University of Southern Queensland

Faculty of Health, Engineering and Sciences

Use of Waste Glass as a Sand Replacement in Road Base Applications

Dissertation submitted by

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In fulfilment of the requirements of

Course ENG4111/4112 – Research Project

towards the degree of

Bachelor of Engineering (Civil)

ABSTRACT

Sand and gravel rank among the world's most extracted natural resources, yet despite their apparent abundance, they are finite. Recycled materials for road construction offer a promising approach to address this challenge.

This dissertation employed a comprehensive research methodology to determine the suitability of recycled glass sand to replace unbound road pavement by incorporating various amounts of recycled glass sand in road base gravel and testing the material properties.

Growing attention is being directed towards sustainable road construction and the utilization of recycled glass. However, the investigation of recycled glass sand in road base applications in Australia remains underexplored. Townsville City Council has yet to adopt standards or life cycle assessment analysis to determine and understand the holistic perspective on the environmental repercussions of using recycled products and quarried sand.

Material testing conducted assesses the suitability of recycled glass sand as a substitute for quarried sand in road subbase material. Townsville City Council's Material Reuse Facility has provided recycled glass sand. Control material will be tested for comparative properties, including particle size distribution, Atterberg limits, optimum moisture content, and California Bearing Ratio. A NATA accredited laboratory will complete chemical testing, including sugars, heavy metals, and organic carbon, to determine the contaminants in the recycled glass.

Recycled glass sand mix results were compared to a natural gravel road base control material for chemical, material, and LCA assessment. This investigation has determined that recycled glass sand effectively replaces road subbase gravel. Material testing results show that recycled glass sand mixes meet sub-base gravel's particle size distribution. Road base mixes combined with RGS require less water to reach optimum moisture content while achieving maximum dry density within 1% of the control material. Recycled glass sand mixes had significant increases in strength properties.

Life cycle analysis assessment results showed reductions in the majority of the damage pathways, reducing the three endpoint impacts: human health, environmental, and resources. The economic assessment also demonstrates significant cost savings.

In conclusion, this research underpins the potential of recycled glass sand as a sustainable alternative in unbound road pavement construction. By examining material properties, environmental impact, and performance compared to traditional road base materials, there are valuable insights for promoting sustainable road construction practices in Australia. This study with the Townsville City Council, offers a promising solution to the scarcity of natural sand and gravel and contributes to reducing the environmental footprint in road infrastructure development.

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CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Madeline Taylor

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ABBREVIATIONS

AS	Australian Standard
CBR	California Bearing Ratio
LCA	Life Cycle Assessment
LCEA	Life Cycle Energy Analysis
LCI	Life Cycle Inventory
LL	Liquid Limit
MDD	Maximum Dry Density
MRF	Materials Reuse Facility
MRTS05	Technical Specification MRTS05 Unbound Pavements, July 2020
MRTS36	Technical Specification MRTS36 Recycled Glass Aggregate
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic Limit
RGA	Recycled Glass Aggregate
RGS	Recycled Glass Sand
TCC	Townsville City Council
TMR	Department of Transport and Main Roads

1. CHAPTER 1 – INTRODUCTION

1.1. Introduction

Australia has a vast road network comprising 874,500 km. Approximately 73% of this network comprises local roads (Department of Infrastructure and Regional Development 2016). Road infrastructure is pivotal in Australian society, facilitating connection, transportation, trade, and economic development. The construction of road infrastructure heavily relies on quarried materials, products that are essential raw materials. Over 200 million tonnes of aggregates are used to construct homes, workplaces, public buildings and roads annually in Australia (Cement Concrete & Aggregates Australia n.d.). Conventional virgin materials used in road construction, such as quarried crushed stone and gravel, impose significant environmental and social challenges.

The extraction of natural resources for road base construction contributes to land degradation, habitat destruction, and carbon emissions from transportation and processing. Transporting these materials from quarries to construction sites adds to carbon emissions and traffic congestion (Ahmet Anil Sezer 2021). Sand and gravel are the most extensively extracted natural resources globally, amounting to approximately 28.6 gigatonnes annually as of 2010. Natural quarried materials have been essential road construction aggregates for many decades. Despite the seemingly abundant presence of sand on the Earth's surface, it is imperative to recognise its status as a finite natural resource that could potentially face depletion in the near future. Excessive sand extraction not only leads to the depletion of this resource but also poses significant risks to marine ecosystems, water availability, water clarity, marine biodiversity, and even contributes to climate-related issues (Aurora Torres 2017).

In response to pressing environmental challenges, there has been a growing global emphasis on sustainable practices and the circular economy to minimise waste generation, conserve resources, and reduce environmental impacts (UN DESA 2022). Within this context, recycling materials for road construction has emerged as a promising approach to address these challenges. Recycled materials offer several advantages over conventional virgin materials in road construction. They divert waste from landfills, alleviating the burden on limited landfill capacity and reducing associated environmental risks. Additionally, using recycled materials reduces the need to extract natural resources, preserving valuable ecosystems and reducing the energy-intensive processes involved in traditional material production (CK. Purchase 2021).

One specific material gaining traction as a potential substitute for conventional road pavement materials is recycled glass. Glass, commonly used in packaging, represents a significant component of municipal solid waste. In Australia, 40% of glass consumed ends up in landfills. In Queensland, this amount is higher at 57% of glass being sent to landfill (blue environment 2023). Recycling glass not only diverts waste from landfills but also aligns with Australia's goal of transitioning toward a circular economy.

Various studies and pilot projects have explored the potential of incorporating recycled glass into road construction worldwide. While literature demonstrates that recycled glass can be processed into cullet or aggregate forms and used as a supplementary cementitious material, geotechnical investigations in this area have been limited (D Kazmi 2021). When properly processed and mixed, recycled glass exhibits favourable characteristics, including strength, load-bearing capacity, and durability, making it a viable candidate for road base applications (M.M. Disfani 2012).

Furthermore, using recycled glass in road construction can reduce the consumption of natural resources, such as aggregates and sand, typically sourced from quarries or riverbeds. By substituting these virgin materials with recycled glass, the strain on natural resource reserves can be eased, reducing the environmental impacts of extraction activities. Incorporating recycled glass in road base construction aligns with the principles of a circular economy, where materials are kept in use for as long as possible, and waste is minimised through recycling and re-utilisation. Closing the loop and transforming glass waste into road infrastructure can extend the lifecycle of glass materials, promoting a more sustainable and resource-efficient approach to road construction (Ai Jen Lim 2020).

1.2. Townsville City Council

Townsville City Council (TCC) has committed to achieving zero waste to landfills by the year 2030 and to become carbon neutral by 2040. Furthermore, TCC has set a target for 2026, mandating that newly developed council assets must incorporate recycled products to divert waste from landfills. This transition from using virgin aggregates and products in TCC Civil infrastructure projects is vital to realising these commendable environmental objectives.

Local governments often operate under limited financial resources compared to their state or national counterparts. Balancing the need to provide essential services within available funding can be a formidable challenge, especially during economic downturns or increased demands. Local governments are responsible for maintaining and developing critical infrastructure such as roads, bridges, water and sewage systems, and public facilities. The pressures of aging infrastructure, population growth, and evolving community needs necessitate ongoing investments, which can strain the resources of local governments.

In the case of TCC, the scope of responsibility covers an expansive area totalling 3,376 square kilometres. Within this jurisdiction, TCC manages and maintains a significant civil infrastructure network, including 1,771 kilometres of roadways, 540 kilometres of pathways, and more than 1,000 kilometres of stormwater drainage systems. Notably, the Townsville Material Recycling Facility (MRF) processes an approximate monthly intake of 200 tonnes of recycled glass waste (RGW). This RGW undergoes processing and is subsequently transported to quarries for stockpiling. Presently, Townsville has substantial stockpiles of waste glass aggregate. These stockpiles of waste glass represent a significant economic opportunity for TCC, aligning with their commitment to sustainable practices, waste reduction, and incorporating recycled materials into their civil infrastructure projects.

1.3. Project Background

There is an increasing interest in sustainable road construction, mainly recycled glass. However, the investigation of glass aggregate in road base applications in Australia remains underexplored. There is a need to assess recycled glass's physical and mechanical properties to evaluate its suitability as a partial replacement in road base. Although research on RGA in road base has been carried out overseas, there has been limited investigation in Australia, and existing specifications impose restrictions on its use in road construction. Recycled glass aggregate is produced in all states of Australia, but there is a scarcity of processing facilities to utilise RGA. The additional utilisation of recycled glass in road construction could result in cost savings and provide environmental benefits, contributing to a circular economy and other sustainability goals.

1.4. Aims and Objectives

The project aims to determine the feasibility of using recycled waste glass as a partial sand replacement in road base construction. The research aims to create a road base product that complies with the Townsville City Council Specification for road subbase pavement.

The specific objectives of this dissertation are as follows:

1. Assess the properties of RGA to assess its suitability for use in road base.
2. Develop an optimal road subbase pavement mix using waste glass as a sand substitute and verify its performance against relevant Australian Standards.
3. Conduct a sustainability assessment and economic assessment to determine the environmental impacts of using RGA in road base construction.

2. LITERATURE REVIEW

2.1. Introduction

Heavy civil engineering is one of the fastest-growing industries worldwide (Stahl 2022). With urbanisation and a growing global population, the demand for the construction industry continues to rise. Roads are vital in providing access to new regions and driving economic and social development. Road infrastructure stands as a critically important public asset for connectivity, influencing living standards at the population level, including access to health services, education, and employment opportunities.

2.2. Road Construction

Road pavement serves two fundamental functions: firstly, to function as an engineering structure capable of resisting vertical and horizontal stresses and maintaining its integrity, and secondly, to provide functional performance properties, including a smooth riding quality that ensures comfort for road users (Austroads 2018a). A typical pavement cross-section is illustrated in Figure 1.

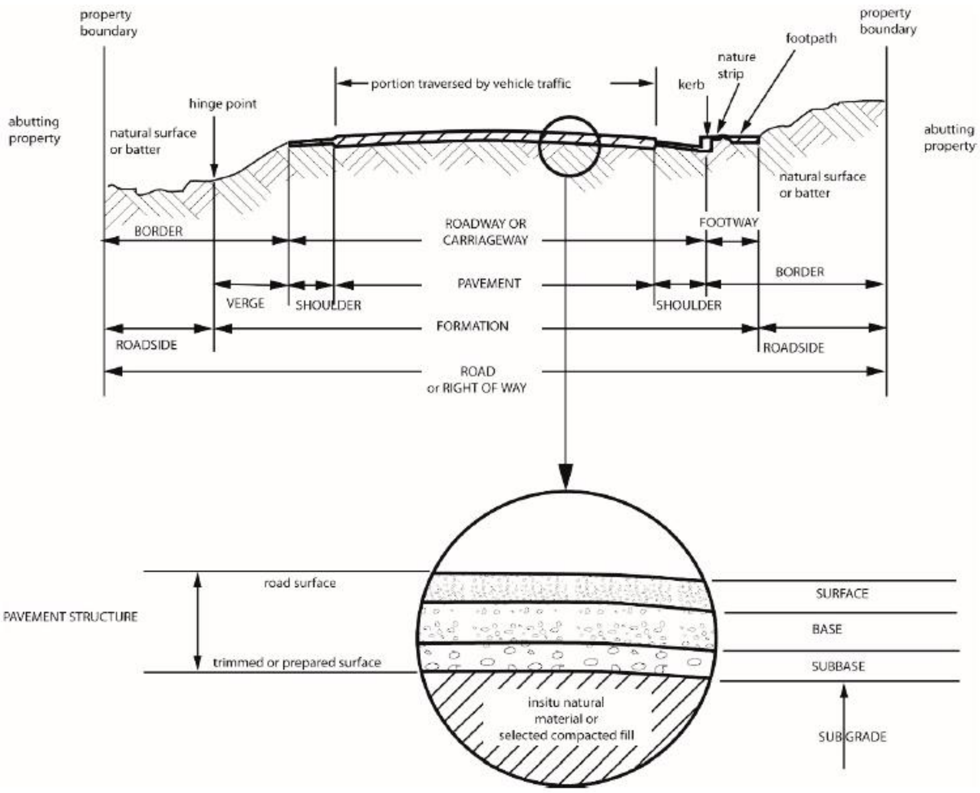

Figure 1 - Pavement Structure and its Role in the Road Formation (Austroads 2018a)

The structure of a road pavement comprises different layers designed to distribute loads to the natural subgrade. The surface layer is typically composed of asphalt or a bitumen seal. The pavement base, located beneath the surface, is the primary load-bearing layer within the pavement structure. The base course is typically constructed using crushed aggregates in granular pavement structures. This base layer must provide the necessary stiffness to reduce stresses in the subbase and subgrade, thus limiting deformation and supporting bituminous surfaces. Additionally, it must exhibit low permeability to prevent water ingress into the lower pavement levels (Austroads 2018b).

The pavement subbase adds structural support and minimises the intrusion of fine particles from the subgrade into the pavement structure. This subbase layer typically comprises lower-grade materials (Pavement Interactive n.d.-a). he pavement subgrade refers to the in-situ material upon which the pavement structure is constructed. It must effectively support the loads transmitted from the pavement structure (Pavement Interactive n.d.-b).

2.2.1. Flexible Pavement

Unbound flexible pavements consist of a thin bituminous surface applied to compacted layers of unbound granular material, which overlay select fill or native soil foundation. These pavements find application across a spectrum, from heavy traffic volume rural highways to light traffic volume urban roads (Griffin 2015). According to the TCC City Plan, unbound flexible pavements are the preferred choice due to their cost-effectiveness. While unbound pavements typically have a greater depth, they demand significantly lower initial capital investment than heavily stabilised, thick asphalt or concrete structures (Griffin 2015).

The load-bearing capacity of unbound granular material stems from the inherent hardness of its constituent grains, particle interlock, inter-particle friction, and, when applicable, cementation bonds (Austroads 2018). Unbound pavements are generally designed with a lifespan of 20 years, assuming even distribution of loading throughout the road's life. The first design consideration is the amount of traffic the pavement is intended to bear. However, not all vehicles exert equally detrimental effects on pavements. Austroads recognises vehicle configurations equivalent to or greater than a Single Axel with Dual Tyres (SADT), where each tire exerts a load of 20kN, imposing an 80kN load in total, contributing to pavement deterioration. All other vehicle configurations above SADT are converted to this configuration to establish an Equivalent Standard Axle (ESA) (Austroads 2019). The second critical consideration in road pavement design is the subgrade's characteristics. When designing unbound flexible pavements, the subgrade is assumed to be the source of failure.

The design of unbound flexible pavements follows the empirical design procedure outlined in Austroads Guide to Pavement Technology Part 2: Pavement Structural Design and the Queensland Department of Main Roads – Supplement to the Austroads Guide to Pavement Technology (Townsville City Plan 2022).

2.2.1.1. Empirical Design Method

For the design of flexible pavements, including those with cement or lime-modified granular materials, Townsville City Council requires the use of the empirical design method (Townsville City Plan 2022). The empirical approach to road design relies on outcomes from experiments or practical knowledge. It depends on observations to uncover connections between input variables and process outputs, as seen in pavement design and performance assessment. While these connections often lack a strictly scientific foundation, they must align with engineering logic, demonstrating trends in appropriate directions and behaving correctly under extreme conditions. Empirical methods are frequently employed as practical solutions when establishing a phenomenon's precise theoretical cause-and-effect relationships proves overly complex (Barry R. Christopher 2006).

The design method is based on an empirical design chart (Figures 2 and 3), which provides the required material thickness over the in-situ subgrade and each course material (base and subbase). Two inputs are necessary to use the charts: Design Traffic in Equivalent Standard Axles (ESA) and California Bearing Ratio (CBR) for materials and subgrade. Equation 2 and Equation 3, respectively, complement the charts. The pavement is designed to ensure adequate coverage over the subgrade and each subsequent subbase layer.

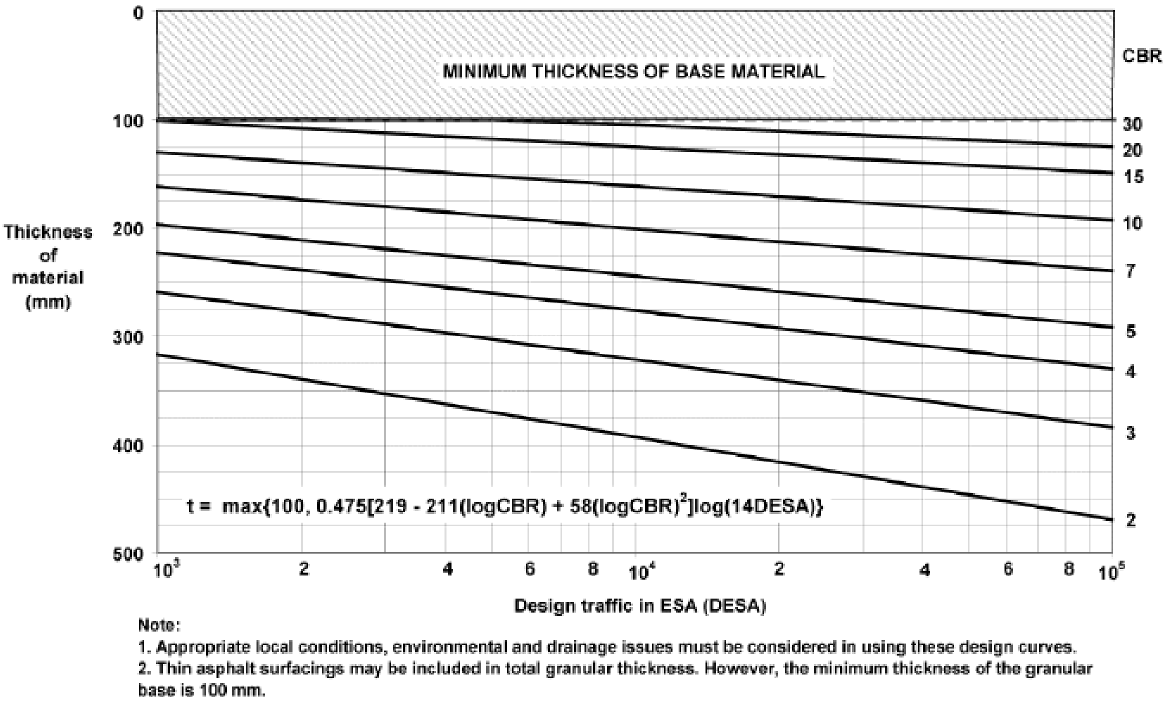

Figure 2 - Empirical Chart for ESA's up to 100,000 (Austroads 2019)

$$t = max\ (100, 0.475[219 - 211(logCBR) + 58(logCBR)^2]\ log(14DESA))$$

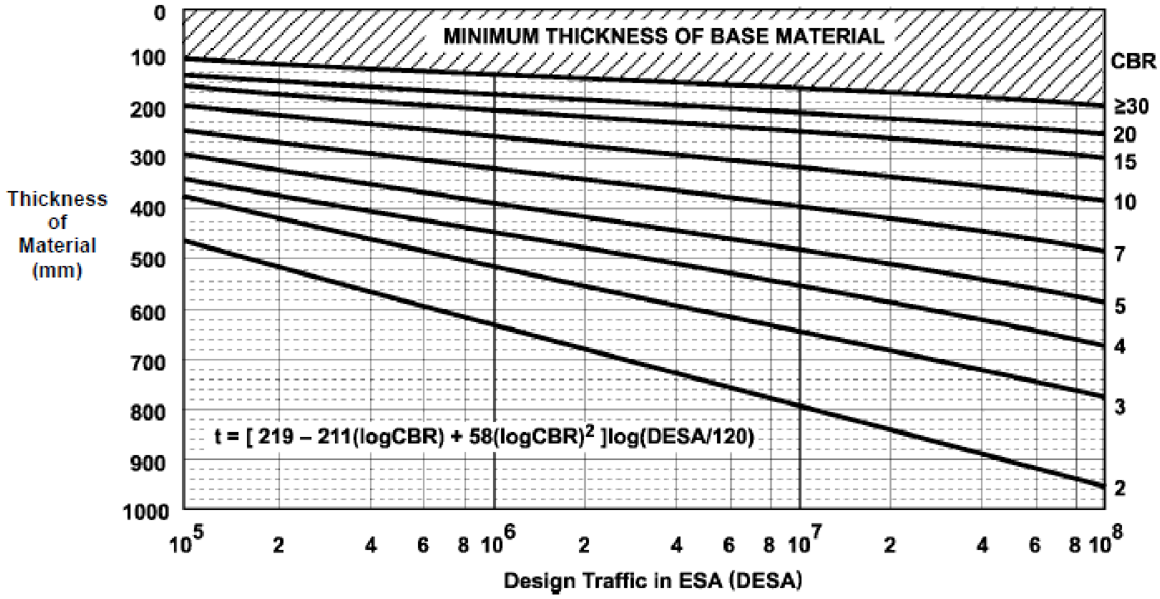

Figure 3 - Empirical Chart for ESA's up to 10^8 (Austroads 2019)

$$t = [219 - 211(logCBR) + 58(logCBR)^2]\log(DESA/120)$$

2.2.1.2. Pavement Structure

Unbound flexible pavements for Townsville City Council usually comprise three layers as follows:

i) Top Layer – Base (CBR80) minimum thickness 150mm – DTMR Type 2.1 (MRTS05).

ii) Mid Layer – Sub Base (CBR45) minimum thickness 125mm – DTMR Type 2.3 (MRTS05).

iii) Working Platform / Capping Layer – (Design subgrade CBR 10 or 15) minimum thickness 150mm.

(Townsville City Council, 2022)

For a material to comply with DTMR Type 2.1 and Type 2.3, it must meet a range of criteria, including fines components (MRTS05 7.2.3), particle size distribution (MRTS05 7.2.4) and California Bearing Ratio requirements (MRTS05 7.2.5).

2.3. Road Base

Road base materials are critical in road construction, providing a stable foundation and structural support to withstand traffic loads and distribute them effectively. Conventional road base materials typically consist of natural aggregates such as crushed stone, gravel, and sand. These materials have been widely used for many years due to their availability, affordability, and desirable engineering properties. Road bases can also comprise manufactured aggregates and cemented materials.

Crushed stone, often sourced from quarried rock formations, is a commonly used road base material. It is produced by mechanically crushing larger stones and screening them to obtain various size fractions. Gravel, on the other hand, consists of rounded particles and is obtained from riverbeds or gravel pits. Sand, primarily composed of small mineral or rock fragments, is used as a fine aggregate in road base mixtures. The largest solid materials extracted globally are crushed rock, sand, and gravel. An estimated 40-50 billion tonnes are extracted annually, with the construction industry consuming half of this volume each year. The aggregate demand is projected to increase to 60 billion tonnes annually by 2030, driven by population growth, urbanisation, and economic expansion. Aggregate extraction in rivers has led to pollution, changes in pH levels, instability of riverbanks, and lowered water aquifers (Programme, 2019).

These conventional road base materials possess fundamental engineering properties that make them suitable for road construction. They provide strength, stability, and drainage capabilities to the road structure. These materials' particle sizes and gradations are carefully selected to achieve optimal compaction, load-bearing capacity, and resistance to deformation.

2.3.1. Road Base Production

Austroads details the process by which granular materials are produced. Hard rock deposits must undergo breaking, achieved through blasting or ripping, to reduce the rock to a size suitable for feeding into the crusher. Six primary types of rock crushers are employed in producing road construction materials: jaw crushers, gyratory crushers, cone crushers, impact crushers, hammer mill crushers, and vertical shaft impact crushers. Crushing relies on either compressing the rock particles between metal surfaces or the high-speed impact of rock against hard surfaces. Quarry plants select the appropriate crusher type depending on the characteristics of the rock deposit. Screens are then used to grade the product into the required size ranges and distribution sizes. Oversized material is returned to the crusher, while smaller material is stockpiled according to size (Austroads 2018).

2.3.2. Material Properties

2.3.2.1. Aggregate Shape

At a fixed porosity, the geometric configuration and characteristics of the stones influence the ability of granular materials to withstand shear forces. Particles with angular contours and a coarse texture outperform those derived from river gravel. River gravel particles have smoother, rounded surfaces. Particles displaying flaky or elongated shapes pose challenges regarding manipulation and compaction, as they tend to fragment during compaction and while in use. Particle shape assessment is conducted on coarse material where the 9.5 mm sieve retains more than 10%. Consequently, this dimension should be used to evaluate particle shape for materials measuring less than 9.5 mm in the Average Least Dimension (Austroads 2018).

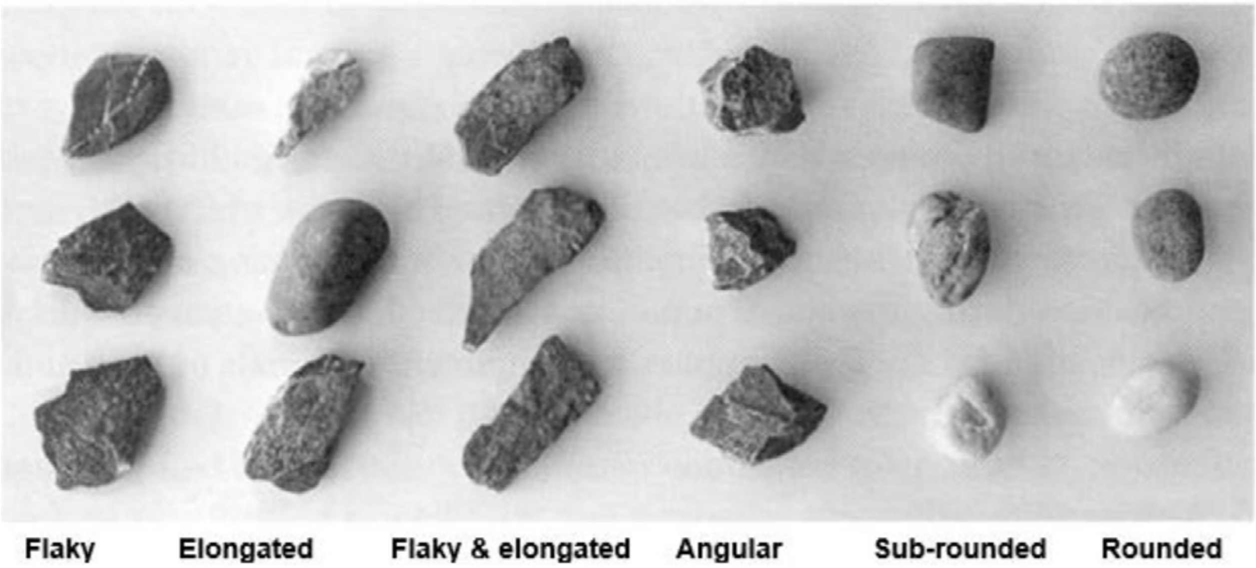

Figure 4 – Shape of Aggregate Particles (Austroads 2018)

2.3.2.2. Fines Percentage and Plasticity

The percentage of fines passing through the 0.425 mm sieve and fines-plasticity significantly affects shear strength. In general, an excessive presence of fine soil prevents interlocking between large gravels, while too few fines reduce the compacted density. High plastic fines reduce shear strength for compacted material due to decreased friction between interlocking particles. For crushed rock (with a maximum size of 20 mm), materials are most stable when the fine content falls within a critical range of 8% to 12%. The impact of fine plasticity on shear strength at fine contents below the optimum level is relatively minor. However, high fines plasticity exerts a more significant influence on higher fines contents. Choosing materials depends on environmental conditions, particularly moisture, material characteristics, and pavement design considerations (Austroads 2018).

2.3.2.3. Particle Size Distribution

The particle size distribution within a granular material, commonly called its 'grading,' is determined by achieving maximum density under specific compaction efforts. The mechanical engagement between particles and their shear strength peaks when the material is densely packed. The material's permeability is also minimised, reducing susceptibility to moisture-induced shear strength fluctuations (Austroads 2018).

Soil should be well-graded and cohesive to facilitate the interlocking of particles, thereby enhancing its bearing capacity. The particle-size distribution curve illustrates the range of particle sizes present in soil and the distribution of various-sized particles. Different types of distributions are depicted in Figure 5. Curve I represents a soil in which most of the soil grains are the same size, known as poorly graded soil. Curve II represents soil in which particle sizes are distributed over a wide range, termed well-graded soil. Curve III represents gap-graded soil characterised by combining two or more uniformly graded fractions (Das 2010).

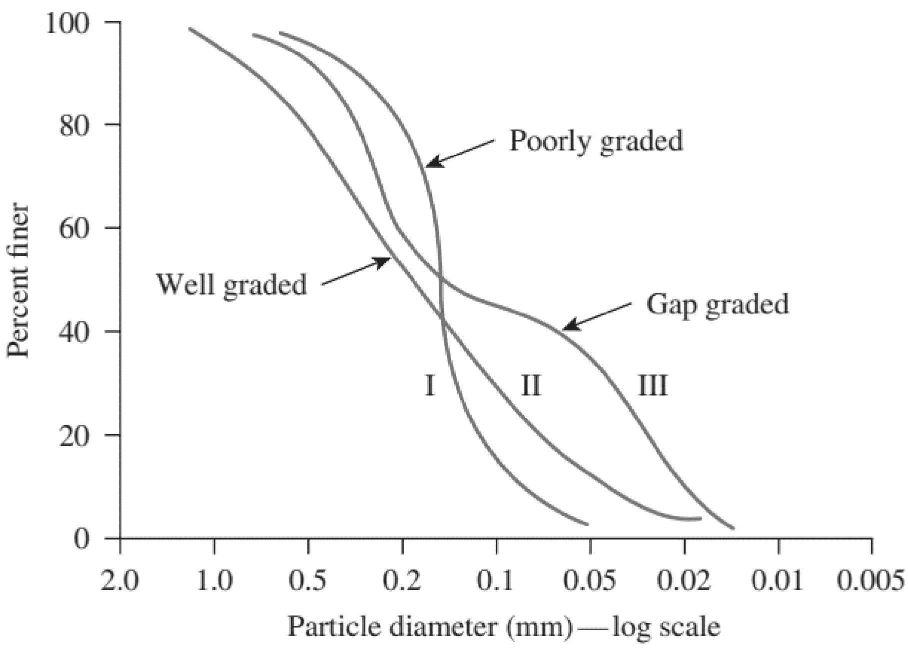

Figure 5 – Particle Size Distribution Curves (Das 2010)

2.3.2.4. Density and Moisture Content

The extent of compaction influences the characteristics of unbound pavement layers, encompassing factors like density, particle alignment, permeability, and shear strength. Typically, as density increases and moisture content decreases, material strength increases. Greater density demands more energy to overcome inter-particle friction and compact the granular material under the applied confining stress. A minimal moisture content can marginally diminish inter-particle friction while introducing apparent cohesion through capillary forces. Nevertheless, excessive saturation may lead to elevated pore pressure and diminished shear strength (Austroads 2018). The material's unit weight specifies the compaction level relative to its maximum dry density (MDD). Maximal density is typically sought to minimise void spaces and establish a robust, enduring pavement layer (Griffin 2015).

2.3.3. Challenges Associate with Road Base Materials

Despite their widespread use, conventional road base materials present several challenges. One significant challenge is the environmental impact of their extraction. Quarrying and mining activities for obtaining crushed stone and gravel can lead to habitat destruction, soil erosion, and visual pollution. The extraction process also consumes energy and water, contributing to concerns about carbon emissions and water scarcity (Gavriletea 2017).

Another challenge is the limited availability of high-quality natural aggregates in certain regions. As demand for road construction materials continues to rise, securing sufficient supplies of virgin materials becomes increasingly challenging and can lead to higher costs and longer transportation distances. Transporting these materials from quarries to construction sites also contributes to traffic congestion, road wear, and associated environmental impacts (Escavy et al. 2022).

The extraction of natural resources for road construction is not a sustainable practice in the long term. The depletion of finite resources, combined with the environmental and social consequences, necessitates a shift toward more sustainable alternatives that reduce reliance on virgin materials (United Nations Environment Programme 2019).

2.4. Need for Sustainable Alternatives

Australia's economy has conventionally relied on extracting and exporting natural resources, with little emphasis on domestic value-adding or manufacturing. Simultaneously, we import large quantities of consumer goods, which end their life as waste and are permanently lost from circulation. A linear economy drives the demand for natural resources and destroys their economic value (CSIRO n.d.).

The traditional linear model worldwide consumes resources and generates waste at a rate 1.7 times what the Earth can regenerate. In a circular economy (Figure 6), all materials are treated as vital resources, products are used for as long as possible, and materials are recovered at the end of their life (Clean Up n.d.).

The concept of a circular economy aims to address complex global issues such as climate change, biodiversity decline, waste generation, and pollution by implementing large-scale, systemic, and location-specific strategies to promote economic growth, complexity, and adaptability. Compared to the worldwide average circularity rate of 8.6%, Australia's economy currently operates at a significantly lower circularity rate of only 3.5%.

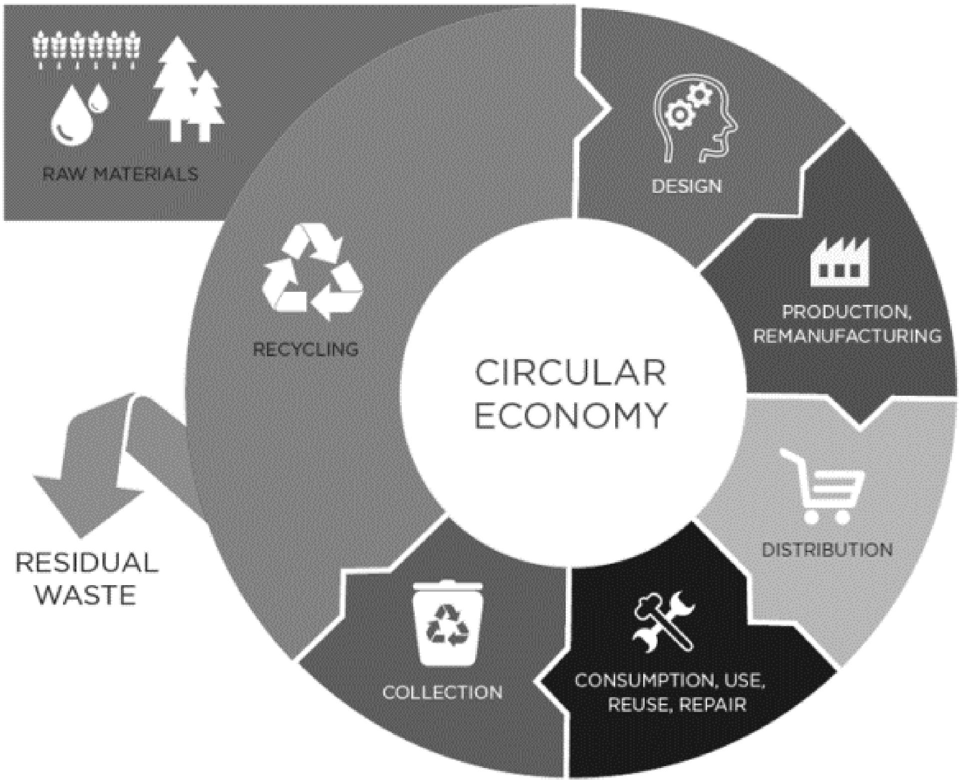

Figure 6 - Circular Economy Model (CSIRO n.d.)

Three fundamental principles underpin the circular economy (CSIRO n.d.):

1. Eliminate waste and pollution
2. Circulate products and materials
3. Regenerate nature

The National Waste Policy further breaks these three fundamental principles into five specific principles for waste management, recycling, and resource recovery (Commonwealth of Australia 2018).

1. Avoid Waste
2. Improve resource recovery
3. Increase use of recycled material and build demand and markets for recycled products
4. Better management of material flows to benefit human health, the environment and the economy
5. Improve information to support innovation, guide investment and enable informed consumer decisions

Australia is committed to reducing waste and utilising recycled materials. To achieve these goals, the Australian Government has set seven national targets:

1. Ban the export of waste plastic, paper, glass and tyres commencing in the second half of 2020
2. Reduce total waste generated in Australia by 10% per person by 2030
3. 80% average resource recovery rate from all waste streams following the waste hierarchy by 2030
4. Significantly increase the use of recycled content by governments and industry
5. Phase out problematic and unnecessary plastics by 2025
6. Halve the amount of organic waste sent to landfill by 2030
7. Make comprehensive economy-wide and timely data publicly available to support better consumer, investment and policy decisions

(Australian Government 2019)

To achieve waste reduction targets the Australian Government sets, including waste glass in road base materials emerges as a sustainable and strategic solution. This approach aligns with several key objectives, including the ban on waste exports, reduced total waste generated, and increased resource recovery rates. By repurposing waste glass in road construction, Australia reduces reliance on landfills and overseas waste disposal and promotes recycled content in infrastructure projects. Furthermore, this practice is vital in phasing out problematic waste materials and supporting data-driven waste management initiatives. Townsville City Council has the ability to contribute to a circular economy as waste glass emerges as a pivotal element in the Government's comprehensive strategy to address waste-related challenges and move towards a more sustainable and circular economy.

2.4.1. Extraction of Natural Quarried Resources

and and gravel are often overlooked foundation materials for economics, yet they account for the largest volume of solid material extracted globally. Sand is ubiquitous in construction and industrial production due to its cost-effectiveness, versatility, and ease of acquisition. However, current extraction rates exceed natural sand replenishment rates, increasing dependence on aggregates and causing global environmental and social concerns. An estimated 40 to 50 billion metric tonnes of crushed rock, sand, and gravel are extracted annually from quarries, pits, rivers, coastlines, and marine environments (United Nations Environment Programme 2019). United Nations' suggested hierarchy of solutions to reducing sand extraction is shown in Figure 7.

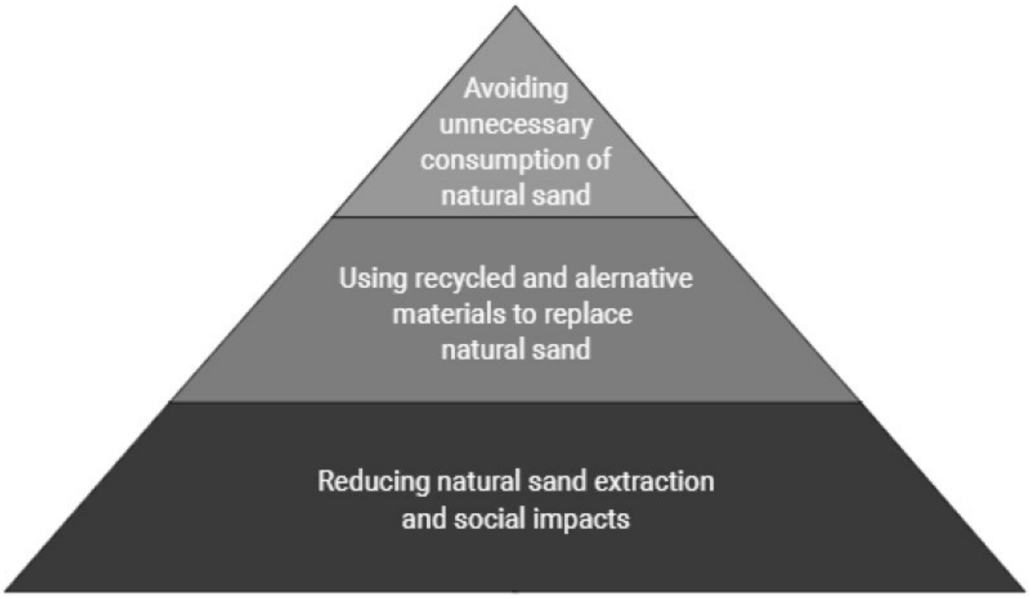

Figure 7 – Suggested hierarchy of available Solutions (United Nations Environment Programme 2019)

Townsville City Council can address this issue by implementing the hierarchy of solutions suggested by the United Nations, which involves reducing natural sand extraction and substituting sand with recycled materials.

From 2001 to 2021, Queensland averaged 44.3 million tonnes of hard rock, sand, and gravel product extraction. Figure 8 illustrates the extraction trends over this period.

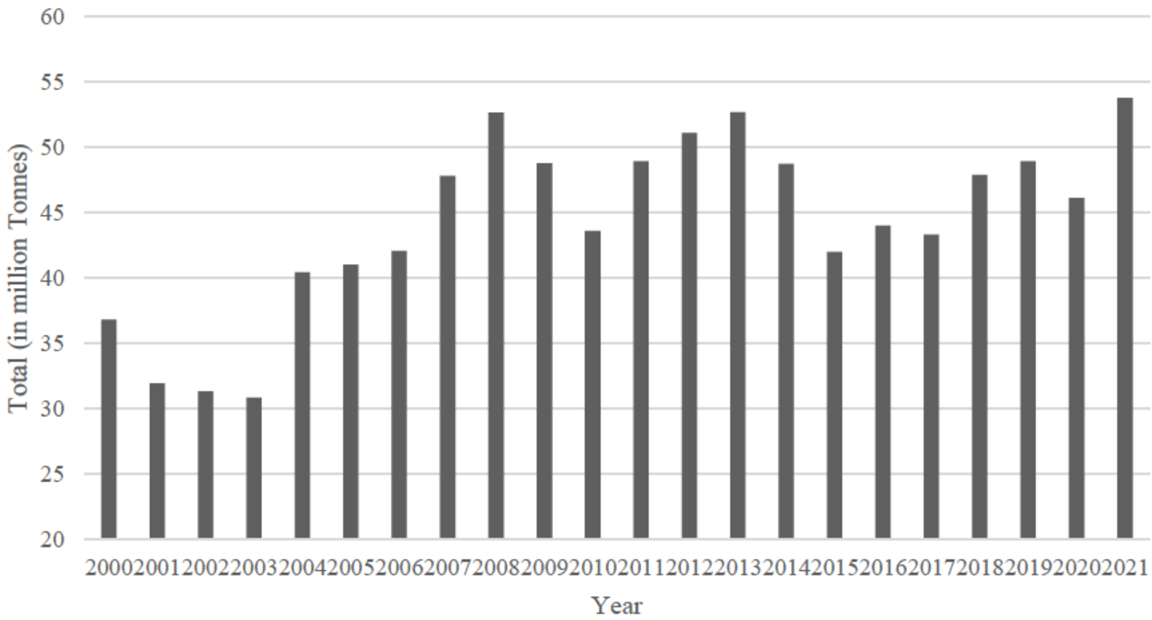

Figure 8 – Queensland Extractive Production 2001 to 2021 (Department of Natural Resources Mine and Energy, 2022)

In 2021, North West Queensland was responsible for 9% of hard rock, sand, and gravel product quarried, amounting to 4.6 million tonnes of quarried product (Figure 9).

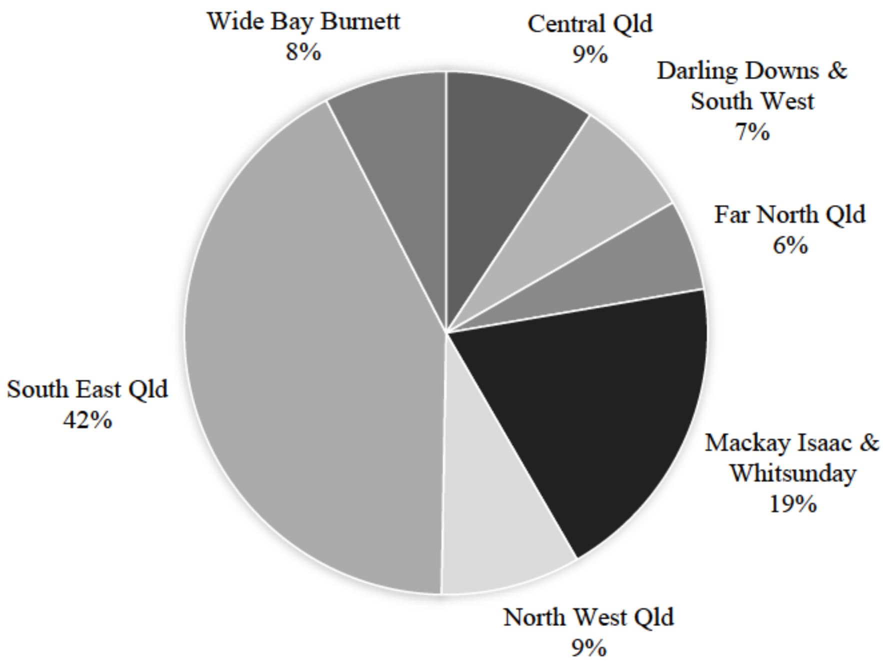

Figure 9 – 2021 Queensland Extractive Industry Production by Region (Department of Natural Resources Mine and Energy, 2022)

Figure 10 further shows the materials produced in the North West Queensland area in 2021, with 35% of quarried material used for road base or subbase applications.

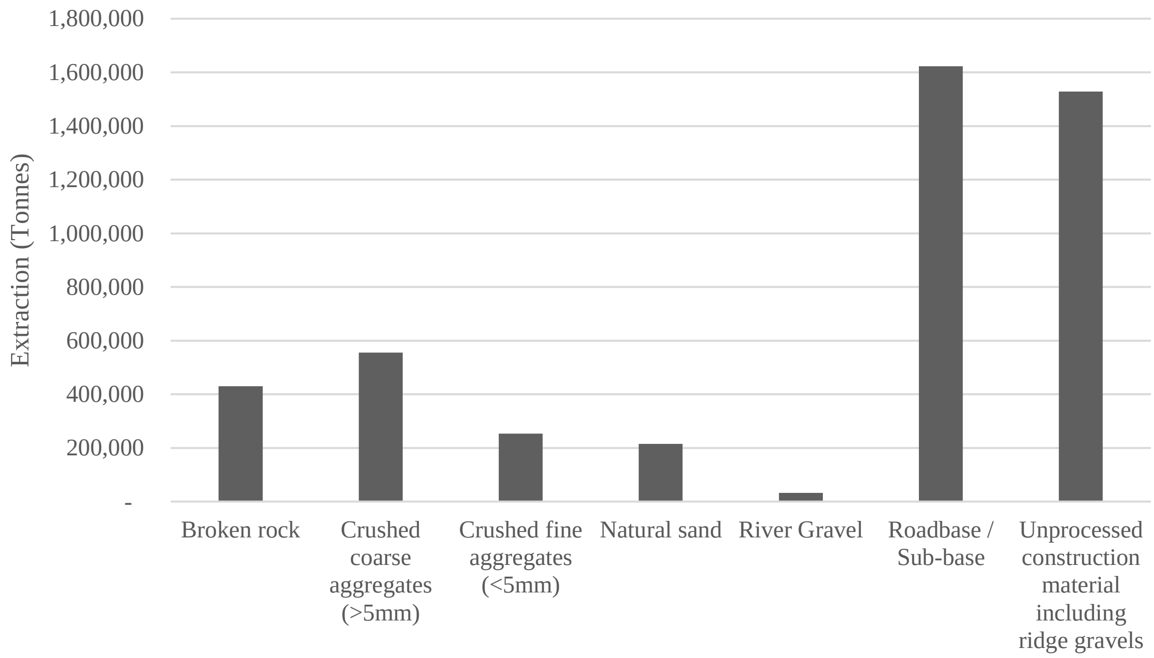

Figure 10 – 2021 North West Queensland Industry Production (Department of Natural Resources Mine and Energy, 2022)

Given the environmental, economic, and social challenges associated with conventional road base materials, there is a growing need for sustainable alternatives. In recent years, recycled glass has emerged as a promising alternative for road base construction. Its unique properties, availability, and potential for recycling make it an attractive material for sustainable road infrastructure development. North West Queensland can reduce the extraction of virgin materials by increasing the percentage of recycled materials allowed in road pavement and promoting the use of recycled glass in pavement as standard practice. This would have the added benefit of increasing the percentage of recovered waste glass, which would help Australia reach the goal of 80% glass recovery by 2030.

2.5. Waste Glass

For over 9000 years, glass has been utilised as one of the earliest man-made materials. Glass is theoretically 100% recyclable and can be recycled continually without degradation in quality (Finkle & Ksaibati 2007). High temperatures are used to melt silica, sodium carbonate, dolomite, and limestone. The mixture is then cooled and solidified to produce glass. Different chemical compositions and additives result in various forms of glass, including vitreous silica, alkali silicate, soda-lime glass (used in containers, float glass, sheet glass, light bulbs, and tempered ovenware), borosilicate glass (used in chemical apparatus, pharmaceuticals, and tungsten sealing), lead glass (used in colour TV funnels, neon tubing, electronic parts, and optical dense flint), barium glass (used in colour TV panels and optical dense barium crowns), and aluminosilicate glass (used in combustion tubes, fibreglass, and resistor substrates) (Hogland, 2014). Glass packaging is produced in three different colours: amber, green, and clear (Allan, 2019). Table 1 details glass production rates, recycling and landfilling rates for different countries.

Table 1 – Generation of Glass Waste Different Countries *(Wahid Ferdous, 2021)*

Country	Production of Glass (Million Tonnes)	Recycling Rate	Landfilling Rate
USA	11.4	21	75
Canada	0.75	40	60
Australia	1.1	57	43
UK	2.4	45	-
Germany	2.5	80	-
Japan		96	-
China	-	20	-
India	21	45	-

Majority of glass packaging waste is collected through mixed collections from households or commercial sites. In 2019 an estimated 126,000 tonnes of glass were collected through the Containers for Change scheme (Allan 2019). The Council of Australian Governments (COAG) noted in 2019 that Australia needs to take more responsibility for its waste generation and establish a plan to ban the export of waste plastic, paper, glass, and tires (Department of Climate Change 2021). As part of the COAG waste export bans, in March 2020, glass waste was banned for export under the Recycling and Waste Reduction Act 2020 (Department of Climate Change 2022).

The National Waste Report 2018 stated that alternative markets for recycled glass, such as in-road base, remain underdeveloped and underutilised in Australia, presenting a significant opportunity for expansion (Consulting, 2018).

Figure 11 shows the trends in the generation and management of glass in Australia from 2006-07 to 2020-21.

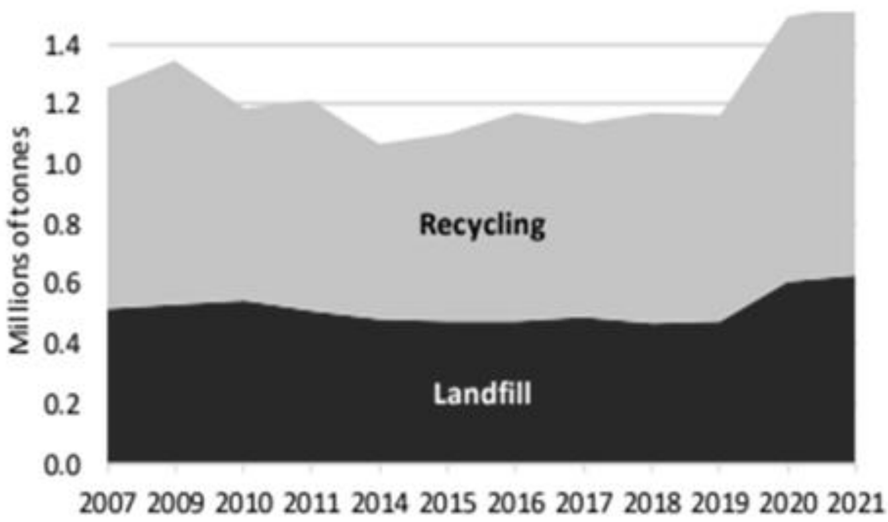

Figure 11 – Australia Management of Glass 2006-07 to 2020-21 (blue environment 2023)

The typical process of recycling glass in Australia in 2017-18 is shown in Figure 12. Approximately 40% of glass is still being sent to landfill, representing a significant missed economic opportunity.

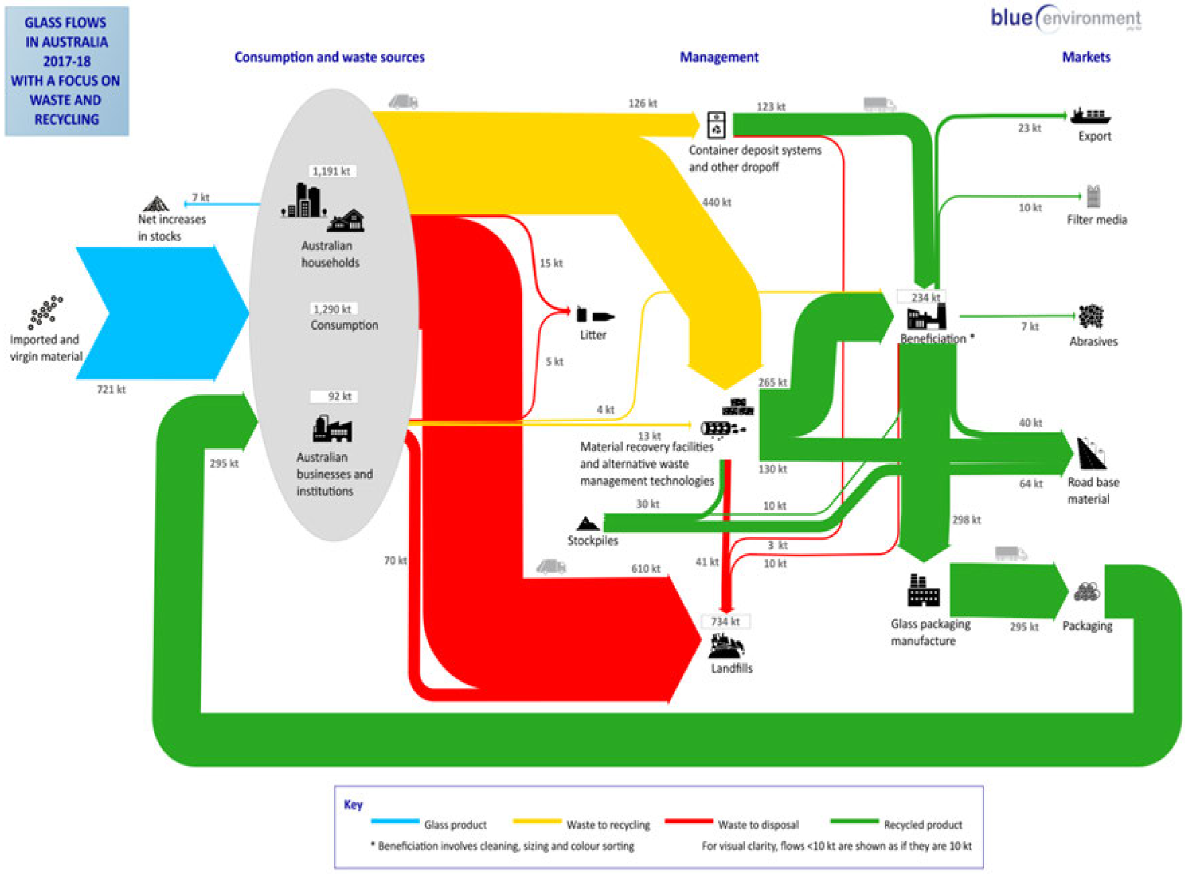

Figure 12 – Glass Packaging Flow Diagram (Allan 2019)

2.5.1. Cleaning and Crushing Process

The specific processing of waste glass heavily depends on the type of plant the MRF operates. Plants can range from simple to complex and elaborate. Townsville's MRF operates under a simple plant configuration, as shown in Figure 13.

Figure 13 – Townsville MRF Recycling Process (Townsville City Council 2018)

1. Glass is collected from households and businesses through the yellow bin and sent to the MRF for processing.
2. An infeed hopper deposits material onto a conveyor.
3. The friction, bounce, and spacing process sorts cardboard from the material.
4. A fine screen breaks glass into smaller pieces.

5. The friction, bounce, and spacing process sorts old newspaper prints from the remaining material. Contaminants are manually removed.
6. A ballistics screen.
7. Magnetics attract and remove steel materials.
8. The material continues over another glass screen, falling onto a conveyor.
9. Aluminium cans repel off the conveyor using high-speed electromagnetic fields.
10. Optical sorting separates the mixed plastics into six individual types.
11. A high-speed rotor implodes the glass, leaving it with smooth edges.
12. The glass is heated to remove remaining sugars and labels before going through a flat rotary mesh screen that separates the glass into three different sizes.
13. Products are baled before being dispatched

(Townsville City Council 2018)

2.5.2. North Queensland Region

The North Queensland Regional Organisation of Councils (NQROC) region has nine active landfills, including one privately owned facility that handles small quantities of building waste (Figure 14). A materials recovery facility (MRF) processes domestic kerbside recyclables from the region, the northern part of Whitsunday Regional Council, commercial recyclables, and container exchange materials.

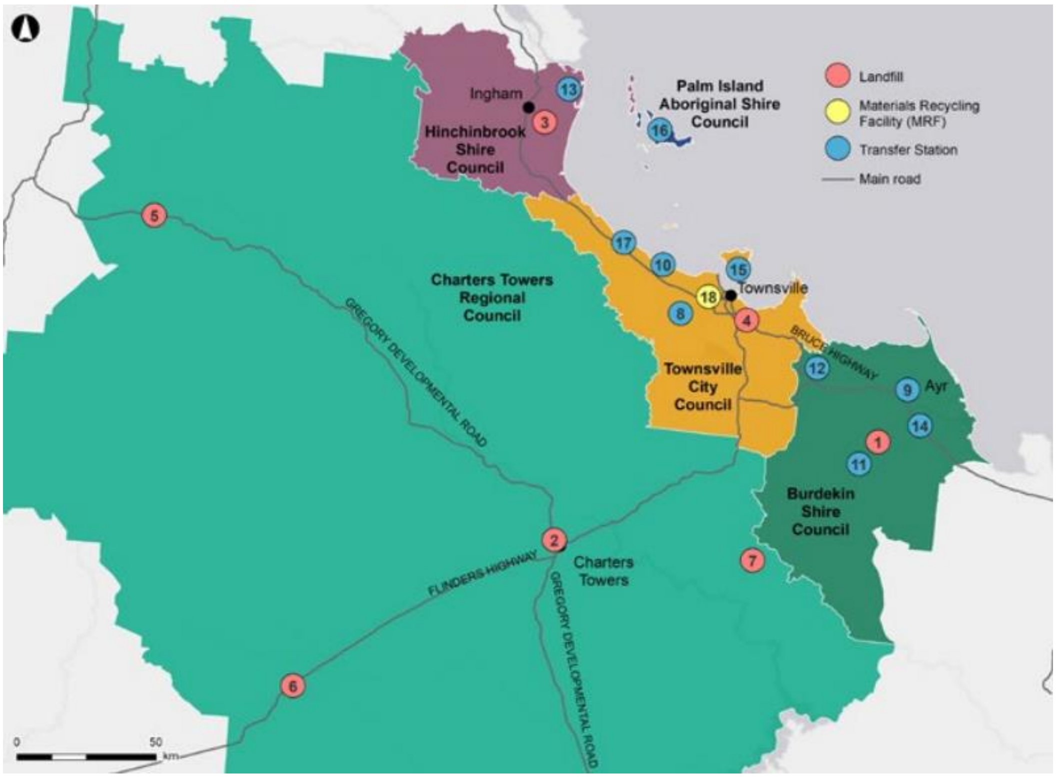

Figure 14 – NQROC Waste Services and Infrastructure (North Queensland Regional Organisation of Councils 2019)

Townsville City Council's Stuart Waste Facility has approximately 20 years of remaining capacity. This capacity must be preserved at all costs to prolong the need for constructing a new landfill.

In November 2022, Townsville City Council audited 500 waste and 500 recycling bins across 17 suburbs. The average household generated 14.73 kg per week of residual waste and 3.67

kg per week of recycling (EC Sustainable 2023). Recyclable glass makes up 29.2% of recyclable materials in recycling bins and 2.4% in waste bins. Figure 15 shows the Mobile Garbage Bins (MGB) composition for general waste and recycling bins.

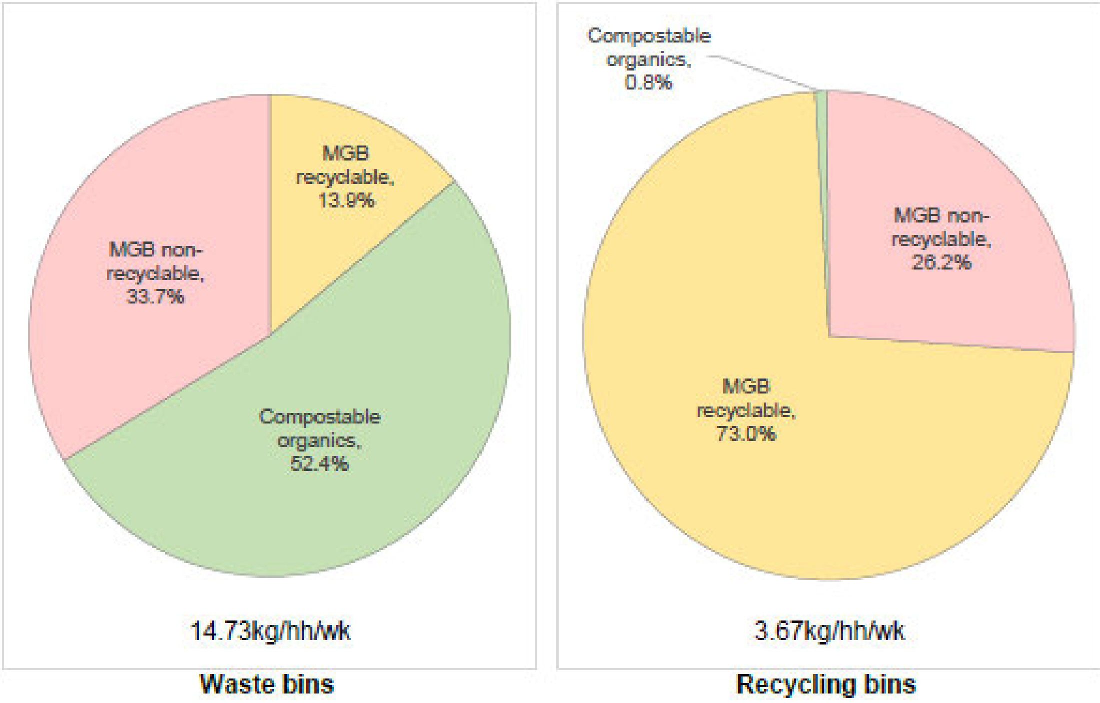

Figure 15 – Generation and Composition of Waste (EC Sustainable 2023)

2.5.3. End of Waste Code

The Department of Environment and Science published the End of Waste Code (EOW Code) for Glass Fines in 2022 in accordance with the Waste Reduction and Recycling Act 2011 (WRR Act). Under section 155 of the WRR Act, waste stops being classified as waste and becomes a resource when it meets the requirements of the EOW Code.

Before operating under the EOW Code, the producer must be a registered resource provider. As per Section 6.3 of the code, glass fines must comply with the following criteria and quality characteristics to use, sell, or give the resource away:

a) Generated by mechanical processing of waste glass; and

b) Contains no more then 2% foreign materials, where no more than 0.5% is labelling and residues; and

c) Does not exceed the quality criteria (Table 2).

Table 2 – Resource Quality Criteria *(Department of Environment and Science 2022)*

Quality Characteristic	Total maximum concentration (mg/kg)
Arsenic	20
Cadmium	1.5
Chromium (total)	40
Copper	120
Lead	100
Mercury	1
Molybdenum	10
Nickle	20
Zinc	300
Electrical Conductivity	2.0dS/m
Total Organic Carbon	2.0%

2.5.4. Physical properties

Crushed glass particles are physically angular and include flat and elongated particles. The degree of processing affects the angularity and the amount of flat and elongated particles. Smaller particles have less angularity and fewer flat and elongated particles (Federal Highway Administration 1998). Crushed glass from different suppliers produces a different particle size distribution and foreign particles based on different machines or processes in crushing waste glass, resulting in different geotechnical properties of recycled glass (Disfani et al. 2011). Previous research has obtained mixed results for the geotechnical parameters of recycled glass. Table 3 presents recycled glass particles' fundamental physical properties based on other research works. The proportion of fine particles is gradually low, and most are within sand or gravel sizes. It is important to note that recycled glass is principally classified as well-graded sand or well-graded gravel.

Table 3 –Physical Properties of Recycled Glass Particles (Research by others)

	USCS Soil Classification	Maximum Particle Size (mm)	Coefficient of uniformity (C_u)	Coefficient of curvature (C_c)	Fine content %	Sand content %	Gravel content %	Specific gravity (G_s)
(Ksaibati, 2007)	SP	25.4	4.5	1.7	0.6	63	36.4	19.6-2.41
(Centre, 1998)	SW	19.2	9.8	1.5	2	70	28	2.49
Su et Chen, 2002	SP	4.75	4.4	1.2	1	99	0	2.54
(Joseph Wartman ; Dennis G. Grubb, 2012)	SW	9.5	6.2-7.2	1.1-1.3	1.2-3.2	70-91.3	5.5-28.8	2.48-2.49
(Dennis G. Grubb, 2006)	SP	9.5	4.5	1.2	0.4	70.4	29.2	2.48
(Ooi, 2008)	SP-SM	9.5	13	0.8	6	91	3	2.5
(Arulrajah et al., 2013)	SW	5	6.2	1.5	2.8	71.2	26	2.49
(M.M. Disfani, 2012)	FRG SW-SM	4.75	7.6	1.3	5.4	90	10	2.48
(M.M. Disfani, 2012)	MRG SW-SM	9.5	16.3	2.2	5.2	48	52	2.5

2.5.5. Chemical properties

Table 4 summarises the typical chemical composition of different colours of glass. Silicon dioxide (SiO2), commonly known as silica, is the primary chemical in all glass forms.

Table 4 – Chemical Composition of Colour Glass *(Abbas Mohajerani, 2017)*

Chemical Composition	Amber Glass (%)	Green Glass (%)	Brown Glass (%)	White Glass (%)
SiO_2	70.66	72.25	72.1	69.82
CaO	9.12	12.35	-	8.76
Na_2O	8.32	10.54	-	8.42
Al_2O_3	6.53	2.54	1.74	1.02
FeO_3	2.52	-	0.31	0.55
MgO	1.45	1.18	-	3.43
K_2O	1.03	1.15	-	0.13
TiO_2	0.27	-	-	-
P_2O_5	0.07	-	-	-
MnO_3	0.04	-	-	-
Cr_2O_3	-	-	0.01	-
SO_3	-	-	0.13	0.20
Na_2+K_2O	-	-	14.11	-
CaO + MgO	-	-	11.52	-

2.5.6. Potential leaching issues

Disfani 2011 investigated fine recycled glass samples for the total concentration (TC) and Australian Standards Leaching Protocol (ASLP), shown in Table 5. As per ASLP, the samples were tested in slightly acidic and alkaline fluid solutions. The results suggested that the samples do not exceed the thresholds for category C of waste and material/contaminated soil per the limits defined in the End of Waste Code for Glass Fines (Department of Environment and Science 2022).

Table 5 – Total Concentration and AS Leaching Protocol *(Disfani et al. 2011)*

Contaminant	TC (mg/kg of dry weight)	ASLP (Acet) (mg/L)	ASLP (Borate) (mg/L)
Arsenic	<5	<0.01	<0.01
Cadmium	0.5	0.004	0.02
Chromium	<5	<0.01	<0.1
Copper	6	0.12	<0.1
Lead	12	0.19	<0.1
Mercury	<0.05	<0.001	<0.01
Nickle	<5	<0.01	<0.1
Selenium	<5	<0.01	<0.1
Silver	<5	<0.01	<0.1
Zinc	34	0.79	<0.1
Cyanide	<5	<0.05	<0.05
MAHs	<0.1	<0.001	<0.001
Benzene	<0.1	<0.001	<0.001
PAHs	<0.1	<0.001	<0.001
Benzo(a) pyrene	<0.1	<0.001	<0.001

2.6. Waste Glass as a Construction Material

Due to its non-biodegradable nature, glass takes significant time to break down naturally. When glass waste cannot be recycled, it is typically disposed of in landfills, leading to environmental concerns. A promising alternative to mitigating the landfill issue involves utilising glass waste in construction. Researchers have examined the utilisation of crushed recycled glass in various construction and environmental applications, including:

- Thermal insulation for prefabricated panels
- Concrete aggregate
- Cement replacement
- Glassphalt (glass-asphalt)
- Trench, pipe and foundation backfill
- Cementitious glass
- Lightweight bricks
- Water filtration systems
- Alternative to granitic sand and gravels
- Glass structures that support sea-bed erosion

(Sustainability Victoria 2018; Phoenix Compactors & Balers 2015)

While glass aggregate as a substitute in road base has been investigated globally, most of these investigations are confined to laboratory experiments, and only a few have been conducted within Australia or explored the practical application of recycled glass in real-world construction scenarios.

2.6.1. Australian Specifications

RCG is permitted as fine material in unbound granular applications in several states across Australia. Table 6 summarises the available specifications for the use of RCG in road pavements.

Table 6 – Transport Agency Specifications for the Use of RCG in Unbound Granular Material (Davcev et. Al 2022)

Transport Agency	Specification	Application
TMR (Qld)	MRTS05, MRST36	Subbase and subgrade (Type 2 materials)
TfNSW (NSW)	QA Specification 3051	Base and subbase material
DoT (Vic)	Sections 702, 801, 813 RC 500.02	Base, subbase and filter material

2.6.1.1. Queensland

Transport Main Roads (TMR) Queensland specification MRTS05 Unbound Pavement allows for 20% of recycled glass in lower quality granular materials; material subtype 2.3 (subbase), 2.4 (lower subbase course) and 2.5 (lower subbase and subgrade). It is important to note that TMR has yet to complete studies incorporating more than 20% recycled glass. The recycled glass must also comply with TMR specification MRTS36 Recycled Glass Aggregate (Transport and Main Roads 2022).

Specification MRTS36 requires RGA to be:

a) nominal size 5mm or less,

b) produced from food and beverage glass,

c) processed to a consistent grade,

d) cubical in shape, and

e) essentially free of contaminates and free from any putrid odour.

(Transport and Main Roads 2022).

2.6.1.2. New South Wales

Transport for New South Wales (TfNSW) limits glass fines to 10% in unbound or modified base and subbase and 10% maximum inbound base and subbase. As per QA Specification 3154, the material must be primarily container glass, clean and washed to ensure it is free from sugars, paper, or other contaminates (Table 7) (Transport for NSW 2020).

Table 7 - – TfNSW Material Requirements *(Transport for NSW 2020)*

Property	Test Method	Acceptance Criteria
Particle size distribution		
Nominated particle size distribution envelope	AS 1141.11	Within nominated particle size distribution envelope
Material finer than 75 μm	AS 1141.12	Report
Dry Density		Report for all properties
Percentage of oversize material		
Flow time	TfNSW T279	
Uncompacted void content		
Dry particle density		Report for all properties
SSD density	AS 1141.5	
Water absorption	AS 1141.5	< 1.0%

Where TfNSW have listed that a report is required there are no conformity criteria, however, the test results must be reported.

2.6.1.3. Victoria

Recycled crushed glass sand (RCGS) has been permitted as a sand replacement in the base and lower course material since 2011. VicRoads Section 813 allows using glass fines as supplementary material in lower trafficked unbound flexible pavements. The total amount of supplementary materials shall not exceed 20% in base material and 50% in subbase. Percentages are based on the total dry mass of the crushed rock product.

Glass fines added to crushed rock mixes shall:

a) be manufactured by crushing recycled glass

b) contain no more than 2% by mass of contaminants such as paper, corks, metals, and other harmful materials

c) primarily container glass and not include glass from ceramics, cathode ray tubes, fluorescent light fittings and laboratory glassware

d) 5mm minus

e) cubical in shape, not sharp edged or elongated.

(VicRoads 2021)

2.6.2. Case studies of road projects in Australia

Queensland

In 2020, TRM Far North District delivered TMR's first project using recycled glass in asphalt. The project delivered a 1.2km asphalt resurfacing project along Malanda - Millaa Millaa Road. Underlying pavement repairs were completed using asphalt with 10% recycled glass and 5% in the surfacing layer. As a result of this project, TMR updated technical specification MRTS30 Asphalt Pavements to allow for recycled glass as a sand fine aggregate substitution in asphalt mixes (Queensland Government 2023).

NACOE Project P94 tested recycled glass from four different suppliers. Tests were limited to using a maximum of 20% recycled glass. Laboratory test results from one supplier showed that material mixed with 20% recycled glass improved characterisation properties compared to the same material with 0% glass (Danielle Garton 2021). Following this project, TMR updated the technical specification review of MRTS05 Unbound Pavements. If recycled glass meets the TMR specification, contractors and suppliers can replace virgin quarried aggregates with recycled ones (Environment Cultural Heritage and Corridor Management Team Program Management and Delivery (PMD) 2021).

2.6.2.1. New South Wales

Canterbury-Bankstown City Council (CBCC) collects approximately 8000 tonnes of glass yearly for comingled collections (Canterbury-Bankstown Council 2022). The Australian Road Research Board (ARRB) completed a project with the CBCC to implement RGA in road rehabilitation projects. Laboratory tests were completed to determine the optimum blend of crushed concrete and RGA. In 2022, CBCC undertook a field trial on Marion Street. A blend of 30% RGG and 70% crushed concrete was used as a granular subbase of 200mm thickness (Grenfell 2022).

In 2010, Waverley Council, in collaboration with various partners, including the New South Wales Department of Environment, Climate Change and Water, New South Wales Roads and Traffic Authority, Institute of Public Works Engineering Australia, and the Packaging Stewardship Forum, established the inaugural site in New South Wales to showcase the alternative utilisation of crushed glass in pavement construction as an approved material for use in the state's road infrastructure. The project involved the construction of two 100-meter pavement sections incorporating glass materials. The first site, at Blair Street, Bondi, used glass as part of the asphalt mixture, while the second site, at O'Brien Street, Bondi, incorporated glass into the concrete pavements. Waverly Council used 15 tonnes of glass in this project (Department of Sustainability n.d.).

Lockhart Shire Council commenced a project in 2015 to reduce crushed glass stockpiles at Kurrajong Recycling. From January 2018 to May 2019, the Lockhart Shire Council removed 5,000 tonnes of the stockpiled glass. The Council undertook trials using RGA in footpath construction, stormwater drainage and unsealed road re-sheeting (Lockhart Shire Council 2019).

2.6.2.2. Victoria

In Melbourne, Brimbank City Council (BCC) collaborated with ARRB to conduct a trial involving the incorporation of fine RGA in asphalt within two residential streets. This trial is divided into six sections covering a total road length of 800 meters from Newbury Street and

Gould Street, Deer Park. Over the next two years, the BCC and ARRB will continue to assess and monitor the road surface's performance. The asphalt composition features 10% recycled glass and 25% recycled asphalt (Australian Road Research Board 2022).

2.6.2.3. Western Australia

Main Roads Western Australia recommend reusing glass as it does not degrade over time. However, reuse is currently not an option in Western Australia due to the absence of glass reprocessing manufacturers. Main Roads Western Australia used approximately 70,000 tonnes of RGA (20% of fill content) on the NorthLink 3 project as a waste solution as embankment fill. The RGA was used to stabilise clay-based soils and materials. The use of RGA led to a reduction in virgin material used and reduced land clearing for virgin material stockpiles (Main Roads Western Australia 2022).

2.6.2.4. South Australia

The Department for Infrastructure and Transport (DIT) delivered the Regency Road to Pym Street. One hundred seventy tonnes of RGA was used at 5% in the lower layers of an arterial road. The Regency Road to Pym Street is the first project in South Australia where RGA has been used as a substitute for natural sand in the road base (Government of South Australia n.d.).

2.6.3. Case studies of road projects utilizing recycled glass in America

While uptake in Australia is slow, there are currently case studies of road projects using waste glass internationally. Correctly sized recycled glass can be used as an unbound aggregate substitute in base and subbase layers (Lee 2007). Table 8 summarises some recommended specifications published by the Federal Highway Association for using fine recycled glass aggregate in road work applications.

Table 8 – Applications of Recycled Glass *(Research by others)*

Recommended Applications	Optimum limit of recycled glass (%)	Blended material with recycled glass	Recommendations	Researcher
Base Subbase	15 30	Natural aggregate	Gradation specification, max debris level 5%	(Federal Highway Administration 1998)
Base Subbase Embankment	15 30 30	Natural aggregate	max debris level 5%	(Centre, 1998)
Base	10 – 20	Natural aggregate	max debris level 5%	(Ooi et. Al 2008)
Structural fill, backfill & embankment	50	Marginal material	NA	(Joseph Wartman ; Dennis G. Grubb, 2012)
Fill	20 – 80	Dredge material	NA	(Dennis G. Grubb, 2006)
Base	20	Natural aggregate	Max size of 12.7mm for recycled glass, relatively free from debris	(Finkle & Ksaibati 2007)
Subbase	30	Crushed rock	Be careful about debris content	(M. M. Y. Ali 2011)
Subbase	30	Crushed concrete	NA	

2.6.4. Properties of Recycled Glass in Road Base

2.6.4.1. Particle Size Distribution

In the Austroads trials undertaken in 2022, the particle size distribution of crushed glass was compared to that of natural sand. RCG products were crushed to achieve a desired particle size distribution falling within the middle of the natural sand particle size distribution envelope, as shown in Figure 16.

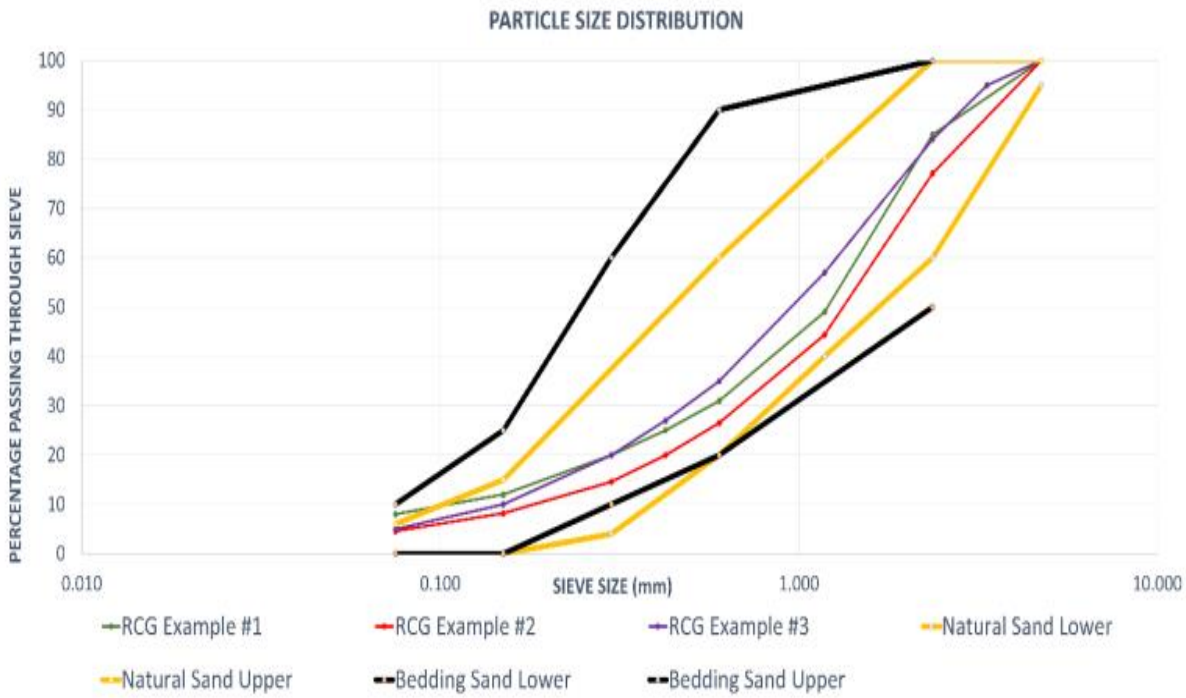

Figure 16 – Natural Sand vs RCG Particle Size Distribution (Petar Davcev, 2022)

RCG products were processed in two different plants. Example 1 RCG was processed at the iQRenew Virtual Quarry in Wyong, NSW, where glass collected through Council kerbside recycling is processed. iQRenew's Virtual Quarry has processed over 200,000 tonnes of recovered glass into an aggregate sand substitution for reuse (iQRenew n.d.). The final glass sand from iQRenew can be seen in Figure 17.

Figure 17 – Contaminated Glass Transformed into Recycled Glass Sand (iQRenew n.d.)

Sample 2 was procured from a CDE Plant (Figure 18). The plant processes up to 150 tonnes per hour of recycled materials. The plant combines washers, screens, dewatering systems, and thickening tanks. Having a closed-loop design, the plant is resource conscious by recycling up to 90% of the wastewater for reuse in the system. The fine materials are captured in the thickening tank, and a mixture of the fines and other materials is a form of sludge that is then used as clean fill or landfilled depending on the contamination levels of the product. The design of the RCG plant enables it to produce two glass sand replacement products in spec ranges 0-2mm and 0-4mm (CDE n.d.-a).

Figure 18 - Recycled Glass from CDE (CDE n.d.-b)

Figure 19 depicts the typical shape of glass aggregates at different size ranges. As the particle sizes decrease, they are more similar to the shape of naturally occurring aggregates used in roadbase.

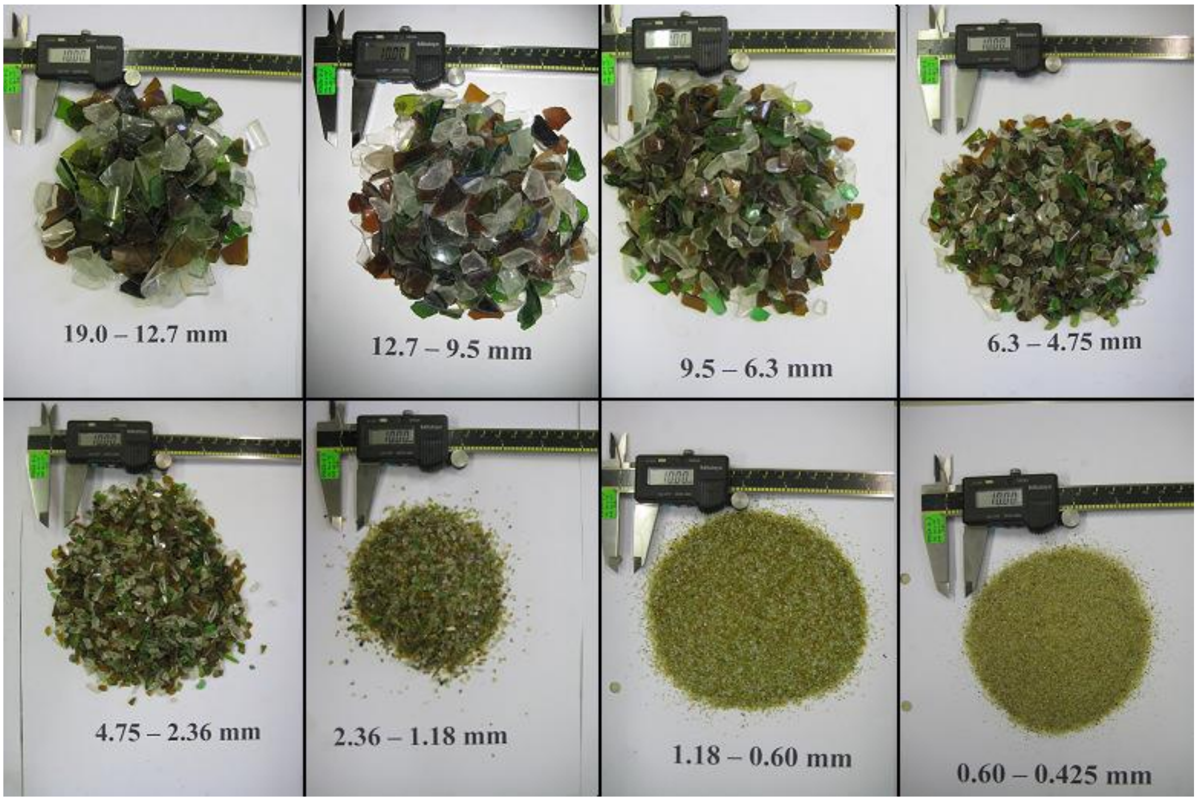

Figure 19 - *Glass Particle Shapes by Size (Disfani 2011)*

2.6.4.2. Compaction – Optimum Moisture Content

Disfani (2011) reported values of Maximum dry density (MDD) and optimum moisture content (OMC) using standard and modified compaction (Table 9).

Table 9 – MDD and OMC test results for RGA *(Research by others)*

Reference	Crushed glass/glass cullet gradation	Maximum dry density (t/m3) compaction test		Optimum moisture content (%) / compaction test	
(Disfani 2011)	4.75 mm minus	1.70	1.78	12.5	10
	9.5 mm minus	1.84	1.99	9.0	8.8
(Wartman 2004)	Crushed glass & gravel (<2mm) (source 1)	1.71	1.87	12.8	9.7
	Crushed glass & gravel (<2mm) (source 2)	1.69	1.78	13.6	11.2
(Pennsylvania Department of Transportation 2001)	Crushed glass & gravel (<2mm) (source 1)	1.72	1.79	13.2	10.8
	Crushed glass & gravel (<2mm) (source 2)	1.79	1.88	11.9	10.8
(Soil & Environmental Engineers 1998)	6.3 mm minus (sample 1)	1.67	1.77	4.7	5.6
	6.3 mm minus (sample 2)	1.68	1.82	5.0	5.2

2.6.4.3. California Bearing Ratio

California Bearing Ratio (CBR) measures soil strength indirectly based on its resistance to penetration. TMR specification MRTS05 requires a CBR of a minimum of 80% for base layers and a minimum of 45% for subbase layers.

CBR findings by others for recycled glass samples are summarised in Table 10. The majority of the CBR results obtained by other research meet the requirements of subbase layers, while several samples met the requirements for base layers.

Table 10 – Summary of CBR Results for Recycled Glass (Research by Others)

Researcher	Recycled Glass (%)	CBR (%)
(Federal Highway	50	42 – 125
Administration 1998)	15	132
(Centre, 1998)	50	30 – 60
	15	132
(Ooi et. Al 2008)	100	75 – 80
(Joseph Wartman ; Dennis G. Grubb, 2012)	100	47 – 48
(M.M. Disfani, 2011)	100	42 – 46
(M.M. Disfani, 2011)	100	73 – 76

2.7. Industry and Community Concerns

Concerns about using recycled waste in construction have been raised, particularly concerning occupational health, safety, and the environment. These concerns include issues related to crystalline silica dust and potential skin or eye injuries during handling (Lim et al. 2020). While dust can be generated during the glass-crushing process, it is essential to note that silica in glass is mainly in an amorphous form, which lacks carcinogenic properties, unlike the crystalline form found in silica sand. Research has concluded that Recycled Crushed Glass (RCG) is, in fact, safer than sand, as it contains less respirable crystalline silica, minimising the risk of exposure (Winder 2011).

Furthermore, it has been reported that crushed glass particles smaller than 19 mm pose no greater risk of skin cuts than other typical construction aggregates. They undoubtedly present fewer hazards compared to larger glass fragments from crushed glass bottles, drinking glasses, and plate glass. Glass particles measuring between 150μm and 6 mm can be considered entirely benign; anything less than 150µm is closer to dust that can be breathed in (Lim et al. 2020).

2.8. Life Cycle Assessment

Life Cycle Assessment (LCA) represents a comprehensive approach that provides a holistic view of the environmental impacts of a product or process throughout its entire life cycle. LCA methodology enables decision makers to assess various processes and recommends the most environmentally sustainable choice for their projects. Within the construction sector, products typically progress through five primary life cycle stages, each of which entails energy consumption and the potential for environmental effects (N. Sivakugan 2016).

The pavement life cycle includes material production, construction, use, Maintenance and Rehabilitation and End-Of-Life, as shown in Figure 20.

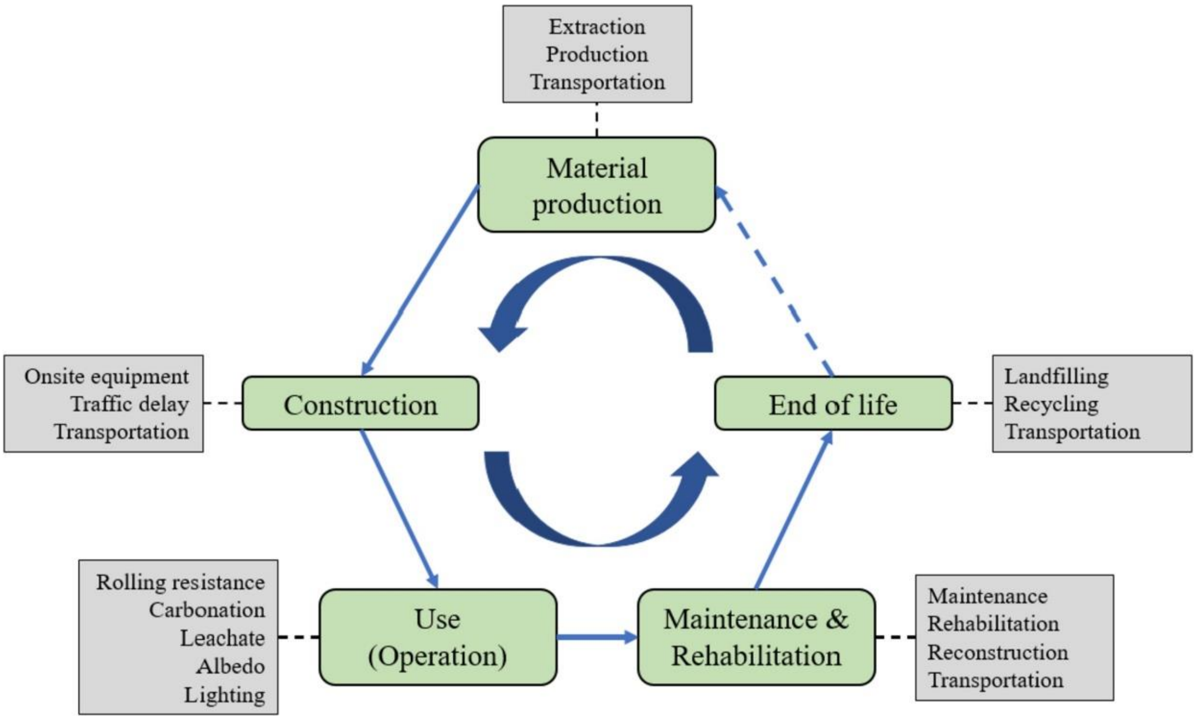

Figure 20 – Lifecycle of Pavement (Jin Li 2019)

2.9. Literature Conclusion

Based on the reviewed literature, it can be concluded that recycled crushed glass (RCG) has the potential to be used as a sustainable substitute in road pavements across Australia. Various state departments have already permitted the use of RCG in unbound granular applications, including subbase, subgrade, base, and filter materials. The specifications for using RCG vary among states, and the percentage of RCG allowed in the pavement mix is also limited. Case studies from Queensland and New South Wales have demonstrated the successful use of RCG in asphalt and road rehabilitation projects, respectively. These projects have led to updates in technical specifications, allowing contractors to use pavement materials that replace virgin quarried aggregates with recycled glass, permitted they meet the respective Government's specifications.

Overall, the use of RCG in road pavements can significantly reduce the amount of glass waste sent to landfills and help achieve sustainable development goals. Further research is required to investigate the long-term performance of RCG in pavement systems and its impact on the environment, human health, and economy.

This research will focus on the development of partially replacing sand at higher quantities in road base and with crushed recycled glass. This study also focuses on assessing the environmental and economic impacts through the alternative use of glass waste.

3. METHODOLOGY

3.1. Introduction

This research studies the application of recycled glass sand (RGS) as a partial replacement for quarried sand in road base. For the dissertation, four samples will be produced using Type 2.3 gravel sourced from a local supplier and recycled waste glass from the local materials reuse facility. The testing methodology has been developed in accordance with Townsville City Plan Planning Scheme Policies. Testing procedures have been adopted from Australian Standards and the Department of Transport and Main Roads (Transport and Main Roads 2023).

3.2. Experimental Procedures

3.2.1. Materials

ownsville City Council's MRF supplied the mixed-coloured soda-lime glass and utilised it as a partial sand replacement. Townsville City Council collects commingled recyclables from rateable properties' recycling bins. The recyclable waste is transported to the material reuse facility (MRF), where the glass is separated from commingled recyclables, crushed, and imploded.

Type 2.3 MRTS05-compliant road base was generously donated from Stradacon Penna Quarry. Stradacon Penna is a local Townsville company that produces quarried products for the Townsville Region. Stradacon Penna is a supplier for Townsville City Council and supplies a large quantity of road base for use in Council projects. Stradacon Penna is also a registered supplier with the Transport and Main Roads Quarry Registration System requirements as per MRTS05.

3.3. Experimental Method

The experimental study included:

a) Recycled Glass Aggregate Pre-Treatment

b) Materials Properties Tests – Particle Size Distribution

c) Optimum Moisture Content

d) California Bearing Ratio (CBR) Test

e) Atterberg Limits

3.3.1. Recycled Glass Aggregate Pre-Treatment

Testing required RGA that conformed to sand particle size. The RGA was air-dried at 100 degrees for 24 hours. Then, using the 600µm and 2.36mm sieve, the RGA was mechanically shaken to remove particles that did not fit within the compliant range. The remaining RGS was passed through a riffle box to ensure a homogeneous mix and split into test lots (Figure 21).

Figure 21 – Recycled Glass Sand (0.6 – 2.36mm)

3.3.2. Road Base Mix

To ensure the uniformity of test lots, the road base is subdivided into consistent samples using a riffle box, following the guidelines set in AS 114.2. Subsequently, each sample of road base undergoes sieving via a mechanical shaker, targeting the specific proportion of sand particles (ranging from 0.6 to 2.36mm). Quarried sand within the test lot is then extracted and substituted with an equal volume of recycled glass sand (RGS). Each lot is subsequently passed through the riffle box to achieve a homogeneous distribution of the RGS throughout the gravel.

Figure 22 - Type 2.3 Gravel with 20% RGS

3.3.3. Material Properties Test

Chemical Testing

Sharp & Howells Chemical Analysis & Materials Testing Laboratory was engaged to complete the chemical testing of recycled glass aggregates. Sharp & Howells operates a chemical analysis laboratory accredited by the National Association of Testing Authorities (NATA) (Sharp & Howells n.d.). The scope of work included testing for conductivity, sugar, heavy metals, and total organic carbon in both unwashed and washed glass samples.

Particle Size Distribution

The particle size distribution of each aggregate sample is to be determined in accordance with AS 1289.3.6.1. This test is a valuable tool to determine the gradation of a material by allowing it to pass through a series of sieves. For this investigation, it was used to determine if samples combined with recycled glass sand met the requirements of gravel specification.

The test involves nesting sieves together in decreasing size from top to bottom. Air-dried test samples were placed in the top sieve and mechanically shaken (Figure 23). The material obtained on each sieve is weighed to determine the percentage of material passing, and the cumulative percentage remaining is calculated to plot the particle size distribution curve (Australian Standards 2009).

Figure 23 - Mechanical Shaker PSD

The particle size distribution for the road base is set in TMR specification MRTS05 Unbound Pavements, as shown below in Table 11.

Table 11 - MRTS05 – Grading Envelopes – Type 2 (containing < 70% recycled materials) (Roads, 2022)

Subtypes	2.1 and 2.2	2.3 and 2.4	2.5
Test Sieve Size (mm)	Percent Passing by Mass		
75.0	100	100	100
37.5	100	90 – 100	85 – 100
19.0	87 – 100	80 – 100	
9.5	67 – 87	60 – 90	55 – 95
4.75	50 – 70	42 – 76	–
2.36	36 – 52	30 – 60	30 – 80
0.425	14 – 24	14 – 28	14 – 60
0.075	7 – 16	7 – 16	7 – 30

3.3.4. Atterberg Limits

The Atterberg limits were determined using the Transport and Main Roads Materials Testing Manual – Part 5, test methods Q104D, Q105 and Q106. Test procedures were conducted on a fine faction soil sample screened on a 425μm sieve.

Liquid limit of soil – one point (Q104D)

A portion of the soil fines was transferred to a mixing bowl, and a small amount of water was added. Using a spatula, the soil fines were mixed thoroughly to form a homogeneous paste. The sample was then placed in an airtight container to cure for a minimum of 12 hours. After curing, the sample was mixed thoroughly and placed into the test cup. The test sample was added to the test cup in thirds, ensuring that any air was removed from each layer. The test sample was then levelled to the surface of the test cup rim in no more than three strokes of a spatula. With the test cup positioned centrally under the penetrometer shaft and cone at its maximum height, the penetrometer was released for 5 seconds, and the depth was recorded. The penetrometer head was returned to its original position cleaned, and the test cup was removed. The soil sample was then returned to the mixing bowl and mixed for 30 seconds.

The penetrometer tests were repeated until two penetration tests were within 1.0mm of each other and a depth range of 10-21mm. Approximately 30g of the soil was removed from the sample and dried to determine the moisture content per Equation 1.

Moisture content:

$$w = \frac{m_b - m_c}{m_c - m_a} * 100 \qquad \text{Equation 1}$$

where

w = moisture content of soil

m_b = mass of container and wet soil

m_c = mass of container and dry soil

m_a = mass of container

(Australian Standards 2005)

Correction factor for penetration values:

$$f = 2.1261p^{-0.2752} \qquad \text{Equation 2}$$

where

f = correction factor for the penetration value of the sample

p = average penetration value

(Transport and Main Roads 2023) Q104D

Liquid limit:

$$w_{cl} = wf \qquad \text{Equation 3}$$

where

w_{cl} = liquid limit of the soil

w = moisture content of the soil

f = correction factor for the penetration value of the sample

(Transport and Main Roads 2023) Q104D

Plastic limit and plasticity index of soil (Q105)

Approximately 50g of the soil/water mixture from the liquid test was used to determine the plastic limit of the soil. Using subsamples of around 10g, the subsample is rolled between the fingers and a glass plate to create approximately 90mm long soil threads. The thread is then broken down into shorter pieces and rolled until they have a diameter of 3mm. All the soil was rolled into threads with a diameter of 3mm before kneading them together again. All of the soil is rolled into threads and kneaded until the crumbing of the threads occurs. Once approximately 10g of the threads reach their plastic limit, they are placed into a container. The process is then continued until a second sample of 10g reaches its plastic limit. The samples are dried to determine the moisture content (Equation 1).

Plastic Limit:

$$PL = \frac{w_1 + w_2}{2} \qquad \text{Equation 4}$$

where

PL = plastic limit of the soil

w_1 = moisture content of first test portion

w_2 = moisture second of first test portion

(Transport and Main Roads 2023) Q105

Plasticity index:

$$PI = LL - PL \qquad \text{Equation 5}$$

where

PI = plasticity index of the soil

LL = liquid limit of the soil

PL = Plastic limit of the soil

(Transport and Main Roads 2023) Q105

Linear shrinkage of soil (Q106)

Using a subsample of soil/water mixture prepared for the liquid limit test was filled in an oiled linear shrinkage mould (stainless steel, length 150mm, width at top 25mm, width at bottom 20mm and depth 15mm). The soil is filled into the corners, and air bubbles are removed by pressing the soil firmly with a spatula. The surplus soil was cut off with a steel ruler. The filled mould was then placed into the oven to dry. After drying, the soil was removed from the mould, and the top and bottom soil bar measurements were recorded.

Linear shrinkage

$$LS = \frac{L_1 - 0.5(L_2 + L_3)}{L_1} * 100 \qquad \text{Equation 6}$$

where:

LS = linear shrinkage of the soil

L_1 = internal length of the mould

L_2 = bottom length of the soil bar

L_3 = top length of the soil bar

(Transport and Main Roads 2023) Q106

3.3.5. Optimum Moisture Content

Determining the optimum moisture content of the soil is a critical parameter that significantly influences its engineering properties and behaviour. AS 1289.5.1.1 provides the standardised method for determining optimum moisture content. This method involves compacting a soil sample at various moisture levels into a cylindrical mould using specified compaction energy. The compacted specimens (Figure 24) were then dried to determine the moisture content and dry density to establish the compaction curve (Australian Standards 2017).

Figure 24 - 30% Recycled Glass Sand Specimen after compaction

Equation 1 was used to determine the moisture content for each sample:

Density of wet soil:

$$\rho = \frac{(m_1 - m_2)}{V} \qquad \text{Equation 7}$$

where

ρ = density of wet soil

m_2 = mass of mould plus baseplate plus specimen

m_1 = mass of mould plus baseplate

V = measured volume of the mould

(Australian Standards 2017)

Density of dry soil:

$$\rho_d = \frac{100\rho}{100 + w} \qquad \text{Equation 8}$$

where

ρ_d = density of dry soil

ρ = density of wet soil

w = moisture content of the specimen

(Australian Standards 2017)

The point on this curve where the maximum dry density (ρ, ρ_d) is attained represents the optimum moisture content (OMC). This pivotal moisture content value ensures the soil has the highest density achievable under compaction. The road base mix must have its optimum moisture content determined to ensure adequate compaction.

3.3.6. CBR Testing

The California Bearing Ratio (CBR) measures the strength of a soil or road base material and is widely used in the design of flexible pavement structures. CBR test is dependent on moisture content and level of compaction. Pre-testing was prepared and completed in accordance with AS 1289.1.1:2001, AS 1289.2.1.1:2005 and AS 1289.5.1.1:2017. The CBR for each sample was tested in accordance with AS 1289.6.1.1:2014.

The moisture content for each test sample was obtained using Equation 1. From the OMC determined for each sample lot, the additional water required to bring the sample to OMC was calculated and added to each sample, which was then left to cure in an airtight container for 24 hours. The sample was compacted in three equal layers using a standard compaction hammer with eight blows around the perimeter and three blows to the middle. A 4.5kg surcharge was added to the compacted soil sample before taking an initial swell measurement and adding the specimen to the water bath for four days. After soaking, the final swell measurement was taken before removing the sample from the water bath.

A surcharge load of 2.25kg was placed on the surface of the soil and placed in the loading machine. The loading machine is set to zero and the displacement measuring device was used to measure penetration. The load is applied at constant rate of penetration at 1.0±0.2 mm/min. The load readings were then read at minimum penetrations of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 7.0, 10.0 and 12.5mm before the penetration is stopped. The load-penetration curve was plotted. The force value is then read at penetrations of 2.5mm and 5.0mm. The greater value of the calculated results is taken as the CBR of the material.

Following penetration the soil is removed from the mould where the top 30mm and remaining specimen were placed in containers before drying to determine the moisture content of each of the samples.

Figure 25 - CBR Tests in Water Bath

Variation between optimum moisture content and moisture content during compaction:

$$w_v = OMC - w_1 \quad \text{Equation 9}$$

where

w_v = moisture content variation between OMC and moisture content during compaction

w_1 = moisture content of the soil during compaction

OMC = optimum moisture content of the soil

Dry density of the specimen before soaking:

$$\rho_d = \frac{1}{V_1} * \frac{m_2 - m_1}{\left(1 + \frac{w_1}{1000}\right)}$$ Equation 10

where

ρ_d = dry density of the specimen

m_2 = mass of the mould plus compacted soil

m_1 = mass of the mould

v_1 = volume of the specimen before soaking

w_1 = moisture content of the soil during compaction

Laboratory moisture ratio (LMR) of the specimen:

$$LMR = \frac{w_1}{OMC} * 100$$ Equation 11

where

LMR = laboratory moisture ratio

w_1 = moisture content of the soil

OMC = optimum moisture content of the soil

Swell:

$$S = \frac{h_2 - h_1}{117} * 100$$ Equation 12

where

S = swell of the specimen

h_2 = reading after soaking

h_1 = reading before soaking

Volume of the specimen after soaking:

$$V_2 = V_1\left(\frac{100 + S}{100}\right)$$ Equation 13

where

V_2 = volume of the specimen after soaking

V_1 = volume of the specimen before soaking

S = swell of the specimen

3.4. Life Cycle Energy Analysis

A cradle-to-gate Life Cycle Energy Analysis (LCEA) was completed to measure the environmental impacts of road base using recycled glass sand to quarried sand. The LCEA was completed in accordance with international standards ISO 14040: Principles and Framework for LCA and ISO 14044 – Requirements and Guidelines for LCA (International Organization for Standardization 2006a) (International Organization for Standardization 2006b). The assessment was completed using SimaPro software.

The cradle-to-gate assessment was consistent with the economic assessment: 1 km of rural road, one lane in each direction, a total of 10 m wide (3.3m lane widths and shoulders). A standard TMR granular cross-section has been adopted, as shown in Figure 26.

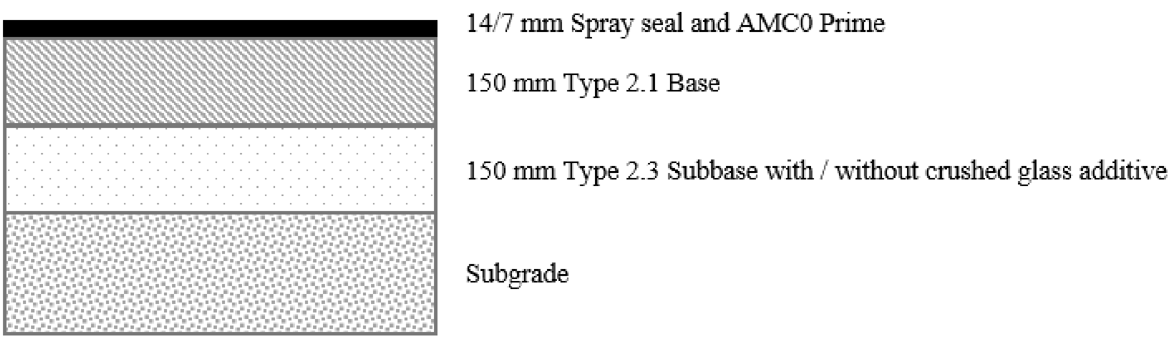

Figure 26 - Pavement Cross Section for LECA

3.4.1. Scenario Formulations

Life cycle assessment was completed for all four scenarios:

Scenario A: Production of 1km of road with standard type 2.3 subbase with naturally quarried aggregates

Scenario B: Production of 1km of road with standard type 2.3 subbase with naturally quarried aggregates and 20% recycled glass sand

Scenario C: Production of 1km of road with standard type 2.3 subbase with naturally quarried aggregates and 25% recycled glass sand

Scenario D: Production of 1km of road with standard type 2.3 subbase with naturally quarried aggregates and 30% recycled glass sand

A summary of the material inputs and associated Ecoinvent database descriptors is provided in Appendix A.

3.4.2. Sustainability Impact Assessment

The sustainability assessment was conducted using Simapro software` The methodology for the assessment was in accordance with ReCipe 2016 method for impact assessment. ReCipe 2016 breaks down the environmental impact into eighteen midpoint indexes and three endpoint indexes. These indicator scores demonstrate the relative severity on an environmental impact category. With a higher indicator, demonstrating a more severe impact on the environment. Figure 27 identifies the relationships between the impact categories, damage pathways and endpoint damage categories.

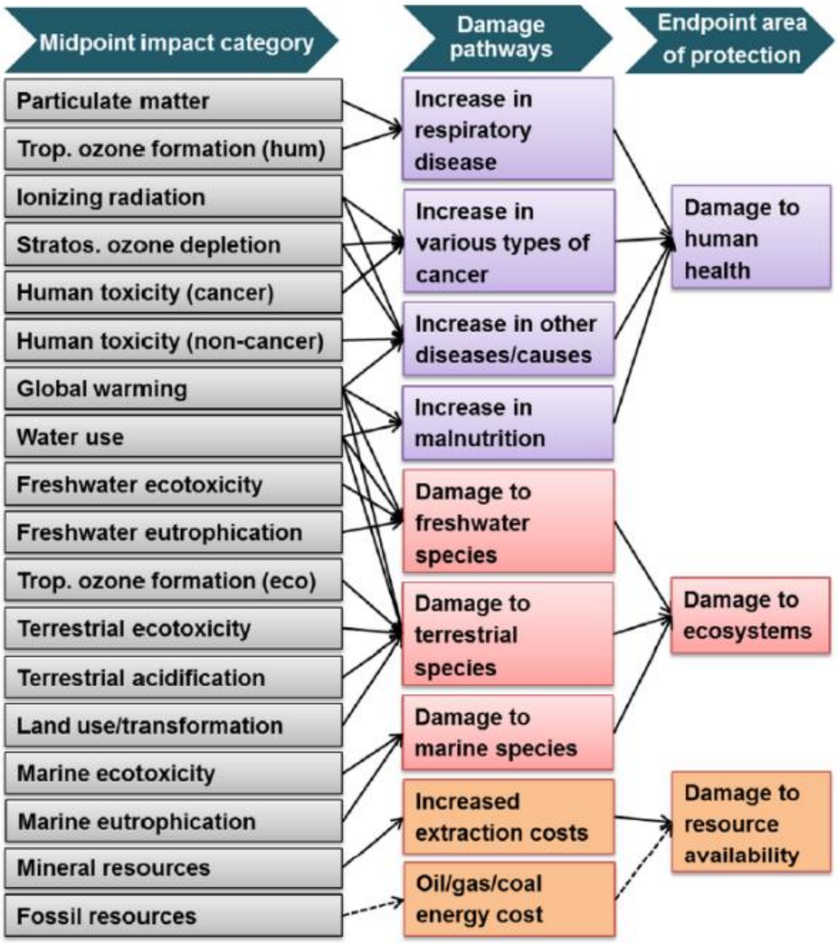

Figure 27 – SimaPro Relationships between midpoint impacts, damage pathways and endpoint impacts (PRé Sustainability 2020)

In this assessment the below midpoint categories (Table 12) as well as the endpoint indicators will be examined.

Table 12 - Midpoint Impact Categories

Impact category	Unit
Global warming	kg CO2 eq
Stratospheric ozone depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation, Human health	kg NOx eq
Fine particulate matter formation	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Terrestrial acidification	kg SO2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Land use	m2a crop eq
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m3

3.4.3. Life Cycle Energy Analysis Inputs

In addition to the ReCipe method, the Cumulative Energy Demand (version 1.11) methodology was used to estimate the energy demand of each of the scenarios. Material and energy inputs for the scenarios were sourced from the Ecoinvent 3 database. Allocation was cut off by classification – unit.

The kg amounts for type 2.1 and type 2.3 were based on a dry density of 2.5 and 2.159 tonnes / m3. The grading distribution was based on laboratory test results (60% gravel size and 40% sand size).

3.4.4. System Boundaries

The scope of this cradle-to-gate LCEA assessment is limited to the production of conventional road base and road base combined with RGS. The system boundary includes extracting each raw material, processing, transportation, production of road base and construction of 1km of road. This assessment included cradle-to-gate impacts only. Maintenance works, transportation and end-of-life rehabilitation works are outside the scope of this assessment. The complete environmental impact (e.g., global warming) for each scenario combines all the individual material impacts required to produce a road formation.

3.4.5. Economic Assessment

The Economic Assessment was conducted in accordance with the engineering cost method in AS/NZS 4536 (AS, 2014) Life cycle costing – An application guide. The functional unit for this Cradle to Gate economic assessment was the same as utilised for the life cycle analysis, as shown in Figure 26. Unit rates for the economic assessment were adopted advice from TCC and are provided in the table below (Table 13). The material quantities for each scenario are shown in Appendix B.

Table 13 - Unit Rates for Analysis

Material / Construction activity	Cost (AUD)
Spray seal + AMC0 Prime	\$19.20 per m2
Type 2.1 Base	\$45.70 per m3 (\$19.2/Tonne)
Type 2.3 Subbase (standard)	\$41.45 per m3 (\$18.4/Tonne)
Type 2.3 Subbase + 20% recycled glass sand	\$37.43 per m3 (\$17.52/Tonne)
Type 2.3 Subbase + 25% recycled glass sand	\$36.66 per m3 (\$17.29/Tonne)
Type 2.3 Subbase + 30% recycled glass sand	\$35.51 per m3 (\$17.07/Tonne)
Insitu mixing, transport and placement	\$10 / m3
Water curing	\$2 / m3

This assessment has considered rates from Townsville City Council suppliers. The RGS material is currently free to obtain from Townsville City Council's MRF; for the economic assessment, the cost of RGS has been considered as \$0.00. For this assessment, the MDD of the material and the OMC were adopted from experimental investigations.

4. RESULTS AND DISCUSSION

4.1. Introduction

A series of tests were undertaken using TMR specification Type 2.3 road base and different proportions of recycled glass. All testing was completed in accordance with Australian Standards specifications in Townsville City Council NATA accredited laboratory. Tests were completed to determine the effects of the different recycled glass sand content on the road base.

4.2. Material Property Results

4.2.1. General Observations

Organics, wood, plastic, metal, ceramic and gravel particles were found in the debris found in the RGA sample (Figure 28). Initial visual inspection of the sample showed that it mainly consists of gravel and sand-sized glass particles mixed with a low percentage of fine material. The sample also had a distinct smell and the presence of some mould, implying there were organics or contaminates in the sample.

Figure 28 - Glass after Crushing at Townsville MRF

4.2.2. Chemical Analysis

Glass sample from Townsville's MRF was sent to Sharp & Howells for chemical testing. Crushed glass was both unwashed and washed and analysed for various concentrations. Table 14 presents the results of the chemical testing.

Table 14 - Results of Chemical Testing

Chemical and other attributes	Unwashed	Washed	Maximum Concentration (MRTS36)
Conductivity, uS/cm	526	63	2000
Sugar	Absent	Absent	NA
Total Organic Carbon, et %	2.8	Less than 0.1	2%
Arsenic, mg/kg	Less than 2	Less than 2	20
Cadmium, mg/kg	Less than 2	Less than 2	1.5
Chromium, mg/kg	Less than 5	Less than 5	40
Lead, mg/kg	12	11	100
Mercury, mg/kg	Less than 0.1	Less than 0.1	1
Molybdenum, mg/kg	Less than 5	Less than 5	10
Nickle, mg/kg	Less than 5	Less than 5	20
Zinc, mg/kg	76	13	300

Cadmium is the only chemical that exceeds the maximum concentration limits specified in MRTS66 when the recycled glass aggregate is not washed. Cadmium is a toxic heavy metal that poses potential health and environmental risks if it leaches into the surrounding soil and water. Depending on the specific circumstances, the slight excess of cadmium may not pose significant risks to human health or the environment. It is recommended that further testing and analysis be conducted to assess the extent of the contamination and potential risks before using the recycled glass aggregate in road base construction. It is important to ensure compliance with regulatory requirements and take appropriate measures to mitigate any potential risks associated with the use of the recycled glass aggregate in road base construction. This may include measures such as dilution, washing, or other treatment methods to reduce the concentration of cadmium to acceptable levels. Therefore, Appropriate remediation measures should also be taken to address the contamination and ensure compliance with regulatory requirements.

4.2.3. Particle Size Distribution (PSD)

Table 15 details the PSD results for each of the sample mixes.

Table 15 – PSD for Test Samples

Sieve Size	Type 2.3	20% RGS	25% RGS	30% RGS
16	100	100.0	100.0	100.0
13.2	95.5	97.3	97.1	96.7
9.5	83.8	86.5	88.0	81.9
6.7	72.0	73.2	76.3	66.1
4.75	62.0	60.4	65.7	53.5
2.36	44.9	42.1	48.4	37.4
1.18	33.8	29.2	35.6	24.5
0.6	25.2	20.3	25.8	16.6
0.425	21.8	17.5	22	14.3
0.3	19.0	15.0	19.1	12.4
0.15	14.8	11.4	14.8	9.6
0.075	12.2	9.4	12.3	7.9

Figure 29 illustrates the particle size distribution of Type 2.3 Gravel and RGS and gravel mixes, determined by sieve analysis. MRTS05 Upper and lower boundaries for Type 2.3 containing less than 70% recycled material are also shown. The PSD curves show that all samples are well-graded, containing an adequate distribution of particle sizes. There is an observed trend of the PSD moving closer to the lower boundary of the allowable limit as the RGS proportion increases. To optimise the use of recycled material while ensuring compliance with specifications, it is recommended that further research be conducted to assess the performance of these materials

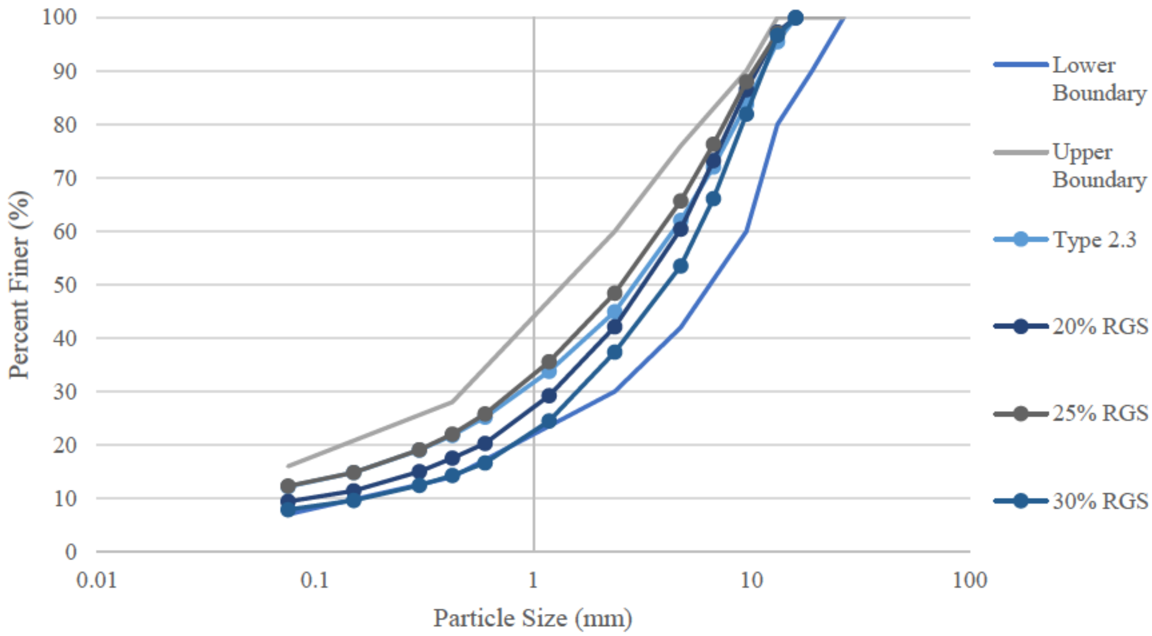

Figure 29 – PSD Results Compared to MRTS05 Grading Envelopes

4.2.4. Atterberg Limits

Atterberg limits tests were completed for the Type 2.3 sample lot on fines sample screened on a 425µm sieve in accordance with Transport and Main Roads Materials Testing Manual – Part 5, test method Q104D. RGS was included from 600µm to2.36mm, so glass particles would not affect Atterberg limit results.

Table 16 implies that the Type 2.3 material meets the MRTS05 specification for use as a subbase material.

Table 16 - Atterberg Limit Results Compared to MRTS05

Property	Type 2.3 Results	MRTS05 Requirements
Liquid Limit (LL) (%)	21.6	≤28
Linear Shrinkage (LS) (%)	2.6	1.5 – 4.5

4.2.5. Optimum Moisture Content

Figure 30 compares each test mix's optimum moisture content and maximum dry density. When comparing Type 2.3 gravel with and without Recycled Glass Sand (RGS), the standard Type 2.3 gravel achieved the highest OMC and MDD. By increasing the RGS content, the OMC was significantly reduced. Increasing the amount of RGS to 20%, 25%, and 30% resulted in reductions in OMC of 15%, 16%, and 20%, respectively. Findings indicate that glass is less porous and less absorbent than natural gravel. When glass is introduced into the mix, it can absorb less water, which means that less water is needed to reach the OMC for compaction. This reduction in water requirement contributes to a lower OMC. The introduction of glass may also affect the interparticle friction characteristics of the material, which, in turn, can impact how easily the particles compact together and, consequently, the moisture content required for optimal compaction.

The density of recycled glass is typically lower than that of natural gravel. As natural sand is replaced with RGS, the overall density of the sample decreases. However, the change in density is minimal, with less than a one percentage decrease in MDD for standard Type 2.3 gravel and gravel incorporated with 30% RGS.

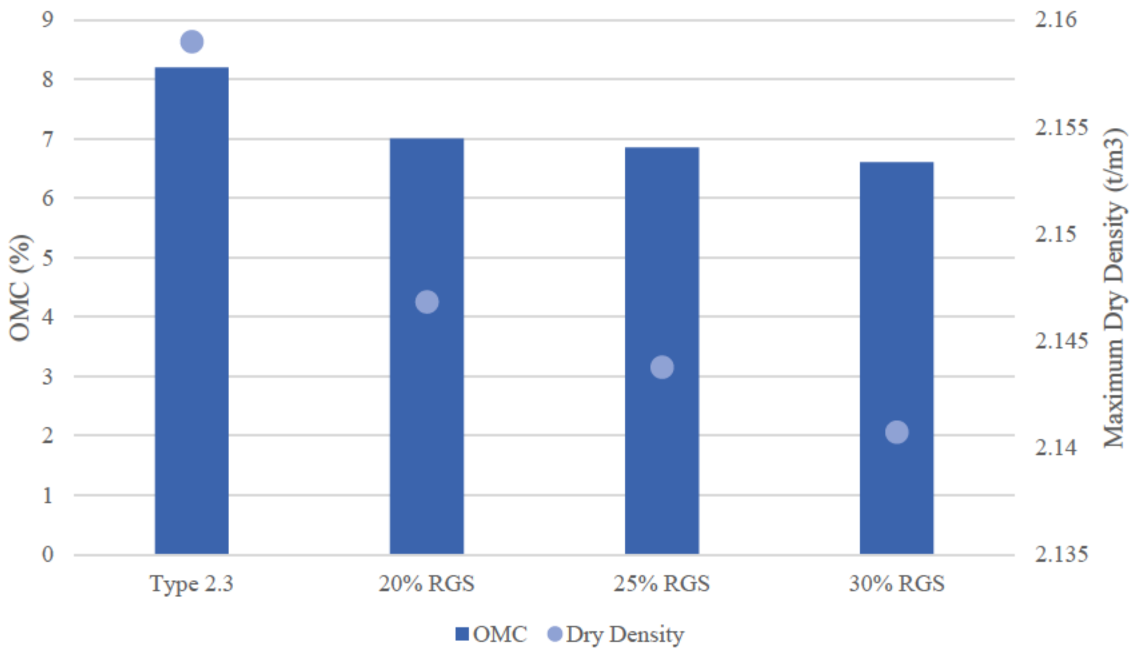

Figure 30 - OMC vs. Dry Density for Each Soil Batch

4.2.6. California Bearing Ratio

MRTS05 states that the target CBR for gravels in subbase construction is 45MPa. Table 17 shows the results for CBR2.5, CBR5.0 and swell. Notably, the standard type 2.3 gravel at CBR2.5 and CBR5.0 did not meet the minimum required CBR. All other mixes met the target at both CBR2.5 and CBR5.0.

Table 17 – CBR and Swell Results for Test Samples

	Type 2.3	20% RGS	25% RGS	30% RGS
CBR2.5	30	70	90	90
CBR5.0	35	90	90	100
Swell	1%	0.1%	0.1%	0.5%

There was an increase in CBR of 61%, 61% and 65% for 20%RGS mix, 25%RGS mix and 30%RGS mix, respectively. Figure 31 shows the corresponding final adopted CBR for each test sample. The results are expected when compared to conventional gravel. The results show that when glass is introduced, the samples are stiffer, and there is less deformation. The stiffness contributes to a higher CBR value as it resists deformation and provides better load-bearing capacity. The stiffness and rigidity of glass particles are also shown to distribute applied loads more evenly across the road base mix. This load distribution results in a more uniform and higher CBR value, again improving the material's load-bearing capacity.

Additionally, the increased presence of glass reduced the moisture absorption of the samples during a four-day bath test. This reduced moisture sensitivity contributed to higher CBR values, as the material's performance was less affected by changes in moisture content. Glass particles, particularly those with angular shapes, can interlock more effectively with other particles in the sample than naturally rounded particles. Improved interlocking enhances friction between particles, increasing resistance to deformation under load and boosting the CBR.

It is worth noting that when the samples were dried, those with glass inclusion exhibited behaviour similar to stabilised soil, enhancing the material's strength. This stabilisation behaviour may be attributed to calcium carbonate in the glass, a substance commonly used to treat poor-quality gravel materials.

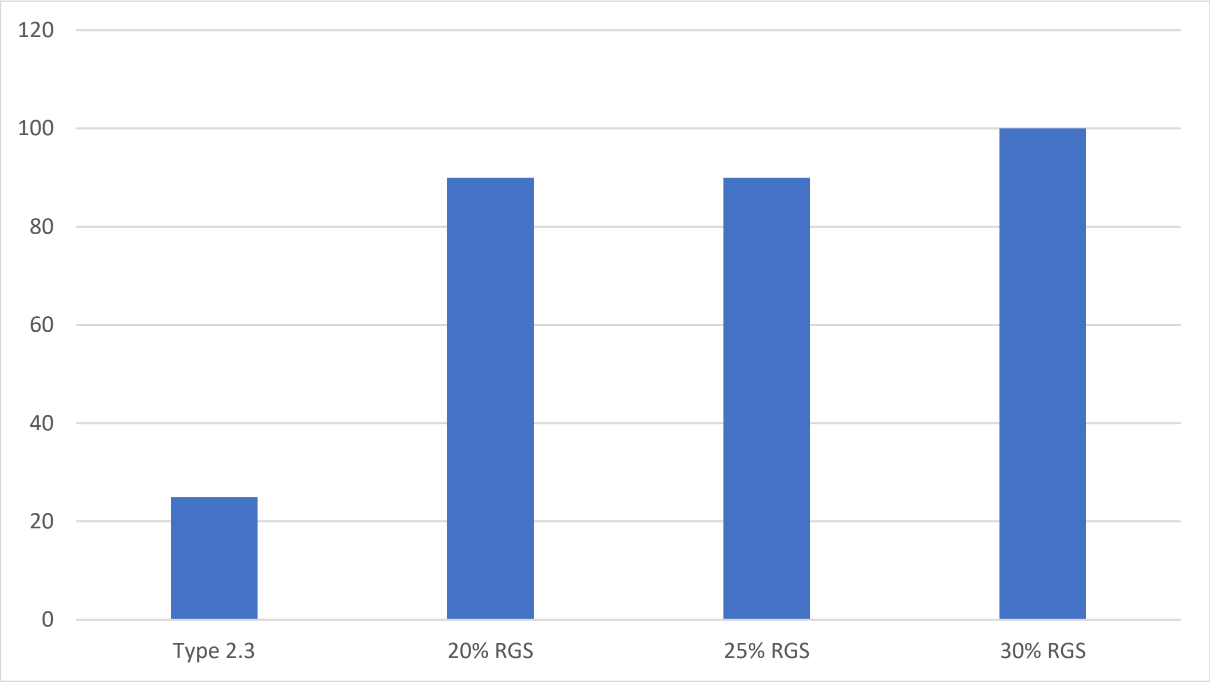

Figure 31 – Final Adopted CBR results

4.3. Life Cycle Analysis

4.3.1. Sustainability Assessment

The life cycle impact categories were completed for the production and construction of 1km of rural road with 100% type 2.3 (Scenario A), 20%RGS (Scenario B), 25%RGS (Scenario C) and 20%RGS (Scenario D). The total impact category from ReCiPe analysis is shown in Table 18. The individual impact categories for materials and construction process are shown in Appendix C.

Eleven of the eighteen impact categories saw decreases in the effect of using RGS compared to natural sand, including a reduction in global warming, ozone formation, human health, fine particulate matter formation, human carcinogenic toxicity, ozone formation terrestrial ecosystems, terrestrial acidification, terrestrial ecotoxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. Two impact categories remained the same: stratospheric ozone depletion and ionising radiation. Finally, five impact categories increased with the inclusion of RGS: human non-carcinogenic toxicity, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity and marine ecotoxicity. An abundance of phosphorus and nitrogen causes eutrophication. It is important to note that the Ecoinvent database utilises ‘Glass cullet, sorted (RoW) | treatment of waste glass from unsorted public collection, sorting, cut- off, U,’ which does not represent entirely represent the RGS used.

Table 18 -Total ReCiPe Analysis Results

Impact category	Scenario A	Scenario B	Scenario C	Scenario D
Global warming (kg CO2)	185000	180000	178000	175000
Stratospheric ozone depletion (kg CFC11)	0.08	0.08	0.08	0.08
Ionizing radiation (kBq Co-60)	10800	10800	10800	10800
Ozone formation, Human health (kg NOx)	740	705	697	672
Fine particulate matter formation (kg PM2.5)	372	367	366	361
Ozone formation, Terrestrial ecosystems (kg NOx)	755	720	712	686
Terrestrial acidification (kg SO2)	864	822	812	794
Freshwater eutrophication (kg P)	76	96	102	107
Marine eutrophication (kg N)	6.36	8.44	8.96	9.48
Terrestrial ecotoxicity (kg 1,4-DCB)	790000	766000	761000	753000
Freshwater ecotoxicity (kg 1,4-DCB)	5100	5350	5410	5470
Marine ecotoxicity (kg 1,4-DCB)	7160	7470	7550	7620
Human carcinogenic toxicity (kg 1,4-DCB)	12100	12200	12200	12100
Human non-carcinogenic toxicity (kg 1,4-DCB)	149000	153000	154000	155000
Land use (m2a)	44100	40400	39500	38600
Mineral resource scarcity (kg Cu)	589	587	587	583
Fossil resource scarcity (kg oil)	66200	64300	63900	62900
Water consumption (m3)	4040	3980	3940	3920

Lifecycle analysis decreased overall on all three endpoint indicators: human health, ecosystems and resources. Figure 32 shows the final endpoint indicator results for the lifecycle analysis.

There was a reduction in human health endpoint impact of 1%, 2% and 3% for 20%RGS mix, 25%RGS mix and 30%RGS mix, respectively. The reduction was associated with reduced global warming, ozone formation (human health), fine particulate matter formation and human carcinogenic toxicity impact categories. Reducing human health indicators reduces the risk of respiratory disease, various types of cancer, other diseases and malnutrition.

Damage to ecosystems was reduced by 3%, 4% and 6% for 20%RGS mix, 25%RGS mix and 30%RGS mix, respectively. Ozone formation (terrestrial ecosystems), terrestrial acidification, ecotoxicity, and land use damage pathways are reduced. Decreasing the risks of damage to freshwater, terrestrial, and marine species ultimately contributes to preserving biodiversity and ecosystem stability.

Finally, resources decreased by 1%, 3% and 5% for 20%RGS mix, 25%RGS mix and 30%RGS mix, respectively. Mineral resource scarcity, fossil resource scarcity and water consumption reduce oil, gas and coal energy extraction. The decrease in resource use has practical implications, particularly in reducing the extraction of oil, gas, and coal energy sources, thereby contributing to sustainability and resource conservation.

The decrease in human health risks implies potential savings in healthcare costs and a higher quality of life for the public. Furthermore, the mitigation of ecosystem damage aligns with the Australian Government and global efforts to protect and preserve biodiversity, which is crucial for the planet's long-term health. Lastly, reducing resource use contributes to the responsible management of natural resources and a reduced environmental footprint.

These results can inform policies and practices promoting sustainability and responsible resource management. They provide evidence for the environmental and economic benefits of incorporating RGS material into road construction.

In conclusion, the LCA results demonstrate the benefits of adopting RGS, showing a path towards a more environmentally responsible and cleaner future.

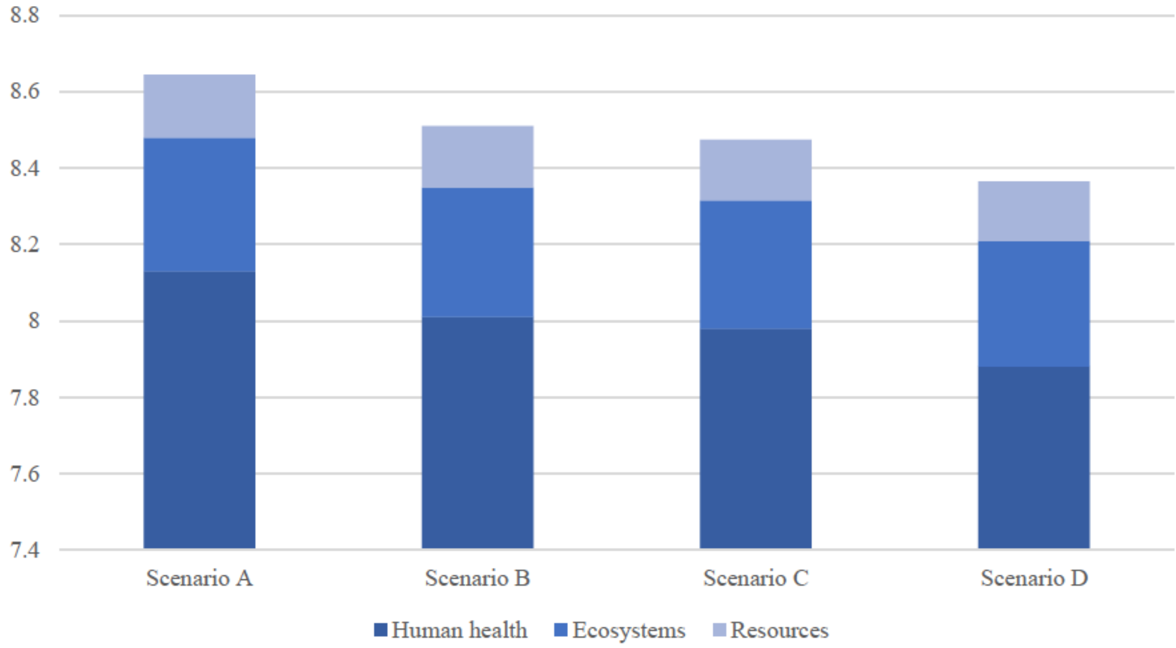

Figure 32 - ReCiPe Final Endpoint Indicators

The embodied energy required for producing RGS mixes exhibited reductions compared to conventional road base construction. Specifically, the 20%RGS mix recorded a 3% reduction, the 25%RGS mix achieved a 3.5% decrease, and the 30%RGS mix demonstrated a substantial 5% reduction in embodied energy requirements. These reductions translate to a notable decrease in the carbon footprint, a marked reduction in overall energy consumption, and a diminished environmental impact. The decrease in embodied energy can be directly attributed to a reduced dependency on the extraction of natural sand, contributing to more sustainable and environmentally responsible road construction practices. The embodied energy results can be seen in Figure 33.

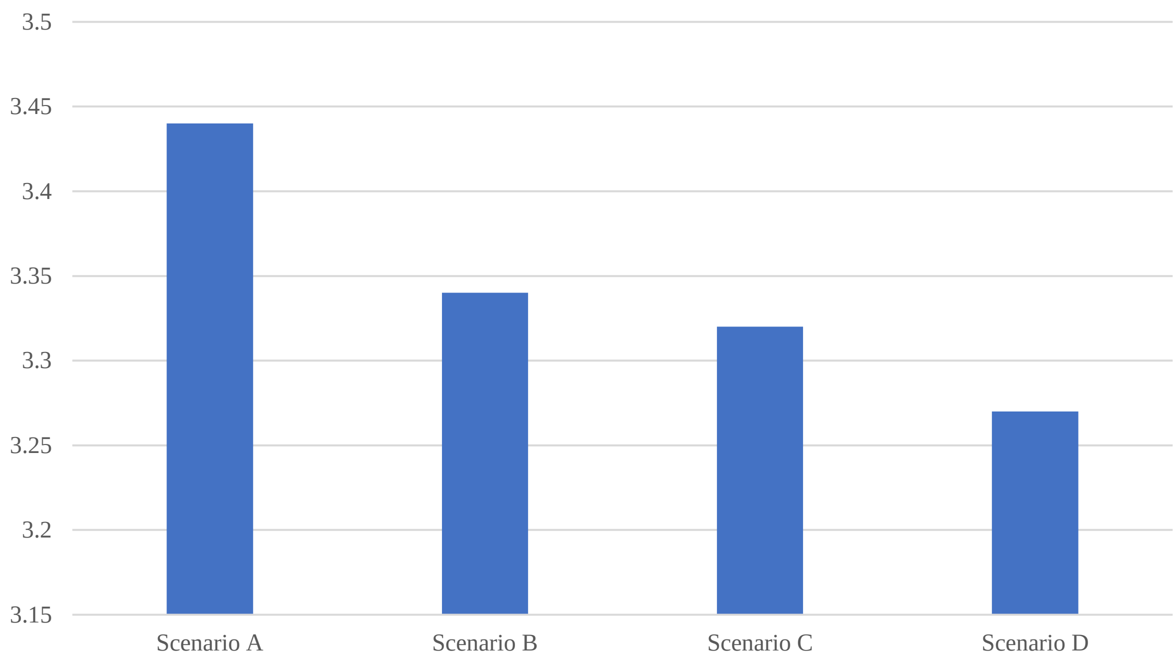

Figure 33 - Embodied Energy Results

4.3.2. Economic Assessment

Table 19 breaks down each scenario's cost of materials and construction activities. This comprehensive breakdown offers a transparent view of the financial underpinnings of the study.

Table 19 - Economic Assessment Results

Material / Construction activity	Scenario A (cost)	Scenario B (cost)	Scenario C (cost)	Scenario D (cost)
Spray seal + AMC0 Prime	$192,000	$192,000	$192,000	$192,000
Base	$68,520	$68,520	$68,520	$68,520
Sub base	$62,175	$56,145	$54,990	$53,265
Insitu mixing, transport & placement	$15,000	$15,000	$15,000	$15,000
Water curing	$531,114	$448,770	$435,660	$411,840
Total	$868,839	$780,465	$766,200	$740,655

Figure 34 shows the overall cost savings for each scenario. Using 20% of RGS in the subbase layer saves approximately $88,000, roughly 10% compared to a conventional road base. 25% of RGS shows increased savings of $102,000, roughly 12% compared to the conventional road base. Further increasing RGS to 30% shows even more significant savings of $128,000, roughly 15% percent compared to the conventional road base.

At the core of these compelling cost savings lies a reduction in the necessity to procure naturally extracted materials from quarries. This approach effectively curtails costs while concurrently fostering sustainability. An additional driving force is the substantial decrease in water consumption, which not only ameliorates water expenses but also elevates the project's environmental stewardship, potentially aligning with regulatory requirements. The economic assessment has found economic benefits to using RGS in road pavement.

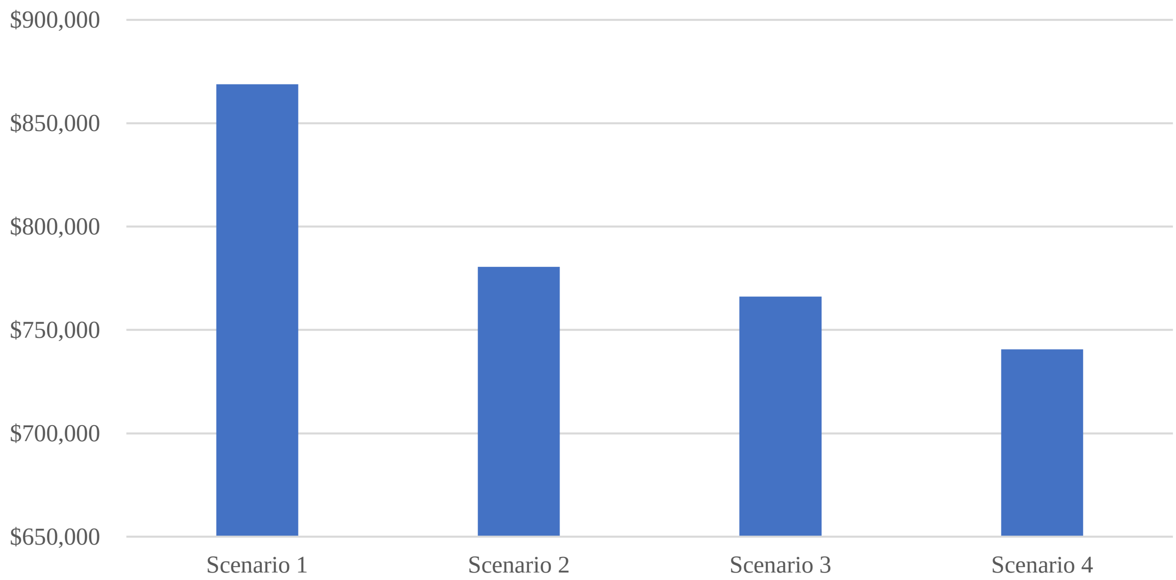

Figure 34 - Economic Assessment Total Cost Results

5. CONCLUSION

5.1. Conclusion

Road infrastructure construction is vital in Australia to provide connection, transport, trade and economic development. However, virgin aggregate materials used in road construction impose environmental risks. There has been a growing emphasis on sustainable practices and the circular economy to minimise waste generation, conserve resources, and reduce environmental impacts in response to environmental issues. Recycling materials for road construction has emerged as a promising approach to address these challenges. This study investigates the feasibility of incorporating recycled glass in road base construction, particularly in Townsville City Council (TCC) civil infrastructure projects.

Limited studies and projects in Australia have explored the potential of incorporating recycled glass into road construction. Recycled glass can be processed into cullet or aggregate forms and used as a sand material. Geotechnical investigations in this area have been limited. However, the test results show that recycled glass exhibits favourable characteristics when processed correctly in gravel, including strength, load-bearing capacity, and durability, making it a viable candidate for road base applications. Furthermore, using recycled glass in road construction can reduce the consumption of natural resources such as aggregates and sand, typically sourced from quarries or riverbeds. By substituting virgin materials with recycled glass, the strain on natural resources can be eased, reducing the environmental impacts of extraction activities.

The first testing stage included chemical on the recycled glass sand by a NATA accredited laboratory. Natural type 2.3 gravel was mixed with 20%, 25% and 30% RGS, and the material properties were tested for particle size distribution, Atterberg limits, optimum moisture content and California bearing ratio. Finally, a life cycle assessment was completed to understand the sustainability impacts and economic assessment.

Chemical testing results showed the promising use of RGS from Townsville City Councils (TCCs) material reuse facility. All heavy metals except for Cadmium were within the allowable limits for use in road construction.

Particle size distributions showed that the road base remained well graded and within the upper and lower bounds with the inclusion of RGS. The optimum moisture content (OMC) of the RGS mixes was significantly reduced. The 30% RGS mix had a reduction of 20% water required to reach OMC compared to conventional road base. Reduced water usage in helps conserve this valuable resource for other essential needs and ecosystem health. Using a sustainable construction practice, can enhance the reputation of Townsville City Council (TCC) and benefit the community.

One of the primary outcomes of this research is the notable improvement in the California Bearing Ratio (CBR) observed when recycled glass sand is used instead of traditional sand. This increase in CBR values increases the stability and load-bearing capacity of the road base materials, which can have far-reaching implications for infrastructure durability and longevity. While not only providing a use for waste materials under the empirical design method pavement materials with higher strength properties reduce the pavement thickness leading to further reductions in natural aggregates and water required.

The life cycle assessment investigation of the environmental impact of substituting natural sand with recycled glass sand has revealed promising results. The utilisation of recycled glass sand in road base mixes has shown a reduced impact on all three endpoint damage impact categories, namely, human health, ecosystem, and natural resources. This outcome aligns with the growing imperative to adopt eco-friendly alternatives in construction to mitigate the adverse environmental effects.

Another notable aspect this research highlights is the potential cost savings associated with incorporating recycled glass sand. It is important for Local Governments with limited funds to utilise economical construction practices. Economical construction practices allows Local

Governments to complete more projects, which improves the quality of life for residents by providing better infrastructure and services.

The use of recycled materials in road construction, particularly recycled glass, offers a promising solution to the challenges posed by traditional road construction practices. Incorporating recycled glass in road base construction aligns with the principles of a circular economy, where materials are kept in use for as long as possible, and waste is minimised through recycling and re-utilisation. The laboratory tests conducted in this study demonstrate that recycled glass can be a viable substitute for conventional road base materials in TCC civil infrastructure projects. This sustainable approach can reduce waste generation, conserve natural resources, and minimize environmental impacts. The findings of this study can inform the development of TCC's civil infrastructure projects, promoting a more sustainable and resource-efficient approach to road construction.

5.2. Recommendations for Further Research

This investigation has provided insight of the suitability of RGS in unbound pavement. The following recommendations are suggested to further develop the findings of this research.

1. Investigate the root cause of Cadmium levels exceeding maximum level. Determine treatment method to reduce Cadmium levels to allowable limits.
2. Evaluate the suitability of recycled glass sand in bound pavement applications.
3. Conduct field tests on low-risk Local Government roads to contribute to a more comprehensive understanding of practical implications.
4. Investigate the stabilising effects of recycled glass in natural materials.

BIBLIOGRAPHY

Ahmet Anil Sezer, AF 2021, 'Environmental impact of construction transport and the effects of building certification schemes', *Resources, Conservation and Recycling*, vol. 172, no. 0921-3449.

Ai Jen Lim, YC, Daniel Dias-da-Costa, Amirali Ebrahimi Ghadi, Ali Abbas 2020, *Recycled Materials in Roads and Pavements - A Technical Review*, LG NSW, viewed 19 April 2023, <https://www.lgnsw.org.au/common/Uploaded%20files/PDF/Technical_Review_Recycled_Materials_in_Roads-Pavements.pdf>.

Aurora Torres, JB, Kristen Lear, Jianguo Liu 2017, 'A looming tragedy of the sand commons', *Science*, vol. 357, no. 6355, pp. 970-1.

Australian Government 2019, *National Waste Policy Action Plan 2019*, Department of Climate Change Energy the Environment and Water, Australian Government, , Canberra, ACT, https://www.dcceew.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf>.

Australian Road Research Board 2022, *ARRB and Brimbank Working Towards 100% Recycled Roads*, Australian Road Research Board, https://www.arrb.com.au/news/arrb-and-brimbank-working-towards-100-recycled-roads>.

Australian Standards 2005, *AS 1289 Methods of testing soils for engineering purposes*, Method 2.1.1 Soil moisture content tests - Determinatino of the moisture content of a soil - Oven drying method (standard method), Australian Standards.

Australian Standards 2009, *AS 1289 Methods for testing soils for engineering purposes*, Method 3.6.1 Soil classification tests - Determination of the particle size distribution of a soil - Standard method of anlysis by sieving, Australian Standards.

Australian Standards 2017, *AS 1289 Methods of testing soils for engineering purposes*, Method 5.1.1: Soil compaction and density tests - Determination of the dry density/moisture content relation of a soil using standard compactive effort, Australian Standard.

Austroads 2018, *Guide to Pavement Technology Part 4A: Granular Base and Subbase Materials*, Particle Size Distribution, Austroads, Sydney, New South Wales, viewed 9 March 2023, <https://austroads.com.au/publications/pavement/agpt04a/media/AGPT04A-08_Guide_to_Pavement__Technology_Part_4A_Granular_Base_and_Subbase_Materials.pdf>.

Austroads 2019, *Guide to Pavement Technology Part 2: Pavement Structural Design*, 4.3 edn, Austroads, Sydney, New South Wales, viewed 9 March 2023, <https://austroads.com.au/publications/pavement/agpt04a/media/AGPT04A-08_Guide_to_Pavement__Technology_Part_4A_Granular_Base_and_Subbase_Materials.pdf>.

Barry R. Christopher, PD, P.E., Charles Schwartz, Ph.D., P.E. and Richard Boudreau, P.E. 2006, *Geotechnical Aspects of Pavements Reference Manual*, Federal Highway Administration, Woodbury, Minnesota, https://www.fhwa.dot.gov/engineering/geotech/pubs/05037/03b.cfm>.

blue environment 2023, *National Waste Report 2022*, E The Department of Climate Change, the Environment and Water Docklands, Victoria, viewed 10 April 2023, <https://www.dcceew.gov.au/sites/default/files/documents/national-waste-report-2022.pdf >.

Canterbury-Bankstown Council 2022, *Canterbury-Bankstown's Trial is Building Safer Roads*, Canterbury-Bankstown Council, Bankstown, New South Wales, https://www.cbcity.nsw.gov.au/media/news/canterbury-bankstown%E2%80%99s-trial-is-building-safer-roads>.

CDE n.d.-a, *Repurpose It*, CDE, https://www.cdegroup.com/us/about/case-studies/repurpose-it-australia>.

CDE n.d.-b, *Waste Glass Washing*, CDE, https://www.cdegroup.com/applications/waste-recycling/waste-glass-recycling>.

Cement Concrete & Aggregates Australia n.d., *Quarry Overview*, Cement Concrete & Aggregates Australia, Mascot, NSW, viewed 22 April 2023, <https://www.ccaa.com.au/CCAA/CCAA/Public_Content/INDUSTRY/Quarry/Quarry_Overview.aspx>.

CK. Purchase, DAZ, BT O'Brien, MK Kowalewski, A Berenjian, AH Tarighaleslami, M Seifan 2021, 'Circular Economy of Construction and Demolition Waste: A Literature Review on Lessons, Challenges, and Benefits', *Materials (Basel)*, vol. 15(1).

Clean Up n.d., *Circular Economy*, Clean Up, Sydney, New South Wales, https://www.cleanup.org.au/circulareconomy>.

Commonwealth of Australia 2018, *2018 National Waste Policy*, DoCCEtEa Water, Commonwealth of Australia, Australia, https://www.dcceew.gov.au/sites/default/files/documents/national-waste-policy-2018.pdf>.

CSIRO n.d., *About*, CSIRO, Canberra, Australian Capital Territory, https://research.csiro.au/circulareconomy/about/>.

D Kazmi, MS, DJ. Williams, SQasim, YP Cheng 2021, 'The potential use of crushed waste glass as a sustainable alternative to natural and manufactured sand in geotechnical applications', *Journal of Cleaner Production*, vol. 284.

Danielle Garton, SH, Didier Bodin 2021, *P94: Optimising the Use of Unbound and Stabilised Recycled Pavement Materials in Queensland - Year 3 (2020-21)*, National Asset Centre of Excellence, https://www.nacoe.com.au/wp-content/uploads/2022/03/P94_Year-3-Final-Report-20-21-Recycled-Pavement-Materials-QLD.pdf>.

Das, BM 2010, *Principles of Geotechnical Engineering 7th Edition*, Cengage Learning, Stamford, Conneticut.

Department of Infrastructure and Regional Development 2016, *Information Sheet 75*, DoIaR Development, Bureau of Infrastructure, Transport and Regional Economics, Canberra, ACT, viewed 22 April 2023, <https://www.bitre.gov.au/sites/default/files/is_075.pdf>.

Department of Sustainability, E, Water, Population and Communities, n.d., *Waverly Council: recycled glass in roads*, E Department of Sustainability, Water, Population and Communities Australian Government, https://www.dcceew.gov.au/sites/default/files/env/pages/9014ac31-f832-48bd-85b9-f02d8ef70fbe/files/waverley-council.pdf>.

Disfani, MM 2011, 'Sustainable use of recycled glass: biosolids blends in road applications', Swinburne University of Technology, Melbourne, Victoria.

Environment Cultural Heritage and Corridor Management Team Program Management and Delivery (PMD) 2021, *Waste Reduction and Recycling Plan Annual Status Report*, Department of Transport and Main Roads (TMR).

Escavy, JI, Herrero, MJ, Lopez-Acevedo, F & Trigos, L 2022, 'The progressive distancing of aggregate quarries from the demand areas: Magnitude, causes, and impact on CO2 emissions in Madrid Region (1995–2018)', *Resources Policy*, vol. 75, p. 102506.

Gavriletea, MD 2017, 'Environmental Impacts of Sand Exploitation. Analysis of Sand Market', *Sustainability*, vol. 9, no. 7, p. 1118.

Government of South Australia n.d., *Regency to Pym Street Project Case Study*, GoS Australia, https://www.greenindustries.sa.gov.au/documents/r2p-circular-procurement-case-study.pdf>.

Grenfell, J 2022, *New ways with recycled crushed glass in roads*, ARRB, Port Melbourne, Victoria, https://www.arrb.com.au/latest-research/new-ways-with-recycled-crushed-glass-in-roads>.

Griffin, J 2015, *P11 Review of Unbound Pavement Material Specifications: Wet/Dry Strength Variation*, National Asset Centre of Excellence, Brisbane, Queensland, http://nacoe.com.au/wp-content/uploads/2016/12/007166_007182_P11_Review-of-Unbound-Pavement-Material_Y12.pdf>.

International Organization for Standardization 2006a, *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*.

International Organization for Standardization 2006b, *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*.

Jin Li, FX, Lanfang Zhang, Serji N. Amirkhanian 2019, 'Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: A review', *Journal of Cleaner Production*, vol. 233.

Lockhart Shire Council 2019, *Case study: Using Recycled Glass in Road Base Project*, LG NSW, https://lgnsw.org.au/common/Uploaded%20files/Environment_Awards/Lockhart_Shire-Using_recycled_glass_in_road_base.pdf>.

M. M. Y. Ali, AA, M. M. Disfani, J. Piratheepan 2011, 'Suitability of Using Recycled Glass-Crushed Rock Blends for Pavement Subbase Applications', *Geo-Frontiers 2011: Advances in Geotechnical Engineering*.

M.M. Disfani, AA, M.W. Bo, N. Sivakugan 2012, 'Environmental risks of using recycled crushed glass in road applications', *Journal of Cleaner Production*, vol. 20, no. 1, pp. 170-9.

Main Roads Western Australia 2022, *Recycled and Sustainable Materials at Main Roads*, MRW Australia, Main Roads Western Australia, https://www.mainroads.wa.gov.au/globalassets/community-environment/sustainability/recycled-materials-reference-guide.pdf?v=4ae25e>.

N. Sivakugan, CTG, R. Tuladhar, and M. B. Kannan 2016, *Civil Engineering Materials* CengageLearning.

Pennsylvania Department of Transportation 2001, *Laboratory evaluation of select engineering related properties of glass cullet*, PennDOT, Harrisburg, Pennsylvania, https://www.dot.state.pa.us/public/Bureaus/design/SEMP/CG/Glass%20Cullet%20Report%20-%20Drexel%20University.pdf>.

PRé Sustainability 2020, *SimaPro database manual Methods Library*, PRé Sustainability, Amersfoort, The Netherlands, https://simapro.com/wp-content/uploads/2020/10/DatabaseManualMethods.pdf>.

Queensland Government 2023, *Case study: Recycled Crushed Glass (RCG)*, https://www.des.qld.gov.au/climateaction/take-action/case-studies/recycled-crushed-glass>.

Sharp & Howells n.d., *Company Profile*, Croydon South, Victoria, https://sharpandhowells.com.au/company-profile/>.

Soil & Environmental Engineers, IR-SA, Inc. 1998, 'A Tool Kit for the Use of Post-Consumer Glass as a Construction Aggregate', viewed 23 March 2023, <https://p2infohouse.org/ref/13/12438.pdf>.

Stahl, A 2022, *5 Industries Experiencing Double-Digit Growth Over The Next Decade*, https://www.forbes.com/sites/ashleystahl/2022/04/08/5-industries-experiencing-double-digit-growth-over-the-next-decade/?sh=3380b28d13ec>.

Townsville City Plan 2022, *Townsville City Plan*, TC Council, Townsville, QLD, viewed 23 April 2023, <http://eplanning.townsville.qld.gov.au/Pages/Plan/Book.aspx?exhibit=current>.

Transport and Main Roads 2023, *Materials testing manual*, Edition 5 edn, Transport and Main Roads, Brisbane, Queensland, viewed 2023, <.

Transport for NSW 2020, *QA Specification 3154*, Granulated Glass Aggregate, Transport for NSW, Sydney, NSW, viewed 6 May 2023, <.

UN DESA 2022, *The Sustainable Development Goals Report 2022*, New York, USA, https://unstats.un.org/sdgs/report/2022/>.

Wartman, J, Grubb D G, Nasim, ASM 2004, 'Selected Engineering Characteristics of Crushed Glass', *Journal of Materials in Civil Engineering*, vol. 16, no. 6, pp. 526-39

Appendix A

Life Cycle Impact Assessment Inputs

Table 1 - Sustainability Assessment Scenario A Inputs

Stage	Item	Ecoinvent 3 database	Unit	Amount
14/7 mm spray seal	Bitumen (Class C170)	Bitumen seal (RoW)|production, Cut-off, U	kg	20,000 kg
	AMC0 prime	Bitumen seal (RoW)|production, Cut-off, U	Kg	9,000 kg
	14 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	246,000 kg (164 m^3)
	7 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	101,562 kg (78 m^3)
Base	Type 2.1 Base 3,600,000 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	2,160,000 kg
		Sand |Global production|Cut-off, U	kg	1,440,000 kg
Sub base	Type 2.3 Sub base 3,238,500 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	1,943,100 kg
		Sand |Global production|Cut-off, U	kg	1,295,400 kg
Construction (excavation, placement, compaction and curing)	Excavator	Excavator, hydraulic digger (GLO)|Cut-off, U	m^3	1500 m^3
	Sprayer (18.5 kW)	Machine operation, diesel 18.64 – 74.57 kW, high load factor| GLO| cut-off, U	hours	16 hours
	Water truck (18.5 kW)	Machine operation, diesel 18.64 – 74.57 kW, high load factor| GLO| cut-off, U	hours	16 hours
	Steel drum roller(18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW, high load factor| GLO| cut-off, U	hours	16 hours
	Vibrating roller (18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW, high load factor| GLO| cut-off, U	hours	16 hours

	Water curing - base	Tap water (RoW)|Cut-off, U	L	288,000 L Based on OMC of 8.0% and Dry density of 2.5 t/m^3
	Water curing – sub base	Tap water (RoW)|Cut-off, U	L	265,557 L *Based on OMC of 8.2% and Dry density of 2.159 t/m^3

Table 2 - Sustainability Assessment Scenario B Inputs

Stage	Item	Ecoinvent 3 database	Unit	Amount
14/7 mm spray seal	Bitumen (Class C170)	Bitumen seal (RoW)|production, Cut-off, U	kg	20,000 kg
	AMC0 prime	Bitumen seal (RoW)|production, Cut-off, U	Kg	9,000 kg
	14 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	246,000 kg (164 m3)
	7 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	101,562 kg (78 m3)
Base	Type 2.1 Base 3,600,000 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	2,160,000 kg
		Sand |Global production|Cut-off, U	kg	1,440,000 kg
Sub base	Type 2.3 Sub base + 20% Recycled glass sand 3,238,500 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	1,943,100 kg
		Sand |Global production|Cut-off, U	kg	1,036,320 kg
		Glass cullet, sorted (RoW)| treatment of waste glass from unsorted public collection, sorting, cut- off, U	kg	259,080 kg
Construction (excavation, placement, compaction and curing)	Excavator	Excavator, hydraulic digger (GLO)|Cut-off, U	m3	1500 m3
	Sprayer (18.5 kW)	Machine operation, diesel 18.64 – 74.57 kW, high load factor| GLO| cut-off, U	hours	16 hours
	Water truck (242 kW)	Machine operation, diesel 18.64 – 74.57 kW, high load factor| GLO| cut-off, U	hours	16 hours
	Steel drum roller(18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours
	Vibrating roller (18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours

	Water curing - base	Tap water (RoW)|Cut-off, U	L	288,000 L Based on OMC of 8.0% and Dry density of 2.5 t/m3
	Water curing – sub base	Tap water (RoW)|Cut-off, U	L	224,385 L *Based on OMC of 7% and Dry density of 2.137 t/m3

Table 3 - Sustainability Assessment Scenario C Inputs

Stage	Item	Ecoinvent 3 database	Unit	Amount
14/7 mm spray seal	Bitumen (Class C170)	Bitumen seal (RoW)|production, Cut-off, U	kg	20,000 kg
	AMC0 prime	Bitumen seal (RoW)|production, Cut-off, U	Kg	9,000 kg
	14 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	246,000 kg (164 m3)
	7 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	101,562 kg (78 m3)
Base	Type 2.1 Base 3,600,000 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	2,160,000 kg
		Sand |Global production|Cut-off, U	kg	1,440,000 kg
Sub base	Type 2.3 Sub base + 25% Recycled glass sand 3,238,500 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	1,943,100 kg
		Sand |Global production|Cut-off,U	kg	971,550 kg
		Glass cullet, sorted (RoW)| treatment of waste glass from unsorted public collection, sorting, cut- off, U	kg	323,850 kg
Construction (excavation, placement, compaction and curing)	Excavator	Excavator, hydraulic digger (GLO)|Cut-off, U	m3	1500 m3
	Sprayer	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours
	Water truck (242 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours
	Steel drum roller(18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours
	Vibrating roller (18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours

	Water curing - base	Tap water (RoW)|Cut-off, U	L	288,000 L Based on OMC of 8.0% and Dry density of 2.5 t/m3
	Water curing – sub base	Tap water (RoW)|Cut-off, U	L	217,830 L *Based on OMC of 6.85% and Dry density of 2.12 t/m3

Table 4 - Sustainability Assessment Scenario D Inputs

Stage	Item	Ecoinvent 3 database descriptor	Unit	Amount
14/7 mm spray seal	Bitumen (Class C170)	Bitumen seal (RoW)|production, Cut-off, U	kg	20,000 kg
	AMC0 prime	Bitumen seal (RoW)|production, Cut-off, U	Kg	9,000 kg
	14 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	246,000 kg (164 m3)
	7 mm aggregate	Gravel, crushed (RoW)|Cut-off, U	kg	101,562 kg (78 m3)
Base	Type 2.1 Base 3,600,000 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	2,160,000 kg
		Sand |Global production|Cut-off, U	kg	1,440,000 kg
Sub base	Type 2.3 Sub base + 30% Recycled glass sand 3,238,500 kg total	Gravel, crushed (RoW)|Cut-off, U	kg	1,943,100 kg
		Sand |Global production|Cut-off,U	kg	906,780 km
		Glass cullet, sorted (RoW)| treatment of waste glass from unsorted public collection, sorting, cut- off, U	kg	388,620 kg
Construction (excavation, placement, compaction and curing)	Excavator	Excavator, hydraulic digger (GLO)|Cut-off, U	m3	1500 m3
	Sprayer	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours
	Water truck (242 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours
	Steel drum roller(18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours

	Vibrating roller (18.1 kW)	Machine operation, diesel 18.64 – 74.57 kW| GLO| cut-off, U	hours	16 hours
	Water curing - base	Tap water (RoW)|Cut-off, U	L	288,000 L Based on OMC of 8.0% and Dry density of 2.5 t/m3
	Water curing – sub base	Tap water (RoW)|Cut-off, U	L	205,920 L *Based on OMC of 6.6% and Dry density of 2.08 t/m3

Appendix B

Economic Assessment Inputs

Table 1 – Economic Assessment Scenario A Inputs

Input – Scenario 1	Units
Spray seal + AMC0 Prime	10,000 m^2
Type 2.1 Base	1500 m^3
Type 2.3 Sub base	1500 m^3
Insitu mixing, transport and placement	1500 m^3
Water curing	265,557 L *Based on OMC of 8.2% and Dry density of 2.159 t/m^3

Table 3 Economic Assessment Scenario B Inputs

Input – Scenario 2	Units
Spray seal + AMC0 Prime	10,000 m^2
Type 2.1 Base	1500 m^3
Type 2.3 Subbase + 20% recycled glass sand	1500 m^3
Insitu mixing, transport and placement	1500 m^3
Water curing	224,385 L *Based on OMC of 7% and Dry density of 2.137 t/m3

Table 4 Economic Assessment Scenario C Inputs

Input – Scenario 3	Units
Spray seal + AMC0 Prime	10,000 m^2
Type 2.1 Base	1500 m^3
Type 2.3 Subbase + 25% recycled glass sand	1500 m^3
Insitu mixing, transport and placement	1500 m^3
Water curing	217,830 L *Based on OMC of 6.85% and Dry density of 2.12 t/m^3

Table 5 Economic Assessment Scenario D Inputs

Input – Scenario 4	Units
Spray seal + AMC0 Prime	10,000 m^2
Type 2.1 Base	1500 m^3
Type 2.3 Subbase + 30% recycled glass sand	1500 m^3
Insitu mixing, transport and placement	1500 m^3
Water curing	205,920 L *Based on OMC of 6.6% and Dry density of 2.08 t/m^3

Appendix C

Simapro Sustainability Impact Assessment Results

Table 1 – Scenario A ReCipe Analysis

Impact category	Unit	Total	Raw materials - 14/7 mm spray seal	Raw materials - Type 2.1 Roadbase	Raw materials - Type 2.3 Sub base	Tap water | tap water production, conventional treatment | Cut-off, U	Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor | machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor | Cut-off, U	Excavation, hydraulic digger | processing | Cut-off, U
Global warming	kg CO2 eq	1.85E+5	3.68E+4	8.14E+4	6.37E+4	1.86E+2	1.98E+3	8E+2
Stratospheric ozone depletion	kg CFC11 eq	0.08	0.02	0.03	0.02	8.54E-5	1.15E-3	4.59E-4
Ionizing radiation	kBq Co-60 eq	1.08E+4	1.56E+3	5.77E+3	3.4E+3	32.79	22.06	10.36
Ozone formation, Human health	kg NOx eq	7.4E+2	90.08	3.5E+2	2.81E+2	0.34	8.5	9.43
Fine particulate matter formation	kg PM2.5 eq	3.72E+2	58.76	1.73E+2	1.35E+2	0.44	2.18	2.21
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.55E+2	94.32	3.56E+2	2.86E+2	0.35	8.66	9.59
Terrestrial acidification	kg SO2 eq	8.64E+2	1.55E+2	3.89E+2	3.1E+2	0.64	4.96	4.34
Freshwater eutrophication	kg P eq	75.57	19	32.55	23.47	0.13	0.29	0.13
Marine eutrophication	kg N eq	6.36	0.74	3.15	2.45	0.01	0.01	3.54E-3
Terrestrial ecotoxicity	kg 1,4-DCB	7.9E+5	1.5E+5	3.49E+5	2.87E+5	6.32E+2	2.29E+3	1E+3
Freshwater ecotoxicity	kg 1,4-DCB	5.1E+3	1.52E+3	2.11E+3	1.44E+3	9.43	8.51	5.24
Marine ecotoxicity	kg 1,4-DCB	7.16E+3	2.05E+3	3E+3	2.08E+3	12.52	13.4	7.93
Human carcinogenic toxicity	kg 1,4-DCB	1.21E+4	2E+3	6.03E+3	3.97E+3	18.37	76.27	52.82
Human non-carcinogenic toxicity	kg 1,4-DCB	1.49E+5	3.04E+4	6.78E+4	5E+4	2.32E+2	1.97E+2	98.15
Land use	m2a crop eq	4.41E+4	2.09E+3	2.23E+4	1.96E+4	4.22	27	11.14
Mineral resource scarcity	kg Cu eq	5.89E+2	1.88E+2	2.41E+2	1.53E+2	1.05	3.16	2.25
Fossil resource scarcity	kg oil eq	6.62E+4	2.99E+4	2E+4	1.54E+4	50.41	6.24E+2	2.52E+2
Water consumption	m3	4.04E+3	6.52E+2	1.72E+3	1.11E+3	5.57E+2	1.54	0.93

Table 2 – Scenario B ReCipe Analysis

Impact category	Unit	Total	Raw materials - 14/7 mm spray seal	Raw materials - Type 2.1 Roadbase	Raw materials - Type 2.3 Sub base	Tap water | tap water production, conventional treatment | Cut-off, U	Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor | machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor | Cut-off, U	Excavation, hydraulic digger | processing | Cut-off, U
Global warming	kg CO2 eq	1.8E+5	3.68E+4	8.14E+4	5.92E+4	1.79E+2	8E+2	1.17E+3
Stratospheric ozone depletion	kg CFC11 eq	0.08	0.02	0.03	0.02	8.22E-5	4.59E-4	6.78E-4
Ionizing radiation	kBq Co-60 eq	1.08E+4	1.56E+3	5.77E+3	3.41E+3	31.53	10.36	12.99
Ozone formation, Human health	kg NOx eq	7.05E+2	90.08	3.5E+2	2.48E+2	0.33	9.43	7.43
Fine particulate matter formation	kg PM2.5 eq	3.67E+2	58.76	1.73E+2	1.31E+2	0.42	2.21	1.61
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.2E+2	94.32	3.56E+2	2.52E+2	0.33	9.59	7.54
Terrestrial acidification	kg SO2 eq	8.22E+2	1.55E+2	3.89E+2	2.69E+2	0.61	4.34	3.78
Freshwater eutrophication	kg P eq	96.38	19	32.55	44.4	0.12	0.13	0.17
Marine eutrophication	kg N eq	8.44	0.74	3.15	4.54	0.01	3.54E-3	3.33E-3
Terrestrial ecotoxicity	kg 1,4-DCB	7.66E+5	1.5E+5	3.49E+5	2.64E+5	6.08E+2	1E+3	1.35E+3
Freshwater ecotoxicity	kg 1,4-DCB	5.35E+3	1.52E+3	2.11E+3	1.7E+3	9.07	5.24	5.01
Marine ecotoxicity	kg 1,4-DCB	7.47E+3	2.05E+3	3E+3	2.4E+3	12.04	7.93	7.89
Human carcinogenic toxicity	kg 1,4-DCB	1.22E+4	2E+3	6.03E+3	4.05E+3	17.67	52.82	46.32
Human non-carcinogenic toxicity	kg 1,4-DCB	1.53E+5	3.04E+4	6.78E+4	5.42E+4	2.23E+2	98.15	1.22E+2
Land use	m2a crop eq	4.04E+4	2.09E+3	2.23E+4	1.6E+4	4.06	11.14	15.9
Mineral resource scarcity	kg Cu eq	5.87E+2	1.88E+2	2.41E+2	1.53E+2	1.01	2.25	1.86
Fossil resource scarcity	kg oil eq	6.43E+4	2.99E+4	2E+4	1.38E+4	48.48	2.52E+2	3.67E+2
Water consumption	m3	3.98E+3	6.52E+2	1.72E+3	1.07E+3	5.36E+2	0.93	0.91

Table 3 – Scenario C ReCipe Analysis

Impact category	Unit	Total	Raw materials - 14/7 mm spray seal	Raw materials - Type 2.1 Roadbase	Raw materials - Type 2.3 Sub base	Tap water | tap water production, conventional treatment | Cut-off, U	Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor | machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor | Cut-off, U	Excavation, hydraulic digger | processing | Cut-off, U
Global warming	kg CO2 eq	1.78E+5	3.68E+4	8.14E+4	5.8E+4	1.7E+2	1.17E+3	8E+2
Stratospheric ozone depletion	kg CFC11 eq	0.08	0.02	0.03	0.02	7.81E-5	6.78E-4	4.59E-4
Ionizing radiation	kBq Co-60 eq	1.08E+4	1.56E+3	5.77E+3	3.41E+3	29.96	12.99	10.36
Ozone formation, Human health	kg NOx eq	6.97E+2	90.08	3.5E+2	2.39E+2	0.31	7.43	9.43
Fine particulate matter formation	kg PM2.5 eq	3.66E+2	58.76	1.73E+2	1.3E+2	0.4	1.61	2.21
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.12E+2	94.32	3.56E+2	2.44E+2	0.32	7.54	9.59
Terrestrial acidification	kg SO2 eq	8.12E+2	1.55E+2	3.89E+2	2.59E+2	0.58	3.78	4.34
Freshwater eutrophication	kg P eq	1.02E+2	19	32.55	49.64	0.12	0.17	0.13
Marine eutrophication	kg N eq	8.96	0.74	3.15	5.06	0.01	3.33E-3	3.54E-3
Terrestrial ecotoxicity	kg 1,4-DCB	7.61E+5	1.5E+5	3.49E+5	2.58E+5	5.78E+2	1.35E+3	1E+3
Freshwater ecotoxicity	kg 1,4-DCB	5.41E+3	1.52E+3	2.11E+3	1.76E+3	8.61	5.01	5.24
Marine ecotoxicity	kg 1,4-DCB	7.55E+3	2.05E+3	3E+3	2.48E+3	11.44	7.89	7.93
Human carcinogenic toxicity	kg 1,4-DCB	1.22E+4	2E+3	6.03E+3	4.07E+3	16.79	46.32	52.82
Human non-carcinogenic toxicity	kg 1,4-DCB	1.54E+5	3.04E+4	6.78E+4	5.52E+4	2.12E+2	1.22E+2	98.15
Land use	m2a crop eq	3.95E+4	2.09E+3	2.23E+4	1.51E+4	3.86	15.9	11.14
Mineral resource scarcity	kg Cu eq	5.87E+2	1.88E+2	2.41E+2	1.53E+2	0.96	1.86	2.25
Fossil resource scarcity	kg oil eq	6.39E+4	2.99E+4	2E+4	1.33E+4	46.07	3.67E+2	2.52E+2
Water consumption	m3	3.94E+3	6.52E+2	1.72E+3	1.06E+3	5.09E+2	0.91	0.93

Table 4 – Scenario D ReCipe Analysis

Impact category	Unit	Total	Raw materials - 14/7 mm spray seal	Raw materials - Type 2.1 Roadbase	Raw materials - Type 2.3 Subbase + 30% crushed gla	Tap water | tap water production, conventional treatment | Cut-off, U
Global warming	kg CO2 eq	1.75E+5	3.68E+4	8.14E+4	5.69E+4	1.66E+2
Stratospheric ozone depletion	kg CFC11 eq	0.08	0.02	0.03	0.02	7.62E-5
Ionizing radiation	kBq Co-60 eq	1.08E+4	1.56E+3	5.77E+3	3.41E+3	29.25
Ozone formation, Human health	kg NOx eq	6.72E+2	90.08	3.5E+2	2.31E+2	0.31
Fine particulate matter formation	kg PM2.5 eq	3.61E+2	58.76	1.73E+2	1.28E+2	0.39
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.86E+2	94.32	3.56E+2	2.35E+2	0.31
Terrestrial acidification	kg SO2 eq	7.94E+2	1.55E+2	3.89E+2	2.49E+2	0.57
Freshwater eutrophication	kg P eq	1.07E+2	19	32.55	54.87	0.11
Marine eutrophication	kg N eq	9.48	0.74	3.15	5.58	0.01
Terrestrial ecotoxicity	kg 1,4-DCB	7.53E+5	1.5E+5	3.49E+5	2.52E+5	5.64E+2
Freshwater ecotoxicity	kg 1,4-DCB	5.47E+3	1.52E+3	2.11E+3	1.82E+3	8.41
Marine ecotoxicity	kg 1,4-DCB	7.62E+3	2.05E+3	3E+3	2.56E+3	11.17
Human carcinogenic toxicity	kg 1,4-DCB	1.21E+4	2E+3	6.03E+3	4.09E+3	16.39
Human non-carcinogenic toxicity	kg 1,4-DCB	1.55E+5	3.04E+4	6.78E+4	5.62E+4	2.07E+2
Land use	m2a crop eq	3.86E+4	2.09E+3	2.23E+4	1.42E+4	3.77
Mineral resource scarcity	kg Cu eq	5.83E+2	1.88E+2	2.41E+2	1.52E+2	0.94
Fossil resource scarcity	kg oil eq	6.29E+4	2.99E+4	2E+4	1.29E+4	44.98
Water consumption	m3	3.92E+3	6.52E+2	1.72E+3	1.05E+3	4.97E+2