Review of Crushed Recycled Concrete and Recycled Ballast Potential in Rail Applications

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Summary

Crushed recycled concrete (CRC) and degraded railway ballast, among other aggregate materials, can be used to reduce construction costs and impacts where these materials are able to be sourced in sufficient quantities more readily than virgin materials. This aims to support a more circular economy approach and reduce greenhouse gas emissions.

When the use of CRC in the rail sector is established, it will add a suitable recycled and engineered product as a viable, load bearing and/or fill material available for new rail construction in Western Australia. To understand the degree to which the use of CRC in Western Australian rail infrastructure is feasible, this project investigated several aspects related to the use of the material, including:

- suitable applications
- standards and specifications of use
- design considerations such as vibration attenuation and resilient modulus
- material performance and durability
- potential for pre-existing contamination (e.g. asbestos from original building applications)
- potential leaching of metals into adjacent layers and components.

The report describes the overall rail structure and its environment for context and as potential applications for CRC and recycled ballast, including both:

- the rail substructure – consisting of all structure below the rails: ballast, sub-ballast, and capping layers, as well as the subgrade and any formation present), and
- the rail environment – consisting primarily of access tracks and service roads.

One of the key findings was that there is a lack of documentation specifying of the use of CRC and recycled ballast in railway application, even where the use of these materials is reported by other sources (i.e. the existence of the use of these materials is reported, but details about how they are used is not available). For this reason, any available detailed information about the use of CRC and recycled ballast that could be applied to use of these materials in railway infrastructure has been included.

The report covers the following areas to investigate the case for the use of CRC and recycled ballast are as follows.

Increased use of CRC and recycled ballast aligns with Western Australia's *Waste Avoidance and Resource Recovery Strategy 2030*, which aims to avoid waste generation, recover more value and resources from waste, and protect the environment through responsible waste management. The strategy sets a target for improvement in the recovery of construction and demolition (C&D) waste from the 2015–16 performance, aiming to increase recovery to 77% by 2025, and 80% by 2030. Further, the *Action Plan 2022–23* encourages the uptake of recovered C&D material as a key focus for waste infrastructure and planning.

Concrete represents over half of all C&D waste in Australia, making it an important candidate for re-use. Likewise, recycled ballast is an important candidate for re-use given the availability of this material in the rail environment. To investigate this, the report documents the waste generation, physical and engineering properties, chemical composition, environmental and WHS factors, current processing practices, and current uses of CRC and recycled ballast.

Concrete recycling, in comparison to the use of virgin gravel and sand, was reported to result in a more favourable outcome in terms of the production of CO_2e, NOx, SO_2 and dust emissions. It was also found that while there is a risk of contaminant material from recycling, with adequate controls in place these risks can be mitigated.

The benefits of using CRC and C&D materials in general predominantly cover cost reductions and valuable environmental impacts, such as reduced use of virgin materials. Other benefits found include social factors,

such as job creation; for every 10,000 tonnes of waste recycled, 9.2 full-time equivalent jobs are created compared to landfill which creates 2.8 jobs.

In conclusion. the literature review found that while CRC and recycled ballast are used in rail applications in Australian jurisdictions other than Western Australia as well as internationally, the research on the safe and effective use of these products in rail applications is not extensive. However, the literature that is available suggests that increased use of these recycled materials could be broadly beneficial in Western Australia where sufficient quantities of the materials and the capacity to process them for reuse exist. The performance requirements of existing standards and specifications that refer to physical properties, engineering, durability, and strength requirements have also been documented.

The review identified a number of potential opportunities for the use of both CRC and recycled ballast in rail applications, outlined in Table S.1.

Table S.1: Potential opportunities for CRC and recycled ballast in rail applications

Application	CRC use	Recycled ballast use
Ballast	✓(1)	✓
Sub-ballast	✓(2)	✓
Capping layer	✓	✓(3)
Access tracks unsealed surface layer	×	✓(3)
Access tracks sealed surface layer	✓	✓(3)
Access tracks (base/subbase)	✓	✓
Aggregate in concrete applications	✓	✓
Drainage/bedding/backfill	×	✓
Embankments/earthworks	✓	✓

1. Up to 25% ballast replacement.
2. May be used with recycled crushed glass and recycled plastic.
3. Crushing and grading required.

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1 Introduction

Recycled materials sourced from construction and demolition (C&D) waste are increasingly being used in construction projects as a means of diverting waste from landfill. Crushed recycled concrete (CRC) and degraded railway ballast (among other aggregate materials) can be used to reduce construction costs where these materials are able to be sourced in sufficient quantities more readily that virgin materials. Additional aims associated with recycled material use are supporting a circular economy approach and reducing greenhouse gas emissions.

The rail industry uses material aggregate in a number of applications, including capping layers, earthworks, sleepers, access tracks, platforms, drainage, and other infrastructure. CRC has been used for these purposes elsewhere in the world, usually in combination with other materials such as crushed rock, and investigations of the material properties of various grades and mixes have been reported in literature.

Establishing the safe and effective use of CRC in the rail sector will add a suitable recycled engineered product as a viable load bearing and/or fill material available for new rail constructions in Western Australia.

To understand the degree to which the use of CRC in Western Australian rail infrastructure is feasible, this report reviews the available literature on several aspects related to the use of the material, including:

- suitable applications
- standards and specifications of use
- design considerations such as vibration attenuation and resilient modulus
- material performance and durability
- potential for pre-existing contamination (e.g. asbestos from original building applications)
- potential leaching of metals into adjacent layers and components.

The report is structured as follows:

- Section 2 summarises the rail track structure and environment.
- Section 3 discusses C&D waste including types, supply and volume, physical, environmental and engineering properties.
- Section 4 reviews current practice in Australia and internationally covering research projects and emerging applications, standards and specifications, environmental and safety considerations, and benefits.
- Section 5 provides a summary of the findings.

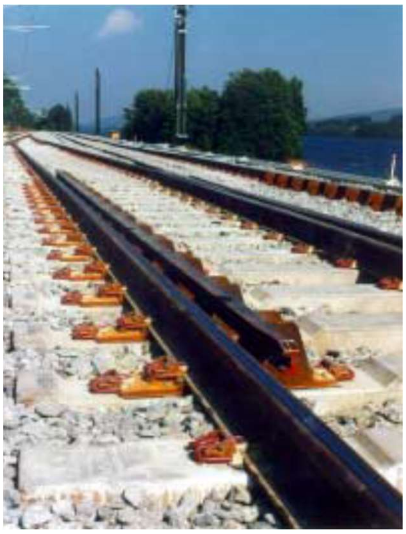
One of the key findings was that there is a lack of documentation specifying of the use of CRC and recycled ballast in railway application, even where the use of these materials is reported by other sources (i.e. the existence of the use of these materials is reported, but details about how they are used is not available). For this reason, any available detailed information about the use of CRC and recycled ballast that could be applied to use of these materials in railway infrastructure has been included.

2 Rail Track Structure and Environment

2.1 Types of Track Structure

The 2 most common types of rail tracks are the traditional ballasted tracks and concrete slab tracks, shown in Figure 2.1 and Figure 2.2 respectively.

Figure 2.1: Ballasted track



Source: Esveld (2001).

Figure 2.2: Slab track

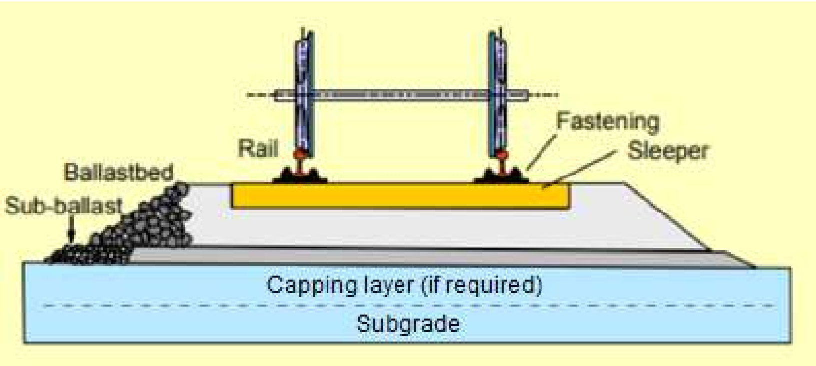
Source: Esveld (2001).

The following sections detail the structure of a traditional ballasted rail track, which is used widely across Australia, and represents 90% of tracks globally (Guo et al. 2022).

2.2 Ballasted Rail Track Components

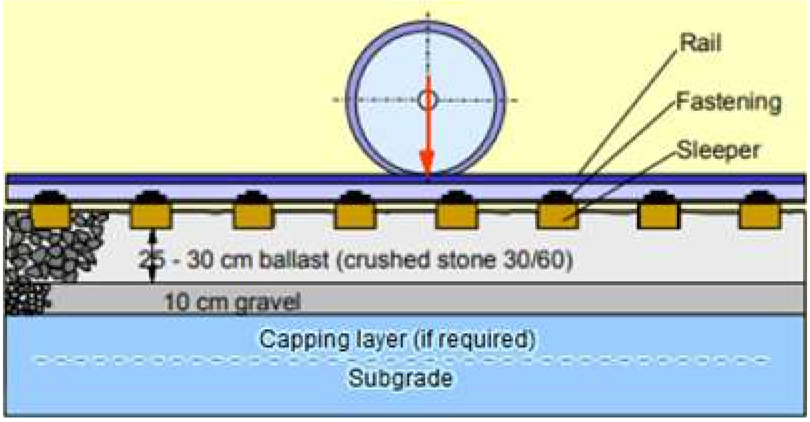
A ballasted rail track is divided into 2 main sections, the superstructure (top of the rail track) and the substructure (below the rail track) (Elkhoury et al. 2018). Figure 2.3 and Figure 2.4 show a cross-section and a longitudinal view of a typical ballast track. The structure of ballasted rail track has been relatively static since the emergence of the railway (Esveld 2001).

Figure 2.3: Cross-section of ballasted rail track



Source: Adapted from Esveld (2001).

Figure 2.4: Longitudinal view of ballasted rail track



Source: Adapted from Esveld (2001).

2.2.1 Superstructure

The superstructure is composed of all components on and above the rails, including the rails themselves, the fastening systems, rail pads and sleepers (Elkhoury et al. 2018). Sleepers are typically comprised of timber or concrete, with more recent technologies exploring the use of plastic and rubber. The sleepers are constructed on a bed of ballast, to distribute the loading to the subgrade (Elkhoury et al. 2018).

2.2.2 Substructure

The rail substructure consists of all structure below the rails, including ballast, sub-ballast, capping layers, as well as formation and subgrade (Elkhoury et al. 2018). The ballast is the top layer of the substructure, on which the framework of the sleepers and rails is built. In accordance with PTA Specification 8190-400-002 *Code of Practice: Narrow Gauge Mainline Track & Civil Infrastructure,* ballast is nominally 60 mm. Ballast acts to resist the vertical, lateral, and longitudinal forces to the sleepers. Aggregate materials used for ballast should have appropriate size, specific gravity, angularity of particles, shear strength, hardness, resistance to weathering, and low contamination levels (Hawari 2007).

The capping layer provides a transition of load between ballast and the formation and is comprised of crushed limestone in Western Australia (Esveld 2001, Imteaz et al. 2021). Formations are preparations of the subgrade such as cutting and embankments to form a flat surface for the laying of substructure elements.

The capping layer is key to providing a stable foundation for the ballast and superstructure. It improves the California Bearing Ratio (CBR) value of the subgrade; distributing loads over a sufficient area to prevent overstress; supporting draining; and preventing the ballast intruding into the subgrade (Radampola 2006). Capping materials require sufficient strength, stiffness, modulus, and drainage capacity (Hawari 2007). The deterioration of tracks is most affected by the condition of the ballast and the capping layer (Hawari 2007). An additional area of the rail structure is the zone of influence. This refers to the area below ground where development, works and activities pose a risk to the structural integrity of the rail corridor. Any works within the zone of influence, for example excavation and construction works, should be closely managed to ensure the structural integrity and safety of the rail environment (Queensland Department of Transport and Main Roads 2018).

2.3 Access Tracks and Service Roads

The efficient running of a property or rail infrastructure within the rail corridor depends on, among other things, ready access to various locations within the property or corridor.

Public Transport Authority (PTA) access tracks and service roads are used for:

- inspecting drainage infrastructure, fences, pipelines, power lines, signals, rolling stock etc.
- fighting fires
- pest control (animal and plant)
- third party access utilities
- cranage pads
- upgrading a structure
- operating a structure
- maintaining a structure.

The use of CRC as a basecourse or subbase material is permitted if the quantity used is over 55% and under 95%, blended with standard materials. As per PTA Specification 8880-450-300 *Access to Infrastructure*, crusher residue from concrete aggregates has a maximum limit of 45%. For crushed recycled rail ballast, if it is not reused in track installations, under the specification it may be considered for use as road subbase and base under the following conditions:

1. Ballast degrades and becomes contaminated over time, including thermite weld, lubricant residues, and so where it is to be reused under a seal, it is necessary for this be washed, crushed, and screened to ensure it meets the required specification for its intended use, with particular reference to aluminium content.
2. Ballast shall comply with the MRWA Specifications 501.09 and 501.11 for use in subbase and base applications respectively, if samples are tested for metallic aluminium and meet a maximum for metallic aluminium of 0.001%.
3. Recycled ballast material shall be tested for contamination. The determination of its reusability shall be dependent on the assessment and categorisation of contamination levels as prescribed in the *Contaminated Sites Act 2003* and Contaminated Sites Regulations 2006.

The regularity of use for these access tracks determines construction and cost. There are basically 2 types of roads or tracks:

- **All weather** – used from the public road to the houses, and sometimes stockyards and silos. Generally gravelled and need to be well sited, constructed and maintained.
- **Dry weather only** – the usual property track. Accessible only in dry weather.

The standards of these tracks are variable, the newer high frequency assets are generally of a higher standard. Access tracks should be planned to give the best and shortest access to each part of the property. All the rules that apply to dry weather only tracks apply to all weather access tracks as well. The only difference is the cost.

A range of parameters applies to the planning, design and delivery of access tracks and service roads near to a railway that are aimed at ensuring the operations of the railway service are maintained in an efficient, reliable, and safe manner. If there is a need to access the rail corridor, safety and legal arrangements are in place as access via tracks and service roads is highly regulated to ensure safety (Day & Shepherd 2014).

The service roads are usually constructed adjacent to the operational tracks and outside the danger zone and kinematic envelope. These roads are constructed with a width of about 3 m with laybys, for the passing of vehicles in the opposite direction, constructed every 200 m depending on the length of the access track. It is important that the tracks and roads are well drained, and that the location of the drains is suitable to channel the surface runoff without causing any adverse impact on the natural drainage (Day & Shepherd 2014).

Generally, the access tracks and service roads are constructed with crushed limestone. Depending on the frequency and traffic demand, the tracks or roads are sometimes asphalt surfaced (Day & Shepherd 2014).

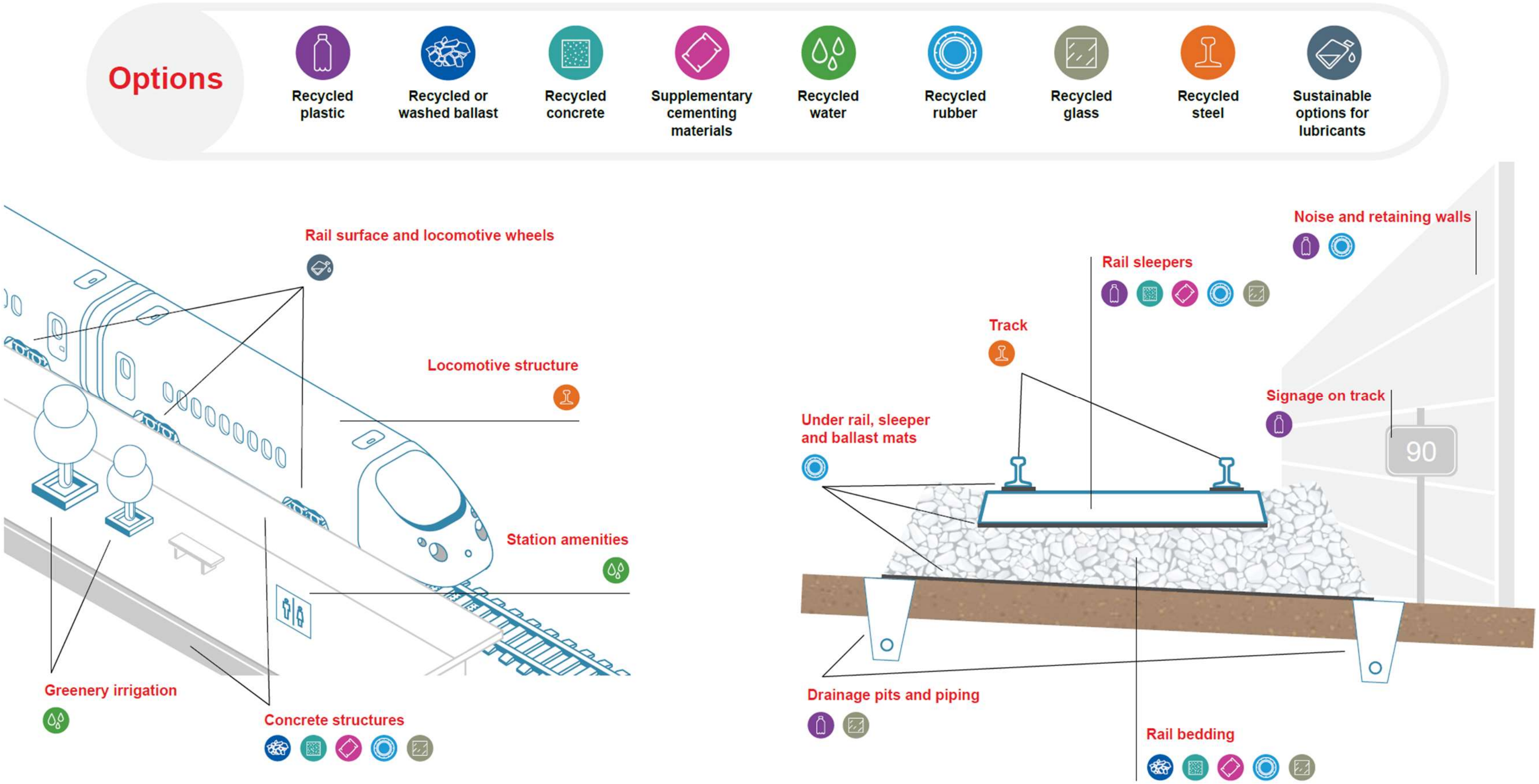
The use of crushed concrete as a surfacing layer in Western Australia can provide cost savings and environmental benefits, but it is important to take precautions to prevent exposure to respirable crystalline silica (RCS), which can be generated during the crushing and handling of concrete (WorkSafe Western Australia n.d.). To prevent RCS exposure when using crushed concrete as a surfacing layer, wetting down or sealing may be required, and workers should use adequate personal protective equipment (WorkSafe Western Australia n.d.).

The use of CRC as a surfacing layer in unsealed surfaces would require further study as the suppression methods explained above theoretically reduce the probability of exposure to RCS; however, additional research is necessary to ensure structural integrity, and address potential issues such as insufficient fines, excessive maximum aggregate sizes, high pH leachates, recementing-induced cracking, and RCS exposure in residential locations.

2.4 Recycled Materials in the Rail Environment

Figure 2.5 provides a high-level outline of the opportunities for use of recycled materials across the rail structure and broader rail environment. This emphasises the many and varied opportunities for recycled materials in the rail industry. This report has a specific focus on the opportunities for CRC and degraded ballast in the rail superstructure and substructure, and associated infrastructure such as access roads in the rail reserve.

Figure 2.5: Opportunities for recycled material use in the rail environment



Source: ACRI et al. (2022).

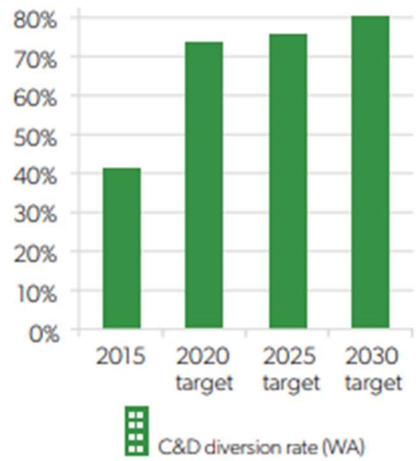
3 Construction and Demolition Wastes

Western Australia's *Waste Avoidance and Resource Recovery Strategy 2030*, herein referred to as the strategy, aims for a low-waste, sustainable circular economy (Waste Authority n.d.a). The strategy sets out 3 key objectives; to avoid waste generation, recover more value or resources from waste, and protect the environment through responsible waste management.

C&D waste is defined as waste from demolition and building activities, such as rail, road, and other forms of construction, representing half of all Western Australia's waste and ~45% of recovered material. It thus presents a significant opportunity to make a marked impact on the broader waste recovery targets and objectives. C&D waste includes concrete and ballast, but also includes asphalt, rubble, brick, and sand.

The strategy sets a target for improvement in the recovery of C&D waste, from the 2015–16 performance, as shown in Figure 3.1, aiming to increase recovery to 75% by 2020, 77% by 2025, and 80% by 2030. Further, the *Action Plan 2022–23* defines encouraging the uptake of recovered C&D material as a key focus for waste infrastructure and planning (Waste Authority n.d.b). Some of the reported barriers for improving C&D recycling include contamination increasing the processing cost, customer perception that recycled materials are unsafe, including the perceived risk of asbestos, and competition with virgin materials (2013–17 data) (Perryman & Green 2019).

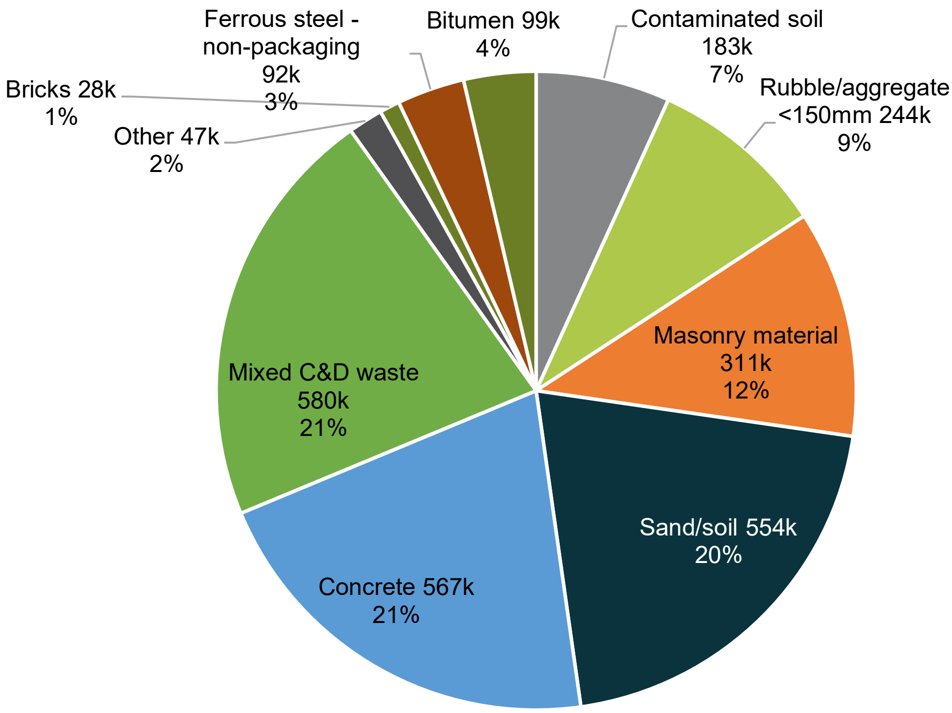
Figure 3.1: C&D recovery in 2015 and the strategy targets for 2020, 2025 and 2030



Source: Waste Authority (n.d.a).

The 2020–21 waste and recycling figures demonstrate a distinct improvement from previous years. C&D accounted for 51% of waste generation in Western Australia (or 3.2 million tonnes), with an 84% recovery rate, surpassing the 2025 target rate of 77% (Waste Authority 2022b). Figure 3.2 outlines the composition of C&D waste recovered in 2020–21, 97% of which is processed locally with Western Australia (Waste Authority 2022b). While this growth is representative of improvements in the waste and recycling industry, there remains a potential for further development of suitable end markets for CRC and degraded ballast.

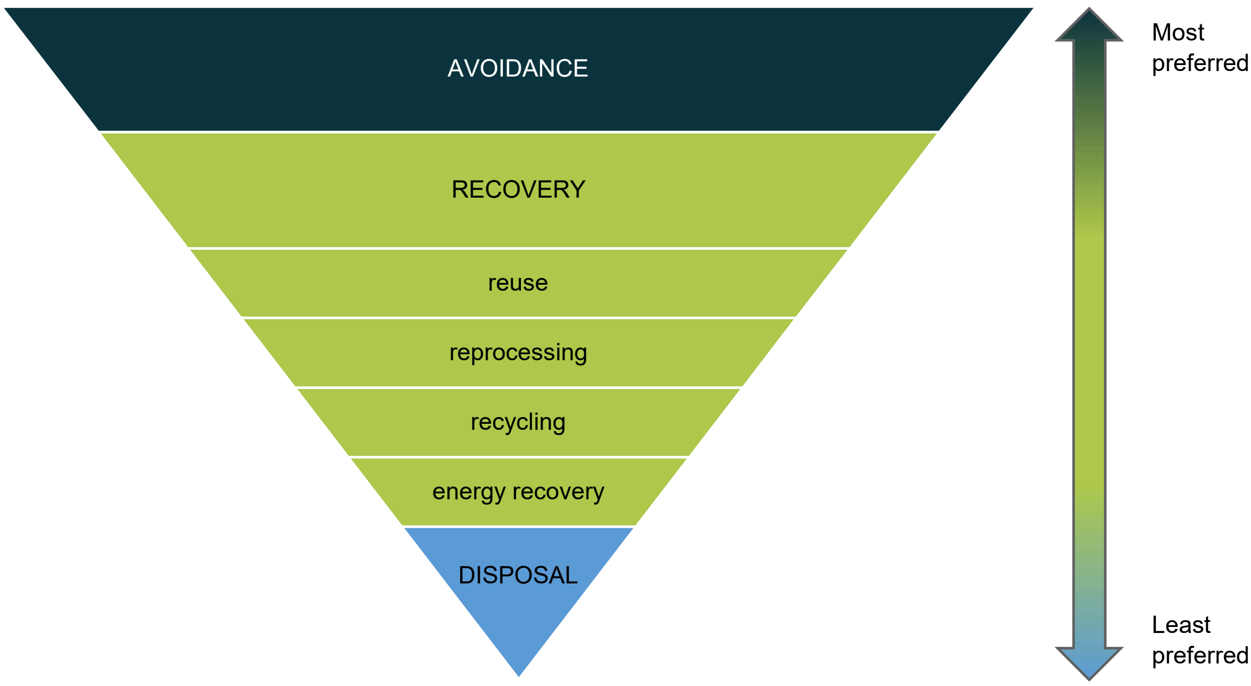
Figure 3.2: Materials recovered from the C&D waste stream in 2020‑21 (tonnes/percentage)



Source: Adapted from Waste Authority (2022b).

The objectives and goals of the strategy align with the waste hierarchy (Figure 3.3) whereby avoidance is the most preferred, followed by recovery mechanisms (reuse, reprocessing, recycling, and energy recovery), with disposal the least preferred (Waste Authority n.d.a).

Figure 3.3: Waste hierarchy



Source: Adapted from Waste Authority (n.d.a).

The Waste Authority's *Construction and Demolition C&D Rollout Plan* built on the broader strategy, with a focus to develop markets for recycled C&D products, support contracting, reform legislation and regulation, improve data, address priority materials, and improve best practice avoidance and recovery (Waste

Authority 2022a). Initiatives are under way to increase the use of recycled C&D products in civil applications, such as the *Roads to Reuse* (RtR) program encouraging state and local governments and the private sector to use C&D products in road applications (Waste Authority 2023).

This research report complements the broader initiatives across Western Australia.

3.1 Crushed Recycled Concrete

The following sections document the waste generation, physical and engineering properties, chemical composition, environmental and WHS factors, current processing practices, and current uses of CRC.

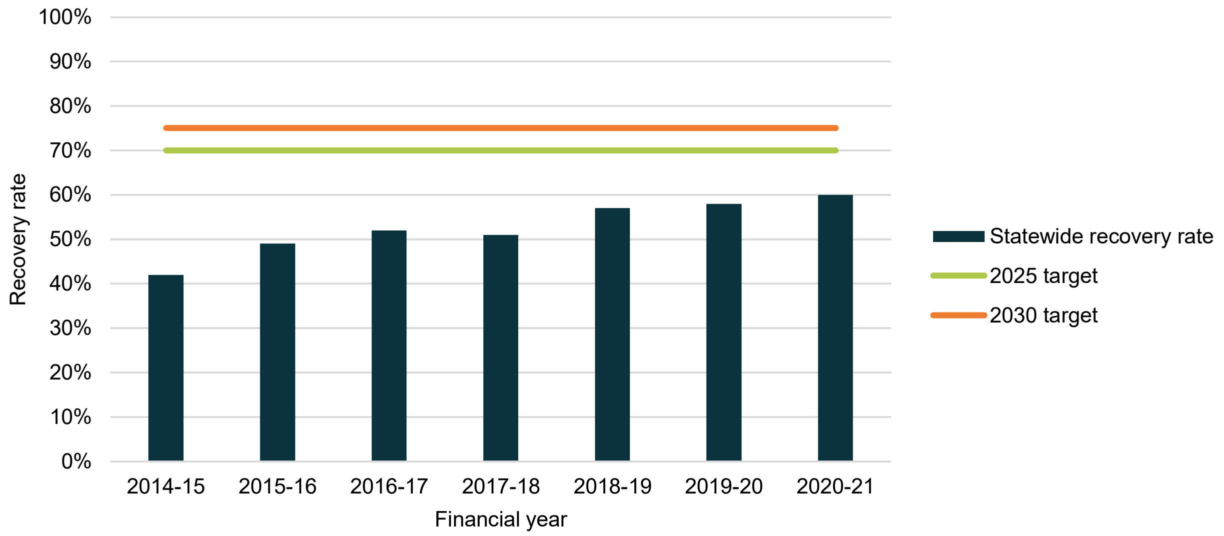
3.1.1 Production and Different Sources

Concrete represents over half of all C&D waste in Australia, and recycling concrete into a usable aggregate often includes crushing, washing, and sieving. It can also involve removing unsuitable material such as timber, steel, and plastics (ARRB 2022a). CRC is approximately 95% concrete, with some gravel, mortar, and cement, and can be generated as a fine or coarse aggregate (ACRI et al. 2022). It should be produced to comply with allowances for grading and foreign material content (Local Government Infrastructure Design Association (LGIDA) 2020).

3.1.2 Supply and Volume

In the 2020–21 financial year, WA had a total waste recovery rate of 60% (Waste Authority 2022c). This is the highest recovery rate in WA since reporting began in 2010 – when the total recovery was 31%. There is still a way to go to reach the 2025 total recovery target of 70% under *the Waste Avoidance and Resource Recovery Strategy 2030* (as shown in Figure 3.4).

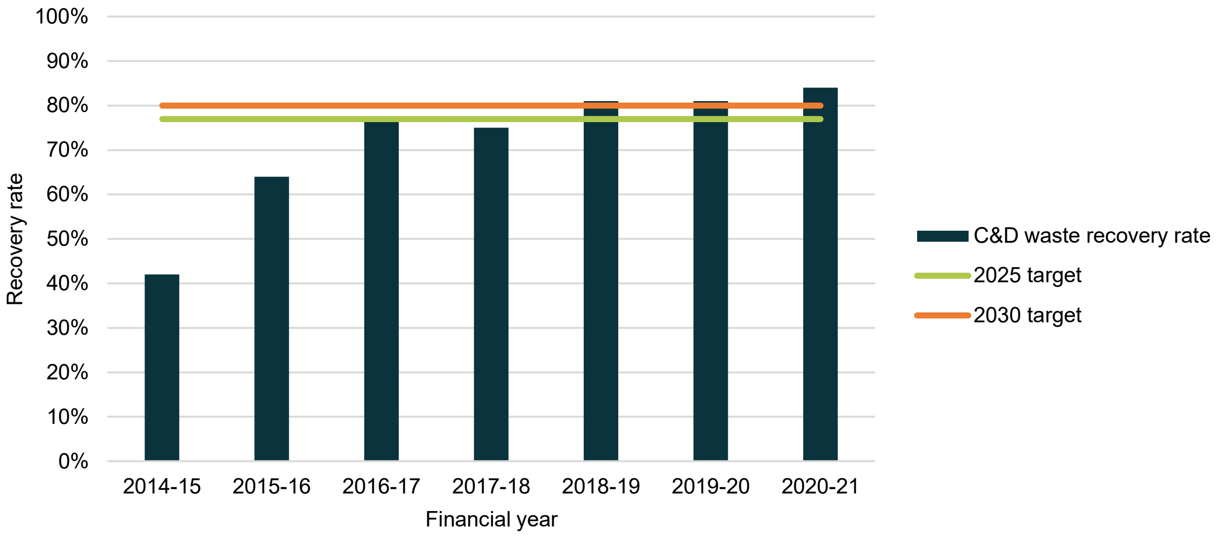
Figure 3.4: State-wide recovery rates benchmarked against strategic targets



Source: Adapted from Waste Authority (2022c).

The main driver of the improved recovery rates over the last few years is the decline in C&D waste disposal and the corresponding increase in the practice of C&D waste recovery. Figure 3.5 shows the C&D recovery rates for 2014–15 to 2020–21 against the strategic targets. The recovery rates meet both the 2025 and 2030 targets of the strategy (Waste Authority 2022c).

Figure 3.5: C&D recovery rates benchmarked against strategic targets

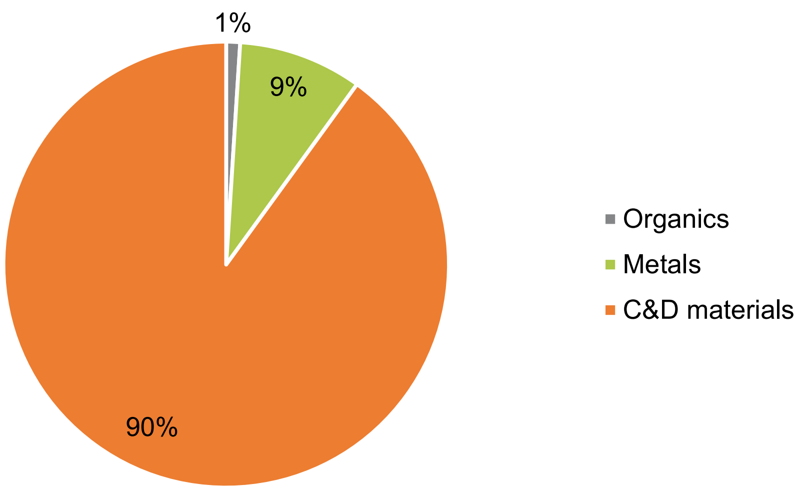


Source: Adapted from Waste Authority (2022c).

However, the data excludes material that is in stockpiles of both unprocessed and processed C&D waste. The Waste Authority indicates there is ~1 million tonnes of C&D waste in stockpiles, with an annual production of some 1.3 million tonnes (Waste Authority 2022c).

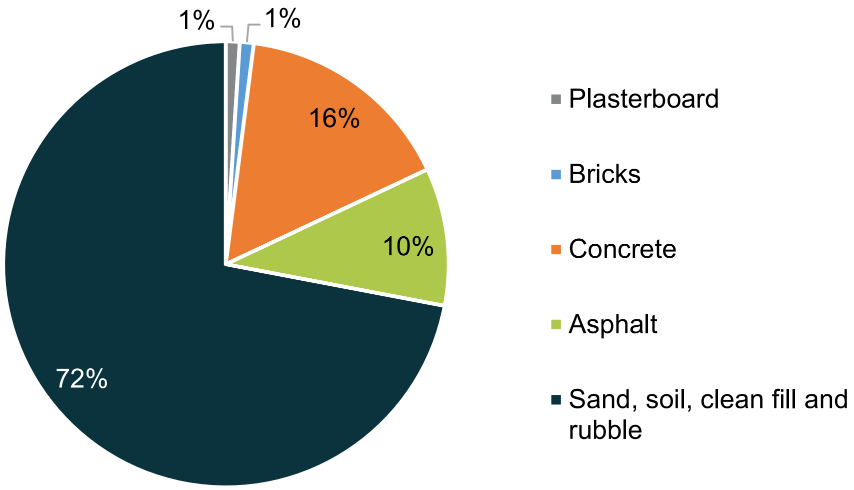
C&D waste is generated from multiple sources including private developers and large government infrastructure projects. The current composition and recovery of the waste generates the categories of recyclables are shown in Figure 3.6 and Figure 3.7. The waste recovery flows and processing destinations are also outlined in Figure 3.8.

Figure 3.6: C&D input waste stream composition 2018‑19



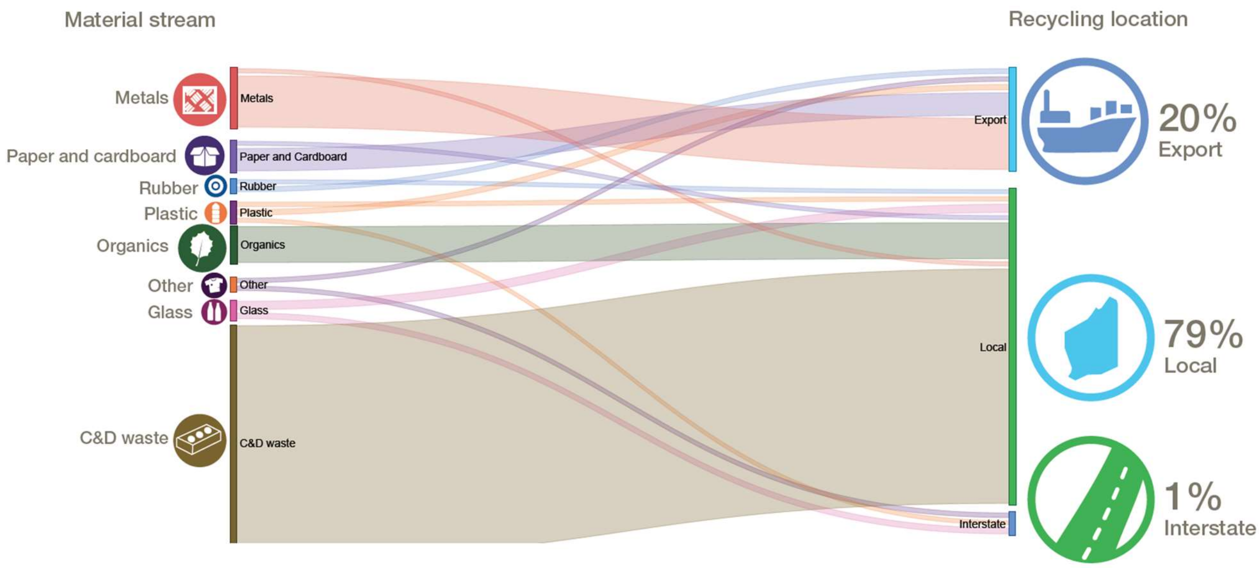
Source: Adapted from Waste Authority (2020).

Figure 3.7: Recycled C&D output composition 2018‑19



Source: Adapted from Waste Authority (2020).

Figure 3.8: Waste recovery flows by processing destination and material category



Source: Waste Authority (2022b).

3.1.3 Physical Properties

The characteristics of CRC are different from natural aggregates, with old cement mortar being the main reason behind this difference. If the size of aggregate increases, then the amount of adhered cement mortar reduces. According to Kisku et al. (2017) for the different sizes of recycled aggregate i.e. 4–8 mm, 8–16 mm and 16–32 mm the mortar content is 60%, 40% and 35% by volume, respectively. The larger the size of the recycled aggregate, the higher its density. Patel and Singh (2018) reported that the aggregate crushing value for recycled aggregates is higher than that of virgin aggregate. Recycled aggregate crushing values were 33% and 45% more than that of virgin aggregates for 10–20 mm and 4.75–10 mm size aggregate, respectively.

3.1.4 Engineering and Mechanical Properties (Durability and Strength)

CRC has been shown to have comparable properties to conventional capping materials, in particle size, Los Angeles abrasion, water absorption and specific gravity, as well as improved stiffness and strength compared to natural capping materials[1] (Naeini et al. 2019). The use of CRC may result in a higher stiffness than standard materials and may even increase over time due to ongoing densification (Mohammadinia et al. 2020, Naeini et al. 2019). CRC is also a high strength product with self-cementing properties, which results in increased stiffness over time (Main Roads Western Australia 2022). It is important to consider this increased stiffness, as too high may result in the ballast layer being crushed between the capping layer and sleepers and thus a reduced design life. Research was not found that details this specific issue further. Thus, individual blends should be assessed for their properties.

With the increased stiffness, Naeini et al. (2019) determined that 100% CRC could still be used in the rail formation as a capping layer. Furthermore, the increased stiffness of the CRC resulted in the opportunity to include other materials with lower stiffness properties, such as recycled glass or recycled plastic, to increase the opportunity to use varied material sources while retaining the performance characteristics.

3.1.5 Chemical Composition

The main chemical composition of CRC is SiO_2, CaO, Al_2O_3, Fe_2O_3, MgO, K_2O, and SO_3. The presence of old cement paste is generally the reason why these compound contents, with the exception of SiO_2, are higher than in natural aggregates. Natural aggregates have a higher SiO_2 content due to the absence of mortar which is present in CRC (Sanchez-Cotte et al. 2020).

It has been suggested that recycled aggregates may have higher sulphate content than natural aggregates, due to the presence of sulphates in cement (de Juan & Gutierrez 2009). A high correlation was found between the adhered mortar content and sulphate content i.e. samples with higher mortar content had higher sulphate content.

Silva et al. (2014) found that recycled aggregates sourced from concrete subjected to marine and estuarine environments may have a high soluble chloride content. This would clearly restrict the use of these recycled aggregates in steel reinforced concrete. The presence of chloride and sulphate in CRC is not prohibited when placed under the formation layer or exposed to groundwater (National Environment Protection (Assessment of Site Contamination) Measure 1999, amended 2013). Table 1C of the measure does not indicate a maximum limit of chloride exposure but has a maximum limit of 500 mg/L if exposed to drinking water. This indicates that CRC exposed to marine environments can be used as a capping layer if the maximum limits are not breached. Specific testing of the CRC sourced will be required to ensure compliance. The use of these aggregates consequently needs a specific approach to guarantee a sufficiently low concentration of chloride or sulphate ions. Chlorides contaminating the recycled aggregate may leach if they are soaked in water. Washing with water is one way of reducing the concentration of the constituents because they are not linked to the cementitious microstructure and are thus easy to remove from CRC. After a thorough washing or total immersion in water for at least 2 weeks, the quantity of chlorides decreases to a point where the recycled aggregates can be used in concrete and even in reinforced or pre-stressed concrete without any risk of corrosion (Debieb et al. 2010).

3.1.6 Environmental Considerations

The Department of Water and Environmental Regulation (DWER) applies the *Landfill Waste Classification and Waste Definitions* to determine if recycled fill is contaminated (DWER 2019a). A consideration for CRC waste is asbestos risk, which is appropriately managed by environmental controls. *Roads to Reuse* suppliers

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[1] The conventional capping materials were sourced from the natural quarries used for railway projects in Victoria and New South Wales, and are noted to be composed of well-graded gravel and sand.

of CRC must meet contamination requirements, including strict asbestos requirements (Waste Authority 2023).

Other considerations that may require further investigation include the risk of leaching from recycled aggregates, and organic matter levels. The impacts of leaching from CRC are further discussed in Section 4.7.

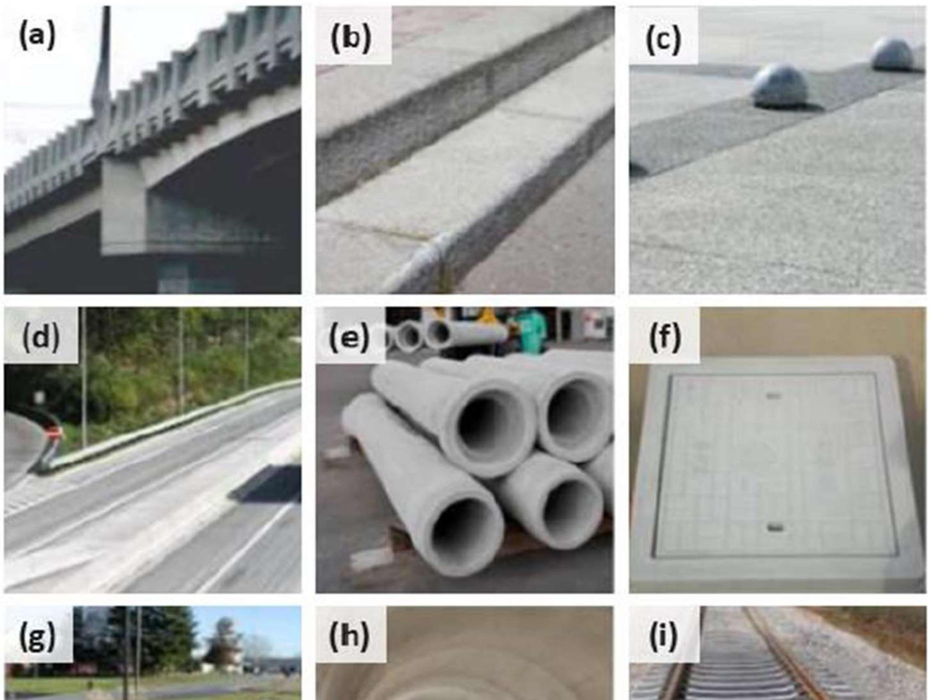
3.1.7 Current Applications

The current uses for recovered C&D waste are typically limited to road construction, and landscaping, though there is potential for broadening its use. CRC is considered a strong, durable material and is frequently used in pavement applications, both unbound and cementitious, across Australia (Nguyen et al. 2021). The CRC allowance across jurisdictions ranges up to 100% in some non-structural fill applications (Nguyen et al. 2021).

CRC is also used in roads and road shoulders, carparks and truck parking, driveways, kerbs, rammed earth walls, construction blocks, as a concrete batch aggregate substitute, and for building construction ground development (Beyer & Cooper 2020).

Concrete is currently used in rail applications such as sleepers, platforms, beams, drainage, and bedding, and feasibly these applications could be replaced with recycled concrete. A number of concrete infrastructure applications are illustrated in Figure 3.9. A case study of Sydney's main rail network lines demonstrated that portions of rail sleepers were comprised of a small volume (< 10%) of recycled concrete (Gharehbaghi et al. 2020).

Figure 3.9: Concrete in infrastructure (a) bridge, (b) kerb, (c) footpath, (d) road pavement, (e) pipes, (f) drain covers, (g) parking lots, (h) tunnels, and (i) sleepers



Source: ARRB (2022a).

In a road environment, CRC may be applicable for use in subbase under asphalt and basecourse in low-traffic roads, according to Main Roads Specification 501 *Pavements.* This specifies CRC use as a subbase material under full depth asphalt pavements. Under full depth asphalt, it has been used in place of limestone, and has reduced landfilling and greenhouse gas emissions (via reduced processing requirements and reduced virgin material extraction) (Main Roads Western Australia 2022). Under the RtR program, over 27,000 tonnes of CRC were used in 2019–20, including on the Kwinana Freeway Widening Project. The material was sourced from the demolition of Subiaco Oval, and was compliant for reuse, including meeting environmental and workplace health and safety (WHS) requirements. With this successful project, Main Roads set a target of reusing 100,000 to 200,000 tonnes of CRC per annum, from 2021–22 onwards (Main Roads Western Australia 2022).

PTA Specification 8880-450-067 *Roads, Busways, Paths and Access Tracks* specifies the use CRC in subbase or basecourse, and of recycled ballast:

- as a subbase and base material in shared paths, paths, local access roads and carparks
- as subbase material only in busways and roadways
- in lateral access tracks as the basecourse with an asphalt surfacing where grade requirements are to be adhered to, otherwise these are to be sealed with an appropriately designed sprayed seal surfacing
- in the maintenance of access tracks with seal.

3.2 Recycled Ballast

The following sections document the waste generation, physical and engineering properties, chemical composition, environmental and WHS factors, current processing practices, and current uses of degraded ballast.

3.2.1 Production and Different Sources

Ballast is a granular material, with a nominal size of 53 or 63 mm (as per AS 2758.7) and is usually purchased as a virgin aggregate material. Ballast is used to bear the load from sleepers and to enable drainage on the line. It is generally high quality igneous or metamorphic rock; in Western Australia blue metal aggregate or natural red pea gravel are often used (Economics and Industry Standing Committee 2014, Guo et al. 2022).

The recycling of ballast occurs in a number of ways, the first of which is cleaning (or returning degraded ballast to a suitable state for reuse as ballast again), which can occur ex situ, i.e. offsite; or in situ, i.e. along the track. This cleaning process may involve removal of smaller particle sizes and washing. As well as the cleaned ballast being reused, the discarded product from the cleaning process may be recycled into new uses. Secondly, degraded ballast may have potential to be reused in limited amounts as ballast or as other applications, without undergoing a cleaning process. Current and emerging reuse applications are discussed in Sections 3.2.7.

Offsite recycling involves removing the spoiled ballast from the rail environment, haulage to a recycling site, cleaning, and preparation back to a suitable standard for use. Very few facilities offer this service (ARRB 2022a). One that does is *Repurpose It* in Victoria, where it can process over 80,000 m^3 within approximately one month (ACRI et al. 2022). *Repurpose It* is located in a metropolitan region, which may contribute to its financial and environmental viability. This would need to be considered for viability in a Western Australian context. There are currently no similar offsite recycling sites in Western Australia.

In situ cleaning occurs directly on the rail track with mobile equipment, and offers the benefits of reusing the material locally, reducing haulage requirements and emissions, and allowing for quick processing. Cleaning is carried out to mitigate the fouling of ballast, such as through coal spillages or affected drainage capacity, and to generally extend the life of the ballast (Cement Concrete & Aggregates Australia 2015). On average, 30% of the ballast is rejected in this process. In situ cleaning has been practised in Australia for around 3 decades (Mirzababaei et al. 2019). Companies undertaking in situ ballast cleaning in Western Australia include Rio Tinto, Aurizon, John Holland and BHP Billiton (Rio Tinto 2020, RMC Rail 2014, Westlink 2014). A proportion of fine ballast waste is generated through the cleaning process, as ballast cleaning sees particles < 30 mm discarded (Mirzababaei et al. 2019). Refer to Section 3.2.7 for a discussion of where this material may be used.

3.2.2 Supply and Volume

Ballast is a common waste product in the rail industry, with for example Melbourne's Metro track renewal in 2019 producing 30,000 tonnes of ballast waste (ARRB 2022a, Cement Concrete & Aggregates Australia 2015). Aurizon in Queensland reportedly rejected 30% of ballast through annual cleaning processes across its 2,670 km of heavy haul track, equating to 322,000 tonnes of ballast waste annually (Mirzababaei et al. 2019).

3.2.3 Physical Properties

Table 3.1 provides a summary of the varied ballast properties and how these are tested and assessed internationally. The key physical and mechanical properties are hardness and strength, and its grading and shape.

Table 3.1: Ballast material selection and testing methods

Property classification	Ballast properties	Testing methods	Evaluation terms
Mechanical properties	Hardness, strength	Los Angeles abrasion test	Abrasion, wear and crushing
	Hardness	Deval abrasion test: dry and wet grinding	Surface wear
	Hardness	MDA test	Surface wear
	Strength	Single particle crush test	Crushing resistance
	Hardness	Scratch hardness	Surface wear-resistance into fines
	Strength	Point load strength test	Fragmentation into small pieces
	Impact toughness	Drop weight test	Resistance to impact loading and crushing
	Hardness	Dorry abrasion test	Surface wear-resistance into fines
	Hardness	Mill abrasion test	Surface wear-resistance into fines
Physical properties	Grading	Gradation measurement	Drainage, compactness
	Grading	Small particle/dust measurement	Drainage properties
	Physical stability	Particle density measurement	Displacement resistance, indirect strength
	Physical stability	Bulk density measurement	Porosity, drainage, track stability (lateral, longitudinal, vertical)
	Shape characteristics	Particle profile measurement	Breakage into multiple small pieces, drainage
Chemical properties	Chemical stability	Damp-dry resistance test	Durability, weathering resistance
	Chemical stability	Freeze-thaw test	Durability, weathering resistance
	Chemical stability	Particle Porous Structure Test	Durability, weathering resistance
	Chemical stability	Particle water absorption	Saturation, weathering resistance
	Chemical stability	Sodium and magnesium sulphate solution test	Durability, weathering resistance
	Chemical stability	Clay clods and friable particles	Durability, initial abrasion level
Ballast layer properties	Ballast layer profile	Bed thickness, shoulder, and slope measurements	Rail stability, elasticity, damping
	Layering	Geometric position testing	Rail stability, comfort

Source: Guo et al. (2022).

3.2.4 Engineering and Mechanical Properties (Durability and Strength)

Since recycled ballast has undergone previous repeated cycles of loading, it contains more micro-cracks compared to fresh ballast and, thereby, is expected to be more prone to crushing (i.e. lower strength). Regression analysis of the single particle strength data indicates that in general, recycled ballast has about 35% lower tensile strength compared to fresh aggregates. McDowell and Bolton (1998) and Nakata et al. (1999) observed a similar trend for sands and limestone. This is because larger particles contain more flaws or defects, and they have a higher probability of defects being present in the particles that will break (Lade et al. 1996). Fracturing of larger particles along these defects creates smaller particles. The subdivided particles contain fewer defects and are less likely to fracture.

Ballast angularity is another key factor that is integral to the performance of ballast, in terms of particle interlocking, drainage flow and elasticity. Recycled ballast, as a result of its prior use, may be more rounded and thus see less interlocking and friction properties (Sun 2017). It is recognised that degraded ballast does see a reduction in angularity and thus when utilising recycled ballast its behaviour and performance needs to be considered to ensure compliance (Indraratna et al. 2006). Relevant ballast specifications (i.e. PTA 8190-400-002 and AS 2758.7) do outline a requirement for angularity and particle dimensional requirements, thus this factor is considered when finding appropriate materials for use as ballast and would be applied to recycled ballast materials. Geogrids and geosynthetics are effective methods to stabilise and thus support the use of recycled ballast (Indraratna et al. 2002).

French researchers (Descantes et al. 2006) explored using video and image processing techniques to visually assess the particle angularity. Descantes et al. (2007) highlighted that the degraded ballast angularity, prior to recycling, was not as low as expected though they did note an angularity reduction after recycling, attributed to the washing device. The techniques explored by Descantes et al. (2006, 2007) have not been applied in practice.

3.2.5 Chemical Composition

Rail activities have a history of contamination through various practices such as the use of arsenic-based herbicides, the presence of asbestos, the use of lubricants and fuels, and transportation of various materials such as lead ore. From these historical and current practices, some of the associated chemical substances of risk include metals, hydrocarbons (total petroleum hydrocarbons (TPHs) and polycyclic aromatic hydrocarbons (PAHs)) and asbestos (Department of Planning, Transport and Infrastructure 2015). There can be significant variability in the risk of any of these substances along the track, and thus reuse of ballast should factor in assessing for these compounds on a case-by-case basis (Department of Planning, Transport and Infrastructure 2015).

There are numerous reported cases of ballast contamination by organic and inorganic species (Wilkomirski et al. 2011). Among the organic compounds, loss of fuel or polycyclic aromatic hydrocarbons have been commonly identified as concerns. Inorganic contamination, heavy metals (mainly Ni, Zn, Fe, Cd, V, Cr, Mn, Cu) from lubricants, track corrosion and wear, and welding residues have been found in trace amounts increasing with the duration of the operation. With the electrification of the Public Transport Authority of Western Australia (PTA) system since 1991, hydrocarbon contamination risk has been significantly reduced and is more likely to be as a result of hydraulic fluids with likely occurrence higher in areas where braking of rolling stock is most frequent.

Asbestos-containing materials (ACM) contamination from past use of asbestos in rail train and carriage brake pads has the potential to exist in ballast profiles that were placed prior to 2004. This is due to the PTA ceasing use of ACM following an Australia-wide ban on the manufacture and use of asbestos and ACM which took effect on 31 December 2003.

3.2.6 Environmental Considerations

Table 3.2 outlines the estimated risk of ACM and hydrocarbons across PTA lines, based on the history of the lines and design life of ballast.

Table 3.2: Estimated risk of ACM and hydrocarbon risk on PTA lines

Line	History	Year electrified	Environmental risk
Fremantle	Opened on 1 March 1881 as the first suburban railway	1991	Considered unlikely that ACM exists within the ballast profile Minor risk of hydrocarbon contaminates within the dual gauge sections south of Victoria Street Station in North Fremantle
Midland	Perth to Guildford was opened in March 1881, extended from Guildford to Chidlow's Well, opening in March 1884	1991	Considered unlikely that ACM exists within the ballast profile Minor risk of hydrocarbon contaminates borne from diesel locomotive use
Armadale	Opened on 2 May 1893 To be extended through to Byford as part of the METRONET program of works	1991	Considered unlikely that ACM exists within the ballast profile Minor risk of hydrocarbon contaminates borne from diesel locomotive use
Thornlie	Opened on 7 August 2005 The Arc Infrastructure freight line runs parallel to the Thornlie Line The Thornlie Line will connect through to Cockburn Station on the Mandurah Line as part of the METRONET program of works		Considered unlikely that ACM or hydrocarbon contaminates exist within the ballast profile for the passenger railway Locomotives on the Arc Infrastructure freight line are diesel powered. The potential for ACM or hydrocarbon contamination is considered higher than on passenger railway lines
Mandurah	Opened in 2007	Line is electrified and never had diesel-powered rolling stock	Considered unlikely that ACM or hydrocarbon contaminates exist within the ballast profile
Joondalup	Opened in 1992 The line will be extended out to Yanchep as part of the METRONET program of works	Line is electrified and never had diesel-powered rolling stock	Considered unlikely that ACM or hydrocarbon contaminates exist within the ballast profile
Forrestfield Airport Link	New line consists of unballasted twin bored tunnel This project was delivered as part of the METRONET program of works		
Morley-Ellenbrook	New 21 km line spurring north from the Midland line just east of Bayswater Station terminating in Ellenbrook		Considered unlikely that ACM or hydrocarbon contaminates exist within the ballast profile

Source: Correspondence with PTA, 7 December 2022.

3.2.7 Current and Emerging Applications

Typically, ballast has been reused in low-grade applications, such as road base or access tracks (ARRB 2022a). South Australia, for example, has used ballast in structural pavement layers, embankments and general earthworks.

However, there is minimal documentation of the use of recycled ballast across the Australian rail industry, excepting the cleaning and reuse of degraded ballast once again as ballast, as discussed in Section 3.2.1. Recycled ballast may in effect be used as 100% ballast again, if it is cleaned and able to meet the standard requirements, or otherwise in combination with fresh ballast (Jia et al. 2019). Important requirements in ballast specifications include durability, size, density, and lack of contaminants, which differs across jurisdictions and operators (Department of Planning, Transport and Infrastructure 2015, Metro Trains Melbourne 2021).

In terms of potential applications, degraded ballast can be used with fresh ballast, in bedding applications. Jia et al. (2019) concluded that 30% recycled ballast, with 70% fresh, was the optimal content, with minimal to no impact on shear strength performance. Greater percentages were explored, however an impact on performance was noticed above rates of 50% recycled. Other applications include recycling ballast into concrete, as an aggregate, for applications such as drainage, decking, and sleepers (ACRI et al. 2022, Macken et al. 2021).

As discussed in Section 3.2.1, fine ballast generated through cleaning may be reused in the rail environment. One such application that has been explored is in construction of unsealed access tracks, with one study to date demonstrating suitable deflection results from the < 26.5 mm waste materials (Mirzababaei 2019). The access track was assessed after 15 months in operation, and was found to be performing well, especially under severe environmental conditions of a significant wet season.

4 Recycled CRC and Recycled Ballast in Rail Applications

4.1 Current Australian Practice

Table 4.1 provides a summary of relevant Australian specifications for the use of CRC and recycled ballast in rail applications. The specifications relate to the various applications in which CRC and/or recycled ballast may be reused (refer to the notes in the cases the standard is referring to only one material).

Table 4.1: National and state specifications (NSW, Qld, WA, SA)

Standard	Jurisdiction	Potential applications	Notes
ARTC ETA-04-01, Ballast Specification.	Nationwide	Ballast	Material from new sources of supply shall be subject to petrographic analysis for approval.
ARTC ETA-02-03, Steel Sleeper Specification.	Nationwide	Structural fill	
		General fill	
		Drainage material	
		Bedding material	
ARTC ETM-08-01, Earthworks, Formation and Capping Material.	Nationwide	Free draining filter material	Requirements for material properties, compaction, and placing are outlined in the standard.
		General fill	
		Formation capping layer	
T HR TR 00192 ST, Ballast.	NSW	Recycled ballast	The requirements and uses are outlined in section 10.2.
TS 01049:1.0 CRN CS 240, Ballast.	NSW	Recycled ballast	Section 8 outlines the standards and requirements for recycled ballast.
TMR MRST04, General Earthworks.	Qld)	General fill	Physical and engineering requirements for the potential applications are outlined in MRTS04.
		Unbound granular drainage layer	
		Backfill material	
		Free-draining granular material	
		Bedding and drainage aggregate	
Specification 302, Earthworks.	WA	Earthworks	The requirements for recycled materials as embankment fills are outlined in section 302.10.
PTA 8800-450-090, Specification: Design of Drainage for PTA Infrastructure.	WA	Bedding material	Outlines the requirements for recycled ballast being used as drainage aggregates.
		Drainage material	
PTA 8880-450-074, Specification: Earthworks, Slope Stability, Geotextiles and Erosion Protection.	WA	Earthworks	Outlines the requirements for recycled ballast being used as engineered fill.
		General fill	
PTA 8880-450-067, Specification: Roads, Busways, Paths and Access Tracks.	WA	Access tracks	Outlines the requirements for recycled ballast being used in access tracks.
Recycled Fill Materials for Transport Infrastructure.	SA	Ballast	Requirements are outlined in section 8.3.2.

4.2 Current International Practice

4.2.1 USA (State of Michigan)

CRC

The State of Michigan was found to have comprehensive standards covering the use of CRC and therefore was used as a case study of international practice from the USA.

The Michigan Department of Transport (MDOT) specifications reflect some of the performance concerns using CRC observed over the years. In the MDOT (2012) *Standard Specifications for Construction*, Section 902.03.B, CRC is only allowed as an aggregate in concrete mixes used for lower-priority applications such as kerb and gutter, valley gutter, sidewalks, concrete barriers, driveways, temporary pavement, interchange ramps with commercial average daily traffic (CADT)[2] less than 250, and concrete shoulders. The specification also specifically states that CRC coarse aggregate may not be used in concrete for mainline pavements or ramps with a CADT greater than or equal to 250, concrete basecourses, bridges, box or slab culverts, headwalls, retaining walls, prestressed concrete, or other heavily reinforced concrete.

The specifications are even more restrictive for the use of CRC fine aggregate as described in Section 902.08, simply stating that it should not be used in new concrete mixtures. In addition, as described in Section 902.05, CRC is not allowed in unbound Class 21AA and 22A dense-graded unbound aggregate base or separation layer when this layer drains into an underdrain, unless at least one of the following conditions exist:

- A vertical layer of at least 12 inches (30.48 cm) of granular Class I, II, IIA, or IIAA is placed between the CRC dense-graded layer and an underdrain, or
- A geotextile liner or blocking membrane placed between the CRC dense-graded layer and the underdrain will act as a barrier to leachate.

Furthermore, in accordance with Section 902.06, CRC is allowed in open-graded aggregate 4G, as long as building rubble or hot-mix asphalt (HMA) is less than 5%. CRC is not allowed in open-graded aggregate 34G or 34R. MDOT permits the use of CRC coarse aggregate in asphalt pavement mixtures (Section 902.09.A), but not fine CRC aggregate. A summary of the allowable uses of CRC is provided in Table 4.2.

Table 4.2: Summary of allowable use of CRC

Type of CRC	Fill/subbase(1)	Dense-graded aggregates(2)	Open-graded aggregates(3)	Hot mix asphalt	Portland cement concrete
Coarse	Yes	Yes	Yes	Yes	Yes(4)
Fine	Yes	Yes	Yes	No	No

1. The Engineer will only allow the use of granular material produced from crushed Portland cement concrete for swamp backfill, embankment (except the top 3 feet below subgrade) and as trench backfill for non-metallic culvert and sewer pipes without associated underdrains.
2. Ensure dense-graded aggregate produced by crushing Portland cement concrete does not contain more than 5.0 per cent building rubble or hot mix asphalt by particle count. The Department defines building rubble as building brick, wood, plaster, or other material. The Engineer will allow pieces of steel reinforcement capable of passing through the maximum grading sieve size without aid.
   Do not use Class 21AA, 21A and 22A dense-graded aggregate produced from crushing Portland cement concrete to construct an aggregate base or an aggregate separation layer when the dense-graded layer drains into an underdrain, unless at least one of the following conditions apply:
   A. vertical layer of at least 12 inches of granular Class I, II, IIA, or IIAA exists between the dense-graded aggregate layer and an underdrain or,
   B. a geotextile liner or blocking membrane, that will be a barrier to leachate, placed between the crushed concrete and the underdrain. Only produce Class 23A dense-graded aggregate from steel furnace slag for use as an unbound aggregate surface course or as an unbound aggregate shoulder.

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[2] The CADT value refers to the average number of commercial vehicles passing a given point or segment on a daily basis.

3. Ensure open-graded aggregate 4G produced by crushing Portland cement concrete does not contain more than 5.0 per cent building rubble or hot mix asphalt by particle count. The Department defines building rubble as building brick, wood, plaster, or other material. The Engineer will allow pieces of steel reinforcement capable of passing through the maximum grading sieve size without aid. Do not use open graded aggregate 34G or 34R produced from Portland cement concrete.
   Also see Special Provision 03SP303(A), Open-Graded Drainage Course, Modified, and Special Provision 03CT303(A 140), Open-Graded Drainage Course, Modified (Portland Cement-Treated Permeable Base Using Crushed Concrete).
4. The Contractor may use crushed concrete coarse aggregate in the following concrete mixtures: curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps with a commercial ADT less than 250, and concrete shoulders. Do not use crushed concrete coarse aggregate in the following: mainline pavements or ramps with a commercial ADT greater than or equal to 250, concrete base course, bridges, box or slab culverts, headwalls, retaining walls, pre-stressed concrete, or other heavily reinforced concrete.

Source: MDOT (2012).

Recycled ballast

There was no available information on the application of recycled ballast in the USA.

4.2.2 United Kingdom

In the United Kingdom (UK) over 1 million tonnes of used track ballast are received by Network Rail's aggregate handling depot yearly (White 2021). This material is recycled and made suitable again for the railway industry.

The types of aggregate materials listed in the report are :

- **Screened recycled aggregate**: Graded to highway works and rail ballast specifications. Reused as a piling aggregate, porous subbase applications and as a recycled option for layers of ballast and sub-ballast above a capping layer.
- **Washed recycled fill sand**: Conforms to BS EN13285 as material for capping and piling mats. Seventy millimetres to dust material suitable for many earthwork uses as a hardwearing aggregate for haul roads, for capping unmade ground and as a general bulk fill product.
- **Washed recycled aggregate**: Compliant with relevant civil engineering specifications. Available as a washed product for use as a Type B filter media for drainage work and for use as a pipe bedding material. Graded to comply with concrete and asphalt specifications as a recycled aggregate.
- **Washed and screened recycled track ballast**: Drainage pipe bedding material. Fully certificated subbase material 40 mm to dust recycled granite material certified for highways and general civil engineering use as well domestic subbase applications such as driveways.
- **Recycled 40–20 mm reclaimed granite**: Aggregate compliant with civil engineering and agricultural drainage specifications. Washed aggregate to be used as Type B filter media for drainage work.

CRC

A quality protocol funded by the UK Department for Environment, Food and Rural Affairs (DEFRA), the Welsh Government, and the Northern Ireland Environment Agency (NIEA) was developed to set out the end-of-waste criteria for the production and use of aggregates from inert waste. The standards, specifications, and quality controls for the use of recycled aggregates, which covers CRC and degraded ballast, is listed in Table 4.3.

Table 4.3: Standards, specifications, and quality controls for the use of recycled aggregates

Product and use	Standard	Specification	Quality controls
Unbound recycled aggregate: Pipe bedding Drainage	BS EN 13242: Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Highways Agency Specification for Highway Works (SHW): Series 500 Highway Authorities and Utilities Committee (HAUC): Specification for the reinstatement of openings in highways (Department for Transport 2021)	BS EN 13242: Level 4 Attestation Evaluation of Conformity to BS EN 16236 SHW: Quality Control procedures in accordance with the Quality Protocol for the production of aggregates from inert waste SROH: Compliance with SHW
Unbound recycled aggregate:	BS EN 13242: Aggregates for unbound and	Highways Agency Specification for Highway Works: Series 600 HAUC:	BS EN 13242: Level 4 Attestation Evaluation of Conformity to BS EN 16236 SHW: Quality

Product and use	Standard	Specification	Quality controls
Granular fill General fill Capping	hydraulically bound materials for use in civil engineering work and road construction	Specification for the reinstatement of openings in highways (Department for Transport 2021), BS EN 13285: Unbound mixtures: Specifications	Control procedures in accordance with the Quality Protocol for the production of aggregates from inert waste SROH: Compliance with SHW
Unbound recycled aggregate: Subbase	BS EN 13242: Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Highways Agency Specification for Highway Works: Series 800 HAUC: Specification for the reinstatement of openings in highways (Department for Transport 2021); BS EN 13285: Unbound mixtures: Specifications	BS EN 13242: Level 4 Attestation Evaluation of Conformity to BS EN 16236 SHW: Quality Control procedures in accordance with the Quality Protocol for the production of aggregates from inert waste SROH: Compliance with SHW
Recycled aggregate for concrete	BS EN 12620: Aggregates for concrete	Highways Agency Specification for Highway Works: Series 1000 BS 8500-2: Concrete	BS EN 12620: Level 4 Attestation Evaluation of Conformity to BS EN 16236 SHW: Quality Control procedures in accordance with the Quality Protocol for the production of aggregates from inert waste SROH: Compliance with SHW
Recycled aggregate for asphalt	BS EN 13043: Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas	Highways Agency Specification for Highway Works: Series 900 HAUC: Specification for the reinstatement of openings in highways (Department for Transport 2021)	BS EN 13043: Level 4 Attestation Evaluation of Conformity to BS EN 16236 SHW: Quality Control procedures in accordance with the Quality Protocol for the production of aggregates from inert waste SROH: Compliance with SHW
Recycled aggregate for hydraulically bound mixtures	BS EN 13242: Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Highways Agency Specification for Highway Works: Series 800 HAUC: Specification for the reinstatement of openings in highways (Department for Transport 2021); BS EN 14227-1 to 5 Hydraulically Bound Mixtures: Specifications	BS EN 13242: Level 4 Attestation Evaluation of Conformity to BS EN 16236 SHW: Quality Control procedures in accordance with the Quality Protocol for the production of aggregates from inert waste SROH: Compliance with SHW

Source: NIEA (2013).

Recycled ballast

A clean, elastic, and homogeneous ballast bed is essential for a smooth and functioning rail system. The ballast bed has a considerable influence on the service life and the quality of the track geometry and consequently the cost-efficiency of the overall track maintenance (Meza et al. 2021). If the condition of the ballast no longer meets specification requirements, it should either be cleaned or replaced. Ballast can be recycled and returned to the existing track network (in 2020, 515,000 tons (467200 tonnes) of ballast were, corresponding to a total of 16% of all installed ballast) (Meza et al. 2021). Ballast that cannot be reused is cleaned, screened, and sold to be recycled elsewhere, for example as aggregate in road construction.

4.3 Europe (Other)

Table 4.4 summarises other European practices in processing and utilising CRC and recycled ballast.

Table 4.4: Examples of international recycling practice

Location	Applications	Recycled materials/ blends	Notes	Reference
Longueau, France	Road base	CRC from concrete sleepers	There were10,000 tonnes of concrete recycled at a crushing facility, from 70,000 sleepers from a line upgrade During crushing concrete aggregate is separated from steel	Groupe RES (2020)
The Netherlands	Road base	CRC and ballast	In 2010, 20% of aggregate materials used in the Netherlands was recycled. The most common reuse of recycled aggregates is in road base. Use is regulated for leaching and asbestos.	Fédération Internationale Du Recyclage (n.d.)

Location	Applications	Recycled materials/ blends	Notes	Reference
Germany	Ballast	Ballast	DeutscheBahn allows for the use of recycled ballast on its tracks, provided it is cleaned and processed to return to the standards of the relevant ballast specifications. In 2020, DeutscheBahn used 3.2 million tonnes of ballast, of which 16% was recycled; 1.5 million tonnes were removed from tracks by cleaning machines or mobile processing plants, of which 0.7 million tonnes was immediately reused	Remex (2023), DeutscheBahn (2020)
Germany	Ballast	Ballast	NovoCrete explored the use of recycled ballast as a base layer for the construction of a transhipment centre. The aim was to reduce disposal of materials and transport costs and impacts	Autark Energy (2014)
Norway	Ballast	Ballast	Approximately 50–75 km of Norwegian rail ballast is cleaned and reused as ballast annually, undertaken by Baneservice	Tangerås (2019)

4.4 Research Projects

Table 4.5 summarises several research projects investigating the use of recycled materials or recycled material blends in railway applications. This summary has not been limited to only CRC and degraded ballast, as there is considerable research covering other aggregate materials and recycled blends that offers insight into potential applications, successes, and challenges.

Table 4.5: Summary of research projects

Applications	Recycled materials and blends	Main findings	Reference
Capping layer	CRC	CRC is a suitable material to be used in the lower structural layers of ballasted rail track.	Linden et al. (2019)
	Recycled glass and CRC	Glass with CRC (blends of 10/90% and 20/80%) was confirmed as an effective material for a capping layer, with suitable deformation and strength properties.	Naeini et al. (2021)
Sub-ballast	CRC in combination with recycled crushed glass and recycled plastic Crushed brick in combination with recycled crushed glass and recycled plastic	Recycled material blends exhibited superior or equivalent performance compared to conventional aggregates.	Naeini et al. (2019)
	Steel furnace slag, coal wash and crumb rubber Coal wash and crumb rubber	Deformation, resilient modulus, shear modulus and damping ratio were assessed for blends of coal wash, steel furnace slag and crumb rubber. Up to 10% rubber is recommended, to enhance the energy dissipation efficiency without compromising the deformation and stiffness responses.	Indraratna et al. (2022)
	Blast furnace slag	Blast furnace slag had better resistance to abrasion than natural crushed stone, improved shear resistance and equivalent particle stiffness.	Jia et al. (2021)
	CRC, recycled plastic aggregate, recycled glass	Typical virgin sub-ballast material, replaced with 40% CRC, 40% recycled glass and 20% recycled plastic. For the plastics sample, the leachate risk of all contaminants, excepting lead, was below Environmental Protection Authority (EPA) Victoria limits. It is noted that the lead risk requires further assessment and may be quite varied dependent on plastic waste streams. Savings per km dual-gauge railway sub-ballast were reported at 52,211 kg CO_2e and $25,542.	Imteaz et al. (2021)
	CRC and crushed brick, with recycled plastic	Permanent strain and resilient modulus of various blends was assessed. The recycled plastic compromised the stiffness of the blends; however, blends had suitable permanent strain characteristics and were overall determined as a suitable material.	Mohammadinia et al. (2020)
Asphalt trackbed layer	Reclaimed asphalt pavement (RAP)	Asphalt trackbed layer (between capping and ballast), with up to 100% RAP; 100% RAP option demonstrated comparable performance to a standard crushed aggregate option.	Kucera et al. (2021)

Applications	Recycled materials and blends	Main findings	Reference
Ballast	Basic oxygen furnace (BOF) steel slag	BOF steel slag satisfied the physical and chemical requirements of standards as a railway ballast material.	Koh et al. (2018)
	Ballast	If fines are removed, degraded ballast was an effective material for use as ballast, presenting acceptable mechanical properties compared to fresh ballast.	Ionescu and Indraratna (2003)
	CRC	The characteristics of CRC for use in ballast, including particle size, abrasion value, water absorption and soundness, demonstrated that CRC was effective up to 25% as a ballast replacement.	Rathnayake et al. (2018)
	Concrete debris and bottom ash	A 50% mix of concrete and standard ballast showed similar properties to the existing track ballast and some improvements in terms of the crushing resistance. Bottom ash as a sole addition did not improve performance, though was able to be used with concrete and standard ballast.	Youventharan et al. (2021)
Concrete	CRC	CRC can achieve similar strength, for 25 MPa mix designs, compared to fly ash and Portland cement concrete with natural aggregate.	Law et al. (2019)
	CRC and ground granulated blast furnace slag (GGBFS)	Used 70% GGBFS and 100% recycled coarse aggregates in the production of concrete. Reduced performance was noted, however environmental improvements were noted, with reduced CO_2e emissions and energy consumption.	He and Gong (2019)
	Recycled ballast and granite scrap	Slump, compaction, and compressive strength was evaluated. Light-weight concrete formed with waste ballast (nominal size 20 mm) and granite, in place of natural aggregate, showed beneficial performance and reduced cost.	Jogi et al. (2020)
Varied geotechnical applications	Crushed recycled glass	Crushed recycled glass is a suitable material for natural and manufactured sand replacement in several geotechnical applications, from a geotechnical, mineralogical, and morphological perspective.	Kazmi et al. (2021)
Pile barrier backfill	Tyre derived aggregate (TDA)	TDA refers to shredded scrap tyres. TDA is used for pile backfill, in replacement of more common backfill materials such as concrete and steel tubular pile. Numerical modelling demonstrates that TDA is comparatively less effective for vibration reduction, though offers environmental and cost benefits.	Fernandez-Ruiz et al. (2020)
Sleepers	Recycled plastic, glass fibre and rubber	A variety of recycled sleeper technologies were assessed. The review highlights that the main challenges to overcome with composite sleepers are strength, stiffness, anchorage capability, permanent deformation, and lateral resistance.	Ferdous et al. (2015)

4.5 Performance Requirements

The following sections outline key existing standards and specifications that refer to physical properties, engineering, durability, and strength requirements. The specifications are categorised by application.

4.5.1 Earthworks

Table 4.6, Table 4.7 and Table 4.8 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in earthworks.

Table 4.6: Standards and specifications, earthworks

Rail operator	Relevant standard or specification	Notes
ARTC	ARTC ETC-08-03	ARTC ETC-08-03 specifies the requirements for earthwork materials to provide a suitable and stable foundation for the ballast and track.
PTA	8880-450-074	The earthwork materials are required to satisfy the requirements of Table 4.7.
MRWA	Specification 302	The earthwork materials are required to satisfy the requirements of Table 4.8.

Table 4.7: Requirements for earthwork materials as per 8880-450-074

Criteria	Test method	Compliance
Compliance with MRWA specifications		Materials for embankment fill shall comply with select fill material criteria as per MRWA Specification 302 *Earthworks* (Table 4.8).
		Materials for earthworks adjacent to or above or supporting structures, roads, busways or carparks shall comply with selected granular fill material criteria as per MRWA Specification 801 *Excavation and Backfill for Structures*. Oversized materials shall not be greater than 37.5 mm.
Recycled materials		Recycled glass and recycled sand materials may be used for embankment fill and backfill behind structures where they are in accordance with the specific requirements of these materials in MRWA Specification 302 (Table 4.8).
		CRC consisting of a uniformly blended mixture of coarse and fine aggregates from construction and demolition materials may be used as embankment fill and backfill behind structures, where it is in accordance with MRWA Specification 501 and PTA Specification 8880-450-067 *Roads, Busways, Paths and Access Tracks*. The technical specification shall be agreed with the PTA prior to design and construction.
		Where site won materials that comply with general fill in accordance with the requirements above are proposed to be used, the details of the materials and proposed application shall be submitted to the PTA for approval.
Chemical requirements		pH > 5.5, chlorides < 5,000 ppm, sulphates < 5,000 ppm, resistivity > 5,000 ohm-cm.
Plasticity index		The fraction of material for earthworks retained on the 0.425 mm sieve shall not have a plasticity index greater than 25%.
Clay content	AS 1726	Material classed as clay in accordance with AS 1726 *Geotechnical Site Investigations* shall not be used for earthworks material.
Landscaping materials		For landscaping, general fill may be used. General fill shall contain no more than 2% organic matter and oversize material no more than 100 mm. The plasticity and clay content requirements above apply.

Table 4.8: Requirements for select fill as per Specification 302

Criteria	Compliance
Particle size distribution	
% passing 37.5 mm sieve	100
% Passing 19.0 mm sieve	80–100
% Passing 9.5 mm sieve	60–100
% Passing 4.75 mm sieve	45–100
% Passing 2.36 mm sieve	30–100
% Passing 1.18 mm sieve	20–100
% Passing 0.425 mm sieve	5–100
% Passing 0.15 mm sieve	3–30
% Passing 75 µm sieve	1–10
Linear shrinkage	≤ 1.0% for portion passing 0.425 mm
Source	Clean and free from vegetation, contamination and dieback-free
Contamination	≤ 1.0%

4.5.2 Capping Material

Table 4.9, Table 4.10, Table 4.11, Table 4.12 and Table 4.13 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in capping material.

Table 4.9: Standards and specifications, capping material

Rail operator	Relevant standard or specification	Notes
ARTC	ETC-08-03	ARTC ETC-08-03 specifies capping materials to be a well graded natural or artificially blended gravel or soil. In addition, it is required to have sufficient physical and strength properties. The requirements of the capping materials as per ETC-08-03 are further summarised in Table 4.11.
TfNSW	T HR CI 12111 SP TS 01109:1.0 (CRN CP 411)	The capping materials are required to satisfy the requirements of Table 4.10.
MTM	L1-CHE-SPE-178	The capping materials are required to satisfy the requirements of Table 4.12.
PTA	8190-400-002	The capping materials are required to satisfy the requirements of Table 4.13.

Table 4.10: Requirements for capping material as per T HR CI 12111 SP and TS 01109:1.0 (CRN CP 411)

Criteria	Compliance
Particle size distribution	
% Passing 26.5 mm sieve	100
% Passing 19.0 mm sieve	95–100
% Passing 9.5 mm sieve	60–90
% Passing 4.75 mm sieve	40–70
% Passing 2.36 mm sieve	30–60
% Passing 75 µm sieve	6–10
Liquid limit	≤ 30% (35% for arid areas)
Plasticity limit	≤ 20%
Plasticity index	4–15%
Linear shrinkage	≤ 4.5%
Maximum dry density	≥ 2.0 t/m³
Soaked CBR (95% standard compaction)	≥ 50%

Table 4.11: Requirements for capping material as per ETC-08-03

Criteria	Test method	Compliance
Classification		
Artificial weathering	RMS T103	Pre-treatment
Repeated compaction	RMS T102	Pre-treatment
Particle size distribution		
% Passing 26.5 mm sieve	AS 1289.3.6.1	100
% Passing 19.0 mm sieve		80–100
% Passing 9.5 mm sieve		55–100
% Passing 2.36 mm sieve		30–70
% Passing 425 µm sieve		12–40
% Passing 75 µm sieve		5–25
Particle shape	AS 1141.14	< 30% passing 2:1 calliper ratio
Flakiness index	AS 1141.15	≤ 40
Wet/dry strength	AS 1141.22	≥ 85 kN wet < 35% variation
Liquid limit	AS 1289.3.1.1 or 3.1.2	≤ 30 (35 for arid areas)
Plastic limit	AS 1289.3.2.1	≤ 20
Plasticity index	AS 1289.3.3.1 or 3.3.2	
Linear shrinkage	AS 1289.3.4.1	

Criteria	Test method	Compliance
Weighted plasticity index	AS 1289.3.6.1/3.3.1	
Maximum dry density	AS 1289.5.1.1	
California Bearing Ratio	AS 1289.6.1.1/5.1.1	≥ 50%
Classification test frequency		1 test per 1,000 t
Permeability		
Permeability	AS 1289.6.7.1	$< 5 \times 10^{-7}$ m/s
Permeability test frequency		Min. 2 tests per source material

Table 4.12: Requirements for capping material as per L1-CHE-SPE-178

Criteria	Test method	Compliance
Particle size distribution		
% Passing 53.0 mm sieve	AS 1289 3.6.1	100
% Passing 37.5 mm sieve		100
% Passing 26.5 mm sieve		100
% Passing 19.0 mm sieve		95–100
% Passing 9.5 mm sieve		60–90
% Passing 4.75 mm sieve		40–70
% Passing 2.36 mm sieve		30–60
% Passing 0.075 mm sieve		6–10
Soaked CBR	AS 1289 6.1.1	≥ 50% compacted to 95% modified dry density
Liquid limit	AS 1289 3.1.1 or AS 1289 3.9	≤ 30%
Plastic limit	AS 1289 3.2.1	≤ 20%
Plasticity index	AS 1289 3.3.1 AS 1289 3.3.2	4–15%
Linear shrinkage	AS 1289.3.4.1	≤ 4.5%
Dry density	AS 1289 5.2.1	≥ 2.0 t/m³

Table 4.13: Requirements for capping material as per 8190-400-002

Criteria	Compliance
Particle size distribution	
% Passing 19.0 mm sieve	55–85
% Passing 19.0 mm sieve	55–85
% Passing 2.36 mm sieve	35–65
Material	Crushed limestone
Calcium carbonate content (%)	60–85
Modified Los Angeles test, weight loss (%)	20–60
Modified maximum dry density	≥ 95

4.5.3 Structural Fill Material

Table 4.14, Table 4.15, Table 4.16, Table 4.17, Table 4.18 and Table 4.19 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in structural fill material.

Table 4.14: Standards and specifications, structural fill material

Rail operator	Relevant standard or specification	Notes
ARTC	ETC-08-03	The structural fill materials are required to comply with the requirements summarised in Table 4.15.
TfNSW	T HR CI 12111 SP TS 01109:1.0 (CRN CP 411)	The structural zone fill materials are required to satisfy the requirements of Table 4.16.
MTM	L1-CHE-SPE-178	The structural zone fill materials are required to satisfy the requirements of Table 4.17.
PTA	8880-450-074	The structural zone fill materials are required to satisfy the requirements of Table 4.18.

Table 4.15: Requirements for structural fill as per ETC-08-03

Criteria	Test method	Compliance
Repeated compaction	RMS T102	Pre-treatment
Particle size distribution		
% Passing 75 mm sieve	AS 1289 3.6.1	100
% Passing 53.0 mm sieve		80–100
% Passing 2.36 mm sieve		15–100
% Passing 425 µm sieve		10–70
% Passing 75 µm sieve		5–30
Liquid limit	AS 1289.3.1.2	≤ 40
Plasticity index	AS 1289.3.3.1	≤ 20
Wet/dry strength	AS 1141.22	≥ 85 kN wet < 35% variation
Emerson class	AS 1289.3.8.1	≥ 3
Weighted plasticity index	AS 1289.3.6.1/3.3.1	≤ 800
Maximum dry density	AS 1289.5.1.1	≥ 1.8 t/m^3
California Bearing Ratio	AS 1289.6.1.1/5.1.1	≥ 8%
Classification test frequency		1 test per 2,000 t

Table 4.16: Requirements for structural fill as per T HR CI 12111 SP and TS 01109:1.0 (CRN CP 411)

Criteria	Compliance
Particle size distribution	
% Passing 53.0 mm sieve	80–100
% Passing 2.36 mm sieve	15–100
% Passing 425 µm sieve	5–70
% Passing 75 µm sieve	0–30
Liquid limit	≤ 40%
Plasticity index	≤ 20%
Linear shrinkage	≤ 6%
Maximum dry density	≥ 1.8 t/m^3
Soaked CBR (standard compaction)	≥ 8%
CBR swell	≤ 1.5%

Table 4.17: Requirements for structural fill as per L1-CHE-SPE-178

Criteria	Test method	Compliance
Particle size distribution		
% Passing 53.0 mm sieve	AS 1289 3.6.1	80–100
% Passing 2.36 mm sieve		15–100
% Passing 0.425 mm sieve		0–70
% Passing 75 µm sieve		0–30
Soaked CBR	AS 1289 Test 6.1.1	≥ 8% compacted to 100% standard dry density
Liquid limit	AS 1289 test 3.1.1 or AS 1289 test 3.9	≤ 40%
Plasticity index	AS 1289 test 3.3.1 AS 1289 test 3.3.2	≤ 20%
Dry density	AS 1289 test 5.1.1	≥ 1.8 t/m^3

Table 4.18: Requirements for structural fill as per 8880-450-074

Criteria	Test method	Compliance
Compliance with MRWA Specifications		Materials for earthworks adjacent to or above or supporting structures, roads, busways or carparks shall comply with selected granular fill material criteria as per MRWA Specification 801 *Excavation and Backfill for Structures*. Oversized materials shall not be greater than 37.5 mm.
Recycled materials		Recycled glass and recycled sand materials may be used for embankment fill and backfill behind structures where they are in accordance with the specific requirements of these materials in MRWA Specification 302 (Table 4.19).
		CRC consisting of a uniformly blended mixture of coarse and fine aggregates from construction and demolition materials may be used as embankment fill and backfill behind structures, where it is in accordance with MRWA Specification 501 and PTA Specification 8880-450-067 *Roads, Busways, Paths and Access Tracks*. The technical specification shall be agreed with the PTA prior to design and construction.
		Where site won materials that comply with general fill in accordance with the requirements above are proposed to be used, the details of the materials and proposed application shall be submitted to the PTA for approval.
Chemical requirements		pH > 5.5, chlorides < 5,000 ppm, sulphates < 5,000 ppm, resistivity > 5,000 ohm-cm.
Plasticity index		The fraction of material for earthworks retained on the 0.425 mm sieve shall not have a plasticity index greater than 25%.
Clay content	AS 1726	Material classed as clay in accordance with AS 1726 *Geotechnical Site Investigations* shall not be used for earthworks material.
Landscaping materials		For landscaping, general fill may be used. General fill shall contain no more than 2% organic matter and oversize material no more than 100 mm. The plasticity and clay content requirements above apply.

Table 4.19: Requirements for glass cullet as per Specification 302

Criteria	Compliance
Particle size distribution	
% Passing 9.5 mm sieve	100
% Passing 4.75 mm sieve	70–100
% Passing 2.36 mm sieve	35–88
% Passing 1.18 mm sieve	15–45
% Passing 0.30 mm sieve	4–12
% Passing 0.075 mm sieve	0–5

Criteria	Compliance
Source	Sourced from food and beverage containers, and building or window glass. Shall not be sourced from hazardous waste, laboratory equipment, televisions, computers, cathode ray tubes, porcelain products or cook tops.
High density materials (brick, tiles, etc.) maximum retained on 0.475 mm (%)	5
Low density materials (plastic, plaster, etc.) maximum retained on 0.475 mm (%)	2
Wood and other vegetable matter maximum retained on 0.475 mm (%)	1
Processing	Cleaned to eliminate odours, shall be processed by a shape crushing plant, not more than 1% of particles with a maximum dimension ratio greater than 5:1 (retained on 0.475 mm).

4.5.4 General Fill Material

Table 4.20, Table 4.21, Table 4.22, Table 4.23, Table 4.24 and Table 4.25 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in general fill material.

Table 4.20: Standards and specifications, general fill material

Rail operator	Relevant standard or specification	Notes
ARTC	ETC-08-03	The general earth fill materials are required to satisfy the requirements of Table 4.21.
TfNSW	T HR CI 12111 SP TS 01109:1.0 (CRN CP 411)	The general earth fill materials are required to satisfy the requirements of Table 4.22.
MTM	L1-CHE-SPE-178	The general earth fill materials are required to satisfy the requirements of Table 4.23.
PTA	8880-450-074	The general earth fill materials are required to satisfy the requirements of Table 4.24.

Table 4.21: Requirements for general fill as per ETC-08-03

Criteria	Test method	Compliance				
		Homogenous embankment	Zoned embankment			
			A	B	C	D
Particle size distribution	AS 1289.3.6.1					
% Passing 150 mm sieve		100	100	100	100	100
% Passing 75.0 mm sieve		100	100	80–100	80–100	80–100
% Passing 37.5 mm sieve		60–100	80–100	60–100	60–100	
% Passing 75 µm sieve		15–30	15–30	8–40	< 50	
Plasticity index	AS 1289.3.3.1	7–30	7–30	7–30	≤ 50	≤ 50
Weighted plasticity index	AS 1289.3.6.1 /3.3.1	500–1,200	500–1,200	< 2,200	< 3,200	< 4,000
Emerson class	AS 1289.3.8.1	≥ 3	≥ 3	≥ 3	No criteria	
California Bearing Ratio	AS 1289.6.1.1 /5.1.1	≥ 3%			≥ 1%	
Classification test frequency		1 test per 5,000 t			1 test per 10,000 t	
Closest depth below formation level (m)		0.35	0.35	1.0	1.5	2.0

Table 4.22: Requirements for general fill as per T HR CI 12111 SP and TS 01109:1.0 (CRN CP 411)

Criteria	Compliance
Compaction level	≥ 95% maximum dry density
Plasticity index	≥ 9%
California bearing ratio	≥ 3%
CBR swell	≤ 2.5%

Table 4.23: Requirements for general fill as per L1-CHE-SPE-178

Criteria	Test method	Compliance
Soaked CBR	AS 1289.6.1.1	≥ 3%
Plasticity index	AS 1289. 3.3.1, AS1289.3.3.2	9–20%
Dispersion – determination of pin hole dispersity classification	ASTM D4647-20	ND1 or ND2
Dispersion – determination of Emerson class number of a soil	AS 1289. 3.8.1	Not to be Class 1 or 2
Collapse strain (wetting induced)	ASTM D4546-14	To be agreed by approved MTM geotechnical engineer
Free swell index	ASTM D4546-14	≤ 2.5%
Soil soluble salt content	ASTM D4542-07	≤ 3.0%
Organic content (dry weight)	ASTM D2974-20	≤ 2.0%

Table 4.24: Requirements for general fill as per 8880-450-074

Criteria	Test method	Compliance
Compliance with MRWA specifications		Materials for embankment fill shall comply with select fill material criteria as per MRWA Specification 302 *Earthworks* (Table 4.8).
		Materials for earthworks adjacent to or above or supporting structures, roads, busways or carparks shall comply with selected granular fill material criteria as per MRWA Specification 801 *Excavation and Backfill for Structures* (Table 4.25). Oversized materials shall not be greater than 37.5 mm.
Recycled materials		Recycled glass and recycled sand materials may be used for embankment fill and backfill behind structures where they are in accordance with the specific requirements of these materials in MRWA Specification 302.
		CRC consisting of a uniformly blended mixture of coarse and fine aggregates from construction and demolition materials may be used as embankment fill and backfill behind structures, where it is in accordance with MRWA Specification 501 and PTA Specification 8880-450-067 *Roads, Busways, Paths and Access Tracks.* The technical specification shall be agreed with the PTA prior to design and construction.
		Where site won materials that comply with general fill in accordance with requirements above are proposed to be used, the details of the materials and proposed application shall be submitted to the PTA for approval.
Chemical requirements		pH > 5.5, chlorides < 5,000 ppm, sulphates < 5,000 ppm, resistivity > 5,000 ohm-cm.
Plasticity index		The fraction of material for earthworks retained on the 0.425 mm sieve shall not have a plasticity index greater than 25%.
Clay content	AS 1726	Material classed as clay in accordance with AS 1726 *Geotechnical Site Investigations* shall not be used for earthworks material.
Landscaping materials		For landscaping, general fill may be used. General fill shall contain no more than 2% organic matter and oversize material no more than 100 mm. The plasticity and clay content requirements above apply.

Table 4.25: Requirements for granular fill material as per Specification 801

Criteria	Compliance
Material	Cohesionless sand or sandy limestone
Particle size distribution	
% Passing 37.5 mm sieve	100
% Passing 19.0 mm sieve	80–100
% Passing 9.5 mm sieve	60–100
% Passing 4.75 mm sieve	45–100
% Passing 2.36 mm sieve	30–100
% Passing 1.18 mm sieve	20–100
% Passing 0.425 mm sieve	5–100
% Passing 0.150 mm sieve	3–30
% Passing 75 µm sieve	1–10
Material	Cohesionless sand or sandy limestone
Linear shrinkage (passing 0.425 mm) (%)	≤1
Oversize material	Free from material > 100 mm

4.5.5 Select Fill

Table 4.26, Table 4.27 and Table 4.28 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in select fill.

Table 4.26: Standards and specifications, select fill

Rail operator	Relevant standard or specification	Notes
ARTC	ETC-08-03	Requirements of select fill are summarised in Table 4.27.
PTA	8880-450-074	Requirements of select fill are summarised in Table 4.28.

Table 4.27: Requirements for select fill as per ETC-08-03

Criteria	Test method	Compliance
Artificial weathering	RMS T103	Pre-treatment
Repeated compaction	RMS T102	Pre-treatment
Particle size distribution	AS 1289.3.6.1	
% Passing 53.0 mm sieve		100
% Passing 2.36 mm sieve		< 50
% Passing 75 µm sieve		< 15
Liquid limit	AS 1289.3.1.2	≤ 30
Plasticity limits	AS 1289.3.2.1	≤ 20
Plasticity index	AS 1289.3.3.1	6–15
Weighted plasticity index	AS 1289.3.6.1/3.3.1	180–300
Maximum dry density	AS 1289.5.1.1	≥ 2.0 t/m^3
California Bearing Ratio	AS 1289.6.1.1/5.1.1	≥ 50%
Particle density	AS 1141.6.1	≥ 2.6 t/m^3
Wet/dry strength	AS 1141.22	≥ 85 kN wet < 35% variation
Aggregate crushing value	AS 1141.21	≤ 30%
Aggregate flakiness index	AS 1141.15	≤ 40%
Degradation factor	AS 1141.25.2	≥ 50

Criteria	Test method	Compliance
Weak p articles	AS 1141.32	≤ 0.5%
Classification test frequency		1 test per 500 t

Table 4.28: Requirements for select fill as per 8880-450-074

Criteria	Test method	Compliance
Compliance with MRWA specifications		Materials for embankment fill shall comply with select fill material criteria as per MRWA Specification 302 *Earthworks*.
Recycled materials		Where site won materials that comply with general fill in accordance with the requirements above are proposed to be used, the details of the materials and proposed application shall be submitted to the PTA for approval.
Chemical requirements		pH > 5.5, chlorides < 5,000 ppm, sulphates < 5,000 ppm, resistivity > 5,000 ohm-cm.
Plasticity index		The fraction of material for earthworks retained on the 0.425 mm sieve shall not have a plasticity index greater than 25%.
Clay content	AS 1726	Material classed as clay in accordance with AS 1726 *Geotechnical Site Investigations* shall not be used for earthworks material.
Landscaping materials		For landscaping, general fill may be used. General fill shall contain no more than 2% organic matter and oversize material no more than 100 mm. The plasticity and clay content requirements above apply.

4.5.6 Bedding Sand

Table 4.29, Table 4.30 and Table 4.31 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in bedding sand (for pipes, culverts and other miscellaneous structures).

Table 4.29: Standards and specifications, bedding sand

Rail operator	Relevant standard or specification	Notes
ARTC	ETC-08-03	As per ETC-08-03, the bedding sand must be well graded natural or crushed quarry product sands sourced from designated sources, free from organic or other materials harmful to pipes, concrete, structures, and the environment. It must comply with the requirements outlined in Table 4.30.
PTA	8800-450-090	Bedding material shall be granular material of low plasticity, such as natural or recycled crushed sand or gravel or crushed rock or crushed clay brick that can be compacted to provide a uniform firm bedding and can be shaped as specified. It must comply with the PSD requirements outlined in Table 4.31.

Table 4.30: Requirements for bedding sand as per ETC-08-03

Criteria	Test method	Compliance
Particle size distribution	AS 1289.3.6.1	
% Passing 6.7 mm sieve		100
% Passing 0.075 mm sieve		0–20
Plasticity index	AS 1141.23	≤ 30%
Test frequency		Two per source

Table 4.31: Requirements for bedding material as per 8800-450-090

AS sieve size (mm)	Test method	Percentage of total sample passing (by mass)
19.0	AS 1289.3.6.1	100
2.36		50–100
0.60		90–20
0.30		60–10
0.15		25–0
0.075		10–0

4.5.7 Drainage Blanket Materials

Table 4.32 and Table 4.33 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in drainage blanket materials.

Table 4.32: Standards and specifications, drainage blanket materials

Rail operator	Relevant standard or specification	Notes
ARTC	ETC-08-03	The requirements for drainage blanket materials are summarised in Table 4.33.
PTA	8800-450-090	Coarse aggregate shall be crushed granite or diorite that is durable, sound, clean, suitable for the environmental conditions and free from all impurities and dust in accordance with AS 1141. This includes the use of decontaminated crushed railway ballast compliant with AS 2758.1 that has appropriate grading and durability characteristics. PTA 8880-450-067 outlines the requirements for the use of crushed recycled railway ballast. The maximum particle size shall not exceed 20 mm, except where railway ballast is specified.

Table 4.33: Requirements for drainage blanket material as per ETC-08-03

Criteria	Test method	Compliance
Particle size distribution		
% Passing 63.0 mm sieve	AS 1141.11.1, AS 1141.12	100
% Passing 37.5 mm sieve		20–100
% Passing 26.5 mm sieve		0–55
% Passing 19.0 mm sieve		0–5
% Passing 75 µm sieve		0–0.5
Los Angeles value (Grading A)	AS 1141.23	≤ 30%
Particle shape	AS 1141.14	< 30% passing 2:1 calliper ratio
Flakiness index	AS 1141.15	≤ 40
Particle density	AS 1141.6.1	≥ 2.3 t/m^3
Water absorption	AS 1141.6.1	≤ 2%
Wet/dry strength	AS 1289.5.1.1	≥ 100 kN wet < 25% variation
Test frequency		One per source

4.5.8 Free Draining Filter Materials

Table 4.34, Table 4.35, Table 4.36 and Table 4.37 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in free draining filter material.

Table 4.34: Standards and specifications, free draining filter material

Rail operator	Relevant standard or specification	Notes
TfNSW	T HR CI 12111 SP TS 01109:1.0 (CRN CP 411)	The free drainage filter materials are required to satisfy the requirements of Table 4.35.
MTM	L1-CHE-SPE-178	The free drainage filter materials are required to satisfy the requirements of Table 4.36.
PTA	8880-450-090	The drainage aggregate materials are required to satisfy the requirements of Table 4.37.

Table 4.35: Requirements for free draining filter materials as per T HR CI 12111 SP and TS 01109:1.0 (CRN CP 411)

Criteria	Compliance
Particle size distribution	
% Passing 53.0 mm sieve	100
% Passing 37.5 mm sieve	90–100
% Passing 26.5 mm sieve	20–55
% Passing 19.0 mm sieve	0–5
% Passing 75 µm sieve	0
Soft and friable particles	≤ 5%
Clay lumps	≤ 0.5%
Los Angeles value (A)	≤ 30%
Wet/dry strength variation	≤ 35%
Point load strength index Is(50)	≥ 1 MPa

Table 4.36: Requirements for free draining filter materials as per L1-CHE-SPE-178

Criteria	Test method	Compliance
Classification		
Particle size distribution		
% Passing 53.0 mm sieve	AS 1289 3.6.1	100
% Passing 37.5 mm sieve		90–100
% Passing 26.5 mm sieve		20–55
% Passing 19.0 mm sieve		0–5
% Passing 75 µm sieve		0
Soft and friable particles	AS 1141.32	≤ 5%
Clay lumps	AS 1141.32	≤ 0.5%
Los Angeles value (A)	AS 1141.23	≤ 30%
Particle density	AS 1141.6.1, AS 1141.6.2	≥ 2.3 t/m^3
The point load strength index Is (50)	AS 1141	≥ 1 MPa

Table 4.37: Requirements for drainage aggregates as per 8880-450-090

Material	Test method	Compliance
Coarse aggregate	AS 1141, AS 2758.1	Crushed granite or diorite that is durable, sound, clean, suitable for the environmental conditions and free from all impurities and dust in accordance with AS 1141 (includes the use of decontaminated crushed railway ballast compliant with AS 2758.1 that has appropriate grading and durability characteristics).
Fine aggregate	AS 1141	Well-graded, clean, sharp and free from clay and organic impurities in accordance with AS 1141.

4.5.9 Access Tracks

Table 4.38 and Table 4.39 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in access track applications.

Table 4.38: Standards and specifications, base and subbase

Rail operator	Relevant standard or specification	Notes
PTA	8880-450-067	Crushed recycled ballast may be used in (sealed) lateral access tracks as base and in maintenance of access tracks. CRC may be used in maintenance of access tracks where not directly adjacent to the rail formation and unsealed lateral access tracks. Further requirements are outlined in Table 4.39.

Table 4.39: Requirements for CRC for access tracks as per 8880-450-067

Criteria	Test method	Compliance
Crushed recycled concrete (subbase and base)	WA 144.1	55–95%
Limits of foreign materials (in accordance with MRWA Table 501.92A, except as stated below)		
Asphalt (as opposed to RAP)*	WA 144.1	15% (subbase) 10% (base)
Low density materials (plastic, plaster, low density brick etc.) retained on 4.75 mm sieve		1.5% (subbase) 1.0% (base)
Organic matter (wood etc.) retained on 4.75 mm sieve		1.0% (subbase) 0.5% (base)
Unacceptable high-density materials (inert metals, glass and ceramics) retained on 4.75 mm sieve		3% (subbase) 2% (base)
Aluminium as a metal (non-oxidised)		0.001%
Asbestos and other hazardous materials		In accordance with DWER *Roads to Reuse* specification
Linear shrinkage (%)	WA 123.1	Max 5 (subbase) Max 1.5 (base)
CBR limits	WA 133.2	Min 60% (subbase) Min 80% (base)

* RAP is not permitted to be added to the processed CRC as opposed to asphalt already present in the raw CRC material.

4.5.10 Ballast

Table 4.40, Table 4.41, Table 4.42, Table 4.43, Table 4.44, Table 4.45 and Table 4.46 summarise the standards and specifications that were reviewed for physical properties, engineering, durability, and strength requirements in ballast.

Table 4.40: Standards and specifications, ballast

Rail operator	Relevant standard or specification	Notes
ARTC	ETA-04-01	As per ETA-04-01, alternative materials, i.e. recycled, must undergo petrographic analysis and must be rejected if found to be harmful to the performance of the ballast, even if they comply with other requirements. Requirements for ballast material as per ARTC ETA-04-01 are summarised in Table 4.41.
MTM	A1341	The requirements of A1341 are outlined in Table 4.42.
V-Line	NIST-2654	The requirements of NIST-2654 are outlined in Table 4.43.
TfNSW	T HR TR 00192 ST TS 01049:1.0 (CRN CS 240)	The requirements of T HR TR 00192 ST and TS 01049:1.0 (CRN CS 240) are outlined in Table 4.44.

Rail operator	Relevant standard or specification	Notes
Australian Standards	AS 2758.7	The requirements of AS 2758.7 are outlined in Table 4.45.
PTA	8190-400-002	Ballast must comply with AS 2758.7, and the additional requirements listed in Table 4.46.

Table 4.41: Requirements for ballast as per ETA-04-01

Criteria	Test method	Compliance
Bulk density	AS 1141.4	≥ 1,200 kg/m³
Particle density	AS 1141.6	≥ 2,500 kg/m³
Particle size distribution		
Nominal size		60 mm
% Passing 63.0 mm sieve	AS 1141.11.1 and AS 1141.12	100
% Passing 53.0 mm sieve		85–100
% Passing 37.5 mm sieve		20–65
% Passing 26.5 mm sieve		0–20
% Passing 19.0 mm sieve		0–5
% Passing 13.2 mm sieve		0–2
% Passing 9.50 mm sieve		–
% Passing 4.75 mm sieve		0–1
% Passing 1.18 mm sieve		–
% Passing 0.075 mm sieve		0–1
Particle shape	AS 1141.14	< 30% passing 2:1 calliper ratio
Flakiness index	AS 1141.15	≤ 30
Crushed particles of coarse aggregate	AS 1141.18	% crushed particles ≥ 75 % uncrushed particles ≤ 5
Aggregate crushing value	AS 1141.21	≤ 25%
Wet attrition value	AS 1141.27	≤ 6%
Los Angeles value	AS 1141.23	≤ 25%
Weak particles	AS 1141.32	≤ 5%
Electrical resistance		A minimum resistance of 1.5 ohms per km

Table 4.42: Requirements for ballast as per A1341

Criteria	Test method	Compliance		
Particle size distribution				
Nominal size		60 mm	50 mm	19 mm screenings
% Passing 63.0 mm sieve	AS 1141.11.1	100	–	–
% Passing 53.0 mm sieve		85–100	100	–
% Passing 37.5 mm sieve		20–65	90–100	–
% Passing 26.5 mm sieve		0–20	20–25	100
% Passing 19.0 mm sieve		0–5	0–15	90–100
% Passing 13.2 mm sieve		0–2	–	30–50
% Passing 9.50 mm sieve		–	0–5	0–15
% Passing 6.70 mm sieve		–	–	0–5
% Passing 4.75 mm sieve		0–1	0–1	–
% Passing 3.35 mm sieve		–	–	0–1
% Passing 1.18 mm sieve		–	–	–
% Passing 0.075 mm sieve		0–1	0–1	–
Bulk density of aggregate	AS 1141.4	> 1,350 kg/m³		

Criteria	Test method	Compliance		
Particle density	AS 1141.6	> 2,500 kg/m³		
Particle shape, by proportional calliper	AS 1141.14	< 30% @ 2:1 calliper ratio		
Flakiness index	AS1141.15	≤ 30%		
Aggregate crushing value	AS1141.21	≤ 25%		
Los Angeles value	AS1141.23	≤ 25%		
Degradation factor source rock	AS 1141.25.2	≥ 40		
Secondary mineral content	AS 1141.26	≤ 25%		
Resistance to wear by attrition	AS 1141.27	< 6%		
Accelerated soundness index	AS 1141.29	≥ 94%		
Weak particles	AS 1141.32	< 5%		

Table 4.43: Requirements for ballast as per NIST-2654

Criteria	Test method	Compliance		
Particle size distribution				
Nominal size		53 mm	37 mm	19 mm
% Passing 63.0 mm sieve	AS 1141.11.1	100	–	–
% Passing 53.0 mm sieve		85–100	100	–
% Passing 37.5 mm sieve		20–65	90–100	–
% Passing 26.5 mm sieve		0–20	20–25	100
% Passing 19.0 mm sieve		0–5	0–15	85–100
% Passing 13.2 mm sieve		0–2	–	0–25
% Passing 9.50 mm sieve		–	0–5	0–5
% Passing 4.75 mm sieve		0–1	0–1	0–1
% Passing 0.075 mm sieve		0–1	0–1	0–1
Weak particles	AS 1141.32	< 3%		
Wet attrition value	AS 1141.27	6–12% depending on the track class		
Aggregate crushing value	AS1141.21	≤ 25%		

Table 4.44: Requirements for ballast as per T HR TR 00192 ST and TS 01049:1.0 (CRN CS 240)

Criteria	Test method	Compliance			
Particle size distribution					
Nominal size		Standard – nominal 60 mm graded ballast		Fine – nominal 50 mm graded ballast	
% Passing 63.0 mm sieve	AS 1141.11.1	100		–	
% Passing 53.0 mm sieve		85–100		100	
% Passing 37.5 mm sieve		50–70		70–100	
% Passing 26.5 mm sieve		20–35		–	
% Passing 19.0 mm sieve		10–20		40–60	
% Passing 13.2 mm sieve		2–10		–	
% Passing 9.50 mm sieve		0–5		20–30	
% Passing 4.75 mm sieve		0–2		10–20	
% Passing 2.36 mm sieve		–		5–10	
Particle shape	AS 1141.14	< 30% @ 2:1 calliper ratio			
Bulk density	AS 1141.4	≥ 1,400 kg/m³			
Flakiness index	AS 1141.15	≤ 30%			

Criteria	Test method	Compliance			
Aggregate crushing value	AS 1141.21	≤ 30%			
Wet attrition value	AS 1141.27	≤ 6%			
Weak particles	AS 1141.23	≤ 5%			
Electrical resistivity	AS 1289.4.4.1	≥ 60 Ω m			

Table 4.45: Requirements for ballast as per AS 2758.7

Criteria	Test method	Compliance			
Particle size distribution					
Nominal size		60 mm	60 mm – graded	50 mm	60 mm (steel sleepers)
% Passing 63.0 mm sieve	AS 1141.11.1	100	100	–	100
% Passing 53.0 mm sieve		85–100	85–100	100	95–100
% Passing 37.5 mm sieve		20–65	50–70	90–100	35–70
% Passing 26.5 mm sieve		0–20	20–35	20–55	15–30
% Passing 19.0 mm sieve		0–5	10–20	0–15	5–15
% Passing 13.2 mm sieve		0–2	2–10	–	0–10
% Passing 9.50 mm sieve		–	0–5	0–5	0–1
% Passing 4.75 mm sieve		0–1	0–2	0–1	–
% Passing 1.18 mm sieve		–	–	–	–
% Passing 0.075 mm sieve		–	–	0–1	0–1
Particle shape	AS 1141.14	< 30% @ 2:1 calliper ratio			
Wet attrition value	AS 1141.27	≤ 6%			
Aggregate crushing value	AS1141.21	≤ 25%			
Loss Angeles value	AS 1141.23	≤ 25%			
Weak particles	AS 1141.23	≤ 5%			
Electrical resistivity	AS 1289.4.4.1	≥ 60 Ω m			

Table 4.46: Requirements for ballast as per 8190-400-002

Criteria	Compliance
Material	Free-draining, crushed igneous or metamorphic rock, composed of hard, strong and durable particles, grain structure that can range from fine through to coarse. Particles angular in shape, with all dimensions approximately equal and free from dust, chemical contamination and cohesive particles.
Track classification	Class N.
Sampling frequency	Before supply, a geological report must be prepared, identifying the geological and petrological characteristics of the parent material. The initial engineering tests for conformity with the specification must be taken from the first 1,500 tonnes of material produced. Thereafter, the frequency of sampling must be every 6,000 tonnes. The sampling scheme must be in accordance with Appendix A, Table A1 of AS 2758 Part 7.
Grading requirements	Nominal size 60 mm (ungraded).
Particle shape	The proportion of misshapen particles retained on the 9.5 mm sieve, using a 2:1 ratio, must not exceed 30%.
Durability assessment	Durability assessment must be by the wet/dry strength variation and Los Angeles value set of tests for Class N ballast.

4.6 Design Considerations

There are novel technologies emerging that provide support in treating the degradation of ballast, such as bitumen stabilisation and geogrids. It is noted that the available research on this topic is related to recycled ballast applications.

An emerging technology to treat the degradation of ballast is bitumen stabilisation. Bressi et al. (2018) discuss the use of bitumen stabilisation for reinforcing existing passenger rail track-beds, reducing the need for maintenance or during new construction. This technology consists of pouring bitumen emulsion at ambient temperature, at rates of 1.44% (w/t) of ballast, directly under the sleeper. Application of this technology within a local context would require further investigation and may be valuable as a topic of future research.

Stabilising ballast aims to increase its durability and reduce degradation. Other mechanisms to stabilise recycled ballast include geogrids and recycled rubber (Indraratna et al. 2002, 2019, 2020, Indraratna & Salim 2003). Indraratna et al. (2019) undertook laboratory tests, mathematical modelling, and numerical modelling to assess the performance enhancement of track by utilising geogrids and rubber, including crumb rubber and rubber mats. The results demonstrated that these tools improved the energy absorption of the structural layers and reduced ballast degradation. Geogrids were demonstrated to improve the lateral strain of the ballast, and crumb rubber incorporated into the sub-ballast improved track stability and reduced ballast breakage, with crumb rubber at 30–40% by weight shown to improve ballast most effectively.

Indraratna and Salim (2003) presented geogrids as a tool to improve the stabilisation of recycled ballast, to mitigate the reduced tensile strength observed in recycled ballast compared to fresh ballast. The degradation of the recycled ballast was able to be reduced up to 45% by using a woven geotextile at the ballast and capping interface. Indraratna et al. (2002) demonstrated similar results with particle breakage reduced between 42 and 48% through the use of geogrid or geogrid-geotextile composite.

Indraratna et al. (2020) built experimental tracks in NSW to assess the benefits of geosynthetics and rubber mats beneath the ballast layer, demonstrating the geosynthetic reinforcement reduced the vertical and lateral displacement of the recycled ballast, and rubber mats reduced ballast breakage, after 40 months of assessment.

4.7 Environmental and Safety Aspects

The following sections outline the environmental and safety aspects of using CRC and recycled ballast as an alternative material to natural aggregates and sand. It focuses on the health and safety risks associated with working with CRC and recycled ballast and comparisons of environmental impacts using natural aggregates, where information is available. The environmental impacts are focused on the contaminants, alteration of pH and the potential of leaching into the environment.

4.7.1 Assessment of Risks to Human Health and Environment

CRC is classified as a hazardous material by Safe Work Australia. Hazard statements include H317 where it may cause an allergic skin rection and H373 where prolonged exposure via inhalation may cause damage to lungs. CRC contains respirable crystalline silica (RCS). Crystalline silica is a common mineral found in many building materials, such as bricks, tiles, concrete and cement-based products, rocks, sands, and clays. Inhalation of RCS can lead to lung conditions such as silicosis (Worksafe Queensland 2023).

When materials containing RCS are processed (e.g. cut, sawn, ground, drilled, polished, and crushed), dust containing RCS will be released into the environment. RCS particles remain airborne for a long time although other dust particles have settled on the ground. The particle size is so small that it cannot be easily detected and can be inhaled directly into the deeper parts of the lungs (Worksafe Queensland 2023).

RCS is a hazardous chemical and a carcinogen. Inhaling it can lead to silicosis, an incurable lung disease that can lead to disability and death. It can also contribute to lung cancer, renal cancer, and chronic obstructive pulmonary disease (Worksafe Queensland 2023). Silicosis usually follows exposure to RCS over many years, but extremely high short-term exposures can cause it to develop rapidly.

Control measures could be implemented by eliminating or minimising the exposure, and the use of respiratory protective equipment (RPE) where a process of elimination is not possible. Examples of higher-order control options include on-tool extraction, water suppression, and isolation. RPE does not eliminate or control RCS from becoming airborne. It should not be used as the primary means of control, but rather in combination with higher-order controls. No respirator can prevent all airborne RCS from being breathed in. A respirator suited to finer particles should be selected under these circumstances.

Estevez et al. (2006) conducted a lifecycle study analysing and comparing the process of crushing concrete and the process of quarrying and processing of primary aggregates using SimaPro 4.0 to evaluate the environmental impacts of using CRC.

The analysis considered the emissions with the highest percentages in several categories of environmental impact:

- CO_2e, due to its major influence on climate change and greenhouse effect on a global scale
- NO_x, due to its contribution to acidification and eutrophication on a regional level
- SO_2, due to its contribution to acidification on a regional level
- dust, due to its important visual and direct impact on the image and health of the environment and its inhabitants on a local scale.

A comparison of these emissions is provided in Table 4.47.

Table 4.47: Comparison of emissions

Emissions to air (g/ton.)	Inventory of concrete recycling		Inventories of SimaPró 4.0			
			Gravel I (g/t)		Sand I (g/t)	
	Transport	Crushing	Transport	Electricity	Transport	Electricity
CO_2e	1,704.44	1,261.3	4,920	2,820	4,920	1,950
NO_x	26.36	19.5	94.2	5.36	94.2	5.49
SO_2	1.62	1.2	12	0.419	12	11.2
Dust	0.17	0.126	0.49	0.0371	0.49	0.873

Source: Estevez et al. (2006).

It was demonstrated that concrete recycling, in comparison to the use of virgin gravel and sand, resulted in a more favourable outcome in terms of the production of CO_2e, NO_x, SO_2 and dust emissions.

The primary source of CO_2e emissions was the transportation processes involved in both natural and recycled aggregates. In natural aggregates, transportation processes accounted for about 63% of the total CO_2e emissions for gravel and 71% for sand, while in recycled aggregates, it represented about 57% of the total emissions. The difference in CO_2e emissions can be attributed to the amount of fuel consumed in the processes, as well as the number of processes involved in natural aggregates, which include quarrying and grinding and crushing, leading to an increase in energy required. Recycled concrete emitted about 1,261 g of CO_2e per tonne due to crushing, while natural aggregates emitted around 1,950 g and 2,820 g per tonne for sand and gravel, respectively.

The total NO_x emissions due to recycling concrete were about 45.86 g per tonne, which was approximately 50% of the total emissions produced during the quarrying and processing of primary aggregates (about 99 g per tonne). The emissions were mainly a result of the use of fossil fuels, with primary aggregates producing 94.2 g of NO_x per tonne due to transportation processes. In contrast, only 5.36 g and 5.49 g of NO_x per tonne were due to electricity consumption for gravel and sand, respectively. Secondary aggregates produced 26.36 g of NO_x per tonne due to transportation processes and 19.5 g of NO_x per tonne during the crushing process.

The emissions of SO_2 produced in the processing of recycled aggregates reached 2.784 g per tonne, which represented 22.4% and 12% of the emissions in the production of natural gravel and sand, respectively. Sand quarrying and grinding processes generated twice the amount of SO_2 emissions than those for gravel, which is explained by the type of energy resources utilised in each case.

The estimation of dust levels took into account the amount of electrical energy and fossil fuel consumed in the processes. It considered the typical dust emissions from power-generation plants in each country and the emissions corresponding to each type of fossil fuel used in thermal energy production. The mechanical actions involved, such as crushing and sand grinding, also contributed to the emission of dust and should be considered to obtain more realistic results.

4.7.2 Protection from Contamination

CRC

CRC that comes from a selected in situ environment could contain pollutants and contaminants. In practice, CRC is often contaminated by various sources of aggressive ions like chlorides and sulphates from de-icing salts, sewage plants or seawater. These contaminants may affect the properties of recycled concrete as well as cause the runoffs from the CRCs to carry the contaminants into the waterways through stormwater drains and drainage layers (Cavalline 2018).

In WA, the presence of asbestos in construction materials and in sacrificial formwork is quite common, making it difficult to ensure that asbestos does not enter the C&D waste recycling streams. The RtR product specification includes strict inspection and testing regime requirements in the supplier's quality system and material acceptance and sampling plan (MASP) to ensure that asbestos levels do not exceed Department of Health maximum acceptance limits. These requirements extend similarly to other potential contaminants hazardous to health and safety (Waste Authority 2020).

In unbound applications, CRC is capable of forming precipitate (i.e. calcium carbonate) and insoluble residue or 'crusher dust'. Calcium salts and lime from CRC are soluble, and calcium-based mineral which is also known as tufa form when these minerals come out of the solution. Formation of this sediment is affected by the minerals present, temperature, and carbon dioxide (Bruinsma & Snyder 1995 cited in Cavalline 2018). Runoff from all CRC can produce sediments and solid precipitates. However, the potential for tufa formation is associated with the amount of freshly exposed cement paste and increases with surface area (smaller particles) and higher paste content. Washing CRC may reduce the potential for accumulation of dust and other fines but does not greatly reduce the potential for tufa formation (Bruinsma & Snyder 1995 cited in Cavalline 2018). When CRC is applied in drained layers, these deposits can affect the permeability of geotextile fabrics, drainable bases, drainage pipes, or other drainage features downstream of the CRC base (AASHTO 2010); this is generally a problem when CRC is used in undrained layers or layers below the drains.

According to ACPA (2008), the total volume of surface water runoff from a project site in comparison to the volume of runoff from areas containing CRC (e.g. in stockpiles or drained pavement layers) is generally low. However, runoff from CRC materials can have characteristics that impact water quality near stockpiles and drain outlets, and methods for mitigating these localised impacts should be considered during both the design and construction phases. High-pH leachate results from primarily dissolution of exposed lime, a by-product of the hydration of cement. This high-pH leachate can negatively impact receiving natural waters, vegetation, and zinc-coated and aluminium pipe (through corrosion), until diluted with rainfall and other surface waters. Typically, these concerns are restricted to small areas surrounding the drainage outlet, since adequate dilution typically takes place within several feet (~1 m) of the point of discharge (ACPA 2008). The high-pH runoff is also often neutralised by infiltration and exposure to soils and rock. Placing drains away from receiving waters, together with the use of conventional stormwater best management practices, such as bioswales have been shown to mitigate issues with high pH. CRC leachate and runoff also typically include small amounts of pollutant materials, including 'heavy' metals such as vanadium, chromium, and lead (Chen et al. 2012, Edil et al. 2012, Sadecki et al. 1996). Although these pollutants can occasionally be present in quantities higher than permissible limits for drinking water, dilution of the runoff and leachate and capture or uptake into environmental systems (i.e. bioswales) have been consistently shown to mitigate their impact on receiving waters, particularly when separation is adequate and/or best management practices are used (Cavalline 2018).

Recycled materials often contain minor amounts of contaminants and/or pollutant materials (Schwab et al. 2014). Concrete from building and demolition debris can include contaminants that are problematic (e.g. asbestos). However, by using concrete from known sources, for example, existing agency infrastructure, the likelihood of contaminants is greatly reduced. Chemicals, metals, sealants, and other materials present in highway concrete used for recycling could also become contaminants. However, these contaminants are not generally present in appreciable amounts (NHI 1998), and over the decades of service of many projects using CRC, environmental impacts associated with contaminated source concrete from bound or unbound applications have not been reported.

Recycled ballast

Railway ballast loses its geotechnical properties over time and cannot be reused within the rail industry but can be sold on to other users to be utilised as a recycled engineering fill. However, it is often contaminated with diesel, grease, lubricating oils, and other deposits from locomotives and carriages (Anderson et al. 2002).

Western Australian legislation does not have specific regulations regarding the use of recycled ballast in rail projects. However, the use of recycled materials in construction projects is guided by policies and guidelines set by the state government, such as the *Waste Strategy 2030*. One potential environmental impact of using recycled ballast is contamination. Recycled materials may contain contaminants such as heavy metals and asbestos, which can pose health risks to workers and the public if not properly handled and disposed of. Therefore, it is important to understand the history of the material and, if necessary, conduct thorough testing and quality control measures to ensure that the recycled ballast meets the required standards for safety and environmental protection.

The Department of Water and Environmental Regulation (DWER) in Western Australia regulates the management of contaminated sites through the *Contaminated Sites Act 2003* and the Contaminated Sites Regulations 2006. Under these regulations, owners and occupiers of contaminated sites are required to assess and manage the risks associated with contamination and take necessary remedial action to protect public health and the environment. In addition, the DWER has developed guidelines for the beneficial reuse of waste materials, including recycled ballast (DWER 2019b). The guidelines outline the criteria for assessing the suitability of waste materials for reuse and provide guidance on the management of potential environmental risks. There is limited research available on the contaminants from recycled ballast in Western Australia.

To point to examples in other jurisdictions, in New South Wales, an order issued by the Environment Protection Authority (EPA) under clause 93 of the Protection of the Environment Operations (Waste) Regulation 2014 (Waste Regulation), imposes the requirements that must be met by suppliers of recovered railway ballast to which ‘the recovered railway ballast exemption 2014’ applies. The requirements in this order apply in relation to the supply of recovered railway ballast for application to land for building or maintaining railway infrastructure or for road construction. The maximum allowable concentration of chemicals and other attributes present in any recovered railway ballast is shown in Table 4.48.

Table 4.48: Maximum allowable concentration of chemicals and other attributes present in any recovered railway ballast

Chemicals and other attributes	Maximum average concentration for characterisation (mg/kg ‘dry weight’ unless otherwise specified)	Maximum average concentration for routine testing (mg/kg ‘dry weight’ unless otherwise specified)	Absolute maximum concentration (mg/kg ‘dry weight’ unless otherwise specified)
1. Mercury	0.5	Not required	1
2. Cadmium	0.5	0.5	1
3. Lead	50	50	100
4. Arsenic	15	15	30
5. Chromium (total)	25	Not required	50
6. Copper	25	Not required	50
7. Nickel	25	Not required	50
8. Zinc	75	75	150
9. Electrical conductivity	1 dS/m	1 dS/m	2 dS/m

Chemicals and other attributes	Maximum average concentration for characterisation (mg/kg 'dry weight' unless otherwise specified)	Maximum average concentration for routine testing (mg/kg 'dry weight' unless otherwise specified)	Absolute maximum concentration (mg/kg 'dry weight' unless otherwise specified)
10. Metal, glass, asphalt, ceramics, and slag	2.5%	Not required	5%
11. Plaster, clay lumps, and other friable materials	0.25%	Not required	0.5%
12. Rubber, plastic, bitumen, paper, cloth, paint, wood and other vegetable matter	0.25%	Not required	0.1%

Source: EPA NSW (2014).

4.7.3 Potential Leaching into Adjacent Layers and Components

Studies have shown that the chemical composition of CRC is primarily inherited from the original concrete mixtures used and the chemicals gathered during operational phases and manufacturing. Hung (2019) noted that the level of pH around road base using CRC has an increasing trend due to leachates with high alkaline, such as calcium hydroxide ($CaOH_2$) and calcium silicate hydrates (Ca_3SiO_5). In understanding the chemical properties of CRC, metals (Al, As, Hg, Cd, Cr, Cu, Pb, Mg, Ba, Ca, Fe Ni, V, and Zn), mineralogical compounds (quartz, calcite, muscovite, and portlandite), anions (Cl-, F-, CN-, and SO42-) and dissolved organic carbon (DOC) are commonly present. Metals and minerals can originate from cement, natural crushed aggregates, and concrete additives such as fly ash (Hung 2019). Demolition, size reduction, and storage may cause changes in chemical forms and mineralogical phases, leading to the release of these chemicals under variable weather conditions (Hung 2019). Similar results were reported by Roque et al. (2016).

Pollutant leaching from CRC is a complex process influenced by many factors, including physical, chemical, and external factors such as permeability, pH, and the amount of water contact. It is necessary to distinguish between monolithic recycled concrete material and granular recycled concrete material due to differences in the dominant processes controlling their leaching characteristics. In monolithic recycled concrete material, leaching is primarily controlled by diffusion, while percolation dominates the leaching behaviour in granular recycled concrete material (Hung 2019).

For intact concrete exposed to above-ground environments, the high pH from calcium hydroxide has minimal environmental impact as the surface concrete rapidly reacts with carbon dioxide (an acid gas) from the air to precipitate calcium carbonate. This tends to block the pores of the concrete slowing both further ingress of carbon dioxide and the leaching out of alkalis if water flows over the concrete (Jefferis 2019). The rate of release of alkalis from intact carbonated concrete is usually sufficiently low that it passes unnoticed except sometimes it drips when calcium leached from concrete reacts with atmospheric carbon dioxide to form stalactites and, where the drips hit a lower surface, stalagmites. These are known as calthemites and will be predominantly calcium carbonate though there may be minor amounts of other minerals (for example, sulphate species). Precipitated calcium carbonate can usefully clog or seal cracks, for example, in retaining walls which may develop a white crust on the exposed face. Of course, more aggressive waters (e.g. higher bicarbonate content or acid content as can occur in some groundwaters) can damage concrete. However, when concrete is crushed the reaction situation is very different. Crushing greatly increases the surface area of the concrete and internal cracks also will be created. The result is that if water flows over CRC, it will leach alkalis and other chemicals at very much greater rates than from intact concrete. Reactions with external agents such as sulphates also will be accelerated (Jefferis 2019).

Experimental leaching tests of CRC produced high leachate pH values between pH 9 to 12, due to weathering of calcium hydroxide within the concrete material (Foy et al. 2019).

Leaching of concrete in the field is likely to produce a high pH leachate plume (Foy et al. 2019). As little information was available regarding the extent of these plumes, it was thought that a high pH plume from cement fill would be neutralised by dilution within a short distance of the site. The extent will be dependent on the chemical and physical conditions in the surrounding area. Further, Foy et al. (2019) investigated the potential for pH to influence the types of metals to leach from CRC, as shown in Table 4.49.

Table 4.49: The influence of pH on metal leaching

Metals where raised pH may promote leaching (> 10)	Metals where raised pH may retard leaching (> 10)	Metals where the influence of raised pH is not clear
Aluminium	Barium	Arsenic
Calcium	Cadmium	Magnesium
Chromium	Copper	Silicon
Mercury	Iron	Sulphur
Molybdenum	Lead	
Selenium	Manganese	
Vanadium	Nickel	
	Technetium	
	Uranium	
	Zinc	

Source: Adapted from Foy et al. (2019).

To make any quantitative estimate of the timescales for leaching it is necessary to know the original mix parameters. However, the Portland cement content of any concrete will be a function of many variables and especially the use for which it was prepared (Jefferis 2019). Those undertaking the crushing and those using the crushed material are most unlikely to have any knowledge of the original mix design including factors that would have been important for its original use such as water and cement ratio – a key factor for the durability of the intact concrete which will, in turn, influence the behaviour of its crushed counterpart. The re-user also will not know what cement type was used nor whether additions (fly ash, ground granulated blast furnace slag, limestone powder etc.) were used – again these will influence the behaviour of the crushed material. Furthermore, the CRC may not be of a single concrete type or come from a single source. It may be a mix of concrete types and sources (Jefferis 2019).

The *Roads to Reuse* (RtR) initiative in Western Australia aims to promote the use of recycled materials in road construction and reduce waste to landfills. The initiative involves the development of specifications for recycled materials, including recycled concrete, and the testing of these materials to ensure compliance with environmental regulations and standards. Additionally, the initiative includes the monitoring of leachate from the recycled materials to assess the potential leaching of contaminants and the implementation of measures to mitigate any adverse impacts on the environment and human health (Main Roads Western Australia 2020).

The product specifications for RtR mandate a rigorous inspection and testing process in the supplier's quality system and material acceptance and sampling plan (MASP). The aim is to ensure that the contaminant levels do not surpass the maximum acceptance limits, which are based on extensive research and set at a safe level. As the material is re-cemented over time, it is expected that the risk of hazardous leaching will decrease (Waste Authority 2020).

According to the RtR product specification, the use of CRC is prohibited within 100 m of a wetland or watercourse, on land that is prone to flooding, or in P1 public drinking water source areas (Waste Authority 2020). These restrictions appear to be overly conservative. In MRWA pavement design, granular pavement layers are not allowed within the capillary rise zone of the water table. If the material is located above this zone, it is unlikely that leaching will occur (Waste Authority 2020).

Recycled aggregates are not recommended to be used as drainage material because of the concerns with permeability, particularly with respect to sulphate attack from impurities in the groundwater or leachate being filtered. Recycled concrete sources from demolition sites may be contaminated by sulphate from plaster and gypsum which induces the possibility of sulphate attack if the recycled aggregates used in concrete are accessible to moisture (Beyer & Cooper 2020).

4.8 Benefits of Using C&D Waste

Sections 4.8.1 and 4.8.2 outline the cost and environmental benefits of using CRC and C&D materials in general.

Other benefits include social factors, such as job creation; for every 10,000 tonnes of waste recycled, 9.2 full-time equivalent jobs are created compared to landfill which creates 2.8 jobs (Waste Authority n.d.a).

4.8.1 Cost-benefit Analysis

The costs and benefits of using CRC, ballast and C&D waste in general, are typically related to the cost of virgin materials, the location of virgin materials and thus haulage costs, and the cost of landfill materials (ARRB 2022b, Waste Authority 2016). There is a significant benefit in cases where materials are removed from sites and reused in the same or nearby region, thus reducing the cost of hauling away the waste material, landfilling, and then purchasing and hauling in virgin materials (Beyer & Cooper 2020).

It is also recognised that processing of concrete to a suitable state for reuse can incur its own costs. Table 4.50 outlines where costs are incurred as well as avoided through the use of CRC. These cost impacts should be factored into cost-benefit analyses for individual use cases.

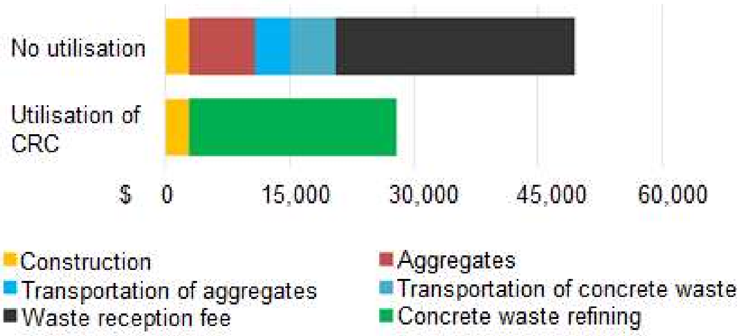
Table 4.50: Cost impacts of using CRC

Cost impact	Concrete waste refining	Utilisation of CRC
No impact		Transport to site (CRC or virgin material) Construction
Additional expenses	Extra site logistics at concrete waste source Crushing and screening Transport to recycler (avoided in case of on-site processing)	Quality control of material and application
Avoided expenses	Landfilling fee	Virgin material extraction

Source: Adapted from Dettenborn et al. (2021).

Furthermore, processing and reuse of concrete at site, if the technology and need for reuse is available, offers the additional benefits of reduced transport. Dettenborn et al. (2021) offers a theoretical example of cost savings, in a Finnish context, whereby concrete material from a demolished bridge is reused on site as a road subbase material, saving over $22,000 (estimated conversion from Euros). The savings are shown in Figure 4.1.

Figure 4.1: Cost impact of concrete waste refining for use in subbase



Source: Adapted from Dettenborn et al. (2021), Australian dollar values estimated from original Euros.

Cost analysis has suggested that there may be up to a 44% reduction in supply cost through replacement of virgin ballast with recycled ballast. The cost, however, can be affected by the distance from the recycling facility or ballast quarry to the project site (ARRB 2022b).

4.8.2 Environmental Benefits (Greenhouse Gas Emissions Savings, Sustainability Aspects)

In general, the environmental benefits of using C&D waste are often tied to the distance between extraction sites and the final usage site, due to the impact of haulage. With the geographical vastness of Western Australia, the opportunity to recycle and utilise materials closer to where they are extracted as waste is a significant environmental factor. Environmental benefits also arise through reducing the volume of virgin materials extracted for construction use (Waste Authority 2016).

Additionally, the manufacture of concrete is a very carbon intensive process (Macken et al. 2021), thus the opportunity to utilise the product in a higher order use at end of life offers a better approach than landfilling (ACRI et al. 2022).

Further environmental benefits include reduced harm to native vegetation and landforms from extractive practices, resource depletion, and reduced waste usage and greenhouse gas emissions (LGIDA 2020, Waste Authority n.d.a, 2016). With the construction industry, concrete is a major producer of CO_2e emissions, with approximately 10% of global CO_2e emissions produced from concrete (Gharehbaghi et al. 2020). Thus, the opportunity to use recycled concrete, to achieve a continued value from the material is beneficial. LGIDA (2020) documents the embodied carbon savings at 30% during processing, compared to virgin materials (if the transport is no more than 5 km more than virgin material). He and Gong (2019) recorded a reduction of over 60% in CO_2e emissions and over 50% reduction in energy consumption, from producing concrete containing GGBFS and 100% recycled coarse concrete aggregate. It should be noted though that it is critical to consider performance, as in cases where reduced performance occurs from recycled content (He & Gong 2019), this can impact the overall benefits across the life of the product.

5 Conclusions

5.1 Summary of Findings

Based on this literature review, CRC and degraded railway ballast, among other aggregate materials, can be used to reduce construction costs, where these materials are able to be sourced more readily than virgin materials. When the use of CRC in the rail sector is established, it will add a suitable recycled engineered product as a viable, load bearing and/or fill material available for new rail constructions in Western Australia.

CRC is a high-strength product with self-cementing properties, which results in increased stiffness over time (Main Roads Western Australia 2022). It was noted that it is important to consider the stiffness, as if it is too high can cause a reduction in performance and design life, thus individual blends should be assessed for their properties. CRC has been shown to have comparable properties to conventional capping materials, in particle size, Los Angeles abrasion, water absorption and specific gravity, as well as improved stiffness and strength compared to natural capping materials (Naeini et al. 2019). This same research demonstrated that 100% CRC could be used in capping layers without any issues.

In terms of the chemical composition, recycled aggregates can contain high soluble sulphate content, and should be avoided if reinforcing steel is used, as this can promote corrosion.

The current uses for recovered C&D waste are typically limited to road construction, clean fill, and landscaping, though there is potential for broadening its use. CRC is currently used in roads and road shoulders, carparks and truck parking, driveways, kerbs, rammed earth walls and construction blocks, concrete batch aggregate substitute, and building construction ground development (Beyer & Cooper 2020).

For recycled ballast applications, recycled ballast has about 35% lower tensile strength compared to virgin aggregates for a railway ballast application. In terms of chemical composition, rail activities have a history of contamination through various practices, such as use of arsenic-based herbicides, asbestos, use of lubricants and fuels and transportation of various material, such as lead ore. From these historical and current practices, some of the associated chemical substances of risk include metals, hydrocarbons (TPHs and PAHs) and asbestos (Department of Planning, Transport and Infrastructure 2015), thus reuse of ballast should factor in assessing for these compounds on a case-by-case basis. Currently recycled ballast is used in low-grade applications such as road base or access tracks (ARRB 2022a). South Australia, for example, has used ballast in structural pavement layers, embankments, and general earthworks (ARRB 2022a). There is minimal documentation of the current use of recycled ballast across the Australian rail industry, excepting the cleaning and reuse of degraded ballast once again as ballast. However, there is potential for ballast to be engaged in varied uses, such as bedding materials, in concrete as an aggregate, drainage, decking and sleepers (ACRI et al. 2022, Macken et al. 2021).

CRC is classified as a hazardous material by Safe Work Australia as it contains RCS. Inhalation of RCS can lead to lung conditions such as silicosis. It is to be noted that RCS is a natural mineral and is found in other building materials, and natural aggregate products; for example, in natural sand such as that found at the beach. The use of CRC as a surfacing layer in unsealed surfaces would require further study as suppression methods explained in Section 2.3 theoretically reduce the probability of exposure to RCS; however, additional research is necessary to ensure structural integrity, potential issues such as insufficient fines, excessive maximum aggregate sizes, high pH leachates, recementing-induced cracking, and RCS exposure in residential locations. In terms of contamination, CRCs are often contaminated by various sources of aggressive ions like chlorides and sulphates from de-icing salts, sewage plants or seawater. These contaminants may affect the properties of recycled concrete as well also as cause the runoffs from the CRCs to carry the contaminants into the waterways through stormwater drains and drainage layers.

It is demonstrated that concrete recycling, in comparison to the use of virgin gravel and sand, results in a more favourable outcome in terms of the production of CO_2e, NOx, SO_2 and dust emissions. The primary source of CO_2e emissions is the transportation processes involved in both natural and recycled aggregates.

In natural aggregates, transportation processes account for about 63% of the total CO_2e emissions for gravel and 71% for sand, while in recycled aggregates, they represent about 57% of the total emissions. The total NOx emissions due to recycling concrete are about 45.86 g per tonne, which is approximately 50% of the total emissions produced during the quarrying and processing of primary aggregates (about 99 g per tonne). The emissions of SO_2 produced in the processing of recycled aggregates reach 2.784 g per tonne, which represents 22.4% and 12% of the emissions produced in the production of natural gravel and sand, respectively. It can also be observed that the dust production from recycled aggregates is about 16% of the dust produced from using natural aggregates.

As outlined in Table 4.5, other opportunities for CRC use include as a capping layer (including as a blend with recycled glass), sub-ballast (including as a blend with glass, plastic, glass, and brick), ballast, and in concrete applications as an aggregate (including as a blend with slag and recycled ballast).

The benefits of using CRC have been identified, predominantly covering cost and environmental aspects. Other benefits include social factors, such as job creation; for every 10,000 tonnes of waste recycled, 9.2 FTE jobs are created, compared to landfill which creates 2.8 FTE jobs.

5.2 Suitability of CRC and Recycled Ballast Reuse in Rail Applications

The literature review has found that while CRC and recycled ballast is used in rail applications in Australian jurisdictions other than Western Australia as well as internationally, the amount of research on the safe and effective use of these products in rail applications is not extensive.

However, the literature that is available suggests that increased use of these recycled materials could be broadly beneficial in Western Australia where sufficient quantities of the materials and the capacity to process them for reuse exist. The review identified a number of potential opportunities for use of CRC and recycled ballast in rail applications, these are outlined in Table 5.1.

Table 5.1: Potential opportunities for CRC and recycled ballast in rail applications

Application	CRC use	Recycled ballast use
Ballast	✓(1)	✓
Sub-ballast	✓(2)	✓
Capping layer	✓	✓(3)
Access tracks unsealed surface layer	×	✓(3)
Access tracks sealed surface layer	✓	✓(3)
Access tracks (base/subbase)	✓	✓
Aggregate in concrete applications	✓	✓
Drainage/bedding/backfill	×	✓
Embankments/earthworks	✓	✓

1. Up to 25% ballast replacement.
2. May be used with recycled crushed glass and recycled plastic.
3. Crushing and grading required.

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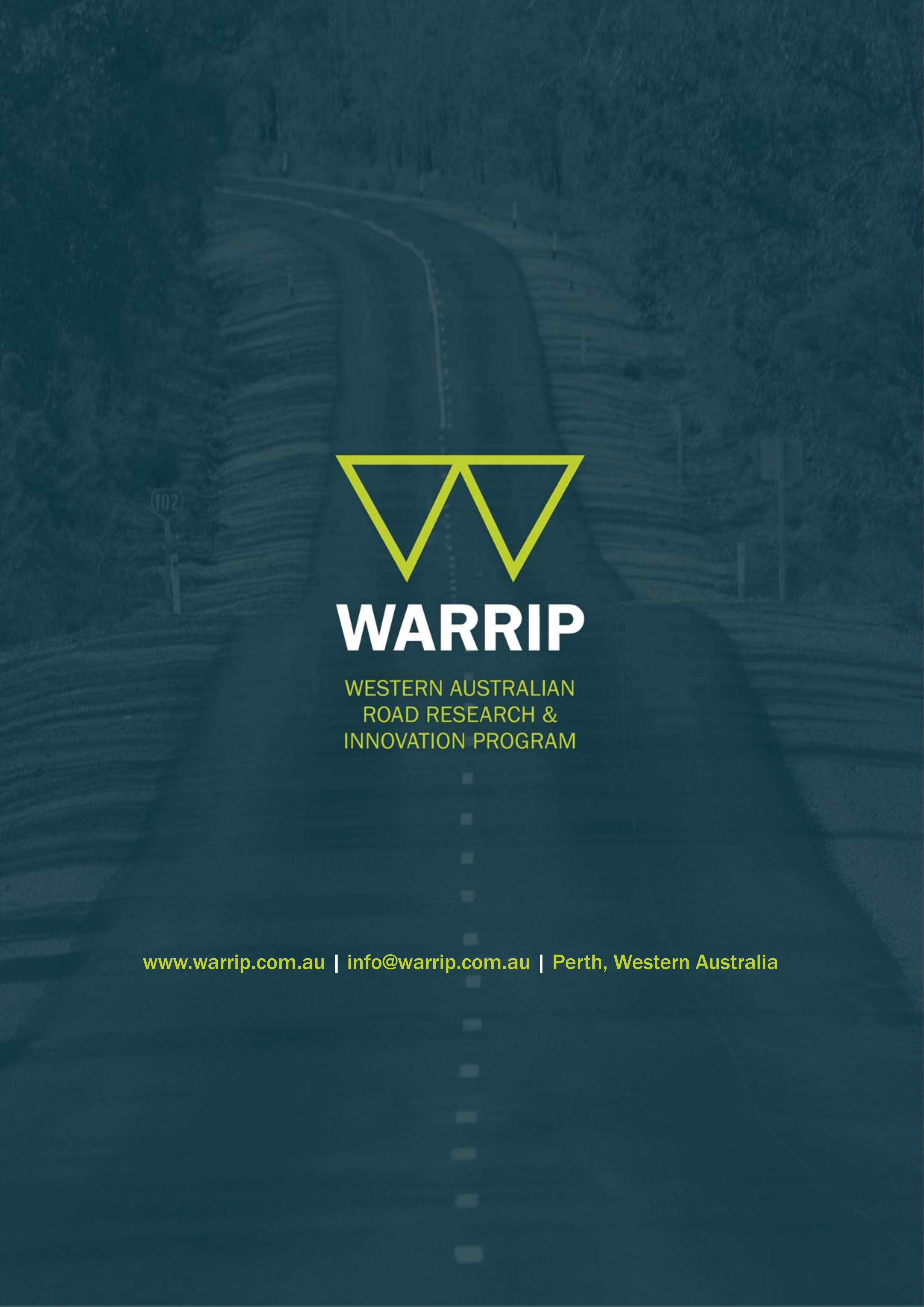

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