reference	TfNSW IC-QA-R31:2020	IPWEA NSW Specification for supply of recycled materials for pavements, earthworks and drainage:2010			TMR MRTS03:2019		TMR MRTS04:2020
Application	Drainage backfill	Drainage backfill			Subsoil drains, backfill	Sand drains	Permeable fill material – drainage blanket material
Grading (% passing AS sieve) (mm)		D75	D20	D10	Type D		
100		100					
75		80–100					
37.5							
26.5			100				
19		5–10	80–100				
13.2			5–10	100			
9.5						100	
6.7							
4.75				0–10	100	90–100	
2.36						70–100	85
1.18						50–100	
0.6						20–70	
0.425							
0.3					< 10	0–40	
0.15						0–20	
0.075		0–5	0–5	0–5		0–5	< 5 (natural) < 10 (manufactured)
Max. plasticity index (PI)	2-12						
pH							
Processing and source	Clean, dry sand				Coarse sand	Natural sand or manufactured sand	
Contaminants		< 5% metal and ceramics, < 0.5% plaster, clay lumps and other friable materials, < 0.5% rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter				Shall be free from soluble salts, organic matter, and other deleterious matter	
Notes	Maximum particle dimension 53 mm					Linear shrinkage (LS) < 3% and 6% (for natural sand and manufactured sand respectively)	

Table 3.11: Summary of material properties for drainage medium applications, continued

Property	SA	Vic					
Specification reference	DIT RD-DK-C1	VicRoads 204:2015		VicRoads 701:2020			VicRoads 702:2019
Application	Bedding	Permeable fill material – drainage blanket material		Bedding	Selected backfill	Ordinary backfill	Granular filter material
Grading (% passing AS sieve) (mm)		A6	B4				
100							
75						100	
37.5		100			100		
26.5							
19		85–100	70–100	100			
13.2			0–70				
9.5		65–100	0–25				
6.7							
4.75	100	48–82					
2.36	70–100	30–60	0–5			5–40	
1.18	35–100	15–40					
0.6		5–25					
0.425							
0.3	25–70	0–10					
0.15		0–5					
0.075		0–3	0–3	5–40			
Max. plasticity index (PI)	8–23			20			
pH							6.0–8.0
Processing and source		Hard, durable, clean sand, gravel or crushed aggregate					Hard, durable and clean sand, gravel or crushed rock
Contaminants	Crushed quarry product only	Free of clay balls and perishable matter		Free from perishable matter and lumps			Free from clay balls and organic matter
Notes	Sa-C, Type C Sand						Material passing 4.75 mm AS sieve shall have a Sand Equivalent value not less than 80

Table 3.12: Summary of material properties for drainage medium applications, continued

Property	WA	ACT			
Specification reference	MRWA 304:2019	TCCS MITS 03I:2019			TCCS MITS 03A:2019
Application	Pipe backfill	Trench drains and drainage mats		Subsoil drains	Drainage backfill
Grading (% passing AS sieve) (mm)					
100					100
75					
37.5					
26.5					
19					
13.2					
9.5				100	50–100
6.7		100			
4.75		85–100	100	98–100	
2.36		0–40	95–100	70–100	30–100
1.18		0–5		30–78	
0.6				2–15	15–50
0.425		0–2	20–80		
0.3			0–30	0–4	
0.15			0–2	0–1	
0.075			0–0.1		0–25
Max. plasticity index (PI)					2–12
pH		6.0–7.0 (where subsoil drains are laid in or adjacent to planted areas)			
Processing and source	Clean sand	Crushed rock or granular material	Granular material	Drainage sand	
Contaminants	Free from rocks, rubble, and sharp objects			Clean, washed	
Notes		Clean, hard, tough, durable particles Type A filter material	Type B filter material	Type E filter material	

Table 3.13: Summary of material properties for drainage medium applications, continued

Property	NT		NZ	
Specification reference	DIPL 2020, *Standard specification for roadworks*: v4.2.		NZTA F/5:2000	NZTA F/2:2013
Application	Bedding	Drainage backfill	Filter sand	Filter material
Grading (% passing AS sieve) (mm)				
100				
75				
37.5		100		
26.5				100
19	100			
13.2				85-100
9.5		30–100	100	80–95
6.7				
4.75			90–100	65–85
2.36	50–100	15–65	80–100	50–70
1.18			50–95	35–55
0.6	20–90		30–75	18–40
0.425				
0.3	10–60		10–30	3–25
0.15	0–25		< 10	< 8
0.075	0–10	5–25	0	0
Max. plasticity index (PI)	6	2–15		
pH				
Processing and source	Recycled crushed glass		Clean, hard sand	Clean, durable stone, or a mix with clean hard sand
Contaminants	Clean granular material free from sticks, stones and other deleterious material			
Notes	A clean granular material, RCG conforming to Specifications for Recycled Crushed Glass as an Engineering Material Section 9 or a mixture of the two.	Maximum particle size 50 mm	Linear shrinkage 2–6%, minimum CBR 30	Crushing resistance of not less than 100 kN

3.4.5 Material Properties for Embankment Fill and Earthworks Applications

Table 3.14: Summary of material properties for embankment fill and earthworks applications

Property	NSW			Qld	
Specification reference	**TfNSW IC-QA-R11:2020**	**TfNSW IC-QA-R44:2020**	**IPWEA NSW Specification for supply of recycled materials for pavements, earthworks and drainage:2010**	**TMR MRTS04:2020**	
Application	**Fill material for embankments in open drains**	**General Earth Fill**	**Select fill**	**Backfill**	
Grading (% passing AS sieve) (mm)				Sand	Coarse sand
200		100			
100			100		
75			95–100		
37.5		60–100			
26.5			50–85		
19					
13.2			40–80		
9.5					
6.7					100
4.75			35–70	85–100	
2.36					
1.18					
0.6	20–60				
0.425					
0.3					
0.15				≤ 5 (natural) ≤ 10 (manufact.)	≤ 10
Max. plasticity index (PI)	15–30		12		
Processing and source				Natural sand, manufactured sand, or a blend	
Contaminants		Free of deleterious material	< 5% metal and ceramics, < 1% plaster, clay lumps and other friable materials, < 0.2% rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter	Free of soluble salts, organic matter and other deleterious matter	
Notes				Linear shrinkage ≤ 3 (natural) ≤ 6 (manufact.)	Linear shrinkage ≤ 3

Table 3.15: Summary of material properties for embankment fill and earthworks applications, continued

Property	SA	Vic			
Specification reference	DIT RD-EW-C2	VicRoads 204:2015			
Application	Trench backfill	Permeable fill material – against structures & for backfill for open jointed pipes			Type A, B, C fill material
Grading (% passing AS sieve) (mm		A4	A5	A6	
200					
100					
75					
37.5					
26.5			100	85–100	
19			90–100		
13.2		100	70–100	65–100	
9.5	100				
6.7	70–100	70–100	28–100	48–82	100
4.75	35–100	0–50	0–28	30–60	
2.36		0–10	0–8	15–40	
1.18				5–25	
0.6	25–70				
0.425		0–5	0–5	0–10	
0.3				0–5	
0.15	8–23	0–3	0–3	0–3	
0.075					
Processing and source	Crushed quarry product only	Crushed to a cubic shape			Crushed to a cubic shape
Contaminants		Free of clay balls and perishable matter			Classified as clean fill
Notes	Sa-C, Type C sand	Hard, durable, clean			Registration required Acquired from VicRoads accredited source

Table 3.16: Summary of material properties for embankment fill and earthworks applications, continued

Property	WA		ACT
Specification reference	MRWA 302:2019		TCCS MITS 02B:2019
Application	Glass cullet for embankment construction	Glass sand for embankment construction	General fill
Grading (% passing AS sieve) (mm)			
200			
100			
75			
37.5			
26.5			
19			
13.2	100		
9.5			
6.7	70–100		
4.75	35–88		
2.36	15–45		
1.18			
0.6			
0.425	4–12		
0.3			
0.15	0–5		
Max. plasticity index (PI)			
Processing and source	Sourced from food and beverage containers, building or window glass	Sourced from recovered C&D waste	
Contaminants	Maximum % retained on 4.75 mm; 5% high density materials (brick, tiles), 2% low density materials (plastic, plaster), 1% organic	Free of contaminated soils and other deleterious materials Maximum % retained on 4.75 mm; 10% high density materials (brick, tiles), 3% low density materials (plastic, plaster), 1% organic	Free of tree stumps, roots, clay, topsoils, steel, organics, and other contaminants
Notes	Comply with Department of Water and Environmental Regulation (DWER) requirements for recycled materials	California Bearing Ratio (CBR) > 12%, linear shrinkage < 3%	Maximum particle size 75 mm (top 150 mm below subgrades), 100 mm (top 600 mm), 300 mm (top 1 m)

Table 3.17: Summary of material properties for embankment fill and earthworks applications, continued

Property	NT	NZ
Specification reference	**DIPL 2020, *Standard specification for roadworks:* v4.2.**	**NZTA F/1:1997**
Application	**Fill material**	**Granular fill material**
Grading (% passing AS sieve) (mm)		
200		
100		
75		
37.5		
26.5		
19		
13.2		
9.5		
6.7		
4.75		
2.36		
1.18		
0.6		
0.425		
0.3		
0.15		< 35
Max. plasticity index (PI)	2–15	
Processing and source		
Contaminants	Free from organic matter	
Notes	Maximum particle size 50 mm (subgrade), 100 mm (other layers) Soaked CBR at 95% MDD of 20%, to AS 1289.6.1.1	

3.4.6 Material Properties for Landscaping Applications

Table 3.18: Summary of material properties for landscaping applications

Property	WA	ACT
Specification reference	MRWA 301:2019 MRWA 304:2019	TCCS MIS 24:2019 TCCS MITS 09C:2019
Application	Inorganic mulch	Inorganic mulch
Grading	15–50 mm Maximum 100 mm	Uniform grading
pH		
Processing and source	Any chipped site vegetation or inorganic materials such as crushed rock, coarse aggregate, river pebbles, or pea gravel, spread as a soil surface protection measure	River stones, pebbles, shale, crushed rock
Contaminants	Must not contain any weed propagules, grass stolons or other extraneous material, and must be free from all matter and substances toxic to plant growth	Free of stones, soil, and other extraneous materials such as building materials/waste
Notes		Shall not be used in urban areas or close to buildings and pedestrian bridges, where there is potential for rocks to be thrown and cause damage to windows, cars or spread mowers

3.4.7 Quality Requirements for RCG, as Specified by Road Agencies

Table 3.19 provides an overview of the different properties required for each road agency in Australia/New Zealand with respect to the use of RCG as a granular material. Detailed information relating to these requirements can be found in Appendix A.

Table 3.19: Summary of quality requirements for RCG, as specified by road agencies

Requirement	NSW	Qld	SA	Tas	Vic	WA	ACT	NT	NZ
Chemical/environmental assessment	X	X	X	X(1)	X(1)			X	
Specific source material only	X	X		X(1)	X(1)	X		X	X
Washed and free from contamination/debris								X	X
Water absorption	X								
Grading requirements	X	X		X	X	X		X	X
Particle shape		X		X	X	X	X		X

1 *Covered through the source material approval process.*

Note: X = requirement specified.

3.5 Technical Specification Framework

3.5.1 Structure of the Technical Specification

The proposed Austroads Technical Specification is articulated around the following sections:

- scope
- glass source
- material properties
- chemical and other material requirements
- testing and conformance.

The following sections provide more detail on, and the basis of the requirements adopted during, the development of the Technical Specification.

3.5.2 Scope and Targeted Applications

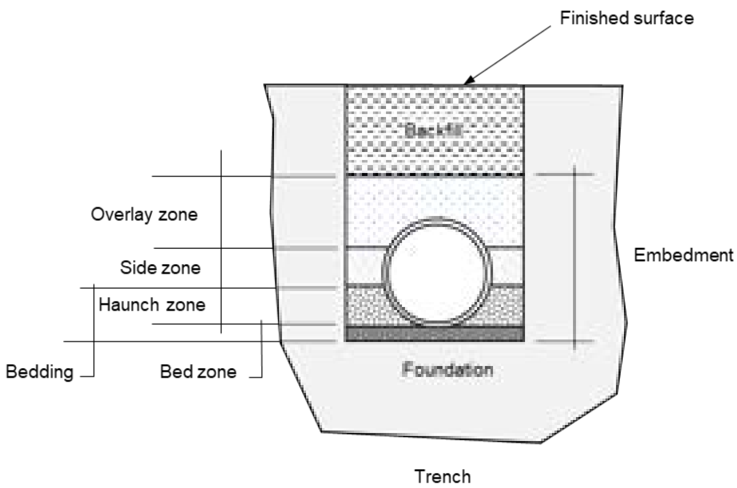
It is anticipated the available information from Sections 2 and 3 can readily support the development of a specification for the supply and manufacture of RCG as a granular aggregate sand replacement for the following applications:

- bedding and haunching of drainage pipes and conduits
- side zone and backfill of drainage pipes and conduits
- bedding and joint filling in segment/block paving applications
- bedding/filter material for drainage medium applications
- embankment fill and earthworks applications
- landscaping applications.

The state and national specifications reviewed for granular applications show a reasonable level of consistency and can form the basis of the development of an Austroads Technical Specification.

Terminology used for buried pipes, conduits and combined services is illustrated in Figure 3.1.

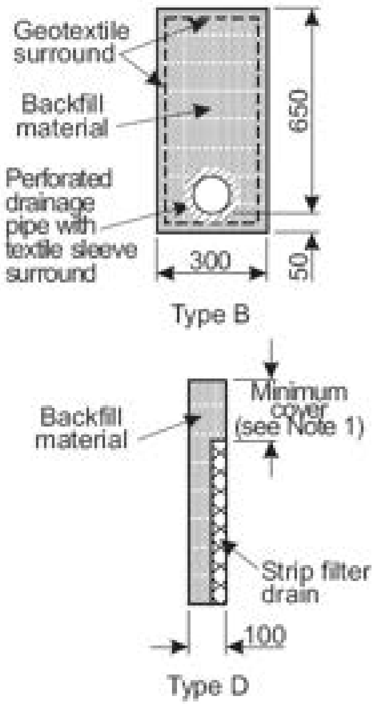
Figure 3.1: Schematic view of bedding, haunch, side and backfill zone of drainage pipes and conduits



Source: Adapted from AS/NZS 3725:2007.

Typical uses for RCG bedding/filter material in drainage medium applications are shown in Figure 3.2, with RCG identified as the backfill material.

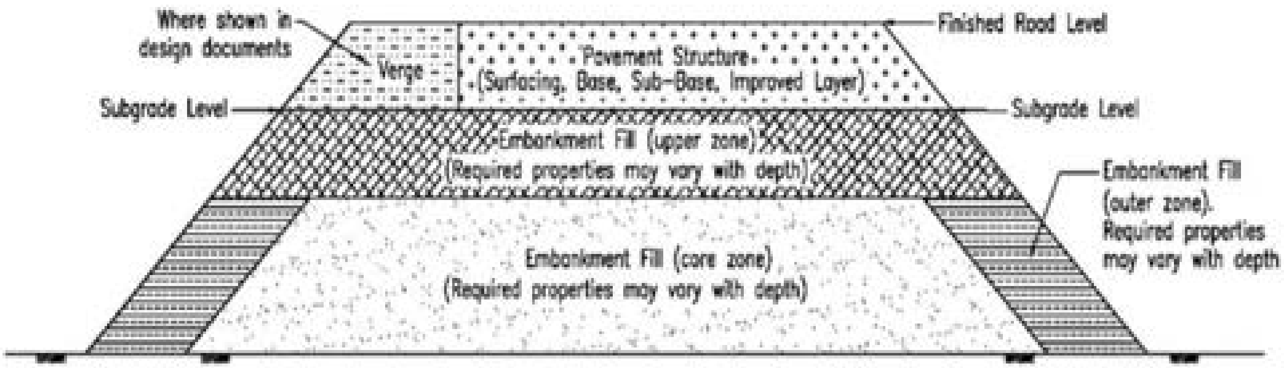
Figure 3.2: Drainage medium applications



Source: Adapted from TMR MRTS03.

Due to health and safety concerns, recycled crushed glass shall be used in the core zone of embankments. Crushed glass shall not be placed within upper or outer zones of the embankment. Core zone is defined as the central zone of an embankment. Upper zone is defined as the top zone of an embankment, excluding pavement and verge. Terminology used for embankment zones is illustrated in Figure 3.3.

Figure 3.3: Embankment zones



Source: Adapted from TMR MRTS04.

3.5.3 Source and Cleanliness

Specified requirements for RCG use, are similar across some states and countries. For all applications, the general material requirement for the source RCG is that it must only contain food/beverage container, building, and/or window glass. Hazardous waste containers, laboratory glassware, laminated glass, light bulbs, cathode-ray tubes and other similar sources of glass shall not be included.

Additionally, the RCG must be inert, clean, hard and durable, and free from any contaminants or other deleterious materials. A limit of foreign material could be specified to meet these criteria. These would include brick, plaster, clay lumps and other friable materials in addition to rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable and organic matter.

3.5.4 Material Physical Properties

From the review of existing specifications and depending on the application, the physical properties anticipated to require RCG specification criteria to be detailed are listed in Table 3.20.

Table 3.20: Suggested specification criteria for various applications

Application	Specification criteria		
	Particle size distribution	Shape	Shrinkage/ plasticity
Bedding and haunch of drainage pipes, conduits, and combined service routes	X	X	X
Side zone and backfill of drainage pipes and conduits	X	X	X
Bedding and joint filling in segment/block paving applications	X		
Bedding/filler material for drainage medium applications	X	X	X
Embankment fill and earthworks applications	X	X	X
Landscaping applications	X		

Note: X = applicable specification criteria.

The CBR data reported in literature (Section 2.3.4) and information from the RCG sand suppliers show CBR values are in excess of the 12% (standard compaction) which is generally required for backfilling material. Also shear strength parameters of RCG sand (≤ 5 mm) are consistent with natural sand properties (Dhir et al. 2018) and RCG sand material is self-draining with low sensitivity to the moisture content. Clean and well graded RCG sand material is expected to perform like natural (non-plastic) sand. The strength and bearing capacity will be provided through the particle size distribution requirements and good compaction during construction achieving maximum dry density. CBR was not retained as part of the requirement proposed for the specification for RCG sand.

From the review of RCG properties and the general requirements for use in granular applications, it is proposed to exclude electrical resistivity requirements for the specification for RCG sand. Electrical resistivity coupled with pH requirements are mainly related to corrosion of steel structures or steel components adjacent to the material. Limits are not included in the road agencies' specifications and have been found only in the WSAA Specification or other water services standard and specifications. Therefore, an electrical resistivity requirement has not been included in the specification limits. However, electrical resistivity of the material will be measured indirectly through the assessment of dissolved minerals (see Section 3.5.6) and the electrical conductivity measurement. Electrical conductivity is the reciprocal property of resistivity and the corrosion risk could be informed from the electrical conductivity values of the RCG sand product. It is, however, preferable to sample and test the RCG sand to determine compliance with the relevant product specification as additional properties might be required and sample preparation can affect to measurement (e.g. density and moisture content).

3.5.5 Grading Envelopes

Proposed grading envelopes

The review of current specifications for bedding and backfilling led to the development of grading envelopes summarising the particle size distribution requirement related to these applications. Overall, three grading envelopes are proposed described as follows:

- Grading Type A (5 mm bedding and backfilling RCG sand): Developed primarily from the grading requirement of AS/NZS 3725:2007 (Table 6) capped to a maximum aggregate size of 5 mm and combined with the Andrews (2010) specification (Table 3.1). This grading envelope defines the limits for both bedding and haunch of drainage pipes, conduits, and combined service routes and side zones and backfill of drainage trenches. Grading envelope Type A is given in Table 3.21 and illustrated in Figure 3.4. A comparison of the grading envelope with the current specification requirement is presented in Appendix D and showed good consistency with Australian standards requirements and the majority of road agencies practice. However, the grading Type A was found to deviate from the requirements of some road agencies.
- Grading Type B (5 mm graded RCG sand): Developed primarily based on the requirement for block paving bedding applications. Table 3.9 showed consistent practice across road agencies and aligned with the Concrete Masonry Association of Australia (2014) requirements. It provides a grading envelope of a well graded 5 mm sand for good particle packing under block pavers and could be used in other applications.
- Grading Type C (2 mm graded RCG sand): Specifications for block pavers joint backfilling are relatively consistent (Table 3.9) and were used to develop this 2 mm well graded RCG sand consistent with the Concrete Masonry Association of Australia (2014) specification. It provides a generic grading envelope for a 2 mm well graded sand.
- Grading Type D (5 mm poorly graded RCG sand): Specifications for use as a drainage medium were developed to ensure a free draining product and to prevent from clogging. The grading of drainage mediums showed inconsistencies between road agencies, with the developed grading loosely aligning with the Type A Filter material requirements in TCCS MITS 03I:2019.
- Grading Type E (5 mm graded RCG sand): Specifications for use as an embankment fill showed are relatively consistent in the use of 5 mm graded RCG sands. The grading requirements have been kept loose to promote the use of other gradings of RCG sand for use in embankment applications.
- Grading Type F (5 mm graded RCG sand): Specifications for use as in landscaping applications are not widely developed in road agencies. The grading requirements have been kept loose to promote the use of other gradings of RCG sand for use in landscaping applications.

Grading envelopes for Types B and C are given in Table 3.22 and illustrated in Figure 3.5. Grading envelopes for Types D, E and F are given in Table 3.23.

Table 3.21: Particle size distribution envelope Type A

AS sieve (mm)	Percentage passing by mass (%)
9.50	100
4.75	85–100
2.36	50–100
0.6	20–90
0.3	10–60
0.15	0–25
0.075	0–10

Figure 3.4: Grading envelope proposed Type A: 5 mm bedding and backfilling RCG sand

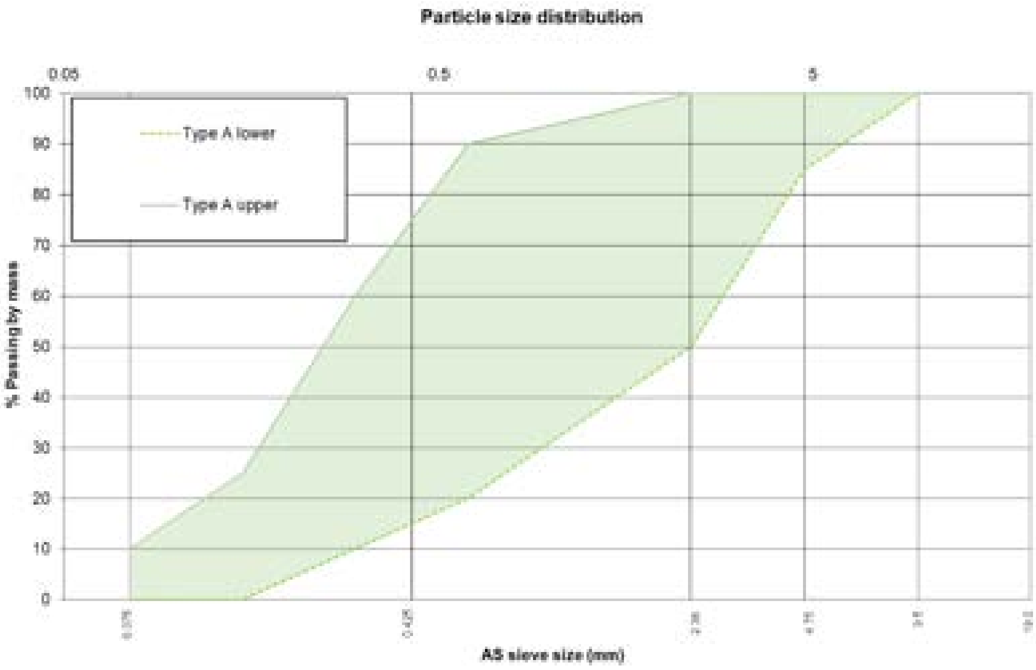


Table 3.22: Particle size distribution envelopes Types B & C

AS sieve (mm)	Percentage passing by mass	
	Type B	Type C
9.50	100	–
4.75	95–100	–
2.36	80–100	100
1.18	50–85	90–100
0.6	25–60	60–90
0.3	10–30	30–60
0.15	5–15	15–30
0.075	0–10	5–10

Figure 3.5: Grading envelope proposed bedding and backfilling RCG sand: Types A, B and C

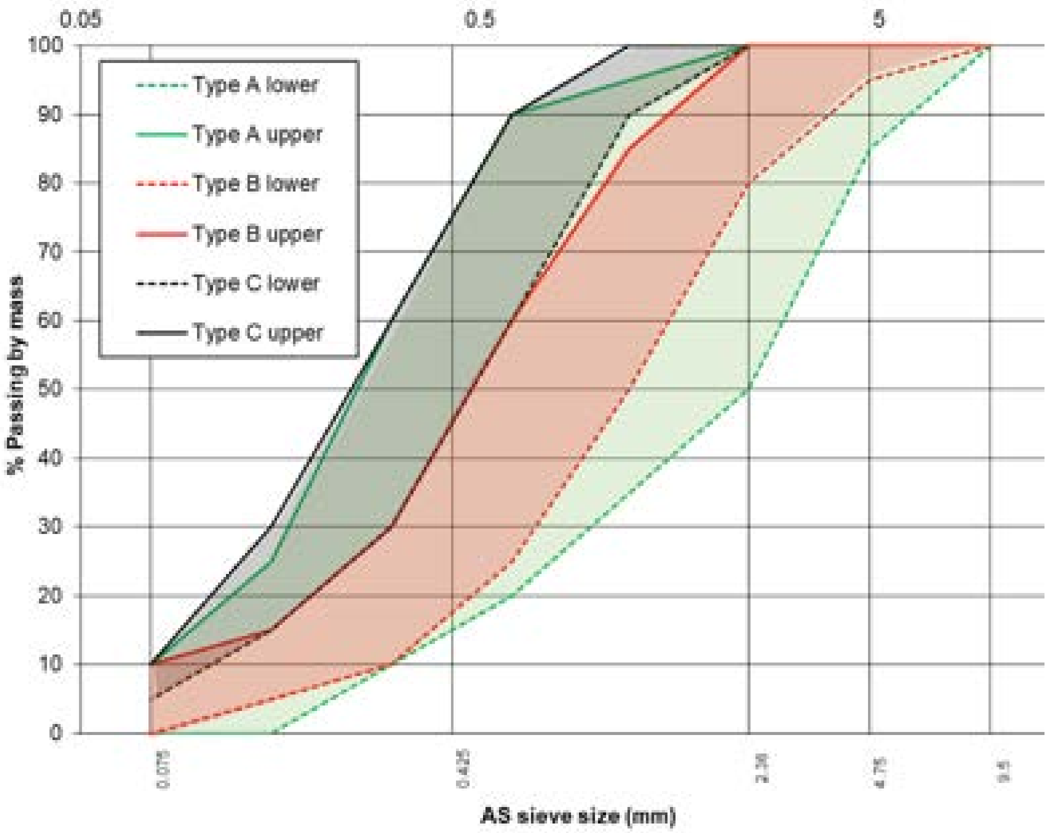


Table 3.23: Particle size distribution envelopes Type D, E & F

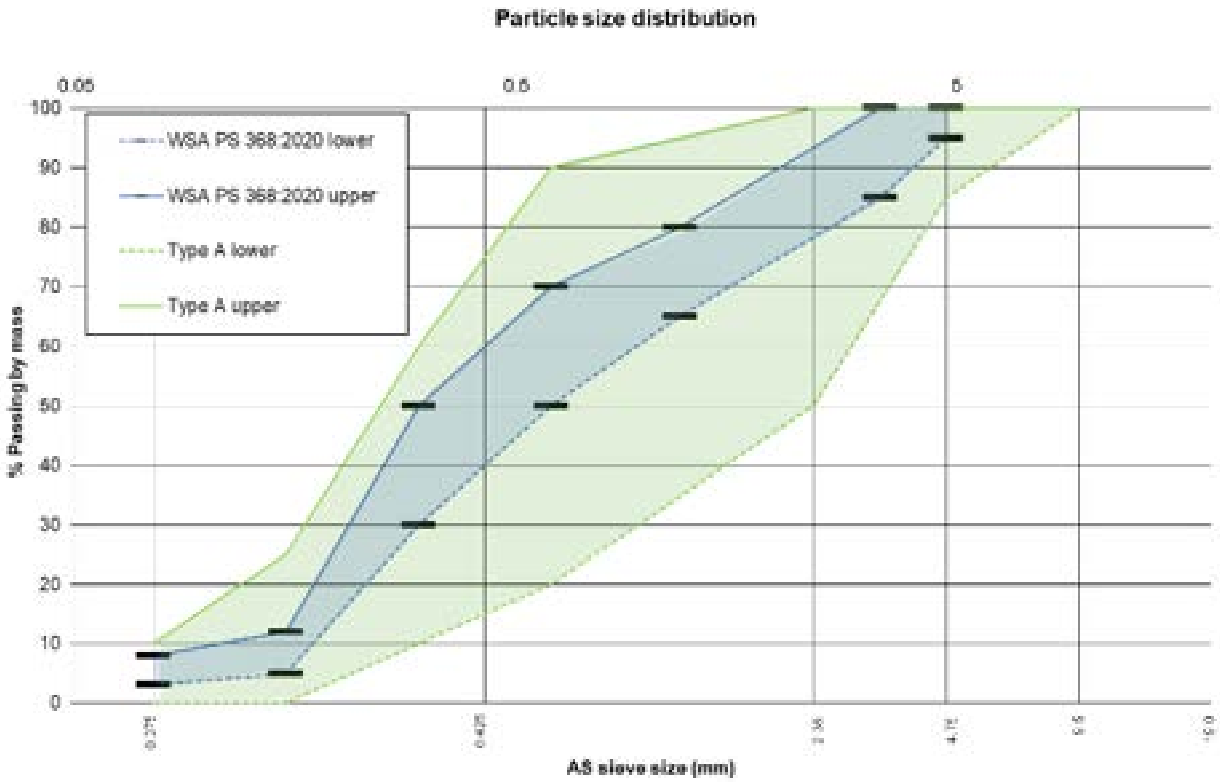
AS sieve (mm)	Percentage passing by mass		
	Type D	Type E	Type F
9.50	–	100	100
4.75	100	70–100	85–100
2.36	–	–	–
1.18	0–2	–	–
0.6	–	–	–
0.3	–	–	–
0.15	–	–	–
0.075	–	–	–

Discussion

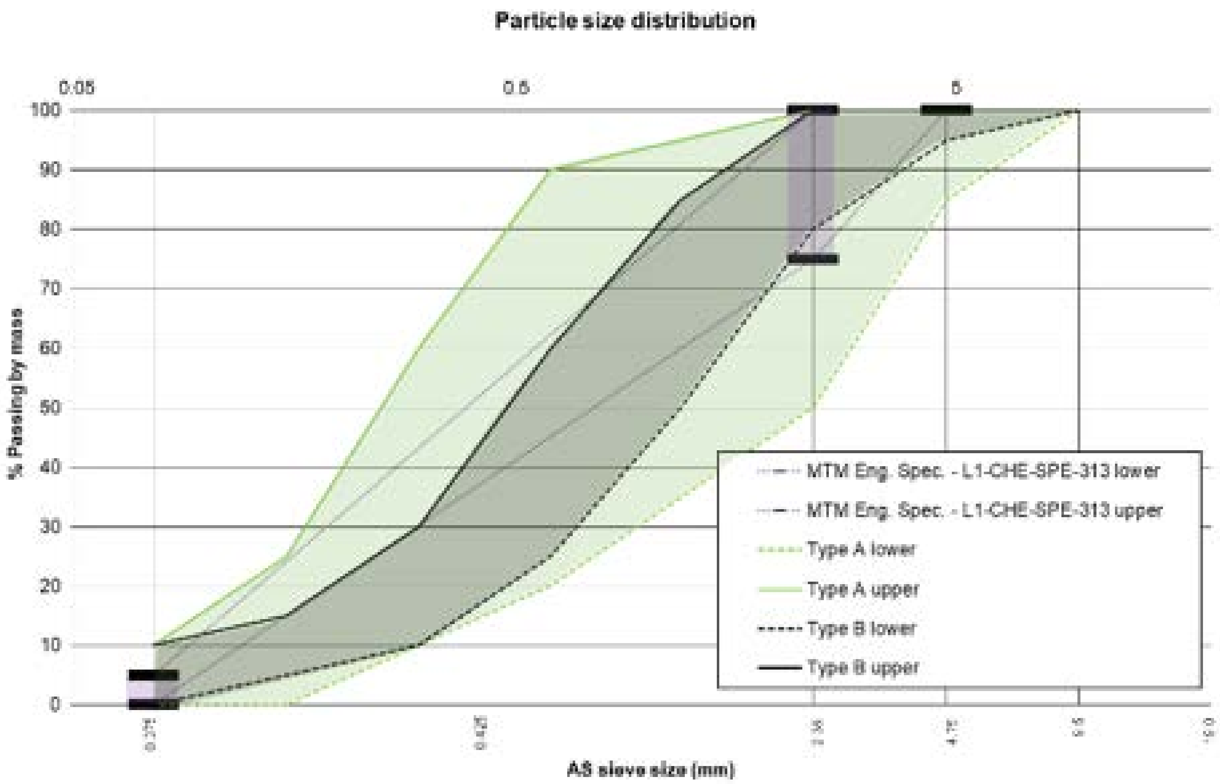
The proposed grading envelopes were compared with existing RCG specifications in use for RCG sand bedding and back-filling applications. The Type A grading envelope has a significantly wider envelope compared with the requirements defined by the Water Services Association of Australia (WSA PS 368:2020) as illustrated in Figure 3.6a. It suggests that WSA PS 368:2020, which also includes additional property requirements (e.g. wet strength, pH and electrical resistivity), should be used for water service embedment applications. Also, Metro Trains Melbourne (see Appendix A.10) developed a specification including grading requirements on a lower number of sieves which would be included in boundaries set by the Type A and Type B envelopes but requires a fine content (passing the 0.075 mm sieve) not exceeding 5% (Figure 3.6b).

Figure 3.6: Comparison of the proposed grading envelope and existing specification requirements

(a) WSA PS 368:2020



(b) MTM Engineering specification L1-CHE-SPE-313



Finally, the grading envelopes were compared against actual RCG sand sample properties using available data that demonstrated that the grading requirements defined are achievable by standard and current processing facilities.

3.5.6 Chemical and Contamination Analysis

In addition to specifying physical properties, source, and cleanliness requirements, it is anticipated that the developed specifications for RCG as a bedding material will also include a chemical analysis of the material to ensure there are no environmental contamination risks, similar to those outlined by NSW EPA (2014a).

3.5.7 Testing and Conformance

Frequency of testing proposed for the specification was selected to be consistent with general practice for compliance testing of crushed rock and natural aggregates, recycled materials and recycled crushed glass (MRTS36:2020).

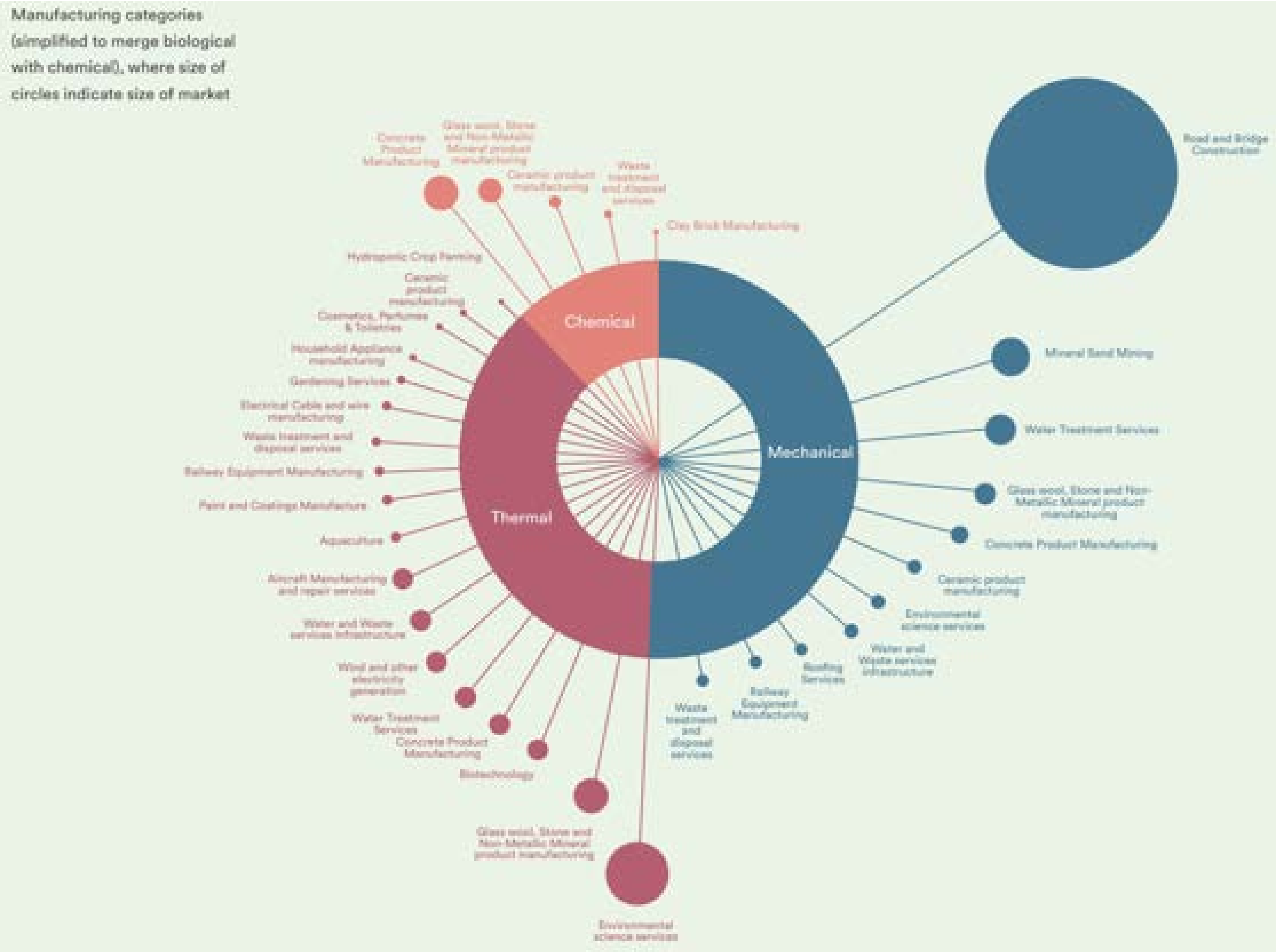
3.6 Novel Applications for Consideration – Foamed Glass: Domestic and International

There is increasing traction and interest in incorporating the use of RCG into many construction and road applications. Many of the current practices which use RCG are based on the mechanical size reduction of glass to a sand like particle size, and sometimes even as substitutes for finer aggregates in filler type applications.

Foamed glass is not a new technology, and it is possible to see foamed glass used commonly in other industries such as glass blowing, glass art and glass homewares such as lamps and vases. Interestingly the growing problem of waste glass that cannot be recycled back into packaging and bottling is pushing innovation to seek smarter ways to utilise and upcycle the valuable recycled glass. In particular, the use of glass in roads and construction is showing lots of interest, with many trials taking place for a vast array of applications, and one of those avenues is the use of foamed glass in construction.

In recent decades lots of research has been undertaken to understand how foamed glass can be produced economically, efficiently and in large scale. For example, a local RMIT study conducted with Sustainability Victoria explored the uses of RCG, and the largest potential markets for it. The review condenses the applications and the size of the potential markets for RCG in Figure 3.7 (Flood et al. 2018), highlighting the largest possible mechanical application for RCG as road and bridge construction.

Figure 3.7: Potential size of markets for glass waste



Source: Flood et al. (2018).

As part of the applications for RCG, foamed glass is covered extensively, and varying trials and methods of foamed glass are stated. Some of the notable examples are summarised below:

- Filtration (Indonesia) – Porous glass fines were trialled as a filtration medium for water contaminated with unwanted minerals and contaminants. The porous glass had pore sizes ranging from 1.6–2.1 mm. It is noted that foamed glass with varying size could be tailored to serve other applications, such as drainage and filtration in the construction of bridges and roads (Flood et al. 2018).
- Lightweight Bricks and Landscaping Products – RCG may be used in landscaping bricks and curbs construction as a sand replacement already, the novel application discussed in this report comments on the porosity and lightweight nature of foamed glass. Specifically, given their porosity and honeycomb type structure, diverse applications could include high surface area sound and particulate pollution absorption panels for freeways and railway sidings and insulative waffle systems to replace polystyrene waffles in building slab construction (Flood et al. 2018).

Other studies such as the effectiveness of recycled waste glass as a contaminated soil mud improver material (Azizul Moqsud & Hayashi 2007), researched utilising the porosity of foamed glass as a filter medium in problem areas where river impurities would not flush out in the ocean due to geographic coves. The technical report published in 2007 discusses the natural geographic issues with fines and mud from rivers that tend to accumulate as sediments on the sea outlets creating silty mud planes. The study studied mixing the tidal sand with foamed glass and trialled it over an area 40 m x 25 m. The soil and foamed glass mix were produced to a 1 m depth and the breakdown of the mixture was 80% clay, 15% foamed glass and 5% sand (Azizul Moqsud & Hayashi 2007). The study observed improved filtration of muddy areas and noted sulphide concentrations decreased in the presence of foamed glass. The oxygen levels were also observed to increase leading to improved soil and water conditions which are more favourable environmental conditions for natural fauna. The recycled foamed glass has shown good success in acting as a filtering and aeration material (Azizul Moqsud & Hayashi 2007).

A study published on the evaluation of interface shear strength properties of geogrid reinforced foamed recycled glass using a large-scale direct shear testing apparatus (Arulrajah et al. 2015), explored combining foamed glass with geogrids. The researchers were from various universities, including Swinburne University in Melbourne, Thailand, and China. The group undertook a study to assess the interface shear strength properties of geogrid reinforced foamed glass using a direct shear testing apparatus. A comparison of performance tests was undertaken comparing foamed glass aggregates and non-foamed glass aggregates. The foamed glass showed promise in use as a backfill when combined with a geogrid. The foamed glass is especially useful in backfill situations that require lightweight applications, particularly for its economic, engineering, and environmental benefits in regions with soft clay deposits, such as coastal regions (Arulrajah et al. 2015).

4. Development of Specification for RCG as a Fine Aggregate Replacement in Concrete

4.1 Introduction

Glass is considered as an inert material that can be used as a partial aggregate replacement in concrete. Studies have shown that the use of waste glass as aggregates had no significant effect on the workability of concrete; however, it decreased the slump, air content and density (Shi & Zheng 2007). A study conducted at CSIRO, Australia demonstrated satisfactory performance in laboratory testing and field premix concrete incorporating up to 20% RCG as a fine sand replacement. There was a 5% reduction in concrete compressive strength at 5% RCG substitution for natural sand in concrete, compared to a 27% reduction at 30% glass substitution level (Sagoe-Crentsil, Brown & Taylor 2001).

However, the major challenge is to avoid Alkali silica reaction (ASR) in concrete when RCG is used as fine sand replacement. ASR, also known as concrete cancer, causes silica to react with alkali in concrete and create microcracking in the cementitious matrix, with deleterious strength losses. However, the ASR potential in concrete can be determined through the composition of RCG. For instance, soda-lime glass has very high-risk potential to display ASR if it is used as aggregates in concrete. Particle size is an important parameter in causing ASR expansion, and the worst particle size (pessimum size) depends on the type of glass. For instance, the pessimum size was reported 1.18 mm for clear (flint) soda-lime glass, 150 μm for Pyrex glass and 75 μm for fused silica. ASR expansion is also dependent upon glass type and colour. Clear soda lime is the most reactive, followed by amber glass. Green glass causes less expansion due to the presence of chromium oxide (Shi & Zheng 2007). As ASR has serious detrimental effects on the performance of concrete, special precautions must be taken when dealing with highly reactive aggregates such as RCG. The study showed that the addition of a binder containing 30% or more class F fly ash significantly minimised the ASR. A few strategies available to mitigate the effect of ASR in concrete are as follows (Pellegrino, Faleschini & Meyer 2019; Shi & Zheng 2007):

1. Grind the glass fine enough to satisfy, at minimum, the US standard mesh #100 (0.150 mm).
2. Use mineral admixtures such as metakaolin, fly ash or blast furnace slag that consumes any alkali available for the ASR reaction.
3. Control the pH of concrete to under 12 to avoid deleterious expansion.
4. Apply a protective coating to the glass particles (e.g. zirconium).
5. Modify the glass chemistry to make it less reactive.
6. Use low-alkali cement.
7. Develop a special ASR-resistant cement.

4.1.1 Advantages of Using RCG in Concrete

Advantages in using RCG in concrete include:

1. Reduced water absorption. Hence, it does not require the defining of the effective water/cement ratio. The lack of water absorption and the smooth surfaces of glass particles improve the flow properties of fresh concrete containing RCG; as compared to natural aggregates, without the necessity of using water-reducing admixture. This leads to reduced cost, higher strength, and enhanced durability (Pellegrino et al. 2019).

2. Dhir et al. (2018) summarised the Los Angeles abrasion values of recycled glass obtained from a number of different research studies based on which Los Angeles abrasion values were reported to be generally in the range of 24% to 42% for recycled glass. Recycled glass has an acceptable resistance to abrasion. However, it is not suitable to be used as a coarse aggregate due to the flaky nature and elongation issue of recycled glass (Dhir et al. 2018). The acceptable hardness and abrasion resistance of glass particles make them suitable aggregates for paving stones, floor tiles and other applications commonly subject to high wear and tear.
3. The most prominent advantage is related to the environmental aspect because its use has a remarkable impact on the solid waste streams of major metropolitan areas, due to concrete being the second most consumed product globally. Furthermore, it cuts waste disposal cost and accelerates the circular economy by saving a large amount of primary raw materials each year.
4. It saves a significant amount of energy and reduces the amount of CO_2, NOx and other air pollutants emitted from the manufacturing of cement clinker and fine aggregates (Shi & Zheng 2007).

4.2 Chemical and Other Material Requirements

As discussed in Section 3.2, the environmental assessment and contamination limits developed in NSW provide a robust framework to the prevention of WHS and environmental risks for short and long-term impacts for RCG in its applications, including concrete. Table 3.4 contains a list of chemical and other attributes that suppliers of RCG must comply with when supplying product under the NSW EPA recovered glass sand order (NSW EPA 2014a).

4.3 Overview of International Practice

In reviewing international standards, it was found that generally the use of RCG in concrete is not covered. Requirements for aggregate materials and fillers are outlined, however specific mention of RCG is not available. A summary, encompassing Europe, the USA and Japan is provided in Appendix G.

4.4 Australian and New Zealand Specifications

4.4.1 Australian Concrete Standards

Table 4.1 lists the Australian specification standards for concrete.

Table 4.1: Australian concrete standards

Document number	Title
AS 1012	*Methods of Testing Concrete.*
AASHTO M318:02 (R2019)	*Standard Specification for Glass Cullet use for Soil-aggregate Base Course.*
AS 1141.4:2000 (R2013)/ Amdt 1-2016	*Methods for Sampling and Testing Aggregates: Bulk Density of Aggregate.*
AS 1141.6.2:1996 (R2016)	*Methods for Sampling and Testing of Aggregates: Particle Density and Water Absorption of Coarse Aggregate: Pycnometer Method.*
AS 1141.11.1:2009	*Methods for Sampling and Testing Aggregates Particle Size Distribution: Sieving Method*
AS 1141.21:1997	*Methods for Sampling and Testing Aggregates: Aggregate Crushing Value.*
AS 1379:2007 (R2017)	*Specification and Supply of Concrete.*
AS 2758.1:2014	*Aggregates and Rock for Engineering Purposes: Concrete Aggregates.*
AS 3600:2018	*Concrete Structures.*

Document number	Title
AS 3972:2010	*General Purpose and Blended Cements.*
AS 3727:1993	*Guide to Residential Pavements.*
AS/NZS ISO 9002:1994	*Quality Systems: Model for Quality Assurance in Production, Installation and Servicing.*

4.4.2 Australian Specification for Fine Aggregates in Concrete

As the replacement of fine aggregates with RCG is the most promising way to incorporate glass fines in concrete, it is important to consider the requirements for fine aggregate materials used in concrete. Table 4.2 summarises the requirements for fine aggregates in concrete, as outlined in AS 2758.1. Australian road agencies require fine aggregates used in concrete to conform to AS 2758.1, with some road agencies placing additional conditions, as discussed in detail in Appendix F.

Table 4.2: Fine aggregates – limits of deviation

Sieve aperture (mm)	Limits of deviation[(1)] Sieve aperture (%)	Recommended mass of sample passing (%)
9.50	–	100
4.75	±5	90 – 100
2.36	±10	60 – 100
1.18	±15	30 – 100
0.60	±15	15 – 80
0.30	±10	5 – 40
0.15	±5	2 – 25
0.075	±5	0 – 20

1 *Limits of deviation are the maximum variations in percentage between submitted grading or the grading of the submitted sample and any particular test result during the term of the supply agreement.*

Source: AS 2758.1:2014.

Furthermore, DoT Victoria requires fine aggregates in concrete to meet the grading specifications as outlined in Table 4.3 (VicRoads 610:2020).

Table 4.3: Summary of Victorian specifications for fine aggregates in concrete

Sieve size (mm)	Per cent passing (%)	Tests	Notes
9.5	100	Grading of fine aggregates	The fine aggregate shall consist of clean, hard, durable, naturally occurring sands, or a combination of naturally occurring sands and manufactured sands, and shall be free from clay, dust, lumps, soft or flaky particles, shale, salt, alkali, organic matter, soil or other deleterious substances.
4.75	90–100	Grading of coarse aggregates	
2.36	75–100	Water absorption of fine and coarse aggregates	
1.18	50–90	Unsound rock content	
0.6	30–70	Flakiness index of coarse aggregate 10 mm and larger	
0.3	10–35	Degradation factor of crusher fines	
0.15	2–10	Organic impurities other than sugar (AS 1141.34:2018)	
0.075	0–3	Alkali reactivity of aggregate sources	
		Wet and dry strength and sodium sulphate soundness for pebble aggregates	

Source: VicRoads 610:2020.

4.4.3 Early Development of Australian RCG in Concrete Specification – CSIRO Study

In 2001, CSIRO in collaboration with industry partners developed a Guide Specification for recycled glass as sand replacement in premix concrete (Sagoe-Crentsil et al. 2001). Based on the study, it was recommended that glass cullet less than 2.46 mm size can perform well as fine aggregate replacement in premix concrete. A 20% cullet replacement limit was recommended for non-structural concrete. Furthermore, Alkali-silica reactivity from the cullet as fine sand replacement can be significantly minimised with the use of binder containing 30% or more Class F fly ash. It may contain up to 2% of impurity and 5% loss on ignition. Glass cullet should fulfil the properties of fine aggregates such as grading, bulk density, foreign material content, durability, absorption and moisture content, contaminants, alkali-silica reaction (ASR).

Test results showed that crushed cullet sand having the size of 2.46 mm minus has a specific gravity between 2.4 and 2.5 and water absorption less than 1.

4.4.4 Australian RCG in Concrete Specifications

The reviewed specifications and requirements for the RCG are detailed in Appendix F. Department of Transport (DoT) VIC, Transport for New South Wales (TfNSW), NSW and Department of Infrastructure, Planning and Logistics (DIPL), NT explicitly mention the requirements for RCG to be used in concrete as a fine aggregate replacement. However, the rest of the Australian states do not provide specifications for the use of RCG in concrete.

Table 4.4 and Table 4.5 summarise the Australian specifications testing method required for the RCG to be used as the fine aggregate replacement.

Additionally, some of the selected national case studies for the use of RCG in concrete footpaths and concrete pavements can be found in Appendix H.

Table 4.4: Australian testing requirements for RCG

Property	Test method
Particle size distribution	
Nominated particle size distribution	AS 1141.11.1
Material finer than 75 µm	AS 1141.12
Dry density	NZS 3111 or TfNSW T279
Percentage of oversize material	
Flow time	
Uncompacted void content	
Apparent particle density	AS 1141.5
Dry particle density	
Saturated surface dry density	
Water absorption	

Source: Table 3254.1, TfNSW IC-QA-3154:2020.

Table 4.5: Production quality control for RCG

Property	Standards and test methods	Requirements
Sugar in aggregate	AS 1141.35	Less than one part in 10 000
Sulfates	AS 1379 AS 1012.20	Report if exceeds 0.01%
Chloride content	AS 1379 AS 1012.20	Report if exceeds 0.01% Max 0.04% for embedded steel reinforcement concrete Max 0.15% for plain concrete
Organic impurities (vegetable matter and wood particles)	AS 1141.34 AS 1289.4.1.1	Test fails if colour is darker than reference colour (AS 1141.34) max 0.5% (AS 1289.4.1.1)
Contaminants	AS 1141.3.1 Test Method (TfNSW T276 or RC 372.04)	Asbestos – 0% Metal – 0.25% by mass Plaster and friable materials – 0.25% by mass Rubber, plastic, bitumen, paper, cloth, paint, wood – 0.3% by mass

Source: Andrews (2010).

4.4.5 New Zealand Specifications

In New Zealand currently, there are no specifications available for the use of crushed glass in concrete applications. The primary standards and specification related to concrete are documented by Standards New Zealand and provided in Table 4.6.

Table 4.6: New Zealand concrete standards

Document number	Title
NZS 3101.1 &2:2006	*Concrete Structures.*
NZS 3104:2010	*Specification for Concrete Production.*
NZS 3106:2009	*Design of Concrete Structures for the Storage of Liquids.*
NZS 3109:1997	*Concrete Construction.*
NZS 3111:1986	*Methods of Test for Water and Aggregate for Concrete.*
NZS 3112.1:1986/A2:2007	*Methods of Test for Concrete: Tests Relating to Fresh Concrete.*
NZS 3112.2:2000	*Methods of Test for Concrete: Tests Relating to the Determination of Strength of Concrete.*
NZS 3112.3:1986	*Methods of Test for Concrete: Tests on Hardened Concrete Other than for Strength.*
NZS 3112.4:1986	*Methods of Test for Concrete: Tests Relating to Grout.*
NZS 3114:1987	*Specification for Concrete Surface Finishes.*
NZS 3116:2009	*Concrete Segmental and Flagstone Paving.*
NZS 3121:2015	*Water and Aggregate for Concrete.*
NZS 3122:2014	*Specification for Portland and Blended Cements (General and Special Purpose).*
NZS 3123:2009	*Specification for Pozzolan for use with Portland and Blended Cement.*
NZS 3124:1987	*Specification for Concrete Construction for Minor Works.*

4.5 Technical Specification Framework

4.5.1 Structure of the Technical Specification

The proposed Austroads Technical Specification is articulated around the following sections:

- scope
- glass source
- material properties
- chemical and other material requirements
- testing and conformance.

The following sections provide more detail on, and the basis of the requirements adopted during, the development of the Technical Specification.

4.5.2 Scope and Targeted Applications

It is anticipated the available information from Sections 2 and 4 can readily support the development of a specification for the supply and manufacture of RCG as a fine aggregate sand replacement for the following applications:

- concrete pavements
- kerb and channel
- maintenance strips
- footpaths
- shared paths
- traffic island infill (non-trafficable)
- footings and plinths for:
  - sign support structures
  - lighting columns
  - traffic signals.

The state and national specifications reviewed for fine aggregate concrete applications show a reasonable level of consistency and can form the basis of the development of an Austroads Technical Specification.

4.5.3 Source and Cleanliness

Specified requirements for RCG use, are similar across some states and countries. For all applications, the general material requirement for the source RCG is that it must only contain glass used for food/beverage containers, building, and/or window glass. Hazardous waste containers, laboratory glassware, laminated glass, light bulbs, cathode-ray tubes and other similar sources of glass shall not be included.

Additionally, the RCG must be inert, clean, hard and durable, and free from any contaminants or other deleterious materials. A limit of foreign material could be specified to meet these criteria. These would include brick, plaster, clay lumps and other friable materials in addition to rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable and organic matter.

4.5.4 Material Properties

As identified in Section 4.4.2, the material properties for fine aggregates in concrete in Australia are specified AS 2758.1 and form the basis of the material properties within the technical specification.

In Appendix F.1, TfNSW IC-QA-R53 explicitly specifies the allowance of granulated glass as fine aggregate replacement in concrete, up to maximum 15% of the total fine aggregate. Furthermore, VicRoads 703:2019 in Appendix F.2 allows for the use of up to 30% of glass fines as a replacement of the total mass of fine aggregated in the concrete mix for shared use paths. These specifications formed the basis of the maximum limits used within the technical specification.

The technical specification is limited to the deviation limits and providing recommendations of the particle size distributions of the supply and manufacture of RCG for use in concrete due to the maximum limits placed upon RCG use as a fine aggregate replacement, as other materials used in the total fine aggregate will change the particle size distribution.

4.5.5 Chemical and Contamination Analysis

In addition to specifying physical properties, source, and cleanliness requirements, it is anticipated that the developed specifications for RCG as a bedding material will also include a chemical analysis of the material to ensure there are no environmental contamination risks, similar to those outlined by NSW EPA (2014a).

4.5.6 Testing and Conformance

Frequency of testing proposed for the specification was selected to be consistent with general practice for compliance testing of crushed rock and natural aggregates, recycled materials and recycled crushed glass (MRTS36:2020).

4.6 Novel Applications for Consideration

4.6.1 Recycled Glass as Supplementary Cementitious Material

It is well known that the production of Portland cement is an energy and emission heavy process. Therefore, the industry is constantly adopting the use of alternatives to reduce the environmental footprint and cost of producing cement, and thus concrete (Sonebi, Ammar & Diederich 2016). One of the most common alternatives is the use of pozzolans, materials mainly composed of silicon dioxide that do not exhibit cementing properties when combined with water alone. However, when incorporated into a system with calcium (lime) and water, they can exhibit cementitious properties. Pozzolans therefore, are known as supplementary cementitious materials (SCM).

Glass is an amorphous material with high silica and calcium content that makes it pozzolanic or even cementitious in nature when it is finely ground (Ismail & Al-Hashmi 2009). Thus, glass can be used as cement replacement in Portland cement concrete or can be used as a fine aggregate replacement for concrete (Mohajerani et al. 2017; Pellegrino et al. 2019). When glass is to be used in concrete, it should be crushed using high-velocity impact equipment to remove sharp edges and make its handling easy. Finely ground glass particles (below 10 μm) have also shown to have pozzolanic properties and can serve as excellent filler material for high performing concrete. Pozzolanic activity is a direct function of the glass particle size. The finer the glass particles are, the higher the pozzolanic activity and it serves as the ideal replacement for cement in concrete (Sonebi et al. 2016).

One of the largest concerns associated with the inclusion of waste glass into concrete is a deleterious ASR, which can form within the concrete matrix at the interface of alkali-reactive siliceous aggregate and cement paste (Tora Bueno et al. 2020). The reaction forms a gel that expands in the presence of water and can cause cracking in the concrete, ultimately making it weak (Tora Bueno et al. 2020).

There are several testing methods available for evaluating ASR in concrete and mortar, the most commonly used test methods are ASTM C1260:2014 and ASTM C1567:2021 because of the expedience in which results are produced. However, the test results may not be as accurate as the results provided by ASTM C1293:2018 (evaluation for a long period, two years). Some of the test methods are not technically viable to evaluate the ASR in concrete when using waste glass as a pozzolan because the tests require the pozzolan to have a maximum alkali content that is lower than the average alkali content in most waste glass.

Workability: there is no established consensus on the effects that ground glass has on workability; a potential explanation for why the slump and flow values differ between publications is that the particle size and morphology of the ground glass being used differs between studies (Tora Bueno et al. 2020). Lu, Duan and Poon (2017) demonstrated the effect of RCG fineness on the flowability of mortar. RCG crushed to 23.8 μm (4 hour grinding time) showed better workability as compared to coarser RCG aggregates (ground for less time). This shows that the particle size distribution of cement, glass powder and glass cullet play an important role in the hardening of the glass mortar.

Mechanical performance: three properties are most commonly evaluated to assess the mechanical performance of concrete: compressive strength, splitting tensile strength and modulus of elasticity. In general, it is found that the optimal replacement level for strength gain as a function of maximum glass inclusion is approximately 10 and 20% (Matos & Sousa-Coutinho 2012). An increase in ground glass replacement, reduces the compressive strength when compared to non-glass containing control mix at earlier ages. However, after significant curing, ground glass mixes can eventually reach a comparable strength to the control mix; this is likely to be due to the slower pozzolanic reaction. It has also been shown that an increase in replacement slows the curing rate (i.e. a 10% replacement reaches similar strength to control at 28 days, while a 20% replacement reaches control strength at 56 days) (Nassar & Soroushian 2012; Afshinnia & Rangaraju 2015a, b and c).

In conclusion, the potential for finely crushed waste glass to be accepted as a partial cement replacement in Portland cement concrete is promising. However, there are limitations such as the decrease in early age strength, the importance of particle size reduction, and uncertainty in durability. Therefore, there is still a need for validation for waste glass to be successfully used as a partial cement replacement.

4.6.2 Foamed Glass Concrete

Many possibilities exist to incorporate foamed glass with material such as foamed concrete, to create lightweight, strong structures, which exhibit interesting properties such as enhancing the materials ability to reduce alkali silica reactions (Filshill 2018). These may prove beneficial as external base covers for bridges in salt water. A study by the University of Wollongong explored foamed concrete with RCG powder (Khan et al. 2019). A totally of 13 mixes of foamed concrete with and without recycled glass powders were assessed. The study focused on the engineering and performance-based parameters achievable when combining foamed concrete and recycled glass.

A comprehensive step-by-step explanation of the process is documented as a part of the study and highlights foamed concrete with 20% recycled glass powder performed with higher compressive strengths and lower plasticity and dry densities compared to the other trials. The concluding evidence of the study highlights recycled glass powder can be used a partial replacement to cement in foamed concrete, commenting on its sustainability its relatively simple particle size requirements of less than 45 μm. The smaller sizing enhances binding properties and reduces the chances of expansive alkali silica reactions (Khan et al. 2019).

5. Conclusions

The development of specifications and guidelines for recycled crushed glass (RCG) as a sand aggregate replacement offers a clear response to the Australian *National Waste Policy Action Plan* (Department of Agriculture, Water and the Environment 2019) and associated jurisdictional goals, supporting the development of a practicable end-market and thereby reducing the amount of glass going to landfill. There is a significant opportunity to increase the use of recycled materials by making sure the right conditions exist for all jurisdictions to confidently use these products in road infrastructure projects.

RCG has already been introduced to selected geotechnical applications for road applications; however, it is crucial for more widespread adoption that concerns about its use are identified, that the short- and long-term effects on the environment are investigated and understood, and that assurance is provided as to safe application via robustly developed specifications. With regard to the potential health hazards, toxicity and environmental pollution impacts the review found that:

- Compulsory protective clothing and equipment should be worn when handling RCG as it should also be for handling natural and manufactured sands of similar sizes.
- There may be a reduced risk of exposure to respirable crystalline silica when working with RCG compared to when working with natural sand – there is no demonstrated increased risk.
- Chemical or physical contaminants were typically not notably identifiable in tested samples, and although the presence of metals and a variety of other organic pollutants were detected, the concentrations were not at any level of concern.

The RCG specification have been based on the following principles:

- RCG should be sourced by the crushing of selected suitable sources of waste glass such as containers (e.g. mostly bottles and jars), free from contamination from food waste, metal, cork, ceramics, etc. Any glass from other items, such as cathode-ray tubes, fluorescent light fittings, or laboratory glassware are not suitable as a material source.
- RCG should be clean, hard, and durable, free from clay, dust, soft or flaky particles, shale, soluble salts, alkali, organic matter, soil, or other deleterious substances. Suitable processing, including sorting, crushing, screening, and potential washing is required to produce a consistent, clean, and free of odour product.
- RCG specifications include criteria for physical properties such as grading, particle shape, and plasticity, which depending on the application are often seen to have some consistency between different regions, with several Australian states typically using the same or similar gradings for equivalent applications.
- The proposed Austroads specification (ATS3050) has been developed based on the requirements for natural sand aggregates and existing recycled glass specifications.
- Clean RCG sand material is of a low hazard to the health and safety of workers, and unlikely to leach concentrations of chemicals which would have a negative impact on the environment when used in geotechnical road infrastructure applications. However, chemical analysis on the material should still be undertaken to understand any environmental risk. Further guidelines relative to the storage requirements and dust suppression measures could also complement the generic Material Safety Data Sheet (MSDS) available for RCG (Winder 2011).

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Appendix A Australian State and Territory Road Agency and New Zealand Requirements for use of RCG

A.1 New South Wales – Transport for New South Wales (TfNSW)

The TfNSW specification for granulated glass aggregate stipulates that glass aggregates shall comply with the conditions of exemption as per *The Recovered Glass Sand Exemption 2014* (NSW EPA 2014b) and that materials shall likewise comply with the requirements of *The Recovered Glass Sand Order 2014* (NSW EPA 2014a). Under TfNSW IC-QA-3154, granulated glass aggregate in NSW shall be made from crushed container glass and is not to include ceramics, cathode-ray tubes, fluorescent light fittings, or laboratory glassware as a material source. The material's water absorption shall be tested in accordance with AS 1141.5:2000 and found to be less than 1.0%, and the material must conform to the grading requirements from Table 1 in AS 2758.5:2009. However, the amount of material finer than 0.075 mm, dry density, percentage of oversized materials, flow time, uncompacted void content, dry particle density and saturated surface dry (SSD) density have no specified conformity requirements, but test results must still be reported.

Specification 3154 outlines that the specification is for RCG for use in pavement applications, and therefore does not specifically cover drainage, embankment fill and landscaping applications.

Beyond the TfNSW specifications, a trial of glass fines as pipe bedding was conducted by DECC NSW and Sydney Water (DECC 2007). This trial employed the use of glass fines in adherence to the following guidelines:

- Australian and New Zealand Environment and Conservation Council (2000), *Australian and New Zealand Guidelines for Fresh and Marine Water Quality: Volume 1: the Guidelines*, ANZECC, Canberra, ACT.
- National Environment Protection (Assessment of Site Contamination) Measure 1999, Table 5-A — Soil Investigation Levels.
- Department of Environment and Climate Change (2004), *Environmental Guidelines: Assessment, Classification and Management of Liquid and Non-liquid Wastes*, DECC, Sydney, NSW.

The trial was led by the Sustainability Programs Division (SPD) of the DECC. Sydney Water and DECC facilitated trialling the following four different gradings of crushed glass:

- < 4 mm (i.e. less than 4 mm particle size)
- 2 mm – 4 mm (i.e. graded product containing particles less than 4 mm but greater than 2 mm in size)
- 1 mm – 2 mm (i.e. graded product containing particles less than 2 mm in size but greater than 1 mm)
- 0.4 mm – 1 mm (i.e. graded product containing particles less than 1 mm in size but greater than 0.4 mm).

The guidelines and specifications used in the trial resulted in glass fines being deemed an acceptable and appropriate material for pipe embedment, friendly to both the site function and the environment.

A.2 Victoria – Department of Transport (DoT)

DoT Victoria (incorporating the former VicRoads) summarises notable allowances of recycled materials across multiple infrastructure applications in their technical note on the use of recycled materials in road pavements (VicRoads TN 107). A certain proportion of RCG is allowed in asphalt and cement treated crushed rock and for unbound applications, the following are noted for RCG:

- allowance of up to 100% by mass glass fines as a granular filter material for subsurface drainage
- allowance of up to 15% by mass of RCG in Class 3 crushed rock, and up to 50% by mass in Class 4 crushed rock, as a nominated supplementary material (VicRoads TN 107). Common applications for these classes of crushed rock include bedding for footpaths, kerbs, channels, culverts, and culvert backfill under pavements.
- Granular filter material shall consist of hard, durable and clean sand, gravel or crushed rock, free from clay balls and organic matter, and shall have a pH value greater than 6.0 and less than 8.0. The portion of granular filter material passing a 4.75 mm AS sieve shall have a Sand Equivalent value not less than 80 (VicRoads 702:2019).

Within the earthwork specification (VicRoads Section 204), the use of RCG material is also allowed in Selected Material applications, wherein it is to comply with Type A product requirements. These requirements allow the blending of recycled materials, including crushed glass, where crushed glass is cubic in shape and can pass the 4.75 mm AS sieve (VicRoads Section 204). While VicRoads Section 204 does not explicitly specify a limit for inclusion of RCG in these Type A, B or C applications, the inclusion of RCG is limited by the overall specification limits to ensure that the RCG does not decrease product performance.

DoT Victoria does not indicate any specification for material properties for landscaping applications.

A.3 New Zealand – New Zealand Transport Agency

NZ standards and specifications do not explicitly state the allowance of RCG sand in bedding material and backfill applications. However, a specification exists for the use of RCG as an aggregate for blended basecourse. This specification is included in the Transit New Zealand Technical specification M/4: *Specification for Basecourse Aggregate* which allows the addition of up to 5% RCG for road base construction. The cullet properties specified include the source of glass, particle grading, particle shape allowances, contamination, and cleanliness.

The specifications for embankment fill properties are highlighted in the NZTA F/1:1997 for granular fill material and NZ does not indicate any standards for landscaping applications.

A.4 Queensland – Department of Transport and Main Roads (TMR)

The TMR specification for recycled glass aggregate (TMR MRTS36:2020) is explicit in its application to use in asphalt and unbound granular road pavements as well as general earthworks. The parent technical specification requirements shall apply to recycled glass aggregate unless the requirements are specifically excluded/amended by MRTS36:2020 (i.e. MRTS04 for general earthworks application, MRTS05 for unbound pavements application, and MRTS101 for aggregates for asphalt application). For these applications, RCG aggregate shall have a nominal particle size of 5 mm or less, be produced from food and beverage container glass, processed to a consistent gradation, cubical in shape, free from any putrid odour, and free from contaminants such as ceramics, other sources of glass (cathode-ray tubes, fluorescent light fittings and laboratory glassware), paper, cork, metals (including heavy metals), brick, plaster, plastic, rubber, wood, clay, paint and other deleterious materials.

The specification for landscaping applications states that top-dressing requirements will be graded sand, specifically produced for the horticultural industry, washed to be cleaned of contaminants.

A.5 Western Australia – Main Roads Western Australia (MRWA)

Within MRWA specifications, opportunities exist for the use of RCG, subject to compliance with the relevant material requirements for a given application. In this regard, the MRWA specification requirements for culverts (MRWA Specification 404) are highlighted, where bedding materials are specified to be basecourse materials or other suitable materials approved by the superintendent. For this application, the following requirements are noted:

- Select bedding materials are to be compacted in accordance with the requirements for embankment construction as provided in the earthworks specification (MRWA Specification 302).
- Other materials shall contain less than 20% by mass retained on the 37.5 mm sieve as determined by MRWA Test Method WA 115.2.

Furthermore, backfill materials (MRWA Specification 302) are specified to be embankment materials installed in accordance with the earthworks specification requirements for 'embankment construction' (MRWA Specification 302). The MRWA Specification 302 permits the use of recycled glass cullet in embankment construction subject to its compliance with specified requirements for foreign material content, particle size distribution and particle shape. The specification also notes that glass cullet shall be sourced from food beverage containers and building or window glass and be cleaned to eliminate odours (MRWA Specification 302).

A.6 South Australia – Department for Infrastructure and Transport (DIT)

The specification for supply of pavement materials (DPTI Master Specification RD-PV-S1) stipulates that Type-C sand be a crushed quarry product only.

A.7 Tasmania – Department of State Growth (DSG)

Generally, DSG specifications are aligned with those for the Department of Transport Victoria. For an overview of the state of specifications surrounding the use of RCG in DSG refer to that given for Victoria in Appendix A.2

A.8 Australian Capital Territory – Transport Canberra & City Services (TCCS)

The TCCS specification for segmental paving (TCCS MITS 07) defines bedding sand as crushed gravel, granulated glass, or natural sand, where the fines fraction shall not contain single-sized, gap graded or excessive fine materials.

TCCS standards and specifications do not explicitly state the allowance of RCG for drainage medium, embankment fill and landscaping applications. TCCS MIS 04:2019 *Subsurface Drainage* does stipulate that should recycled materials be utilised as a filter material they shall be tested for contaminants in accordance with TCCS MITS 00C:2019 *Erosion and Sediment Control.*

A.9 Northern Territory – Department of Infrastructure, Planning and Logistics (DIPL)

The DIPL standard specification for roadworks (DIPL Specification v4.2), specifically section 11 – Miscellaneous Concrete Works, allows the use of RCG in accordance with the relevant recommended specification provided in section 9 of Andrews (2010).

Similarly, DIPL Specification v4.2 in section 12 – Drainage Works, also allows the use of RCG as a bedding material in accordance with the relevant recommended specification provided in section 9 of Andrews (2010) (reproduced in Table 3.1 of this report).

The same DIPL drainage specification section also allows mixed blends of RCG and clean granular materials free from sticks, stones and other deleterious materials with a PI less than 6. The grading requirements for RCG and mixed blends are consistent with Table 6 in AS/NZS 3725:2007.

A.10 RCG in Australian Rail Infrastructure

The use of recycled glass sand as a replacement for bedding sand is also used within the rail industry. There are a variety of approvals and specifications for its use across rail networks.

As mentioned in Appendix A.5, MRWA allows the use of RCG cullet in earthworks for embankments (MRWA Specification 302). This specification is also applicable to rail infrastructure, as the Public Transit Authority of Western Australia defers to MRWA for this application but may, however, require project-specific approvals.

For Rail Projects Victoria (RPV), a compliance paper for the use of RCG on the regional rail network with V/Line was developed, detailing an Alex Fraser RCG product readily available around Melbourne (Rail Projects Victoria 2019). While V/Line has not yet included this in their documented specifications, the use of RCG in their projects on a fit-for-purpose basis is allowed. Notably, this product does not require Type Approval (generic process for rail authorities to accept novel or modified products for use on their infrastructure) but must still meet the following:

- The final product must be equivalent or superior to the product it is replacing.
- The final product must be safe for utilisation from a WHS and environmental perspective.
- All risks are managed in accordance with the V/Line Safety Management System (SMS).

Meanwhile, Metro Trains Melbourne (MTM) has developed a RCG sand specification, in partnership with Victoria's Level Crossing Removal Project (LXRP). This specification is also outlined in Table A 1.

Table A 1: Recycled glass sand in rail infrastructure

Property	VIC	
Reference	Metro Trains Melbourne (MTM) L1-CHE-SPE-313	Rail Projects Victoria (2019)
Application	May be used as replacement for quarried sand as bedding and embedment materials; for Combined Service Route (CSR) and drainage piping Must not be used for direct buried cables including sandpits and turning pits Other applications subject to approval	Replacement for quarried sand or other raw materials Bedding and embedment materials; for Combined Service Route (CSR) and drainage piping
Grading (% passing AS sieve)		
4.75 mm	100	
2.36 mm	75-100	
0.075 mm	0-5	
Processing and source	Inert recycled glass material Glass from hazardous waste containers, laboratory glassware, reinforced and laminated glass, light bulbs, fluorescent lighting, and cathode-ray tubes shall not be included	
Contaminants	Free of any perishable matter Classified as Clean Fill under EPA regulations	
Notes	Application must comply with AS/NZS 2566.1, AS/NZS 2566.2 and AS/NZS 3725 Products shall meet VicRoads Code of Practice 500.02:2017 Registration of Crushed Rock Mixes Manufactured under a third party certified Quality Assurance System	Provides supporting documentation including documents from Alex Fraser, City West Water, Vinidex, Sustainability Victoria etc. Outlines compatibility of the material in terms of geotechnical, health and safety, environmental and infrastructure impacts

Appendix B International Practice for RCG in Granular Applications

Many international countries' transport departments have specifications and regulations which allow crushed glass to be substituted for conventional aggregates or used as an aggregate component in a wide range of geotechnical applications. In particular, the USA, which has both a history of employing glass cullet since 1990 and has a large count of transport jurisdictions, has collectively published a high number of specifications for various geotechnical applications. Given the context of this project, this section summarises a selection of international standards and specifications focusing on the use of crushed glass as a suitable replacement or supplement for natural granular sand for bedding (i.e. pipe bedding), drainage medium, embankment fill, and landscaping applications.

B.1 Virginia Department of Transportation, USA (VDOT)

The Virginia Department of Transportation (2020) indicates that crushed glass may be used for construction in backfilling applications. The allowable substitution of crushed glass, however, is limited to applications using material of a maximum size of 9.5 mm (3/8 in.).

According to the Virginia Department of Transportation (2020) specifications, crushed glass is permitted to be used in the specified applications. The crushed glass must consist of particles of kerbside-collected or waste glass and must be free from sources of glass that include lead crystal, automotive glass, TV monitors, lighting fixtures, and electronics applications. The amount of paper, capping materials, or other non-glassy materials, excluding fragments of broken ceramics and pottery, must not exceed a total of 5% by weight. 100One hundred per cent of the crushed glass shall pass a 9.5 mm (3/8 in.) sieve and not more than 5% shall pass a 0.075 mm (No. 200) sieve. Crushed glass conforming to the specified grading requirement may be directly substituted for size No. 25 and 26 aggregates in backfilling and pipe bedding applications.

When the crushed glass is employed in constructing roadway embankments, the use of crushed glass must be limited within the boundaries of the embankment. The crushed glass must be a minimum of 2 ft (0.61 m) inside the side slope and contain a minimum of 2 ft of soil embankment cap (Virginia Department of Transportation 2020). Crushed glass may constitute up to 90% (by weight) of these areas of the embankment where glass is used, except where 100% crushed glass is used for drainage medium applications including blankets.

For the embankment construction, alternate 4 in. (101.6 mm)-layers of glass and soil needs to be placed and be mixed and blended during compaction. The uncompacted soil and glass layers must have a maximum thickness of 8 in. (203.2 mm). Alternatively, the blend of soil and crushed glass can be pug milled to a visually consistent blend and then be placed in lifts of a maximum 8 in. (203.2 mm). This process may also be directed by the engineer, as another option. Also, the density and moisture requirements for the embankments incorporating crushed glass must be similar to the ones from the conventional soil embankments. Also, crushed glass is permitted to be used as a crusher run aggregate for backfilling and bedding pipe applications.

B.2 New York State Department of Transportation, USA (NYSDOT)

The New York State Department of Transportation (NYSDOT 2017) specifies that recycled glass meeting the requirement of glass backfill can be used for embankment construction. NYSDOT (2017) indicates the material requirements and methods for assessing glass backfill material that is generally used as fill materials. Crushed glass for this application must have a maximum particle size of 9.5 mm (3/8 in.) and shall be subject to visual inspection by the regional geotechnical engineer. The glass may contain no more than 5% by volume of ceramics, china, plastic, paper, plate glass products, or other deleterious materials. Also, of particular note for drainage medium applications, glass is not permitted to be placed in contact with synthetic liners, geotextiles, geogrids, or other geosynthetic materials. Also, for the embankment application, glass must not be placed in contact with geotextiles, synthetic liners, geogrids, or other geosynthetic materials.

Recycled glass meeting the requirement of glass backfill is accepted for the replacement for underdrain filter material generally used in drainage systems. In this case, the crushed glass must have a maximum particle size of 12.7 mm (1/2 in.), and 90–100% shall pass a 9.5 mm (3/8 in.) sieve, and not more than 5% by weight shall pass a 0.075 mm (No. 200) sieve.

B.3 South Carolina Department of Transportation, USA (SCDOT)

The South Carolina Department of Transportation (2007) specifies that a maximum of 25% of recycled glass (by weight) can be mixed with the materials for the construction of embankments. Recycled glass aggregate for this application shall have a maximum particle size of 12.7 mm (1/2 in.). It is indicated that recycled glass must not be used in the top 18 in. (457.2 mm) of the embankment.

Also, recycled glass aggregate meeting the gradation requirements of coarse aggregate No. 57 may be used for constructing aggregate underdrains using granular filter materials. Additionally, recycled glass can be used as fine aggregate underdrain material while meeting the gradation requirements for aggregate No. FA-12 or FA-13 (for aggregate No. FA-12 and FA-13, 100% by weight pass a 3/8 in. sieve and 90–100% by weight pass No. 4 sieve). When the recycled glass is used as the underdrain aggregate, it shall be covered with a minimum of 6 in. (152.4 mm) of mineral aggregate (or suitable earth material) that needs to be compacted to make sure that the glass aggregate will not be exposed.

For both applications, the amount of non-glassy materials and impurities must be limited to 1% (by weight of recycled glass) with no mirror glass. Recycled glass aggregate shall be free of toxic and organic materials, hazardous materials, and hypodermic needles, and it must meet the South Carolina Department of Health and Environmental Control regulations as a non-hazardous material. Neither the lead nor the silver content for the recycled glass shall be more than 5 ppm.

B.4 Oregon Department of Transportation, USA (ODOT)

According to the Oregon Department of Transportation (2020), reclaimed glass may be substituted for selected granular backfill while meeting specified requirements. 100% of the reclaimed glass (mixed waste cullet) as an aggregate substitute shall pass a 12.7 mm (1/2 in.) sieve and not more than 5% by weight shall pass a 0.075 mm (No. 200) sieve. The glass material must also be clean, hard, and durable, with a maximum debris content of 10%, which is defined as any deleterious material that impacts the performance of the backfill. Impurities in the RCG can be visually checked by sampling a specimen of processed cullet.

The maximum glass cullet content to be used for the non-structural fill application is 100%, with a maximum debris level of 10% and a maximum compaction level of 90%. The glass cullet needs to be transported to the project site and be placed in the trench in loose lifts of 8 in. (203.2 mm) or less after adding water to achieve the proper moisture content. Each layer of material shall be compacted by steel wheel vibratory rollers or as directed. Following compaction, an engineer is required to check the density and gradation by field or laboratory testing as deemed appropriate.

It should be noted that in the 2021 edition, which updated the 2018 version, the use of reclaimed glass as a substitute for granular drainage blanket material and sand drainage blanket has been removed.

B.5 Washington State Department of Transportation, USA (WSDOT)

According to the Washington State Department of Transportation (2020), glass cullet may be employed as or blended uniformly with, naturally occurring materials for aggregates. The recycled glass included in the blended material and the final blended product must meet the requirements for the specific type of aggregate.

Washington State Department of Transportation (2020) provides the maximum allowable amount of glass cullet for each application. For example, the maximum allowable amount by weight of glass cullet to be used as backfill for sand drains, sand drainage blanket, or gravel backfill for pipe zone bedding, is 20%. Other applications and their associated allowable amount of glass cullet are specified but are not detailed here as they are beyond the scope of this project.

Significantly, toxicity testing and certification for toxicity characteristics are required for recycled materials (recycled glass in the context of this report) only if they are imported to the site. Otherwise, if they are sourced from the contracting agency's roadways, toxicity testing will not be required.

Washington State Department of Transportation (2020) further specifies that glass cullet must meet the requirements of AASHTO M318 including the physical properties and deleterious substances requirement (AASHTO M318:2019). According to AASHTO M318, glass cullet must be crushed and 100% of the glass cullet shall pass the 9.5 mm (3/8 in.) sieve. Glass cullet shall consist of broken food and beverage containers and may contain no more than 5% by mass of glass cullet of ceramics, china dishes, or plate glass. It also shall be free of odour. Any deleterious materials such as food residue, container tops, foil, wood, paper, or labels must be limited to a maximum of 1% by mass of the glass cullet while not having more than 0.05% by mass of paper. Glass cullet must be free of TV or other cathode-ray tubes, fluorescent lightbulbs, and any toxic or hazardous materials as defined by the state or local jurisdiction. Also, extraneous soil-like materials are limited to a maximum of 2% by mass of the glass cullet (AASHTO M318-02:2019).

B.6 Alaska Department of Transportation and Public Facilities, USA (State of Alaska DOT&PF)

The Alaska Department of Transportation and Public Facilities (2020) indicates that crushed glass may be mixed with soil/aggregate material for use in the embankment construction. A maximum of 10% crushed glass/glass cullet (by weight) can be uniformly blended with aggregates. Crushed glass/glass cullet shall be free of paper, metals, soil, plastic, organic material, hazardous material, and other deleterious substances. Up to 2% debris content is allowed in crushed glass. Also, the maximum particle size of crushed glass shall be 9.5 mm (3/8 in.). The uniformly blends glass/natural soil must meet the gradation requirements of the selected material specified in Alaska DOT&PF (2020). According to this specification, the allowable glass types to be used consist of beverage and food container glass, building window glass, and plain ceramic or china dinnerware. On the other hand, the prohibited glass types are light bulbs, laboratory glass, glass from automobiles, cathode-ray monitor tubes, or porcelain.

When soil/aggregate with glass cullet is used in the embankment construction, the mix shall not be placed within 4 ft (1.2 m) from the face of the embankment slope, within 150 ft (45.7 m) from any surface water body, and in the areas where culvert placement is needed. Also, the glass/soil mix must not be in contact with geosynthetic material (Alaska DOT&PF 2020).

B.7 Idaho Transportation Department, USA (ITD)

Idaho Transportation Department (2018) specifies that embankments may be constructed with recycled glass as a substitute for soil, aggregate, rock, or other materials. The recycled glass shall be sourced from a waste stream in Idaho and must meet the requirements of AASHTO M318:02 (R2019).

AASHTO M318:02 (R2019) requirements are presented in Appendix B.5.

B.8 State of Connecticut Department of Transportation, USA (ConnDOT)

Connecticut Department of Transportation (2020) indicates that recycled glass may be used in embankment construction. In this case, recycled glass must be properly mixed with other materials. The maximum glass content anywhere in the embankment must be 25% (by weight). It is specified that the mix including glass must not be placed within 5 ft (1.5 m) from the face of the embankment slope. The maximum particle size of recycled glass for this application shall be 1 in. (25.4 mm).

B.9 Ministry of Transportation of Ontario, Canada

The Ontario Provincial standard specification (OPSS.MUNI 1010:2013) provided by the Ministry of Transportation of Ontario (MTO) specifies the material requirements for aggregates to be used in road pavement and geotechnical applications. Granular A and B type I materials may contain no more than a combined total of 15% by mass of crushed glass and ceramic material. Granular A is defined as the requirements for dense graded aggregates to be used as backfill, base in a pavement structure, and granular shouldering. Granular B is defined as the requirements for well-graded aggregates to be used as granular backfill and granular subbase in a pavement. The combined amount of deleterious material must be limited to 1% by mass. Glass and ceramic material must be processed to remove the deleterious organic materials, and 100% of the processed glass and ceramic material shall pass a 13.2 mm sieve. MTO indicates that when reclaimed materials are allowed to be used in an application, they must be homogeneously mixed with other materials.

According to OPSS.MUNI 1010:2013, glass is defined as processed glass obtained from the recycling stream that is free of organic material, plastic, and metal. Also, deleterious material is defined as the materials from the recycling stream other than glass, ceramic, reclaimed concrete materials, and reclaimed asphalt pavement. Wood, plastic, clay brick, clay tile, wallboard, gypsum, and gypsum plaster are examples of deleterious material.

It is noted here that, for pipe bedding, embedment material, and trench backfilling around underground infrastructure, OPSS specifies dense-graded recycled concrete material. For this application, materials shall not contain glass or ceramic material.

B.10 Department of Transport, United Kingdom (UK)

The *Manual of Contract Documents for Highway Works (MCHW), Volume 1, Specification for Highway Works (*SHW) (Standards for Highways 2016) specifies materials and the method of operation for highway construction in different series related to various applications. Series 600 provides the specification for ‘Earthworks’ including supplements for Scotland, Wales, and Northern Ireland, in which the requirements for the use of crushed glass as an aggregate in starter layers, general fill, below water, drainage layers to reinforce soil and anchored earth structures, fill to reinforce soil and anchored earth, lower bedding for corrugated steel buried structures, fill to structures, or lower trench fill are included.

In this series, recycled material that complies with BS EN 13242 is permitted to be used. Additionally, where ‘recycled aggregate’ (i.e. aggregate resulting from the processing of inorganic or mineral material previously used in construction) is used in this Series, the maximum amount of crushed glass shall be 25%. However, where ‘recycled aggregate except recycled asphalt’ is used in this Series, it must contain no more than 5% crushed glass. When recycled glass is used as an aggregate in these applications; crushing and screening are required for processing.

Appendix C Current Bedding Sand, Drainage, Embankment Fill, and Landscaping Specifications and Applications

C.1 New South Wales – Transport for New South Wales (TfNSW)

For bedding sand in stormwater drainage applications, TfNSW IC-QA-R11 refers to bedding and haunch materials as Type BH Select Fill. Here, the particle size distribution must be within the limits set out in Table 6 in AS/NZS 3725:2007, based on Test Method TfNSW T201:2012, and the plasticity index (PI) shall be no more than 6 based on Test Method TfNSW T109:2012. Meanwhile, Type SO Select Fill is designated for side fill and overlay zones with a maximum particle dimension of 53 mm and a PI between 2 and 12, determined by Test Method TfNSW T109:2012. It should be noted that, for use at pipe connections, controlled low strength flowable fill shall be used. Furthermore, it is highlighted that this specification states that select fill is different from 'selected materials' so the requirements within the specification (TfNSW IC-QA-R11) for selected materials have no bearing on bedding and backfill in drainage applications.

In other bedding applications, such as bedding for footpaths, and bicycle and shared paths, the TfNSW specification for general concrete paving (TfNSW IC-QA-R54) specifies the use of Class 2 densely graded base (DGB) for footpaths (75 mm thick), and bicycle and shared paths (150 mm thick). For this application, it is identified that RCG will not comply with the material requirements for Class 2 DGB bedding but may still be a suitable substitute.

TfNSW IC-QA-R31:2020 *Vertical Wick Drains* outlines that clean dry sand may be used as a backfilling medium. Further specification of the sand material is not included.

TfNSW IC-QA-R11:2020 outlines the requirements for fill material to be used in construction of embankments in open drains. The material must have 20–60% passing 0.425 mm, as determined by TfNSW Test Method T107:2012, and a plasticity index of 15–30, as per TfNSW Test Method T109:2012).

TfNSW IC-QA-R178:2020 *Vegetation,* IC-QA-R179:2020 *Landscape Planting* and IC-QA-M321:2020 *Landscape Maintenance* do not encompass rock mulch blends for garden beds, sand paths or other landscaping applications where RCG may be applicable as a replacement for virgin aggregates.

C.2 New South Wales – IPWEA

IPWEA NSW (2010) *Specification for Supply of Recycled Materials for Pavements, Earthworks and Drainage* provides requirements for drainage medium, applicable as backfilling material for stormwater pipes, sewer pipes or sub-surface drainage lines. Pipelines covered by AS/NZS 3725:2007, *Design for Installation of Buried Concrete Pipes* are excepted. Table 3.10 provides the particle size distribution for drainage medium classes D75, D20 and D10, which may include glass fines, as well as other recycled materials. Other materials include concrete, RAP, clay brick tile, crushed rock, masonry, fly ash and crushed glass fines. D75 and D20 may include 50% by mass glass fines, whereas D10 may include 100% glass fines. Contaminant requirements for the recycled blends as follows; < 5% metal and ceramics, < 0.5% plaster, clay lumps and other friable materials, < 0.5% rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter.

IPWEA NSW (2010) *Specification for Supply of Recycled Materials for Pavements, Earthworks and Drainage* provides requirements for select fill. which may encompass 10% RCG fines. Other recycled materials such as concrete, RAP, clay brick tile, crushed rock, masonry, and fly ash are also allowed. The recycled blend particle size distribution is outlined in Table 3.10 and contaminant limits are as follows: < 5% metal and ceramics, < 1% plaster, clay lumps and other friable materials, < 0.2% rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter. The maximum plasticity index required is 12.

C.3 Victoria – Department of Transport (DoT)

For bedding and select backfill materials the current DoT specification (VicRoads Section 701), makes no mention of sand specifically but instead refers to ‘bedding’ and ‘selected backfill’ materials, where both material applications have a maximum PI requirement of 20 and for each application, the following grading requirements apply (VicRoads Section 701):

- Bedding materials shall have 100% passing the 19 mm AS sieve and 5–40% passing the 0.075 mm AS sieve.
- Selected backfill materials shall have 100% passing the 37.5 mm AS sieve and 5–40% passing the 0.075 mm AS sieve.

Significantly the current specification for block paving (VicRoads Section 712) refers to bedding and joint filling sand that shall consist of ‘naturally occurring’ grains.

Granular filter materials for use in subsurface drainage (VicRoads Section 702) must be hard, durable, and clean sand, gravel or crushed rock. Materials shall be free from clay balls and organic matter, have a pH of 6.0–8.0 and material passing the 4.75 mm AS sieve shall have a Sand Equivalent value (quantification of relative abundance of sand versus clay/fine particles) of not less than 80.

Under VicRoads 204:2015 *Earthworks* permeable fill material for use as drainage blanket material shall be hard, durable, clean sand, gravel, or crushed aggregate. Material shall be free from clay balls and perishable matter, as well as meet the grading required for Grade A6 or B4, outlined in VicRoads Section 702 (and provided in Table 3.11).

VicRoads Section 204 states that permeable fill material, types A, B and C are utilised against structures, for backfill and open jointed pipes. The fill materials should be crushed in a cubic shape, free of clay balls and perishable matter but can have a mixture of hard, durable, clean sand, gravel or crushed aggregate. Type A material should be free of topsoil, deleterious and/or perishable matter and the material should pass a 19.0 mm AS sieve which is compacted at 98% of maximum dry density and at optimum moisture content.

VicRoads Section 720 *Landscape Works* does not encompass rock mulch blends for garden beds, sand paths or other landscaping applications where RCG may be applicable as a replacement for virgin aggregates.

C.4 New Zealand

The primary standards and specifications relating to bedding and backfill materials used in New Zealand are provided in Table C 1 and Table C 2. These are primarily New Zealand Transport Agency (NZTA) documents, with some example specifications from several territorial authorities. It is noted that while these documents may not explicitly state the allowance of RCG sand in these applications, RCG sand products may already be able to comply with the specified requirements for certain activities.

Table C 1: Bedding material standards and specifications – New Zealand

Source	Reference	Notes
NZTA	NZTA F/3:2010 *Specification for Pipe Culvert Construction*	AS/NZS 3725:2007 *Design for Installation of Buried Concrete Pipes* AS/NZS 2566.1:1998 (reconfirmed 2018) *Buried Flexible Pipelines* AS/NZS 2566.2:2002 *Buried Flexible Pipelines*
NZTA	NZTA F/2:2013 *Specification for Pipe Subsoil Drain Construction*	Bedding material shall be filter material with a crushing resistance ≥ 100 kN when tested in accordance with NZS 3111:1986 (section 14) and complying with the grading presented in NZTA F/2 section 3.3.
NZTA	TNZ F/5:2000 *Specification for Corrugated Plastic Pipe Subsoil Drain Construction*	Bedding material shall be a filter material of clean hard sand, with a particle size up to 10 mm and shall comply with the grading provided in section 2.2 of TNZ F/5.
NZTA	TNZ F/6:2003 *Specification for Geotextile Wrapped Aggregate Subsoil Drain Construction*	Bedding material requirements are as per those given in TNZ F/2, or TNZ F/5.
Christchurch City Council	CSS Part 4:2015, *Construction Standard Specification Part 4: Water Supply 2019x*	Pipes shall be bedded with NZTA M/4: AP20 (basecourse aggregate) material unless otherwise specified.
Dunedin City Council	*Road Maintenance and Management Rural Contract Technical Specs* TS 30 and TS 33, 2015	For tactile pavers, dust with a top size of 5 mm shall be used as a bedding course beneath the pavers. This bedding sand or AP20 basecourse aggregate (NZTA M/4) shall comply with NZTA M/10. Bedding of pipes shall be on granular material complying with NZS 4452:1986.
Hastings District Council	Altered requirements to section 5 NZS 4404:2010 – Wastewater	The type of bedding for rigid pipes up to 525 mm diameter, and for those greater than 600 mm (reinforced concrete) shall be in accordance with AS/NZS 3725:2007. For all other pipes, bedding material shall comply with AS/NZS 2566.1:1998 (reconfirmed 2018).

Table C 2: Backfill material standards and specifications

Source	Reference	Notes
NZTA	NZTA F/3: 2010 *Specification for Pipe Culvert Construction*	Selected, Ordinary, or Loose fill are any materials that meet the requirements of the appropriate installation specification, but do not qualify as Type W or Type U in TNZ F/1:1997. (For Ordinary fill placed within 1.5 m of the finished surface, the material must be suitable for use as a subgrade).
NZTA	NZTA F/2:2013 *Specification for Pipe Subsoil Drain Construction*	Backfill material shall be filter material with a crushing resistance ≥ 100 kN when tested in accordance with NZS 3111:1986 (section 14) and complying with the grading presented in NZTA F/2 Section 3.3.
NZTA	TNZ F/5:2000 *Specification for Corrugated Plastic Pipe Subsoil Drain Construction*	Backfill material shall be a filter material of clean hard sand, with a particle size up to 10 mm and shall comply with the grading provided in section 2.2 of TNZ F/5.
NZTA	TNZ F/6:2003 *Specification for Geotextile Wrapped Aggregate Subsoil Drain Construction*	Backfill material for the geotextile lined trench shall be a clean, open course graded drainage aggregate with a crushing resistance ≥ 100 kN when tested in accordance with NZS 4407:2015 test 3.11, and complying with the grading presented in Section 2.2 of TNZ F/6:2003.
Christchurch City Council	*Construction Standard Specification Part 3 – Utility Drainage*, and *Part 4 – Water Supply* 2019	Backfill material in roads shall conform to the requirements of NZTA M/4 for an AP40 basecourse material.
Dunedin City Council	*Road Maintenance and Management Rural Contract Technical Specifications* TS 30, T33, 2015	For footpath reconstructions backfill material shall be a B40 material. Backfill for drainage and earthworks shall use a clean granular basecourse material.
Hastings District Council	Hastings District Council (2020) includes altered requirements to section 4 NZS 4404:2010 – Stormwater Drainage and section 6 NZS 4404:2010 – Water Supply Altered requirements to section 5 NZS 4404:2010 – Wastewater	Backfill materials shall comply with NZTA F/1 and NZTA B/2 for reinstatement in stormwater drainage construction. For backfill within the road carriageway, construction shall comply with NZTA B/2 with materials complying with NZTA M/3 and M/4. Backfill for reinforced concrete rigid pipes up to 525 mm diameter, and for those greater than 600 mm diameter, shall comply with AS/NZS 3725:2007.

C.5 Queensland – Department of Transport & Main Roads (TMR)

For bedding and backfill material applications, the TMR specification for drainage, retaining structures and protective treatments (TMR MRTS03) specifies that bedding and haunch zone materials shall be placed in accordance with Clause 19 of the general earthworks specification (TMR MRTS04). Meanwhile, for backfilling of culverts, this shall be conducted in accordance with sections 15 and 20 of the specification for general earthworks (TMR MRTS04).

Regarding TMR MRTS04, the specification states that materials for bedding and haunch zones shall be of a combination of gravel, loam, and sand, with materials being free from soluble salts, organic matter, and other deleterious materials. The specification also outlines three available options for grading: Well Graded, 20 mm Nominal, and 10 mm Nominal (TMR MRTS04). Under the given requirements, it is expected that RCG could be crushed to comply with the specified particle size distribution for Well Graded bedding materials.

TMR MRTS04 also outlines the requirements for sand, for use a fill material, where it may be natural sand, manufactured sand, or a blend. 85–100% shall be passing 2.36 mm, with ≤ 5% passing 0.75 mm for natural sand and ≤ 10% for blended or manufactured sand. Linear shrinkage shall be ≤ 3 for natural sand and ≤ 6 for blended or manufactured sand. Coarse sand may also be used, defined as 100% passing 4.75 mm, ≤ 10% passing 0.300 mm and ≤ 3 linear shrinkage. Again, coarse sand may be natural, manufactured, or blended.

TMR MRTS16 *Landscape and Revegetation Works* does not encompass rock mulch blends for garden beds, sand paths or other landscaping applications where RCG may be applicable as a replacement for virgin aggregates.

C.6 Western Australia – Main Roads Western Australia (MRWA)

The MRWA specification requirements for culverts (MRWA Specification 404) specifies bedding materials to be basecourse materials or other suitable materials approved by the superintendent. For this application, the following requirements are:

- Select bedding materials are to be compacted in accordance with the requirements for embankment construction as provided in the earthworks specification (MRWA Specification 302).
- Other materials shall contain less than 20% by mass retained on the 37.5 mm sieve as determined by MRWA Test Method WA 115.2.

Furthermore, backfill materials (MRWA Specification 302) are considered to be embankment materials installed in accordance with the earthworks specification requirements for ‘embankment construction’ (MRWA Specification 302) details can be found in Table 3.7. In addition, the MRWA specification for segmental paving (MRWA Specification 505) provides requirements for bedding and joint filling sand based on grading (refer to Table 3.9).

MRWA Specification 304 *Landscaping and Revegetation* outlines the requirements for mulch, including inorganic mulch, to be used in revegetation and landscaping applications. Mulch is defined as any chipped site vegetation or inorganic materials such as crushed rock, coarse aggregate, river pebbles, or pea gravel, spread as a soil surface protection measure. Mulch must be clean of any weed, grass stolons, seeds and other extraneous materials and matter and substances toxic to plant growth. MRWA Specification 301 *Vegetation Clearing and Demolition* outlines the grading requirements, such that mulch materials must be between 15 mm and 50 mm, with none greater than 100 mm.

C.7 South Australia – Department for Infrastructure and Transport (DIT)

The DIT specifications for the installation of stormwater drainage (DIT Master Specification RD-DK-C1) and for trench excavation and backfill (DIT Master Specification RD-EW-C2) both specify the use of Type-C sand as a bedding material. However, for trench excavation and backfill controlled low strength material may also be used as backfill for non-utility service trenches.

Furthermore, Type-C sand is also specified for use in the bedding of block pavers in the DIT specification for the construction of minor pavements (DPTI Master Specification RD-PV-C5). Here, joint filling sand requires 100% passing a 1.18 mm sieve with a maximum of 10% by mass passing the 0.075 mm sieve. Bedding and joint filling sand are also required to be free from soluble sands and contaminants that are likely to cause efflorescence.

Supporting these application requirements, the specification for supply of pavement materials (DPTI Master Specification RD-PV-S1) stipulates that Type-C sand be a crushed quarry product only. However, the recycled materials section of this specification does allow contractors to submit proposals to use recycled materials, or blast furnace slag, as an alternative to quarry materials. With this, there is an additional requirement to undertake a comprehensive environmental assessment if the recycled material is not made from construction and demolition materials or blast furnace slag. This environmental assessment shall be consistent with the Environmental Instruction 21.6 *Recycled Fill Materials for Transport Infrastructure* (Department of Planning Transport and Infrastructure 2015).

DIT Master Specification PR-LS-D1 *Landscape and Urban Design* and PR-LS-C1 *Landscaping General* do not encompass rock mulch blends for garden beds, sand paths or other landscaping applications where RCG may be applicable as a replacement for virgin aggregates.

C.8 Tasmania – Department of State Growth (DSG)

Generally, DSG specifications are aligned with those for the Department of Transport Victoria. For an overview of the specifications surrounding the use of RCG in DSG refer to that given for Victoria in Appendix C.3.

C.9 Australian Capital Territory – Transport Canberra & City Services (TCCS)

The TCCS specification for segmental paving (TCCS MITS 07) defines bedding sand as crushed gravel, granulated glass, or natural sand, where:

- The fines fraction shall not contain single-sized, gap graded or excessive fine materials.
- Crusher dust, dolomite, fatty sands, loams and packing sands are all considered unsuitable.

Also, within this specification (TCCS MITS 07), the grading requirements for bedding sand are noted as different from joint filling sand. This is consistent with most of the other state road agency specifications around Australia.

Furthermore, the TCCS specification for underground services, specifically stormwater drainage (TCCS MITS 03A), states the following:

- Materials for bed and haunch zones shall be select fill with a maximum PI of 6 in accordance with AS 1289.3.2.1:2009 and AS 1289.3.3.1:2009.
- The grading requirements for bed and haunch zones are noted to be consistent with Table 6 in AS/NZS 3725:2007.
- Materials for side fill and overlay zones shall be a select fill with a PI between 2 and 12 in accordance with AS 1289.3.2.1:2009 and AS 1289.3.3.1:2009.
- Grading requirements for side fill and overlay zones are consistent with Table 7 in AS/NZS 3725:2007 but include an additional requirement of a maximum aggregate dimension of 50 mm (TCCS MITS 03A).

The TCCS specification for subsurface drainage, TCCS MITS 03I, outlines the requirements for filter material to be used in trench drains and drainage mats. Type A filter material may be a crushed rock or granular material, and Type B may be granular material, meeting the grading requirements outlined in Table 3.12. Both materials must also have a pH between 6 and 7, where the subsoil drains are laid in or adjacent to planted areas. The particles must be clean, hard, tough and durable. Type B material just also meeting the following requirement for coefficient of saturated permeability: at least 8 m/day after three hours of flow when compacted to its maximum dry density in conformance with AS 1289.5.5.1:1998 (R2016), and then tested to conform to ASTM D2434:2019.

Type C filter material may be composed of crushed rock, have a maximum particle size of 37.5 mm, 5% maximum passing 9.5 mm (as per AS 1141.11.1:2009). Type D filter material may be composed of uncrushed river gravel, have a maximum particle size of 75 mm and 5% maximum passing 9.5 mm (as per AS 1141.11.1:2009). Type C and D filter materials must have a minimum wet strength of 100 kN and maximum 10% fines wet/dry variation of 30% (as per AS 1141.22:2019).

Type E filter is to be clean, washed drainage sand. The grading requirements are outlined in Table 3.12. Furthermore, the sand shall have a pH between 6 and 7, where the subsoil drains are laid in or adjacent to planted areas.

The requirements for general fill material are outlined in TCCS MITS 02B *Bulk Earthworks*. Material must be free of tree stumps, roots, clay, topsoils, steel, organics, and other contaminants. Fill for the top 150 mm below subgrades shall have a maximum particle size of 75 mm, and fill for use in the top 600 mm shall have a maximum particle size of 150 mm. Material used in top 1 m below subgrades shall be free of particles over 300 mm.

TCCS specification for *Soft Landscape Design* (TCCS MIS 24) outlines the requirements for inorganic mulch materials, including river stones/pebbles and shale/crushed rock mulch. The material should not be used in urban areas or close to buildings and pedestrian bridges, where there is potential for rocks to be thrown and cause damage to windows, cars or spread mowers. Moreover, additional inorganic mulch requirements are described in MITS 09C *Planting*. Inorganic mulch must be free of stones, soil and other waste such as building material. Materials shall have a uniform grading and sample is required for approval prior to delivery. Additional Australian Standard AS 4454:2012 *Composts, Soil Conditioners and Mulches* is defined as the reference specification.

The use of sand or glass as a replacement for other forms of inorganic mulch is not included in these documents. Furthermore, sand paths or other landscaping applications where RCG may be applicable as a replacement for virgin aggregates are not included.

C.10 Northern Territory – Department of Infrastructure, Planning and Logistics (DIPL)

Any backfill materials for drainage works are specified in section 12 of DIPL Specification v4.2 (Department of Infrastructure, Planning and Logistics Specification 2020) to be select fill, conforming to the requirements given in section 4 – Earthworks of the same specification. Section 4 states that select fill shall be gravel, decomposed rock or broken rock, free from organic matter and clay lumps. The CBR shall be a minimum of 30 based on a 4-day soaked test at 95% MDD according to AS 1289, and the PI shall be 2–15% with a linear shrinkage between 2–6% (DIPL Specification v4.2).

DIPL 2020, *Standard Specification for Roadworks v4.2* does not encompass rock mulch blends for garden beds, sand paths or other landscaping applications where RCG may be applicable as a replacement for virgin aggregates.

Appendix D Particle Size Distribution Limits from Specifications

D.1 General

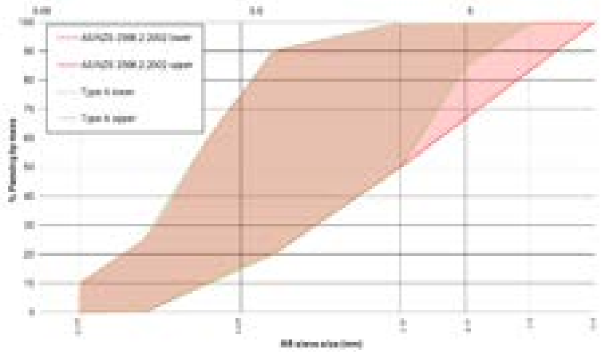
Grading envelopes Type A (Section 3.5.5) were primarily developed based on AS/NZS 2566.2:2002 and AS/NZS 3725:2007 and Andrews (2010) specification. The following figures show the comparison between the grading Type A requirements with current standards and road agencies' specifications for bedding and haunch (Appendix D.2) and side fill and backfill (Appendix D.3) applications.

D.2 Bedding and Haunch Material Grading Comparison

The Type A grading envelope is compared with AS/NZS 2566.2:2002 and AS/NZS 3725:2007 (Figure D 1) and with road agencies' (Figure D 2) specification limits for bedding and haunch application. The green area defined by the Type A grading envelope and the light red areas illustrate the specification limits. The legends in these figures are too hard to read.

Figure D 1: Comparison of grading envelopes Type A with AS/NZS specification limits

(a) AS/NZS 2566.2:2002: Buried Flexible Pipelines Part 2



(b) AS/NZS 3725:2007 Design for Installation of Buried Concrete Pipes

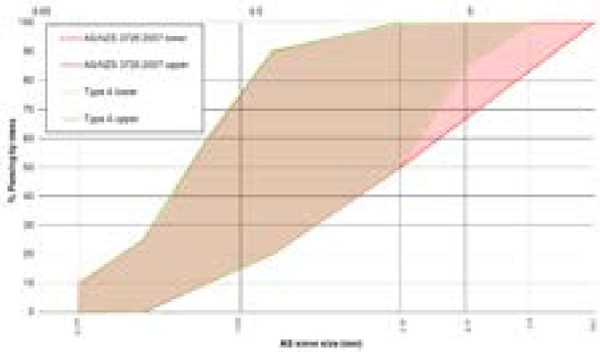
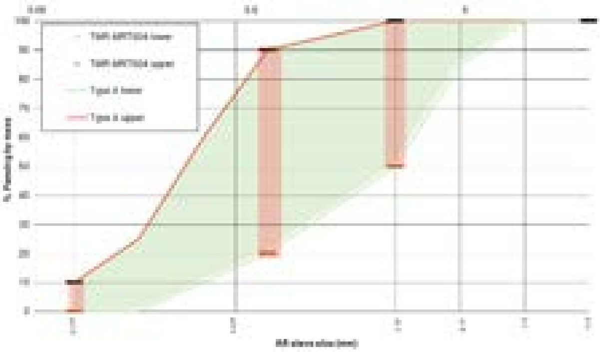
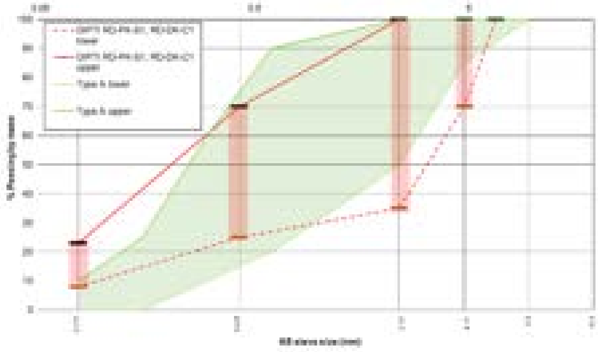


Figure D 2: Comparison of grading envelopes Type A with specification limits

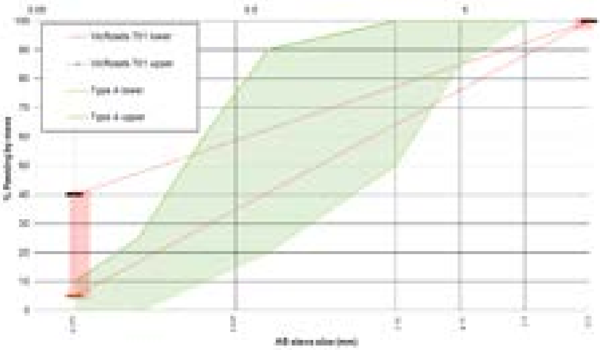
(a) TMR MRTS04



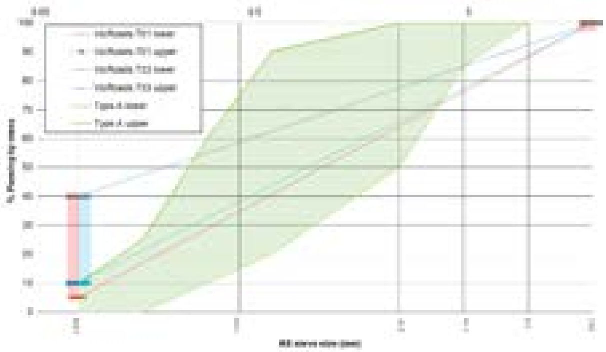
(b) DIT RD-PV-S1, RD-DK-C1



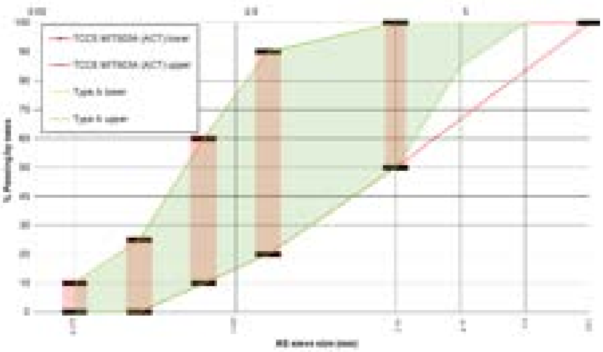
(c) VicRoads Spec. 701



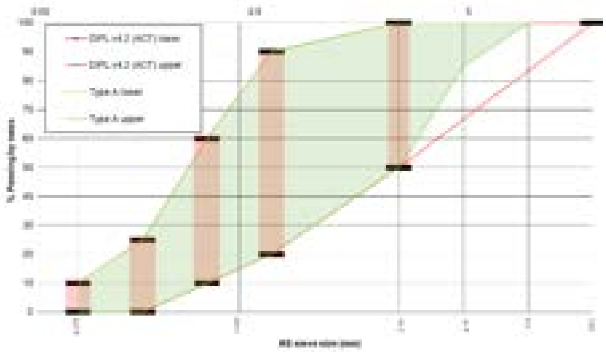
(d) VicRoads Spec. 733 – Conduits and Pits for Underground Wiring and Cabling



(e) ACT – TCCS MITS 03A



(f) NT – DIPL v4.2

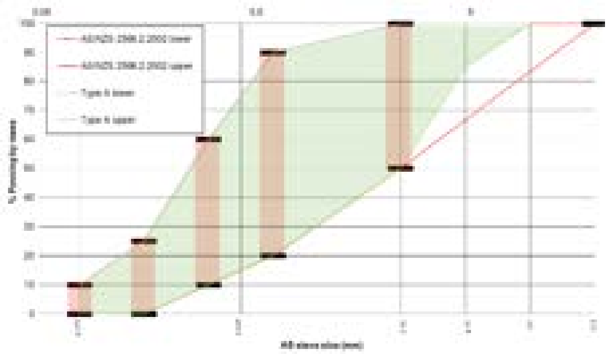


D.3 Side and Backfill Material Grading Comparison

The Type A grading envelope is compared with AS/NZS 2566.2:2002 and AS/NZS 3725:2007 (Figure D 3) and with road agencies' (Figure D 4) specification limits for side and backfill application. The green area defined by the Type A grading envelope and the light red areas illustrate the specification limits.

Figure D 3: Comparison of grading envelopes Type A with AS/NZS specification limits

(a) AS/NZS 2566.2:2002: Buried Flexible Pipelines Part 2



(b) AS/NZS 3725:2007 Design for Installation of Buried Concrete Pipes

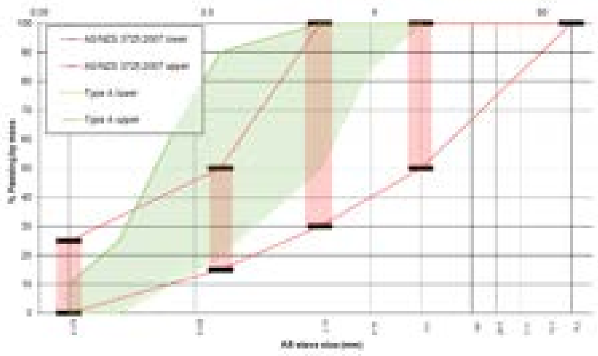
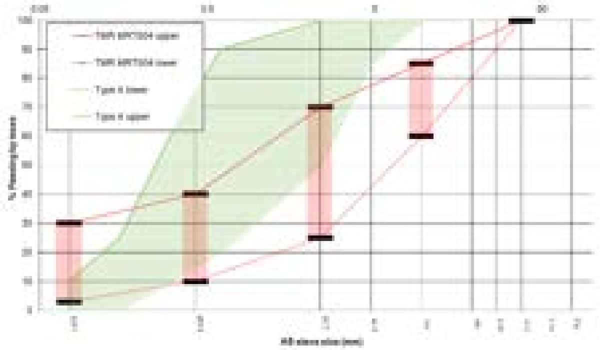
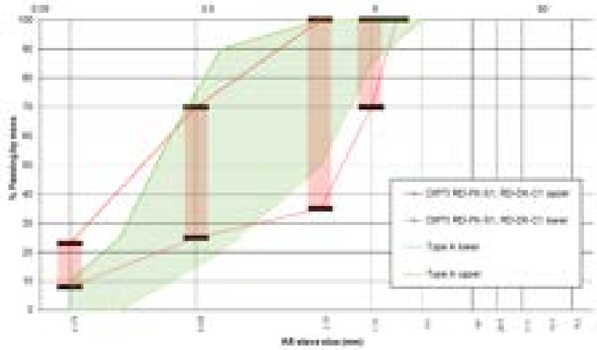


Figure D 4: Comparison of grading envelopes Type A with specification limits

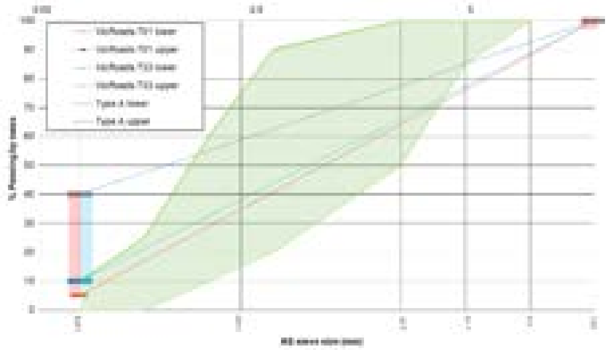
(a) TMR MRTS04



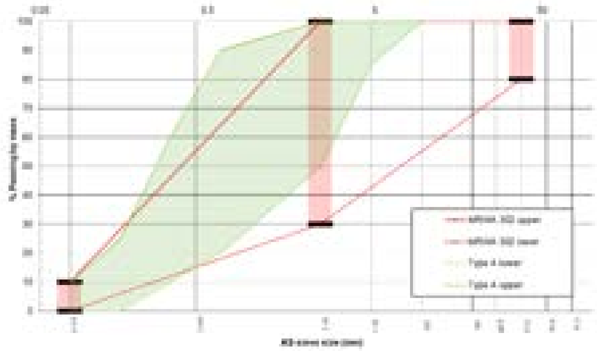
(b) DIT RD-PV-S1, RD-DK-C1



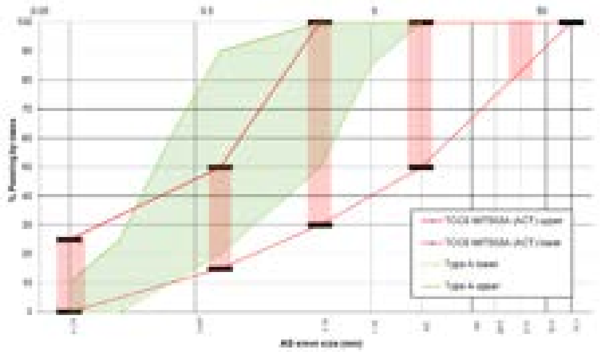
(c) VicRoads Spec. 701 and 733 and DSG 701



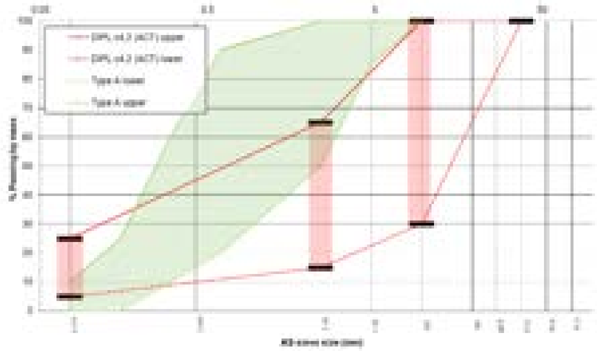
(d) MRWA 302



(e) ACT – TCCS MITS 03A



(f) NT – DIPL v4.2



Appendix E Case Studies – Granular Applications

E.1 Recovery and Processing

In WA, the Roe Regional Organisation of Councils (RoeROC) is a regional waste management group made up of the Shire of Corrigin, Shire of Kulin, Shire of Kondinin and Shire of Narembeen. These four Councils cover an area of 19 046 km^2 – more than a third of the area of the state.

In 2012, RoeROC was responsible for introducing the first mobile glass crusher for WA (Australian Food and Grocery Council 2012). The addition of the Komplet MT5000 mobile crusher has allowed bottles and jars collected locally to be crushed and used as a replacement for fine aggregate in civil construction. Applications include use in asphalt and concrete pavements, kerb and guttering, pole footings, pipe bedding and in the road base (Australian Food and Grocery Council 2012).

To achieve this utilisation of the mobile crusher, each council setup a local drop off facility as part of the project. However, the Shire of Corrigin was the lead Council for the management and delivery of the project. The approximate total glass diverted from landfill up to October 2014 was 430 tonnes, with 290 tonnes used in civil applications (Quarry 2020). This is much lower than the original predictions of around 800 tonnes per year at the inception of the scheme (Australian Food and Grocery Council 2012).

Several operational challenges, as follows, were noted as contributing to these lower recycling rates:

- a major breakdown of the crusher occurred in early 2013 resulting in over a month of downtime
- crushed glass particles sticking together in the crusher because of wet glass stockpiles following winter rains
- the lack of an appropriate collection program in the Shire of Kulin was noted but rectified by May 2013 by installing community bins at the local transfer station and recreation centre
- the Shire of Narembeen had issues with the storage of glass in 166 litre drums making the handling of drums and crushing of glass difficult
    - RoeROC has since purchased self-tipping bins for each of the partner Councils to address collection and handling issues
- several councils noted problems with access to qualified and experienced operators for the crusher
- the transport of the crusher between councils (approximately 50 km) was challenging to regular crushing.

Due to these challenges, RoeROC set a revised glass recycling target of 400–500 tonnes by 2017 (Quarry 2020).

In Victoria, Alex Fraser Group is a major materials recycler across the greater Melbourne region. In 2014, CPB Contractors commenced construction on the 185 000 m^2 Melbourne International Roll-On Roll-Off and Auto Terminal (MIRRAT) in Webb Dock West. For this, Alex Fraser supplied several recycled materials to CPB Contractors, including RCG sand and cement stabilised recycled sand. A total of 8349 t of recycled sand were used on this project however the specific application for the RCG sand is unknown (Roads and Infrastructure Australia 2016).

Also, in Victoria, RCG was used as a substitute for virgin sands on the Kororoit Creek Road Level Crossing Removal Project (Level Crossing Removal Project 2019). The material was manufactured locally from inert RCG and employed as bedding for combined service routes, and as backfill for drainage piping. In using this material, the project reported the benefits of both cost savings (due to the shorter transport distances) and claimed safe handling of the materials with lower respiratory hazards than traditional sand. More details around the use of recycled crushed glass in the rail infrastructure is provided in Appendix A.10

E.2 International Specification Development

E.2.1 Clean Washington Center (CWC), USA

CWC (1997 and 1998) developed model specifications based on the behaviour of materials under laboratory experiments. The recommended gradation specification for the applications discussed here are shown in Table E 1.

Table E 1: Recommended gradation specification

Sieve size	19 mm (3/4 in.)	6.35 mm (1/4 in.)	2 mm (No. 10)	0.425 mm (No. 40)	0.075 mm (No. 200)
Per cent passing (by weight)	100	10–100	0–100	0–50	0–5

Source: CWC (1997 and 1998).

CWC (1997 and 1998) summarised the specification for the use of glass cullet based on the following applications as included in Table E 2:

- general backfill applications such as:
  - light-loaded or non-loaded conditions such as fill placed under pedestrian sidewalks or landscaping fill
  - fill that supported heavy stationary loads such as beneath footings and slabs
  - fluctuating loads such as under reciprocating pumps and compressors
- utility applications (using glass cullet aggregate as bedding and backfill material for utility trenches)
- roadway embankment construction
- drainage applications including retaining wall backfill, footing drains, French drains, and drainage blankets
- landfill cover and underground storage tank backfill.

Furthermore, CWC (1997 and 1998) reported that since the permeability of glass cullet having the size of 1/4 in. minus (6.3 mm) and 3/4 in. minus (19 mm) are about the same as those for natural sand, and natural gravel, respectively, fill material with 100% glass cullet may be used for the constructions in the drainage, landfill cover and underground storage tank backfill applications.

A maximum of 100% glass cullet is allowed to be used as backfill material for utility trenches and underground storage tanks up to the last 610 mm (e.g. two ft) below the final grade. The last two ft may have 15% to 100% glass cullet depending on the load conditions on the backfill.

Also, CWC (1998) reported that the provided specification for the utility application is applied to backfill which is not subjected to surcharge loading from roadways or slabs. However, if the trench backfill in this application is within five ft (1.52 m) of a loading area, the specification for the ‘general backfill’ section in Table E 2 shall be adopted.

Table E 2: Specifications for the use of glass cullet for different applications

Application	Loading condition or application detail	Max. glass cullet content (%)	Max. debris content (%)	Max. compaction level (%)
General fill and backfill	Non-loading general fill	100	10	85
	Stationary loads (light)	100	10	95
	Stationary loads (heavy)	30	5	95
	Fluctuating loads	15	5	95
	Lateral loads	100	10	95
Embankments	–	30	5	90
Drainage	Retaining wall backfill	100	5	95
	Foundation drain	100	5	95
	Drainage blanket	100	5	90
	French drain	100	5	90
Landfill cover	–	100	10	90
Underground storage tank backfill	–	100	5	90
Utility trench bedding/backfill • Water & sewer pipes • Electrical conduit • Fiber optic lines	–	100	5	90

Source: CWC (1997 and 1998).

In addition, CWC (1998) presented the level of importance that material properties and engineering characteristics were considered to have on the performance of glass cullet for each application, as shown in Table E 3. In this table, ‘H’ and ‘L’ represent the high and low levels of importance, respectively.

Table E 3: The level of importance for material properties and engineering characteristics for the use of glass cullet in construction applications

Application		Material properties				Engineering characteristics		
		Specific gravity	Gradation	Workability	Durability	Compaction	Permeability	Shear strength
General backfill	Non-loading general fill	H	H	H	L	L	L	L
	Stationary loads	H	H	H	L	H	L	H
	Fluctuating loads	H	H	H	H	H	L	H
Embankment		H	H	H	L	H	L	H
Drainage	Foundation drainage	H	H	H	L	H	H	L
	Drainage blanket	H	H	H	L	H	H	L
	French drain	H	H	H	L	H	H	L
Landfill Cover		H	L	H	L	H	L	L
Underground storage tank fill/backfill		H	L	H	L	H	L	L
Utilities	Pipe trench bedding/ backfill	H	L	H	L	H	L	L
	Conduit bedding & backfill	H	L	H	L	H	L	L
	Fibre optic cable bedding & backfill	H	L	H	L	H	L	L

Source: CWC (1998).

E.2.2 Hong Kong

In Hong Kong, So et al. (2016) and So et al. (2015) investigated the use of recycled glass cullet as an engineering fill in reclamation and earthworks. For this, a series of laboratory experiments were carried out on crushed pure glass samples of sizes of 3 mm minus and 20 mm minus to evaluate the physical and engineering properties of glass cullet produced by local suppliers in Hong Kong. The laboratory tests were conducted on samples of 100% glass cullet and no tests were performed on the glass-soil mix. From testing, they summarised that the main raw material for glass is quartz which is the crystal form of silica, and glass cullet does not release any toxic substance into the environment. Additionally, they observed that the grading of glass cullet samples remained virtually the same after light impact and vibratory compaction which indicated the physical durability of glass cullet. The glass cullet also showed lower water absorption compared to natural granular soils making it not susceptible to volume change upon compression. The glass cullet showed lower specific gravity which may result in a lower active pressure on the back of retaining structures in that application. So, Hui and Lee (2016) and So et al. (2015) summarised that the grading of 3 mm minus and 20 mm minus glass cullet fell within the specified envelope by CWC (1998) for drainage fill and structural fill, respectively.

So et al. (2016) and So et al. (2015) concluded that glass cullet has quantifiable engineering properties similar to those of granular soils and indicated that with proper engineering control, the use of glass cullet as fill material in both earthworks and reclamation is acceptable. They proposed the following technical requirements and recommendations for grading, material and testing requirements, construction control, and design considerations for the use of 100% glass cullet as engineering fill.

Proposed grading requirements

So et al. (2016) recommended that the grading of glass cullet to be used in earthworks should meet the requirements specified in 'The Government of the Hong Kong Special Administrative Region – Hong Kong General Specification for Civil Engineering Works' as well as the recommended gradation as shown in Table E 4.

Table E 4: Proposed gradation specification

Sieve size (mm)	20	6.3	2	0.425	0.075
Per cent passing by mass (%), (BS test sieve)	100	10–100	0–100	0–50	0–5

Source: So et al. (2016).

Proposed material requirements

So et al. (2016) recommended that the glass cullet material for earthworks should meet the requirements specified in 'The Government of the Hong Kong Special Administrative Region – Hong Kong general specification for civil engineering work' as well as the following additional requirements:

- Glass cullet from crushing of glass beverage bottles or from other approved glass products must be used. The prohibited glass products include glass cookware, tempered glass, cathode-ray tubes, fluorescent lamps, etc.
- The maximum allowable non-glass materials (debris content) must be limited to 2% by weight.
- The maximum allowable organic content shall be limited to 0.2% by weight.

Proposed testing requirements

In addition to following the testing requirements specified in 'The Government of the Hong Kong Special Administrative Region – Hong Kong General Specification for Civil Engineering Works', the glass cullet samples shall be tested for organic matter and debris contents. Debris shall be manually separated from the bulk mass of glass material. Also, liquid limit and plasticity index tests shall be removed from the testing requirements So et al. (2016).

Design and construction considerations

So et al. (2016) summarised that for the use of glass cullet in earthworks, 100% glass cullet may be employed for supporting facilities with the stationary load of a maximum of 20 kPa. Glass cullet is not allowed to be used within two meters below the slope surface or one meter below utilities. Also, glass cullet should not be placed in contact with geogrids or synthetic liners.

Regarding the construction considerations, So et al. (2016) pointed out that a water content close to the optimum moisture content is not required for the compaction due to the insensitivity of the compaction performance of glass cullet to the change in moisture. For each layer, the compaction shall be conducted in layers of a maximum of 200 mm in loose thickness. The maximum dry density of glass cullet samples shall be obtained using the specified test method. Additionally, the in situ density shall be frequently tested following the 'Hong Kong General Specification for Civil Engineering Works' for 'the areas of fill in excavations for structures, pits and trenches, and on formations' to confirm the degree of compaction.

E.2.3 Indiana, USA

Siddiki, Kim and Salgado (2004) presented the results from research on geotechnical applications of different waste materials including crushed glass in Indiana, USA. The research discussed the engineering properties, post-construction evaluation, economic benefits, and specifications development for the future use of waste materials. The post-construction evaluation was conducted based on a demonstration project completed by the Indiana Department of Transportation (INDOT) in 2001, which aimed to develop special provisions to use crushed glass as a backfill material around drainage pipes.

Siddiki, Kim and Salgado (2004) concluded that the following criteria were required for the use of 100% crushed glass as bedding material:

- The source of the crushed glass must be food containers and glass beverages that were processed by equipment designed to crush glass into aggregate.
- The produced material shall be relatively free of labelling paper, bottle caps, and other unsuitable materials.
- 100% crushed glass shall have particle size gradation as shown in Table E 5.

Table E 5: The recommended gradation specification

Sieve size	12.5 mm (1/2 in.)	4.76 mm (No. 4)	2 mm (No. 10)	0.425 mm (No. 40)	0.075 mm (No. 200)
Per cent passing	85–100	45–85	25–70	10–30	0–10

Source: Siddiki, Kim and Salgado (2004).

It was reported that the use of crushed glass was comparable to 'granular fill' specified in INDOT specifications. Based on the site observations and construction data, the embankment and pavement continued to perform well, and the project concluded that the use of crushed glass can result in significant cost savings and a positive environmental impact.

E.3 International Use as Bedding and Backfill Material

E.3.1 Pipe Backfill Project, PennDOT Highway Project, Pennsylvania, USA

In Berks County in Pennsylvania, USA, Pennsylvania Department of Transportation (2005) conducted a project using 700 tons of crushed glass as pipe bedding and backfill in a 100% substitution for conventional aggregates. Provisional specifications were issued with the requirement that the crushed glass met AASHTO No. 8 gradation and construction specifications for PennDOT projects (Publication 408) Type C (Pennsylvania Department of Transportation 2020) coarse aggregate quality requirements.

They reported that crushed glass met minus 9.5 mm (3/8 in.) gradation and the Type C, coarse aggregate specifications. However, during the compaction, the crushed glass showed a tendency to slide which made the compaction difficult. Therefore, Pennsylvania Department of Transportation (2005) decided to use crushed glass only as pipe bedding material. They found that although the specifications (minus 9.5 mm gradation) were met, the material did not have the required gradation. They pointed out that the upper gradation ranges could contain some elongated glass pieces which may contribute to the compaction difficulty. Suggested solutions were to undertake the mandatory full gradation testing of the supplier stockpile, to limit the use of crushed glass to the pipe bedding application only, and/or to use crushed glass meeting the requirement of AASHTO No. 10 gradation. It was also noted that compaction should be closely monitored.

E.3.2 Glass Cullet as Fill/Bedding Material, Washington, USA

In Tumwater, Washington, crushed glass cullet was employed as a 100% substitute for natural aggregate including sand and pea gravel as fill/bedding material to construct a slab-on-grade foundation capillary break, and for waterline pipe zone bedding in a residential building project (Northwest EcoBuilding Guild 2018). The required testing to evaluate the suitability of this material to be used as fill/bedding/backfill material was related to appearance, absence of hazardous substances, permeability, and compaction.

Glass cullet manufactured from the crushed post-consumer bottles and/or by glass cullet supply companies were crushed to a 9.5 mm (3/8 in.) minus size and sifted of debris/impurities. The ratio of coarse and fine material sizes met the Washington State Department of Transportation (WSDOT) requirement of the sieve test. Samples were also tested for copper and lead content.

Field tests were performed to ensure the material conformed to the allowable debris level. To check that the product was unyielding and firm under the load, compaction was also conducted using the roll test method. In this study, the crushed glass cullet provided a highly workable, low cost, permeable, and structurally stable (equal or better) substitute for natural aggregate which is also clean and safe for the environment (Northwest EcoBuilding Guild 2018).

E.3.3 RCG as a Bedding Sand for Slabs & Pavers, United Kingdom

Reid et al. (2008) stated that recycled glass has been employed as bedding sand for slabs and pavers in Surrey and some London Boroughs, where natural sand would have to be brought from a considerable distance and was also expensive. This material is marketed as EcoSand, the raw material is post-consumer waste glass collected by local authorities recycling programs. The glass is crushed, graded to size, and washed to produce a clean glass sand.

E.4 Use of RCG in Drainage, Embankment Fill, and Landscaping Applications

E.4.1 Murrawal Rd, Central Coast Council, New South Wales

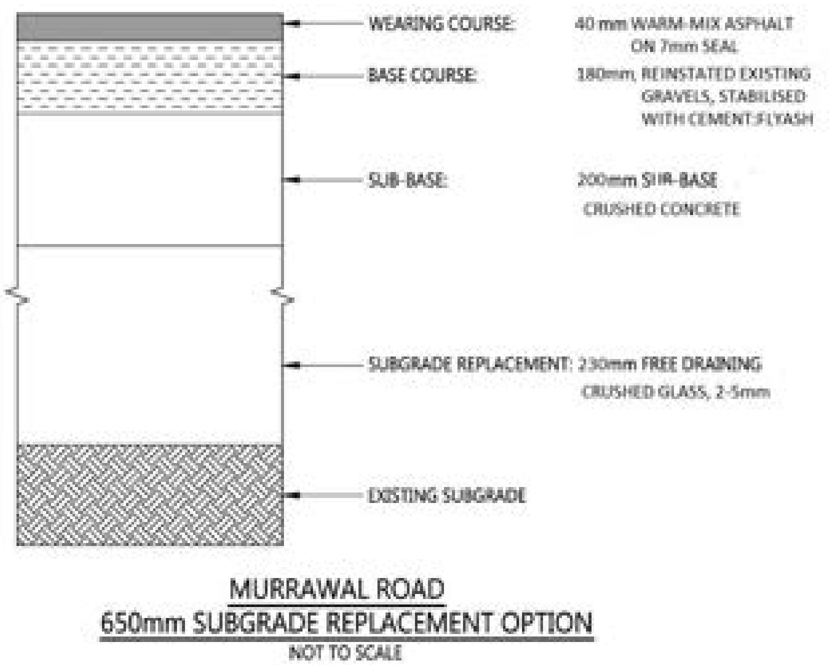
Central Coast Council conducted some trials utilising RCG including pipe drainage, kerb and channel, pavement and wearing course replacement. The selected site for these trials was Murrawal Road. The projects aim was to find a recycled replacement for each of the materials used in multiple layers of the construction process. Typically, the council uses:

- 50 mm asphalt (wearing course)
- 7 mm seal (Primerseal)
- 100 mm cement modified (base course)
- 200 mm 20DGS (subbase)
- 300 mm coarse sand (subgrade improvement).

This presents the council with opportunities to include recycled materials in their infrastructure, including the use of RCG.

Originally there was no formal performance-based inspection planned, other than the visual on-site and once complete observations. However, the relevant stakeholders agreed to arrange some beam tests and to monitor ongoing findings. Figure E 1 depicts the recycled materials used in this trial. The opportunity to use crushed glass in a free draining subgrade layer arose. This section details the experience gained from this trial.

Figure E 1: Murrawal Road RCG trial



Drainage tests on the 5 mm minus is that it is not free draining. Central Coast council asked the recycler to remove everything under 300 microns. This was difficult for the supplier, so they went for 2–5 mm. Sand is typically flood compacted, but the 2–5 mm glass did not flood in but was placed normally in one lift. Two passes with the roller seemed to achieve good compaction. General construction staff were happy with the placement of the material.

Once complete, both council and contractor were happy with the results. In winter, the fines stick to the larger particles, so it makes it difficult to screen fines. The operator is struggling to keep up with the demand. This is the biggest problem. A couple of projects are returning to virgin sands due to lack of supply.

Free draining properties is a standard that the geotechnical engineers specify due to issues with low lying areas. The geotechnical engineers main concern was breakdown of material over time, creating fines. Glass has only been used in local roads. Recycled glass supplier supplied some extensive testing that showed that the glass met EPA guidelines. It goes through a washing process to achieve this. 0–2 mm glass fines are sent to a contractor for concrete and asphalt mix design. The recycler is producing three products, one 5 mm minus sand, course 2–5 mm, 2 mm minus.

E.4.2 Crushed Glass-dredged Material Blends in the Embankment and Structural Fill Applications, USACE-Philadelphia, USA

Grubb et al. (2006) reported the preparation of three crushed glass-dredged material blends using 20%, 50%, and 80% crushed glass contents and evaluating the suitability of these materials in the embankment and structural fill applications. It was indicated that the overall objective of this project was to identify the applications for the use of crushed glass and dredged material in urban construction. It should be noted that the embankment using 100% dredged material was also constructed which is not discussed here.

The blending and the construction of the trial embankment were carried out at the United States Army Corps of Engineers (USACE) Fort Mifflin site in Philadelphia. The embankment was constructed on the ground surface comprising 8 m of firm compacted silty and sandy soils that were underlain by deeper silty soil of fluvial origin. The embankment was constructed following the required procedures in PennDOT (2004) with some exceptions. According to Grubb et al. (2006), the trial embankment was constructed with the rectangular core dimensions of about 3.6 m high by 3.6 m wide by 15.2 m long with 3:1 ramps and 2:1 side slopes. However, the side slopes were often constructed with 1.5:1.

The glass was crushed and sieved using a 9.5 mm (3/8 st) sieve. The embankment with 20% crushed glass was compacted to a minimum of 90% modified Proctor compaction. This value for the embankment with 50% and 80% crushed glass was considered as a minimum of 95% modified Proctor compaction.

The Cone Penetrometer Test (CPT) was undertaken at three locations of each trial embankment. The average cone tip resistance of about 1, 1.5, and 2 MPa were obtained for the embankments with 20%, 50%, and 80% crushed glass, respectively. From the field testing results, an improvement in the geotechnical performance of dredged material was observed by the addition of crushed glass (Grubb et al. 2006). Based on the geotechnical improvement of dredged material in addition to the environmental evaluation of the blends as well as the economic analysis, they concluded that both crushed glass and dredged material provide beneficial opportunities to be used on a large scale in the urban environment.

A subsequent project by Grubb, Wartman and Malasavage (2008) evaluated the CPT resistance of trial embankment after completion of the construction and after 360 days. They reported that cone tip resistance of embankment with crushed glass-dredged material blends increased with aging (by a factor of two to three-time). Additionally, an increase of up to 8 degrees in effective friction angles of the aged materials (relatively undisturbed samples) was observed compared to the original laboratory prepared crushed glass-dredged material blends specimens. They reported that the increase in strength after 360 days seemed to be related to the silica cementation process rather than the formation of carbonates.

E.4.3 Recycled Glass in Backfill Applications, Wisconsin, USA

Stevens (2007) reported that Brown County, Wisconsin used 34 tons of three-colour recycled glass mix for the backfill applications in two projects in the Village of Howard. For both projects, a 2 ft wide storm sewer trench was excavated. In the first project which was conducted in 1994, a concrete storm sewer pipe was connected to the main sewer line. Then, the broken glass was used as the backfill material in a 2.5 ft layer on the pipe.

In the second project, a PVC storm sewer pipe was used and connected to the main sewer line. However, 2 ft of broken glass was used as the backfill material in the trench after covering the pipe by 3/4 in. (19 mm) crushed stone. This was done to avoid the potential abrasive damage of the glass on the PVC pipe. Then, more crushed stone and asphalt was used to cover the broken glass material. The broken glass sizes of 3/8 in. (19 mm) minus were used for this project. It was also reported that compacting the glass material was not a concern for this application. Stevens (2007) pointed out that as of 1996, no surface cracks or unusual settlements were reported for this project.

E.4.4 Use of RCG in Topsoil Mixes, Washington State, USA

In Washington state, Moller and Leger (1998) evaluated the growth performance of plants in topsoil mixes incorporating RCG cullet. The study included topsoil with 50% compost and 50% sand as the standard case and investigated the effect of crushed glass cullet replacement of three portions of the sand (10%, 30%, and 50% crushed glass instead of the sand portion). The four soil media were examined and compared 10 weeks after three plant species were grown.

It was reported that the plants grown in the 50% and 10% glass cullet mixes showed small but statistically significant differences in terms of biomass and height compared to the ones grown in 50% sand topsoil mix (slightly lower biomass and shorter height in the glass mix). However, there was an insignificant difference between the mix with 30% glass cullet and the standard mix of 50% sand.

Additionally, it was noted that the 50% glass cullet mix drained more quickly compared to the 10% glass cullet, 30% glass cullet, and 50% sand media. Also, this mix was reported to have a higher water holding capacity (WHC) compared to other tested topsoil mixes.

The project concluded that using RCG instead of sand in the topsoil mix with the 3/5 replacement ratio is feasible and can result in the plants with equal or higher growth size relative to the normal sand/compost mix. Also, the benefits of cost savings as well as saving natural materials by the use of crushed glass in this application were reported.

There has been limited case studies or specification developments for the use of RCG in landscaping application. However, the results and information from this study on the growth of vegetation in a crushed glass/soil mix help to more specifically employ the RCG in landscaping applications in the future.

Appendix F Australian and New Zealand Requirements for Applications in Concrete

F.1 New South Wales – Transport for New South Wales (TfNSW)

TfNSW IC-QA-R53:2021 refers to the concrete for general work. These specifications conform with general concrete applications such as drainage structures, footings and plinths, lighting columns and traffic signals, kerbs and gutters, safety barriers and paving for bicycle path/shared paths, footpaths, medians, and driveways. Concrete includes both unreinforced and reinforced concrete. The specifications explicitly specify the allowance of granulated glass as fine aggregate replacement in concrete, up to maximum 15% of the total fine aggregate. However, aggregates used in the manufacture of concrete must comply with AS 2758.1:2014. It must satisfy the fine aggregate durability requirements specified in AS 2758.1:2014 clause 9.2 and satisfy the wet strength and wet/dry strength variation requirements for exposure classifications A1, A2 or B1.

All aggregates used in concrete must be assessed and classified for Alkali-Aggregate Reaction (AAR) using the accelerated mortar bar test method in accordance with test method TfNSW T363. Where the aggregates classified as reactive by TfNSW T364 should not be used.

TfNSW IC-QA-R83:2020 for concrete pavement base also allows the use of granulated glass content up to a maximum of 15% of the total fine aggregate in accordance with TfNSW IC-QA-3154:2020. Fine aggregates size must be less than 4.75 mm and conform to AS 2758.1:2014. Fine aggregate requirements and test methods for the use in concrete pavement base are summarised in Table F 1. All aggregates should also comply with AAR test and classified as reactive, slow reactive and non-reactive.

Table F 1: TfNSW IC-QA-R83:2020 Table R83.2

Property	Requirement	Test Method
Material finer than 75 µm	TfNSW R83 Fig R83.1	AS 1141.11
Material finer than 2 µm	TfNSW R83 Fig R83.1	AS 1141.13
Methylene Blue Adsorption Value (MBV)	TfNSW R83 Fig R83.1	TfNSW T659
Bulk Density (compacted)	1200 kg/m^3 minimum	AS 1141.4 Procedure 7.2
Water Absorption	5.0% maximum	AS 1141.5
Soundness (sodium sulphate)	6.0% max weighted average loss	AS 1141.24
Organic impurities	Pass/Fail (AS 1141) and 0.5% maximum (AS 1289)	AS 1141.34 and AS 1289.4.1.1
Sugar content	less than 1 part in 10,000	AS 1141.35
Acid insoluble residue	60% minimum	Texas DOT test Tex-612-J
Micro-Deval loss	15% maximum	ASTM D7428
Flow Cone time	27 seconds maximum	TfNSW T279
Glass content	15% maximum	TfNSW 3154

Source: TfNSW IC-QA-R83:2020.

F.2 Victoria – Department of Transport (DoT)

VicRoads 703:2019, *General Concrete Paving*, specifies materials required for binder-based concrete paving for edgings, footpaths, other surfacing, and shared-use paths. Concrete for shared use paths may contain up to 30% glass fines as a replacement of the total mass of fine aggregated in the concrete mix. Whereas concrete aggregates for general concrete paving shall comply with VicRoads 610:2020 (specifications of fine aggregates are listed in Table 4.3).

Underground concrete stormwater drains should comply with following specifications:

- Precast reinforced concrete box culverts shall comply with the requirements of VicRoads 619:2017.
- Portland cement-based conventional precast reinforced concrete pipes shall comply with the requirements of AS/NZS 4058:2007. Aggregates for precast reinforced concrete pipes shall comply with the requirements of VicRoads 703:2019.
- Fibre-reinforced concrete rigid pipes shall comply with the requirements of AS 4139:2003 (R2018) and shall have a design life of 100 years.
- Cast-in-place concrete edgings, paths and other surfacing shall comply with the requirements of VicRoads 703:2019.

Concrete aggregate requirements for VicRoads 703:2019 should comply with VicRoads 610:2020 that states:

- Fine and coarse aggregate for concrete should be in accordance with the requirements of AS 2758.1:2014. The fine aggregate shall consist of clean, hard, durable, naturally occurring sands, or a combination of naturally occurring sands and manufactured sands, and shall be free from clay, dust, lumps, soft or flaky particles, shale, salt, alkali, organic matter, soil or other deleterious substances.
- Fine aggregate shall be tested for impurities in accordance with AS 1141. The potential alkali-silica reactivity of the coarse and fine aggregates shall be determined using either the VicRoads Test Method RC 376.03:2016, Accelerated mortar bar test - alkali-silica reactivity of aggregate, or the VicRoads concrete prism test method RC 376.04:2013 as described in the VicRoads Code of Practice RC 500.16:2018.

It is noted that VicRoads 610:2020 and VicRoads 703:2019 do not provide specifications for the use of recycled materials in concrete.

F.3 Queensland – Department of Transport & Main Roads (TMR)

TMR MRTS70:2018 is applied to the construction of concrete and bridge structures. Whereas TMR MRTS39:2018, *Lean Mix Concrete Sub-base* and TMR MRTS40:2018, *Concrete Pavement Base* are applicable for concrete pavements. TMR MRTS25:2018 and TMR MRTS26:2017 are used for *Steel Reinforced Precast Concrete Pipes* and *Fibre Reinforced Concrete Drainage Pipes,* respectively. These TMR specifications do not explicitly mention the usage of recycled material in concrete.

RCG may be used as a replacement for fine aggregates in both concrete and concrete pavement applications should conform with the requirements and testing of fine aggregates. For general concrete applications (TMR MRTS70:2018) fine aggregates shall consist of natural sand, or a combination of natural sand and crushed fine aggregate containing not less than 25% natural sand. The percentage of natural sand may be wholly replaced with crushed fine aggregate where satisfactory performance can be demonstrated in concrete mixes, for precast prestressed concrete piles, deck units and girders. Particles shall be clean, hard, and durable and free from clay and other aggregations of fine material, soil, organic matter, and other deleterious material.

For concrete pavement applications, fine aggregate shall conform to AS 2758.1:2014 (Table 4.2). Aggregates shall be tested for ASR in accordance with AS 1141.60.1:2014, except where AS 1141.60.1:2014 is not suitable for the type of aggregate being tested, or its suitability is unknown, test in accordance with AS 1141.60.2:2014.

Aggregates requirement for steel reinforced precast concrete pipes, precast concrete culverts, and fibre reinforced concrete drainage pipes shall conform with specification TMR MRTS70:2018.

F.4 Western Australia – Main Roads Western Australia (MRWA)

MRWA Specification 901:2018, *Concrete-general Works*, does not specify the use of RCG in concrete. The MRWA Specification 901:2018 states that the fine aggregates for concrete should be natural sand or a combination of natural and manufactured sand and conform with the requirements of AS 2758.1:2014. All aggregates shall comply with AAR testing requirement (AS 2758.1:2014) (Table 4.2). Aggregates classified as reactive or slow-reactive shall not be used. Concrete applications in precast reinforced concrete pipes, pre-cast reinforced concrete box culverts, drainage structures, fencing and limestone retaining walls should comply with MRWA Specification 901:2018.

F.5 South Australia – Department for Infrastructure and Transport (DIT)

The DIT specification for the supply of concrete (DIT Master Specification ST-SC-S7) does not mention the use of recycled material in concrete as an aggregate replacement. However, fine aggregate for concrete shall comply with the requirements of AS 2758.1:2014 (Table 4.2). Particle shape of aggregates shall comply with clause 9 ‘Verification Requirements and Records’. Moreover, the aggregate should satisfy the AAR test and conform with VicRoads Technical Note 30 (*Alkali Silica Reaction in Concrete*). *Recycled Fill Materials for Transport Infrastructure Environmental Instruction 21.6* (Department of Planning, Transport and Infrastructure 2015) provides the framework for the soil materials, asphalt, ballast, road base, concrete and timber sleepers that are generated and reuse on transport infrastructure activity. However, there are no specific guidelines provided in the document for the use of recycled glass.

The specifications for normal class concrete (DIT Master Specification ST-SC-S1) specify that concrete constituent materials shall be tested in accordance with AS 1379:2007 (R2017) and comply with specifications (DIT Master Specification ST-SC-S7, *Supply of Concrete*). Shared path pavements and minor pavements should also comply with normal class concrete (DIT Master Specification ST-SC-S1) or geopolymer concrete (DIT Master Specification ST-SC-S2).

F.6 Tasmania – Department of State Growth (DSG)

Generally, DSG specifications are aligned with those for the Department of Transport Victoria. As such, for an overview on the state of specifications surrounding the use of RCG in DSG refer to that given for Victoria in F.1.

F.7 Australian Capital Territory – Transport Canberra & City Services (TCCS)

According to the specification TCCS MITS 10, *Concrete Works*, fine aggregate specifications and testing requirement shall comply to standard AS 2758.1:2014 clause 9.2. Constituent materials for drainage structure concrete (TCCS MITS 03D:2019), concrete paths, driveways, medians (TCCS MITS 06B:2019), concrete kerbs and open drains 06a should comply with TCCS MITS 10:2019, *Concrete Works*. Any recycled material for road opening and restorations should be submitted for approval (TCCS MITS 03H:2019). For precast box culvert (TCCS MITS 03C:2019), general concrete specifications should comply with AS 1379:2007 (R2017) and concrete material requirements follows TCCS MITS 10:2019.

Bedding sand for segmental paving (TCCS MITS 07:2019) including concrete segmental paver, can be crushed gravel, granulated glass, or natural sand where:

- the fines fraction shall not contain single-sized, gap graded or excessive fine materials
- crusher dust, dolomite, fatty sands, loams and packing sands are all considered unsuitable.

F.8 Northern Territory – Department of Infrastructure, Planning and Logistics (DIPL)

The DIPL standards specifications for roadworks (DIPL 2020, *Standard Specification for Roadworks*: v4.2.), section 11 – Miscellaneous Concrete Works, allows the use of RCG in accordance with the relevant recommended specification provided in section 9 of Andrews (2010).

According to Andrews (2010), RCG material should be manufactured from food and beverage glass containers, drinking glasses, window (or flat) glass and plain ceramic. RCG should not include hazardous waste containers, reinforced and laminated glass, light bulbs, fluorescent tubes, and cathode-ray tubes. Moreover, source material should be free from of contaminants such as paper and cardboard, plastic, fabrics, and toxins. For blending of RCG with fine aggregates or natural occurring sand, the final RCG may require washing to remove fine particles (i.e. finer than 0.75 um) and remove traces of sugar and other impurities. DIPL 2020, *Standard Specification for Roadworks*: v4.2. section 11 in accordance with Andrews (2010) allows RCG up to a maximum of 30% by mass of total fine aggregates in the blend. Quality requirements for manufactured RCG are given in Table 4.3. The RCG used for blending with other materials should have a maximum nominal size of 5 mm to produce other products or use as a fine aggregate. RCG coarser than 4.75 mm shall not have more than 1% particles with maximum to the minimum dimension of 3:1.

Appendix G International Requirements for Applications in Concrete

G.1 Europe

In EN 206:2013+A1:2016 (*Concrete: Specification, Performance, Production and Conformity*) aggregates for concrete are according to EN 12620:2015, *Aggregates for Concrete*. This standard specifies the properties of aggregates and filler aggregates obtained by processing natural, manufactured, or recycled materials for use in concrete. Recycled aggregates are considered to be aggregates resulting from the processing of inorganic material previously used in construction (mainly recycled concrete RCA).

EN 12620:2015, *Aggregates for Concrete* covers recycled aggregate with densities between 1500–2000 kg/m^3 with appropriate caveats and recycled fine aggregate (4 mm) with appropriate caveats.

For other recycled materials from secondary sources, however, the work on standardisation has not been completed and more time is needed to clearly define the origins and characteristics of these materials. In the meantime, such materials when placed on the market as aggregates must comply fully with EN 12620:2015 and national regulations for dangerous substances (see Annex ZA of EN 12620:2015) depending upon their intended use. Additional characteristics and requirements may be specified on a case-by-case basis depending upon experience of use of the product and defined in specific contractual documents.

The proportions of constituent materials in coarse recycled aggregate shall be determined in accordance with (EN 933-11:2009/AC:2009) and shall be declared in relevant categories EN 12620:2015.

The German Institute for Standardisation specifies recycled aggregates for concrete in accordance with DIN EN 12620:2015 – Part 101: Types and regulated dangerous substances and DIN EN 12620:2015 – Part 102: Type testing and factory production control.

There are also other European standards relevant to aggregates shown in Table G 1.

Table G 1: European aggregate standards

Document number	Title
EN 13043:2013	*Aggregates for Bituminous Mixtures and Surface Treatments for Roads, Airfields and Other Trafficked Areas.*
EN 13055-1:2002	*Lightweight Aggregates Part 1: Lightweight Aggregates for Concrete, Mortar and Grout.*
EN 13055-2:2004	*Lightweight Aggregates Part 2: Lightweight Aggregates for Bituminous Mixtures and Surface Treatments and for Unbound and Bound Applications.*
EN 13139:2002	*Aggregates for Mortar.*
EN 13242:2013	*Aggregates for Unbound and Hydraulically Bound Materials for use in Civil Engineering Work and Road Construction.*
EN 13383-1:2013	*Armourstone Part 1: Specification.*
EN 13450:2002	*Aggregates for Railway Ballast.*

There are separate EN standards for each end use – concrete, mortar, asphalt, etc. This is sensible as each end use faces its own challenges and issues, e.g. drying shrinkage of aggregate is important for concrete but meaningless for asphalt. However, each end use also faces some very similar issues. The committees responsible for aggregate standards have been working recently to establish if the differentiated approach is necessary, or if a more consistent approach can be adopted.

G.2 USA

A high number of states' Department of Transportations in the USA have specifications and guidelines for the use of crushed glass as an aggregate in drainage or embankment fill applications as detailed in Section 3.3. However, there are very limited specifications in the USA for the use of recycled glass as fine aggregate and filler aggregate in concrete. Due to this limitation, it might be sufficient that the material to be used for this application satisfies the requirements of the existing concrete aggregate standards based on each specific guideline. The limited specifications for this application might be due to the risk of alkali-silica reaction (ASR) with the use of recycled glass in concrete that is discussed earlier in this section.

G.2.1 Oregon Department of Transportation, USA (ODOT)

Section 02695 – Reclaimed Glass (Mixed Waste Cullet) of Oregon Standard Specifications for Construction (Oregon Department of Transportation 2020) provides the specifications of waste glass as a substitute of aggregates. Mixed Waste Cullet shall be 0–1/2 in. (0–12.5 mm). It shall be clean, hard, and durable. No more than 5% by weight shall pass a No. 200 sieve (0.075 mm). The following are the specifications for various concrete applications outlined in the Oregon Standard Specifications for Construction (Oregon Department of Transportation 2020). Concrete material used in applications should comply with Section 2001 – Concrete:

- Section 00759 – Miscellaneous Portland Cement Concrete Structures
- Section 00755 – Continuously Reinforced Concrete Pavement
- Section 00756 – Plain Concrete Pavement.

G.2.2 State of Connecticut Department of Transportation, USA (ConnDOT)

An act (PA 03-65-SB 1031) concerning the beneficial use of recycled material by has been developed by the Connecticut Government that allows the use of recycled glass as a fill material. The act states that the waste glass may be used as aggregate for asphalt or concrete, or any other subgrade construction application in which crushed recycled glass would substitute for sand or stone aggregate, provided the crushed recycled glass does not constitute more than 10% of fill by volume, as defined by regulations.

Under the act, crushed recycled glass must be composed of glass food or beverage containers and less than 5%, by volume, of plastic, metal, paper, or other solid waste, that (1) have been combined by processing source-separated recyclable solid waste at an intermediate processing facility, (2) cannot be marketed for reuse in glass manufacture, (3) have components that measure 3/8 in. (9.53 mm) or less in diameter, and (4) are virtually inert and pose neither a pollution threat to ground or surface water nor a fire hazard.

G.3 American Society for Testing and Materials (ASTM)

ASTM C33/C33M:2018, *Standard Specification for Concrete Aggregates*, defines the requirements for grading (Table G 2) and quality of fine and coarse aggregate (other than lightweight or heavyweight aggregate) for use in concrete.

Fine aggregate shall consist of natural sand, manufactured sand, or other recycled aggregate, or a combination thereof.

Note 2 in ASTM C33/C33M:2018 states:

> *This standard only addresses properties of aggregates considered necessary for use in concrete and the associated test methods contained within this standard. Certain recycled aggregate sources may contain materials and properties not addressed as part of the document specifications, limits, or test methods. Recycled aggregates may require evaluation for environmental considerations (air quality, water quality, storage) using the appropriate local, state, and federal test methods in effect at the time of use.*

Coarse aggregate shall consist of gravel, crushed gravel, crushed stone, air-cooled blast furnace slag, or crushed hydraulic-cement concrete, or other recycled aggregate (see Note 2 of ASTM C33/C33M:2018), or a combination thereof, conforming to the requirements of this specification.

Table G 2: Grading requirements for fine aggregates

Sieve size (mm)	Per cent passing (%)
9.5	100
4.75	95–100
2.36	80–100
1.18	50–85
0.6	25–60
0.3	5–30
0.15	0–10
0.075	0–3.0(1, 2)

1 *For concrete not subject to abrasion, the limit for material finer than the 75-μm sieve shall be 5.0% maximum.*
2 *For manufactured fine or other recycled aggregate, if the material finer than the 75-μm sieve consists of the dust of fracture, essentially free of clay or shale, this limit shall be 5.0% for concrete subject to abrasion, and 7% maximum for concrete not subject to abrasion.*

Source: ASTM C33/C33M:2018.

G.4 International Specifications – Other

Japanese Industry Standards provides the specifications for the recycled aggregate for concrete. However, in these specifications recycled aggregate are defined as recycled concrete aggregates (RCA). There is no specific mention of RCG aggregates in the specifications. Specification document list for recycled aggregates to be used in concrete Class H, Class M and Class L are listed in Table G 3.

Table G 3: Japanese industry standards

	Recycled aggregates for concrete – Class H	Recycled aggregates for concrete – Class M	Recycled aggregates for concrete – Class L
Waster absorption of aggregates	Coarse – 3% or less Fine – 3.6% or less	Coarse – 5% or less Fine – 7% or less	Coarse – 7% or less Fine – 13% or less
JIS standards	JIS A 5021:2018	JIS A 5022:2018	JIS A 5023:2018
Purpose of JIS standard	Standard for recycled aggregate used for concrete for general use which improved quality as aggregate by advanced treatment such as crushing and abrasion of concrete waste	Standard for recycled aggregate produced by a comparatively simple method such as crushing and abrasion of concrete waste for concrete which is hardly affected by drying shrinkage and freezing and thawing	Standard for recycled aggregate of relatively low strength concrete using recycled aggregate produced by crushing concrete waste

Appendix H Case Studies – Concrete Applications

H.1 Use of RCG in Concrete

H.1.1 Concrete Footpath Field Trial with Crushed Glass and Recycled Plastic, Victoria

In a study by Wong et al. (2020), field trials of concrete footpaths were constructed using recycled plastic waste (RPW) and RCG at Geddes Crescent Park in Hoppers Crossing, Victoria, Australia (Wyndham City Council partnered with Swinburne University (Infrastructure Magazine 2019)). The construction project was conducted by a local construction company. The concrete footpath had a length of about 339 m, a width of 1.5 ± 0.05 m, and a depth of 100 ± 5 mm. The concrete mix consisted of general purpose (GP) cement, gravel with a size of 20 mm minus, sand, RPW, and RCG. The concrete design mix of 10% RCG, 10% RPW in a grade M40 concrete was used for this project. RPW and RCG were sourced from kerbside wastes by pulverisation supplied by a local recycling company. RPW and RCG had particle sizes of a maximum of 5 mm, and 3 to 8 mm, respectively. A section with only M40 concrete was also constructed as the control section.

A range of laboratory testing including unconfined compressive strength test, indirect tensile strength test, and water absorption on the concrete mix samples as well as a non-destructive field test at various points on the concrete footpath using the Schmidt hammer were conducted by Wong et al. (2020).

The results were then compared against the local council standard for concrete footpath construction. It was reported that based on the results of laboratory and non-destructive field tests, the concrete design mix with 10% RCG and 10% RPW satisfied the local authorities standard in Victoria. The project concluded that this concrete design mix using RCG and RPW showed the potential to be employed in the concrete footpaths application which can result in a remarkable reduction in the amount of glass and plastic wastes in landfills Wong et al. (2020).

H.1.2 RCG in Concrete Footpath Field Trials in Cairns, Queensland

In Queensland, a field trial to use recycled glass within low-risk infrastructure projects such as concrete pedestrian and cyclist footpaths was undertaken by Cairns Regional Council (Flanders 2019, Affleck 2019). In this project, the existing 1.6 m concrete footpath located in White Rock, Cairns was demolished due to its poor condition and not meeting the standards, and a new 2 m wide compliant footpath with an overall length of 108 m was constructed. The footpath construction complied with Far North Queensland Regional Organisation of Councils (FNQROC) standard drawing S1035 with the exception of using N32 grade instead of the specified N25 grade concrete (Flanders 2019, Affleck 2019).

This trial consisted of different concrete mix designs using RCG 40%, RCG 60%, and RCG 40%-TMR as a partial replacement for the natural 4 mm coarse sand. The 40%-TMR fine aggregate replacement RCG mix had additional cementitious material in order to satisfy TMR MRTS70:2018, *Concrete*. The trial also included one standard N class concrete mix as the control mix. The adopted mix designs for this study are shown in Table H 1.

It was reported that the RCG mixes for the footpath trial were selected and confirmed based on the available laboratory tests previously conducted at James Cook University. The grading of RCG reported by Affleck (2019) is presented in Table H 2 (the particle size distribution test was carried out as a part of the previous study at James Cook University).

A 100 mm thick concrete footpath with SL72 mesh located centrally was used for the footpath design and the target characteristic strength for all four tested mix designs was 32 MPa. Also, the target slump was considered equal to 80 mm ±15 mm (Flanders 2019, Affleck 2019).

From the visual inspection, (Flanders 2019, Affleck 2019) reported that both RCG 40% and RCG 40%-TMR mixes showed successful physical performance. However, the RCG 60% mix showed exposed glass material on the finished surface of the concrete footpath. Therefore, it was concluded that further works are required to rectify the issue and to reduce the risk to public safety and health.

Additionally, it was reported that based on the results of slump test, compressive strength test, workability, curing, finishing as well as the cost analysis from each of the RCG mixes in the field trial, the optimum mix designs to be used in the concrete footpaths were the control mix and the RCG 40% mix. RCG 40% mix showed acceptable strength and workability and achieved the highest performing results compared to the RCG 40%-TMR and RCG 60%. It was concluded that RCG 60% mix should not be considered for further field trials.

The project also conducted an economic and environmental analysis. They concluded that the mix designs incorporating RCG showed negligible economic benefits (slightly cheaper compared to the control mix) but resulted in significant environmental benefits by employing recycled glass material and thus, reducing the amount of glass sent to landfill as well as saving natural coarse sand materials (Flanders 2019, Affleck 2019).

Table H 1: Cairns field trials concrete mix design proportions

Concrete mix		RCG 40% TMR	RCG 60%	RCG 40%	Control
Cementitious materials	Cement Australia Townsville GP (kg/m^3)	255	263	255	241
	Cement Australia Callide FA (kg/m^3)	85	88	85	80
Coarse aggregate	Edmonton stone (10 mm) (kg/m^3)	801	805	801	795
Fine aggregate	Barron coarse sand (4 mm) (kg/m^3)	0	0	0	487
	Tableland fine sand (kg/m^3)	316	312	316	215
	Edmonton fine sand (kg/m^3)	316	105	319	380
	4 mm RCG (kg/m^3)	405	600	405	0
Admixtures	SIKA Plastiment-45 (mL/100 kg)	450	450	450	450
	SIKA Retarder-N (mL/100 kg)	50–100	0	0	50–100
Water	Design water (L)	156	156	156	155
	Design W/C ratio	0.45	0.45	0.46	0.49

Source: Affleck (2019).

Table H 2: Particle size distributions of RCG

Sieve size (mm)	6.7	4.75	2.36	1.18	0.6	0.425	0.3	0.15	0.075
RCG per cent passing (%)	100	99.8	88.9	44.7	15.9	8.7	6.0	3.0	2.0

Source: Affleck (2019).

H.1.3 RCG in Concrete Pavements in Woolgoolga to Ballina Pacific Highway Upgrade Project, New South Wales

In New South Wales, the Woolgoolga to Ballina Pacific Highway upgrade project used RCG into the concrete mix in two pavement trials as a substitute for sand (Nairn 2020, Transport for NSW 2019). This demonstration trial for the use of RCG (10% and 15% RCG) was funded by the NSW Environment Protection Authority, and the demonstration work was carried out by Lendlease Engineering. This project used over 220 tonnes of glass which is equivalent to over 1 million bottles from the local landfill (Nairn 2020, Transport for NSW 2019). Transport for NSW (TfNSW) specifications (specifications IC-QA-R82 and IC-QA-R83) allow the maximum of 15% RCG replacement as fine aggregate (sand) for concrete pavements while RCG meets TfNSW's specifications requirements.

For this project, the glass was collected from Lismore City Council's waste collection system, was sorted, and then was crushed into sand at the Council's material recovery facility to produce RCG. Then the glass was delivered to onsite batch plants for cleaning. Finally, the crushed glass was mixed with sand before being processed into the concrete. From the initial laboratory investigations, Nairn (2020) and Transport for NSW (2019) stated that the produced RCG was suitable to be used in the concrete pavement and it was noted that RCG did not have an adverse effect on the quality of the concrete. It was also reported that the RCG mix met TfNSW's specifications for concrete pavement.

The washing of RCG was performed as a single and double wash. The particle size distribution of unwashed, single, and double wash RCG are shown in Table H 3. The single wash RCG was reported to satisfy the requirements and be sufficient for the concrete pavement application.

The project concluded that RCG as fine aggregates in concrete pavements resulted in environmental benefits by diverting the waste materials from landfills as well as the reduction in extracting and using the natural aggregates. Additionally, it was noted that no significant increase in the risk of cuts or health-related hazards was provided for the use of RCG in this application. Also, stockpiling or washing was reported to reduce the sugar-based impurities. No notable change in the 7-day and 28-day compressive strengths was observed for IC-QA-R83 base concrete and IC-QA-R82 lean mix concrete in the trials with 10% and 15% RCG. Also, no remarkable difference in the skid and abrasion resistance of the base concrete incorporating RCG was reported compared to the normal concrete without glass (Nairn 2020).

Due to the high silica and alkali content in the glass material, it is generally considered a risk from alkali-silica reaction (ASR) in this application. However, Nairn (2020) stated that the use of fly ash of more than 20% resulted in the required mitigation so that RCG for fine aggregate replacement will not provide destructive expansion of concrete.

Table H 3: Particle size distribution of unwashed, single wash, and double wash RCG from Lismore City Council

Particle size distribution (% passing) (mm)	Unwashed	Single wash	Double wash
6.7	100	100	100
4.75	99	99	98
2.36	75	71	71
1.18	50	42	41
0.600	31	22	21
0.425	24	16	14
0.300	17	10	9
0.150	10	4	4
0.075 (≤ 7 R83 fine aggregate properties)	6	2	2

Source: Nairn (2020); Transport for NSW (2019).

H.1.4 RCG in Concrete Pavements, Waverley Council, New South Wales

Waverley Council reportedly provided the first site in New South Wales for the use of RCG in the pavement construction application in 2010 (in partnership with New South Wales DECC and Water, New South Wales Roads and Traffic Authority, Institute of Public Works Engineering Australia and the Packaging Stewardship Forum) (Department of Sustainability, Environment, Water, Population and Communities 2011). They established two sites of pavement incorporating RCG, one at Blair Street, Bondi, and the other site at O’Brien Street, Bondi. The site section at O’Brien Street used RCG for fine aggregate replacement in concrete pavement. It was reported that 7.5 tonnes of glass cullet were substituted for only the concrete pavement site project. The project also noted the economic benefits of using crushed glass as a substitute for natural sand by saving tonnes of virgin aggregates.

H.1.5 Recycled Glass and Powdered Glass in Concrete Pavement in South of Sydney, New South Wales

Dumitru et al. (2013) detailed the field trials to use RCG as a natural sand replacement, and powdered glass as a cementitious material replacement in concrete pavements in New South Wales. The project was undertaken at Boral’s Dunmore Quarry, South of Sydney.

Forty-five per cent replacement of natural sand material with RCG and about 15% replacement of cementitious materials with powdered glass were chosen for the mix designs in these concrete pavement trials. The adopted mix designs for this study are shown in Table H 4. Also, it was reported that the pavement design was a normal concrete road pavement with a lean mix subbase, two coat seal, and anchor trench steel Dumitru et al. (2013).

Dumitru et al. (2013) summarised that the 35 MPa mix with 45% RCG as natural sand replacement showed a slightly lower slump and slightly lower air content compared to the control mix with no recycled glass. The compressive strength was reported to be higher than the design 35 MPa, with the compressive strength after 91 days of about 55 MPa which was well within the specification requirements (cylinders taken from the concrete pavement). Also, it was reported that the flexural strength of concrete pavement incorporating RCG at 91 days was as high as 6 MPa, but it did not achieve the required 4.5 MPa flexural strength at 28 days. Additionally, the drying shrinkage was lower than the control mix without RCG.

Dumitru et al. (2013) reported that the assessment of concrete pavement field trials by the visual inspection after one year in service indicated that the pavements were in a good condition in both trials (with RCG and with powdered glass). However, the abrasion resistance in both trials was lower compared to the control mix.

The project concluded that both RCG as a partial natural sand replacement and powdered glass as a partial cementitious material replacement in concrete pavements can satisfy the current required specifications for concrete pavement except the abrasion resistance which was lower than the control mix.

Table H 4: Concrete mix design used for the field trials in south of Sydney, NSW

Mix	Control	Glass sand 45%	Glass powder 15%
Cementitious (kg/m^3)	395	397	337
Glass powder (kg/m^3)	–	–	**60**
Coarse sand (DSS) (kg/m^3)	664	367	664
Glass sand (kg/m^3)	–	**292**	
10 mm Dunmore (kg/m^3)	325	327	325
20 mm Dunmore (kg/m^3)	749	755	749
Water (incl. Admix.) (kg/m^3)	185	175	185
AEA-940 (ml/m^3)	300	200	300
POZZ-300RI (mL/100 kg)	200	200	200

Source: Dumitru et al. (2013).

H.1.6 RCG in Footpath Concrete Trial – Bryce St, St Lucia, Brisbane

A University of Queensland (UoQ) Study conducted by Ho (2018) was undertaken to review the partial replacement of cement with ground limestone in concrete. As the project progressed, the further addition of including RCG as an aggregate replacement was assessed.

To trial the research, Brisbane City Council agreed to have a section of footpaths and surface finishing constructed with the mixes, and the footpath application was specifically chosen to test the trials as it represents very low structural risk.

The three trial mixes were designed by UoQ and targeted a compressive strength of 32 Mpa. The trialling of the three chosen mixes was to substantiate the laboratory trials of those mixes with real world applications. The outcomes of the trials would build on any workability, production and laying considerations. The conventional footpath concrete uses a maximum aggregate size of 10 mm with a compressive strength of 25 MPa. The trial mixes used a maximum aggregate size of 20 mm with a compressive strength of 32 MPa.

Of the three trials, the 2nd and 3rd trials incorporated RCG.

Description of the onsite Trial 2 – A Glass and Concrete (20 mm) + Super Plasticiser additive was constructed early morning. The mix had a slump of 210 mm, compared to a normal footpath concrete mix which would have a slump of 120 mm. The addition of the super plasticiser produced a high viscosity mixture and reduced its workability. The percentage of super plasticiser added was 0.6% by weight of cement. The fine and course components of the mix had 60% and 25% replaced with RCG, respectively. It was noted the required finish was difficult to achieve due to the high viscosity and high maximum aggregate size.

Description of the onsite Trial 3 – A combination of Limestone, Glass and Concrete (20 mm) with super plasticiser. The mix had a limestone percentage of 25% with cement and RCG representing 25% of the volume of aggregates. Recorded slump of the mix was 230 mm.

As this was a relatively recent trial in May 2018, the period for monitoring the trial is set at 5 years. The trials are currently undergoing monitoring and there is scope to further monitor once the 5-year period is completed.

H.1.7 RCG in Footpath Concrete Thesis – Brisbane

A research thesis (Morton 2017) was produced investigating the use of recycled glass in concrete footpaths. Multiple laboratory trials of varying RCG additions were trialled and the performance results were compared back to a reference commercially used concrete mix used for footpaths.

The structural performance of the concretes has been judged by strength, shrinkage, workability, and potential for ASR. Based on the results of these trials an optimal concrete mix with partial aggregate replacement with RCG. The mix design for the optimal RCG Concrete mix is shown in Table H 5.

Table H 5: Mix characteristics for optimal recycled glass concrete mix

Optimal recycled glass concrete mix		
Mix characteristics	W/C ratio	0.35
	% RCG aggregate	35
	Glass size (mm)	0.85
Mix design	Cement	290
	Fly ash	193

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