ANNUAL SUMMARY REPORT

O25 – Use of Recycled Materials in Earthworks and Drainage 2021–22 (Year 2)

ARRB Project No.:	016841
Project Managers:	TMR: Peter Reynolds ARRB: Javad Yaghoubi
Quality Manager:	James Grenfell
Author/s:	Javad Yaghoubi, Behnam Ghorbani, Jaspreet Pooni
Prepared for:	Queensland Department of Transport and Main Roads

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AN INITIATIVE BY:

Summary

The objective of this project is to identify how recycled materials may be reutilised as earthworks and drainage materials. Following the extensive review of literature and findings in Year 1, Year 2 has focused on investigating the engineering and environmental characteristics of recycled crushed concrete (RCC), reclaimed asphalt pavement (RAP) and coal combustion products (CCP), including both fly ash (FA) and bottom ash (BA), through extensive laboratory testing. The objective was to explore the impact of utilising these recycled materials in earthworks from performance, environmental, and work, health and safety (WHS) points of view. A suitably qualified professional (SQP) was engaged to conduct the environmental and WHS assessment.

This report presents the results and findings of Year 2. In addition, the findings of Year 1 on recycled crushed glass (RCG) are also included.

The key findings are summarised below.

RCC

- The obtained samples were initially procured and intended to be assessed against the requirements for use in drainage applications, although suitability of their use in other earthwork applications was also investigated. The 9 different samples were single sized gravel, single sized sand, or well-graded sand and were mainly suitable to be used as a free-draining backfill material, bedding material, fill and backfill materials, depending on the gradation.
- In relation to the total concentration of analytes in the RCC proposed to be used for pavements or drainage materials, the SQP's advice is that there are no issues of concern in relation to human health or the environment (terrestrial or aquatic).
- In relation to the pH of the RCC, it was concluded that there are no issues of concern where used in bound pavement materials or in compacted materials beneath sealed and unsealed surfaces; however, it is not considered appropriate to use RCC as a surface layer for unsealed roads. The pH of the leachate derived from RCC (where contact with rainfall may occur) would be buffered by soil, surface water and groundwater and the potential for adverse effects on aquatic ecosystems is considered to be low. For materials to be used in drainage, the SQP recommends that the pH of the material should be ≤ 9. Given this is impractical for RCC, the SQP recommends that RCC (with pH > 9) may be used for drainage provided the material is not used in areas closer than 30 m from a receiving waterway. More testing is required to ascertain the suitability of RCC for drainage applications.

RAP

- Two types of RAP, 1 profiled from a site in Queensland and 1 processed from a local Queensland supplier, were sourced for the laboratory characterisation. Queensland Department of Transport and Main Roads (TMR) prefers RAP to be reused in asphalt; however, where RAP is not suitable for this end in asphalt (for example it may be mixed with other pavement or embankment materials), it may be considered for use in earthworks. The tested samples were classified as well-graded gravel and were found suitable for usage in embankments, subgrade treatments, and backfilling applications. The primary concern with the use of RAP in embankments is the compressibility due to the potential softening of the bitumen, particularly at elevated temperatures, which might affect the long-term stability and serviceability of embankments.

- There are no issues of concern in relation to risks to human health or the environment (terrestrial or aquatic) with the use of RAP in embankment materials, drainage lines or pavement materials. This also includes stockpiled materials in road corridors.
- The RAP samples had high shear strength properties, and, hence, are suitable to be used in embankment and back fill applications. Although at applied pressures higher than 50 kPa (increasing from 50 kPa to 100 kPa) at 35 °C, a relatively large settlement was observed, this settlement was immediate. Results indicate that the residual binder in the RAP samples did not cause a creep behaviour. Using RAP in embankments is recommended to be limited to heights of less than 3 m until further testings (in progress – Year 4 of O25) are completed.

CCP

- CCP samples included blend of FA and BA (from ash pond), FA (from both dry and wet storage area) and BA (as produced unprocessed). The FA samples were classified as silts with low plasticity, and the BA samples as silty sands. Some CCP samples met the requirements for Class A2 fills. Despite the low plasticity of the CCP samples, which might cause compactability and stability issues, due to the high angle of friction, low compressibility, and low unit weight, CCP is considered suitable for use as a construction material for applications such as structural and non-structural fills for example, in the core zone of embankments. It can potentially be used in backfill and bedding applications, provided there are no issues related to electrical and heat conductivity of CCP for the proposed application.
- The assessment of risk to human health revealed that requirements (for workers) remain unchanged from the requirements that apply to workers using and handling conventional unbound aggregate material. Workers involved in the manually handling of unbound CCP should utilise personal protective equipment (PPE) detailed in the safety data sheets (SDS) for these materials. Where the activities have the potential to result in the generation of dust, PPE should include respiratory protection in compliance with the SDS. Workers involved in the cutting of bound materials that include CCP (e.g. concrete) where dust may be generated (i.e. dry cutting) should wear respiratory protection in compliance with the relevant SDS.

  Further review of the CCP data, for all chemicals detected, did not identify any issues of concern in relation to human health or the environment where the material is used in compliance with the End of Waste (EoW) code. Further consultation with Department of Environment and Science is recommended to assess the potential to review the EoW code requirements for the use of CCPs in waterways.

RCG

- From an engineering perspective, the shear and strength properties of RCG are similar to those of natural sand. In some fill (core zone of embankment), drainage and bedding applications, up to 100% RCG can be used (details in Section 5.2).

The laboratory testing results indicated that there is potential for the use of recycled materials in earthworks and drainage applications. A field trial can provide conclusive evidence of their actual performance and build further confidence in using recycled materials in the intended applications However, it is recommended to identify options and applications where field trails and demonstration projects are required. Some applications, dependent on the case, could be implemented into specifications without field trials.

The assessed materials were found fit for purpose for the intended applications. Where materials were not compliant with gradation requirements, screening could resolve the non-compliance. This report highlights the significant potential of recycled materials as alternative earth fill and drainage materials and aims to provide proof of concept on how recycled materials can be successfully implemented in these applications.

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1 Introduction

1.1 Background

TMR has committed to be an environmentally, socially and economically sustainable organisation that plans, delivers and manages a transport system that connects Queensland now and in the future. It has also committed to the following principles:

- being a leader in sustainable practice in how operations are performed
- limiting pollution, waste and consumption of resources to sustainable levels
- building a transport system that is resilient and connects Queensland now and in the future.

The aim of this project is to facilitate and increase the use of recycled materials in earthwork and drainage applications, and to provide the specification framework to ensure that the quality and durability requirements of infrastructure are also achieved. The first year of the project focused on reviewing the current practice regarding the use of recycled materials in earthworks and drainage in Australia and some overseas countries. The key findings from the literature review conducted in Year 1 included:

- Recycled materials are widely accepted for use in earthworks and drainage applications throughout Australia, the USA and the UK.
- VicRoads permits the use of recycled materials in the greatest number of applications, although limits are not specified.
- The Northern Territory Department of Infrastructure, Planning and Logistics (DIPL) permits up to 100% recycled crushed glass (RCG) by mass in bedding material for drainage works, the highest proportion in granular support layers of the road agencies reviewed.
- Washington Department of Transportation permits up to 100% recycled crushed concrete (RCC) by mass for non-structural fill and in (limited use) structural pavement layers.
- The UK Department for Transport permits up to 50% reclaimed asphalt pavement (RAP) and 25% RCG in non-structural backfill, drainage layers and (limited use) pavement structural layers. The use of bottom ash (BA) is also permitted in non-structural fill applications, although there is no specified limit.
- Oregon Department of Transportation permits up to 100% RCG by mass in non-structural and drainage layers.
- RCG passing the 4.75 mm sieve has the potential to improve the engineering properties of drainage layers, embankment, structural fill and subgrade applications at quantities of 20–30% by mass. Non-structural applications such as pipe bedding may incorporate up to 100% RCG by mass.
- BA may be suitable as an aggregate replacement for subbase materials and embankment fills. Additionally, it may also be used for utility bedding and drainage layers.

1.2 Year 2 Objectives and Methodology

Following the recommendations of Year 1 of the project for the use of recycled materials in earthwork and drainage works, 3 types of recycled materials, namely RCC, RAP, and coal combustion products (CCP) were nominated for Year 2 and their suitability for these applications was investigated through extensive laboratory testing. The scope of Year 2 was to evaluate the engineering and environmental properties of recycled materials in earthwork and drainage applications. The following tasks have been addressed during the second year:

- Sourcing recycled materials:

  Nine different samples of RCC were procured from 3 different local suppliers in Queensland. Three RAP samples including 2 processed RAP samples, from a local Queensland supplier, and 1 RAP sample profiled from a site in Queensland were procured. Nine different CCPs sampled at 5 different locations at a power station in Queensland were procured. Five additional CCP samples, including fly ash (FA) and BA and some blends, from another 5 power stations in Queensland were procured and assessed.
- Engineering characterisation

A laboratory testing program was used to characterise physical and mechanical properties of recycled materials, and to assess their suitability as earthwork and drainage materials. The testing program included particle size distribution, Atterberg limits, and wet/dry strength variation. For RAP, additional testing was undertaken to evaluate the shear strength and compressibility properties at elevated temperatures (35 °C). For CCP, additionally, compaction, California Bearing Ratio (CBR), Emerson class, pinhole dispersion, hydraulic conductivity and direct shear tests were also undertaken.

- Environmental assessment

A suitably qualified professional (SQP) was engaged to conduct the environmental and work health and safety assessment. The environmental assessment was undertaken to:

  - determine the potential impacts of these recycled materials on human health and the environment and,
  - assess compliance with the Queensland End of Waste (EoW) code requirements

Assessments have been based on the available literature as well as the results of determining total concentrations of contaminants (TCC) and column leachate tests conducted, where required, on the studied materials.

1.3 Report Structure

Section 1 of this report presents the background, objectives and methodology adopted for the project. Sections 2, 3 and 4 present the environmental assessments, as well as the results of physical and mechanical tests conducted on the RCC, RAP and CCP samples, respectively. Section 5 summarises the findings from Year 1 of the project on the use of RCG in earthworks and drainage applications. The main findings and recommendations based on Year 2 are summarised in Section 6. The environmental assessments are presented in Appendix A to Appendix C.

2 Recycled Crushed Concrete

2.1 General

Recycled crushed concrete (RCC) is a common recycled construction material, generally obtained from the demolition of concrete structures. Due to its favourable shear strength properties, RCC has been used in various applications, particularly as unbound base and subbase material in pavements. Up to 100% RCC can be used in unbound granular layer material of Type 2 (TMR 2022). This section summarises the experimental results on the engineering properties of the RCC samples sourced from various suppliers in Queensland, to evaluate their suitability for earthworks and drainage applications. The obtained samples were initially intended to be assessed against the requirements for use in drainage applications, although suitability of their use in other earthwork applications was also investigated.

2.2 Testing Program

The details of the assessment program for environmental and engineering characterisation assessments of the RCC samples are presented in Table 2.1 and Table 2.2, respectively.

Table 2.1: Environmental assessment of RCC

Test/assessment	Number of tests/samples
Total concentrations of contaminants (TCC)	9
Column leachate	11 (1)
SQP assessment	✓

1. Including tests on 2 no-fines (no particles smaller than 75 µm) RCC samples.

Table 2.2: Experimental testing for assessment of physical and mechanical properties of RCC

Test	Number of tests/samples
Particle size distribution (AS 1289.3.6.1)	9
Atterberg limits (AS 1289.3.2.1, AS 1289.3.3.1, AS 1289.3.4.1)	3
Wet/dry strength variation (AS 1141.22)	3

2.3 Health, Safety and Environmental Risk Assessment

This section outlines the advice and conclusions provided by the SQP in relation to the use of RCC in earthwork and drainage applications. The report is attached in Appendix A.

The objectives of the review undertaken and presented in this report were to determine if the proposed use of RCC in road embankments and in drainage:

- has the potential to impact human health
- has the potential to impact the environment
- requires any additional management measures for the use of the material.

To obtain the total concentration of contaminants, the following analyses were conducted on the RCC samples:

- total recoverable hydrocarbons (TRH)
- volatile and semivolatile organics
- organochlorine and organophosphorus pesticides
- polychlorinated biphenyls (PCBs)

- acid herbicides
- cyanide (total), fluoride (total)
- metals (antimony, arsenic, barium, beryllium, boron, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, silver, vanadium, zinc).

In addition, 3 of the samples were analysed for the leaching of metals using the Australian standard leaching procedure (ASLP). The ASLP leach testing procedure involves the crushing of the material (to a maximum of 2.4 mm particle size), use of water at a set ratio of soil:water at a set pH (pH 4 was used in the tests) and vigorous shaking with the material for an extended period of time (16 hours). This method does not necessarily reflect leaching that can occur in situ, particularly with the recycled crushed concrete as supplied, in particular the coarse materials that may be used in drainage (i.e. 10 mm and 20 mm).

To obtain a better understanding of the potential for water runoff from recycled crushed concrete to have elevated pH, 20 mm crushed concrete samples (as supplied – no further crushing undertaken) were sent to a certified laboratory for column leach tests. The samples were tested under 3 different conditions:

- unwashed (i.e. as received)
- twice washed
- wetted and washed.

In addition to the above, 2 additional samples comprising no-fines (unwashed) crushed concrete were also analysed.

The leach test involved the following stages:

- Stage 1 – Fast flushing: This work involved 9 cycles of fast flushing with approximately 2.3 to 2.4 L high-purity water being passed through each column of crushed material. The pH of the water exiting the material (i.e. elutriate following each flush) was measured.
  The data from this stage of testing indicated the following:
  - following all flush tests, the pH of the elutriate remained in the range 10.3 to 11.9
  - with each flushing round, the pH of the elutriate generally decreased slightly, for all samples analysed
  - the pH was highest for the no-fines crushed concrete samples analysed
  - the pH of the materials tested that were twice washed were lower than the unwashed samples, and the materials that were wetted prior to the test, had a lower pH than all other samples.
- Stage 2 – Slow drip: This work involved further assessment of leaching from the material evaluated in Stage 1. The columns were sealed off to slow the movement of water through the material. The material was wetted with 1 L high-purity water, after which a drip feed of high-purity water was added at a rate of 7–9 mL/min. Elutriate collected over 24 hours was collected and measured at the same time each day, for 4 consecutive days.
  The data from this stage of testing indicated the following:
  - the pH of elutriate following drip feeding of water remained in the range 10.4 to 11.9, which is similar to the range reported following the Stage 1 testing
  - at the end of each day, the pH of the elutriate for many of the samples had no specific trend, with the pH varying over each day
  - the pH of the no-fines (unwashed) materials was highest, noting that the pH generally decreased each day
  - the pH of the materials tested as samples BS21/307 and BS21/328 that were twice washed or wetted prior to the test, had a lower pH than the other samples.

Overall, the wetted samples and in particular sample BS21/328 resulted in the lowest pH after the 9 flushes during Stage 1 and reported lower levels of pH in Stage 2. Hence moistening the sample and leaving it for 72 hrs gave lower pH elutriates than 2 washes (where there was much more water contact with the material).

Based on the available information, including analysis of RCC samples, and the proposed use of RCC, the following can be concluded:

- The characteristics of recycled crushed concrete are consistent with specifications for the use of these materials for pavements and drainage in NSW, Western Australia and South Australia.
- The characteristics of recycled crushed concrete indicate that the material is not considered to be regulated waste in Queensland.
- In relation to the chemical composition of recycled crushed concrete proposed to be used for pavements or drainage materials, there are no apparent risk issues of concern in relation to human health or the environment (terrestrial or aquatic). Specifically:
  - concentrations detected in recycled crushed concrete are below criteria protective of risks to human health
  - measured leachate concentrations are below drinking-water guidelines
  - where relevant the concentrations reported in recycled crushed concrete are not of concern to terrestrial environments
  - concentrations detected in recycled crushed concrete are not considered to be of concern in relation to aquatic environments.
- In relation to the pH of recycled crushed concrete the review undertaken has concluded the following:
  - workers handling recycled crushed concrete (particularly fresh materials) should wear gloves and eye protection and other personal protective equipment (PPE) as detailed on relevant safety data sheets for the product
  - there are no risk issues of concern for the general public who may come into direct contact with residual recycled crushed concrete materials or surface water runoff
  - there are no risk issues of concern for recycled crushed concrete where used in bound pavement materials or in compacted materials beneath sealed and unsealed surfaces
  - it is not considered appropriate to use recycled crushed concrete as a surface layer for unsealed roads
  - the pH of the leachate would not result in any increased risk issues of concern for metals
  - the pH of the leachate derived from recycled crushed concrete (where contact with rainfall may occur) would be buffered by soil, surface water and groundwater and the potential for adverse effects on aquatic ecosystems is considered to be low
  - while no significant risks to human health or the environment have been identified, the following measures should be considered to minimise the potential for pH to impact on the offsite environment, where recycled crushed concrete may be used for drainage
    - the materials to be used should have a pH ≤ 9
    - if the pH > 9 it may be used for drainage provided the material is not used in areas closer than 30 m from a receiving waterway.

2.4 Physical and Mechanical Properties

Nine samples of RCC were sourced from 3 different suppliers for experimental characterisation. Three samples (1,2, and 3) were obtained from 3 different suppliers A, B and C. From each supplier, 3 different gradations were procured (20 mm nominal – gradation 1, 10 mm nominal – gradation 2 and crusher dust – gradation 3). Accordingly, samples were named SXGY, X being the supplier and Y being the gradation number. For instance, SAG1 stands for RCC sample from Supplier A with gradation number 1. Table 2.3 and Figure 2.1 present the particle size distributions (PSD) of the supplied RCC samples, as well as the requirements of bedding, drainage, granular fill, and unbound drainage applications specified in MRTS04 *General Earthworks* (TMR 2021a). PSD additional characteristics (D10, D30, D60, Cc, Cu etc.) are summarised in Table 2.4.

The RCC samples SAG1, SAG2, SBG1, SBG2, SCG1, and SCG2 contained a limited portion of fines (≤ 1%). These samples had a relatively gap-graded PSD and were classified as poorly graded gravel (GP) according to the Unified Soil Classification System. It is expected that such materials will exhibit high permeability and can be considered as free-draining materials, which makes them suitable for drainage applications. The SAG3 sample contained 28% gravel, 70% sand, and 2% fines, classified as poorly graded sand (SP) based on the PSD curve, coefficient of uniformity (Cu), and coefficient of curvature (Cc). The remaining 2 RCC samples, SBG3 and SCG3, had higher fine contents (6–8%) and were classified as well-graded sand (SW).

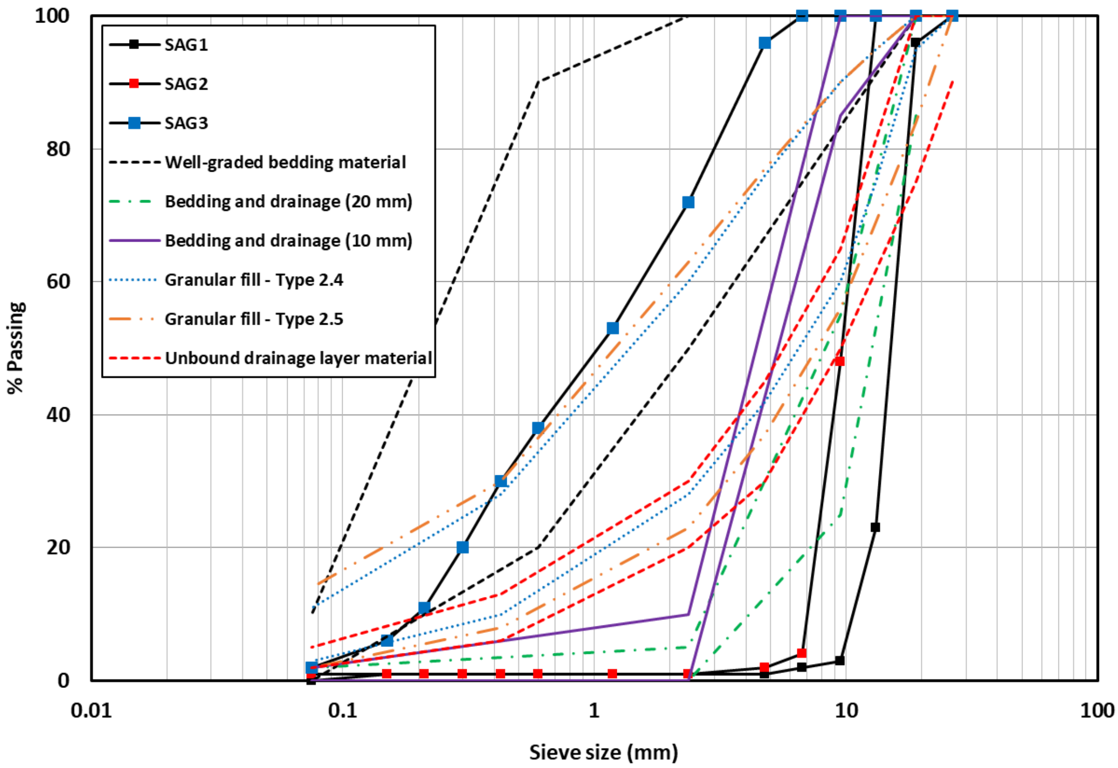
Table 2.3: PSD of RCC sourced from different suppliers and the requirements of MRTS04

Sieve size (mm)	Supplier									MRTS04 limits					
	A			B			C			Well-graded bedding material	Bedding and drainage aggregate (20 mm nominal)	Bedding and drainage aggregate (10 mm nominal)	Granular fill (Type 2.4) [1]	Granular fill (Type 2.5) [1]	Unbound drainage material
	SAG1	SAG2	SAG3	SBG1	SBG2	SBG3	SCG1	SCG2	SCG3						
	Percent passing (%)														
26.5	100			100			100			100	–	–	100	100	90–100
19	96			83	100		67			–	85–100	100	95–100	84–100	75–100
13.2	23	100		7	79		16	100		–	–	–	75–95	69–95	–
9.5	3	48		1	31		2	54		–	25–55	85–100	60–90	56–90	50–65
6.7	2	4	100	1	1	100	1	10		–	–	–	–	–	–
4.75	1	2	96	1	0	98	1	3	100	–	–	–	42–76	37–77	30–45
2.36	1	1	72	1	0	78	0	1	88	50–100	0–5	0–10	28–60	23–63	20–30
1.18	1	1	53	1	0	52	0	1	66	–	–	–	–	–	–
0.6	1	1	38	1	0	34	0	1	44	20–90	–	–	–	–	–
0.425	1	1	30	0	0	27	0	1	34	–	–	–	10–28	8–30	6–13
0.3	1	1	20	0	0	21	0	0	26	–	–	–	–	–	–
0.212	1	1	11	0	0	21	0	0	18	–	–	–	–	–	–
0.15	1	1	6	0	0	11	0	0	13	–	–	–	–	–	–
0.075	0	1	2	0	0	6	0	0	8	0–10	0–2	0–2	3–11	2–14	2–5

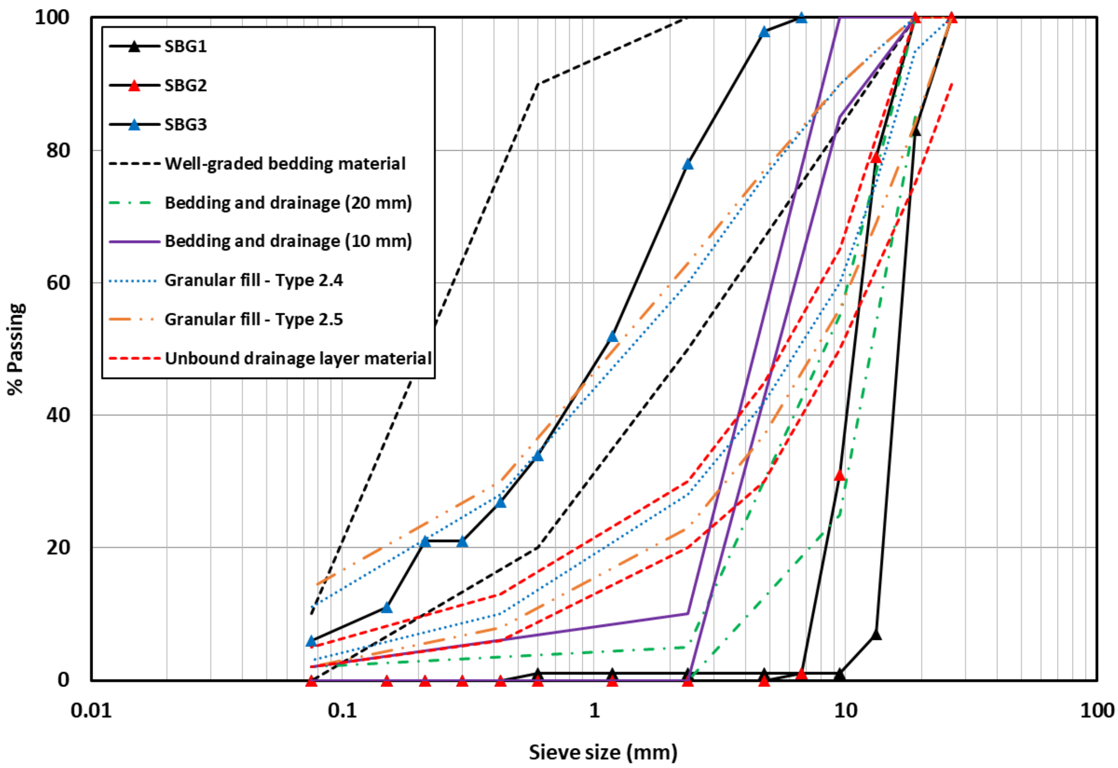
1. PSD requirements stated in MRTS05 (TMR 2022).

Source: TMR (2021a).

Figure 2.1: PSD curves of RCC samples from a) supplier A, b) supplier B and c) supplier C



a)



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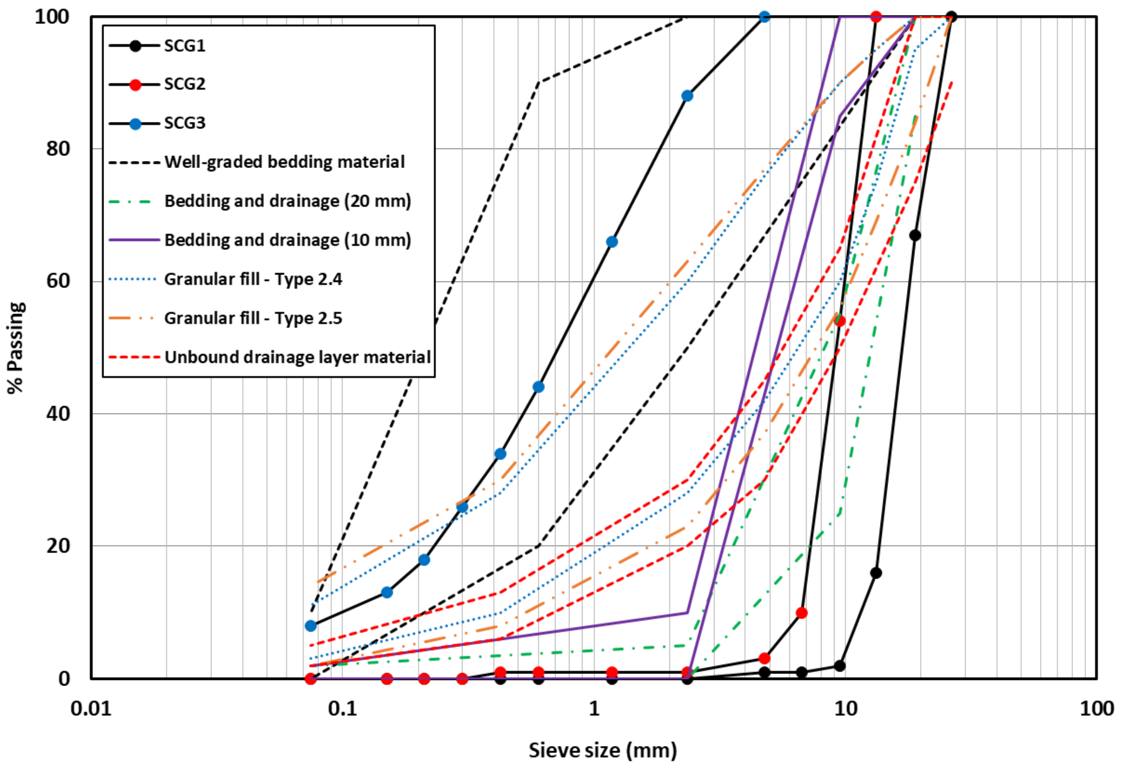


c)

Notes:

- SAG1: RCC sample from Supplier A with Gradation number 1.
- SBG1: RCC sample from Supplier B with Gradation number 1.
- SCG1: RCC sample from Supplier C with Gradation number 1.

Table 2.4 also includes the Atterberg limits, and wet/dry strength variation test results obtained for the RCC samples from each supplier. The wet/dry strength variation tests were undertaken on the SAG1, SBG1, and SCG1 (the coarser aggregates), while the Atterberg limits were determined for SAG3, SBG3, and SCG3 (the finer aggregates). All the supplied RCC samples were non-plastic, and the values of liquid limit, plastic limit, and linear shrinkage were not obtainable.

According to MRTS04, free-draining backfill materials should have a maximum particle size of 19 mm, maximum linear shrinkage of 3%, with a maximum of 5% aggregates passing the 0.15 mm sieve, as summarised in Table 2.4. SAG2, SBG2, and SCG2 can be used as a backfill material behind retaining walls.

MRTS04 also allows well-graded bedding materials to be used for the foundation, bedding and haunch zone of drainage structures and services. The well-graded bedding material is required to meet the PSD requirements summarised in Table 2.3, in addition to having a maximum linear shrinkage value of 6%.

The PSD curves for SAG3, SBG3, and SCG3 were within the specified limits of MRTS04, while the remaining RCC samples failed to satisfy the PSD requirement. The requirements for 20 mm and 10 mm nominal-sized bedding and drainage aggregates, specified by MRTS04 are also summarised in Table 2.3, indicating that the gradations require amendments to comply with the specifications.

The requirements of MRTS04 for Class A1 and Class A2 embankment fill materials are summarised in Table 2.4. The coefficient of uniformity (Cu) value for samples SAG3, SBG3, and SCG3 was 8.1, 11.4 and 9.7, respectively, which met the minimum limit of 5 for Class A2 fill materials. Therefore, these materials may be considered for use for the construction of embankments with homogenous cross-section, with a batter slope of ≤4, and height of ≤ 3 m, or in the core section of embankments with zoned cross-section and height of ≤ 10 m. The same requirements apply to the fill used in subgrade treatments.

Table 2.4: **Engineering properties of RCC samples and requirements of MRTS04**

Property	Supplier									MRTS04 limits		
	A			B			C			Embankment fill (Class A1)	Embankment fill (Class A2)	Free draining granular material
	SAG1	SAG2	SAG3	SBG1	SBG2	SBG3	SCG1	SCG2	SCG3			
PSD parameters												
Maximum aggregate size (mm)	26.5	13.2	6.7	26.5	19	6.7	26.5	13.2	4.75			19
Passing 0.15 mm sieve (%)	1	1	6	0	0	11	0	0	13			≤ 5
D10 (mm)	10.8	7.1	0.2	13.4	7.5	0.1	11.6	6.7	0.1			
D30 (mm)	13.8	8.4	0.4	15.0	9.4	0.5	14.8	8.0	0.4			
D60 (mm)	16.1	10.4	1.6	17.2	11.7	1.5	18.2	10.0	1.0			
Cc	1.1	1.0	0.6	1.0	1.0	1.2	1.0	1.0	1.2			
Cu	1.5	1.5	8.1	1.3	1.6	11.4	1.6	1.5	9.7		> 5	
Gravel content (%)	99	99	28	99	100	22	100	99	12			
Sand content (%)	1	0	70	1	0	72	0	1	80			
Fines content (%)	0	1	2	0	0	6	0	0	8	≥ 15		
Soil classification	GP	GP	SP	GP	GP	SW	GP	GP	SW			
WPI*	NO	NO	NO	NO	NO	NO	NO	NO	NO	< 1200	< 1200	
Emerson class number	–	–	–	–	–	–	–	–	–	> 3		
Moisture content (%)	5.3	6.7	12.6	4.5	4.3	7.5	3.8	4.4	9.6			
Atterberg limits												
Liquid limit (%)	–	–	NO	–	–	NO	–	–	NO			
Plastic limit (%)	–	–	NO	–	–	NO	–	–	NO			
Plasticity index (%)	–	–	NP	–	–	NP	–	–	NP	≥ 7		
Linear shrinkage (%)	–	–	NO	–	–	NO	–	–	NO			≤ 3

Property	Supplier									MRTS04 limits		
	A			B			C			Embankment fill (Class A1)	Embankment fill (Class A2)	Free draining granular material
	SAG1	SAG2	SAG3	SBG1	SBG2	SBG3	SCG1	SCG2	SCG3			
Wet/dry strength variation												
Nominal size (mm)	20	–	–	20	–	–	20	–	–			
Size fraction (mm)	19–9.5	–	–	19–9.5	–	–	19–9.5	–	–			
Wet strength (kN)	93	–	–	91	–	–	84	–	–			
Dry strength (kN)	105	–	–	95	–	–	97	–	–			
Wet/dry strength variation	11	–	–	4	–	–	13	–	–			

NO: not obtainable; NP: non-plastic; WPI: weighted plasticity index (PI × percent passing 0.425 mm sieve).

Source: TMR (2021a).

Therefore, SAG3, SBG3, and SCG3 could be used as fill materials placed within 1.5 m below the subgrade level. According to MRTS04, Class A1, Class A2, and Class B fill materials passing the 25 mm test sieve can also be used as earth backfill materials. Thus, SAG3, SBG3, and SCG3 could be used in some backfill applications. According to the MRTS04, fill materials used in embankments, subgrade treatments and backfills shall have a minimum 4-day soaked CBR of 3% when tested at 97% standard compaction and optimum moisture. However, no information was available on the CBR values of the tested samples.

MRTS04 specifies that Type 2.4 material may be used as unbound granular drainage layer material in the construction of subgrades and is required to meet the PSD limits summarised in Table 2.3. The PSD curves of the RCC samples indicated that none of the supplied samples conformed to the specified PSD envelopes. It should be noted, however, that the RCC materials assessed were sourced from each supplier's general stockpiles for 10 mm, 20 mm and crusher dust products. The grading limits for the sampled materials were not specified by TMR with the suppliers for the testing of these materials. Each supplier from which material was acquired has the capability to manufacture RCC to meet TMR grading requirements. For the purpose of this assessment therefore, the non-conforming gradings should not exclude these materials for future use for these applications.

Table 2.5 presents the suitability of the investigated RCC for earthwork and drainage applications.

Table 2.5: Suitability of the investigated RCC for earthwork and drainage applications

Application		Sample no.								
		SAG1	SAG2	SAG3	SBG1	SBG2	SBG3	SCG1	SCG2	SCG3
Embankments	Class A1 earth fill material	x	x	x	x	x	x	x	x	x
	Class A2 earth fill material	x	x	✓	x	x	✓	x	x	✓
	Class B, C and D earth fill material	x	x	x	x	x	x	x	x	x
Subgrade	Fill material (used within 1.5 m below subgrade level)	x	x	✓	x	x	✓	x	x	✓
	Granular fill for subgrade improvement	x	x	x	x	x	x	x	x	x
	Unbound drainage material	x	x	x	x	x	x	x	x	x
Backfill	Earth backfill material	x	x	✓	x	x	✓	x	x	✓
	Free draining granular material	✓	✓	x	✓	✓	x	✓	✓	x
	Bedding material and drainage (WG)	x	x	✓	x	x	✓	x	x	✓
	Bedding and drainage (20 mm nominal)	x	x	x	x	x	x	x	x	x
	Bedding and drainage (10 mm nominal)	x	x	x	x	x	x	x	x	x
Note		No information available on the CBR of the samples.								

x = not suitable, ✓ = suitable, WG = well-graded.

3 Reclaimed Asphalt Pavement

3.1 General

Reclaimed asphalt pavement (RAP) is asphalt that has been milled or excavated from existing pavements, or unused asphalt returned from job sites (TMR 2022). The Queensland waste recovery statistics for 2018–19 show that asphalt was the second highest recovered product (Queensland Government 2020). RAP is a high-value product typically reused in asphalt as both the amount of new aggregate and bitumen needed for mixes can be reduced, leading to significant economic and sustainability benefits (TMR 2022). While the use of RAP in production of hot-mix asphalt has become a common practice and should be the preferred use, there remain opportunities for incorporating RAP in other applications, such as embankment fills and drainage. This is particularly suited to RAP products which would not be suitable for asphalt production.

The details of the assessment program for environmental assessments and engineering characterisation of RAP are presented in Table 3.1 and Table 3.2, respectively.

Table 3.1: Environmental assessment of RAP

Test/assessment	Number of tests/samples
Total concentrations of contaminants (TCC)	3
Column leachate	NR (1)
SQP assessment	✓

1. Not required as per the SQP advice.

Table 3.2: Experimental testing for assessment of physical and mechanical properties of RAP

Test	Number of tests/samples
Particle size distribution (TMR Q103A)	6
Atterberg limits (TMR Q104A, TMR Q105, TMR Q106)	1
Direct shear (large-scale)	2
One-dimensional consolidation (large-scale)	2
Bitumen content (TMR Q118)	1
Maximum dry density and optimum moisture content under standard compactive effort (TMR Q142A)	1

3.2 Health, Safety and Environmental Risk Assessment

The section outlines the method, advice and conclusions provided by the SQP in relation to the use of RAP in earthwork and drainage applications. The report is included in Appendix B .

The objective of the review undertaken and presented in this report was to determine if the proposed use of RAP in road embankments and in drainage:

- has the potential to impact human health
- has the potential to impact the environment
- requires any additional management measures for the use of the material.

To obtain the total concentration of contaminants, the following analyses were conducted on the RAP samples:

- total recoverable hydrocarbons (TRH)
- volatile organics
- organochlorine pesticides (OCPs)

- organophosphorous pesticides (OPPs)
- polychlorinated biphenyls (PCBs)
- acid herbicides
- semivolatile organics, which include polycyclic aromatic hydrocarbons (PAHs)
- cyanide, fluorine, pH
- metals (antimony, arsenic, barium, beryllium, boron, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, silver, vanadium, zinc)
- dioxins and furans
- polybrominated diphenyl ethers (PBDEs).

Based on the available information, including analysis of RAP samples, and the proposed use of RAP, the following can be concluded:

- No detectable concentrations of PAHs were reported in the RAP evaluated.
- Some metals were detected, however the concentrations reported were low and consistent with the characteristics expected for natural materials or clean fill, including gravel and sand commonly used in road applications and embankments.
- The presence of TRH is expected to reflect some non-PAH hydrocarbons, but also natural organic matter and polar metabolites from the weathering of RAP.
- In addition to the above, there were no issues of concern in relation to risks to human health or the environment (terrestrial or aquatic), the use of RAP in embankment materials, drainage lines or pavement materials. This also included stockpiled materials in road corridors.

The assessment undertaken has considered the use of 100% RAP in these applications. This is conservative for the proposed use in embankment materials, drainage and pavement materials within road corridors. Mixing of RAP with other fill or pavement materials for reuse in various road applications would not change the outcomes detailed above.

It is recommended that suppliers of RAP provide results of analysis of these materials (in relation to pH, metals, TRH and PAHs) to TMR to demonstrate the characteristics of the RAP provided remain consistent with the materials evaluated in this assessment. It is noted that RAP should not be used in drainage materials where the pH is 11 or higher.

3.3 Physical and Mechanical Properties

Two samples of RAP, 1 profiled from a site in Queensland and 1 processed from a local Queensland supplier, were sourced for the laboratory characterisation. TMR prefers RAP to be reused in asphalt; however, where RAP is not suitable for this end in asphalt (for example it may be mixed with other pavement or embankment materials), it may be considered for use in earthworks. For preparation of the samples for testing, for each sample, 3 sub-samples were prepared and subject to different drying conditions: dried at ambient temperature, at 50 °C and at 105 °C.

3.3.1 First RAP Sample (G1)

Table 3.3 and Figure 3.1 present the PSD of the profiled RAP samples. The tested samples had a maximum particle size of 19 mm and were classified as well-graded gravel (GW). While samples dried at different temperatures met the upper limit of Type 2.5 material, the curves for G1-50 °C and G1-105 °C were slightly below the lower limit for particles smaller than about 2 mm. Generally, G1-50 °C and G1-105 °C samples had higher gravel contents and lower fine contents than G1-ambient. This could be attributed to the adhesion between particles caused by the bituminous coating at 50 °C and 105 °C.

The Atterberg limits were only determined for the G1-50 °C sample, as summarised in Table 3.4.

Table 3.3: PSD of profiled RAP samples and requirements of MRTS04

Sieve size (mm)	Source			MRTS04 limits				
	G1-ambient	G1-50 °C oven	G1-105 °C oven	Well-graded bedding material	Bedding and drainage aggregate (20 mm nominal)	Granular fill (Type 2.4) (1)	Granular fill (Type 2.5) (1)	Unbound drainage material
	Passing (%)							
26.5	100	100	100	100	–	100	100	90–100
19	100	99	98	–	85–100	95–100	84–100	75–100
13.2	96	89	90	–	–	75–95	69–95	–
9.5	89	78	78	–	25–55	60–90	56–90	50–65
6.7	76	61	60	–	–	–	–	–
4.75	60	44	43	–	–	42–76	37–77	30–45
2.36	38	25	24	50–100	0–5	28–60	23–63	20–30
0.6	–	–	–	20–90	–	–	–	–
0.425	12	6	4	–	–	10–28	8–30	6–13
0.075	2.6	0.9	0.5	0–10	–	3–11	2–14	2–5

1. PSD requirements stated in MRTS05 (TMR 2022).
Source: TMR (2021a).

According to MRTS04, free-draining backfill materials should have a maximum particle size of 19 mm, maximum linear shrinkage of 3%, with a maximum of 5% aggregates passing the 0.15 mm sieve. While the information on the percentage of the aggregate passing the 0.15 mm sieve was not available, the values of D5 (the diameter that 5% of the material passes) were calculated. The D5 values for G1-ambient, G1-50 °C and G1-105 °C were 0.16 mm, 0.36 mm, and 0.52 mm, respectively, which indicated that the maximum percentage of aggregates passing the 0.15 mm sieve was lower than 5% for all samples.

Therefore, the profiled RAP sample would be suitable for use as a free-draining backfill material. MRTS04 also allows well-graded bedding materials to be used for the foundation, bedding and haunch zone of drainage structures and services. The PSD of the profiled RAP materials was outside the limits of MRTS04 for bedding materials. The RAP samples also did not conform to the specified PSD requirements of MRTS04 for 20 mm nominal bedding and drainage materials.

Figure 3.1: PSD curves of profiled RAP samples

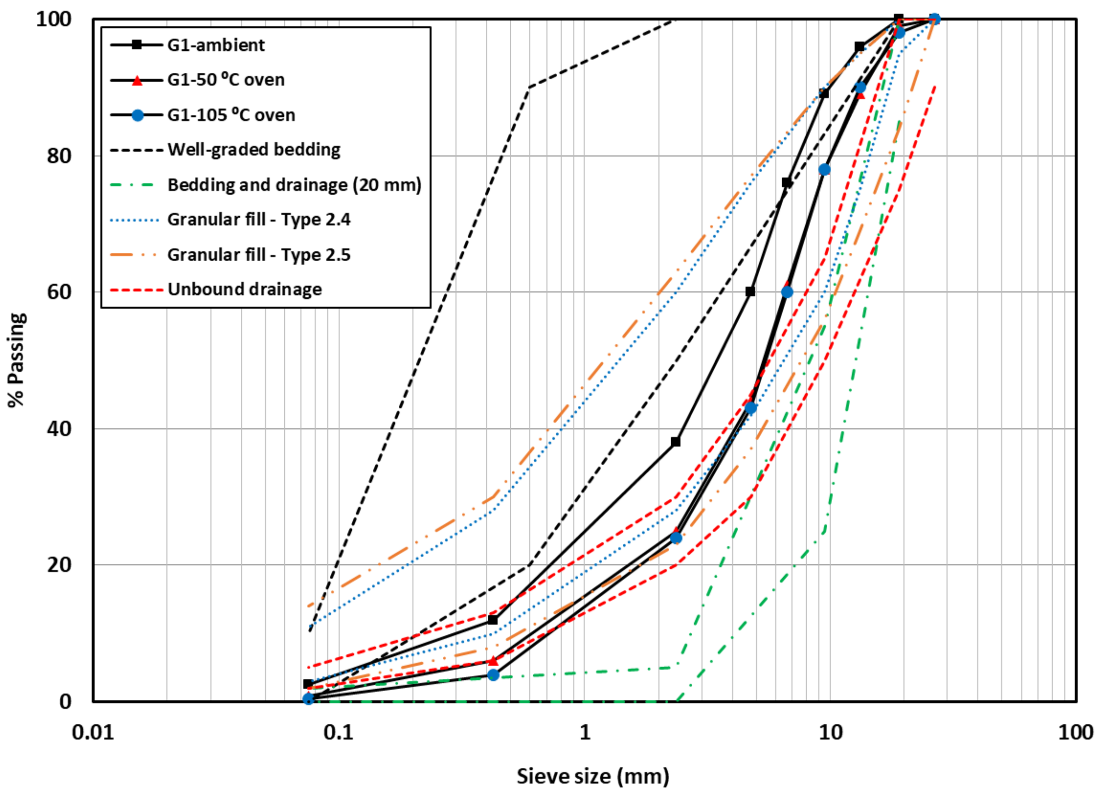


Table 3.4: Physical properties of profiled RAP samples and requirements of MRTS04

Property	Source			MRTS04 limits	
	G1-ambient	G1-50 °C oven	G1-105 °C oven	Embankment fill (Class A2)	Free draining material
Moisture content (%)	–	5.4	–		
PSD parameters					
Maximum aggregate size (mm)	19	19	19		19
Passing 0.15 mm sieve (%)	≤ 5	≤ 5	≤ 5		≤ 5
D10	0.4	0.8	1.0		
D30	1.8	3.0	3.1		
D60	4.8	6.6	6.7		
Cc	1.9	1.6	1.4		
Cu	13.6	7.9	6.7	> 5	
Gravel content (%)	62.0	75.0	76.0		
Sand content (%)	35.4	24.1	23.5		
Fines content (%)	2.6	0.9	0.5		
Soil classification	GW	GW	GW		
WPI	–	14.4	–	< 1200	
Atterberg limits					
Liquid limit (%)	–	23.8	–		
Plastic limit (%)	–	21.4	–		
Plasticity index (%)	–	2.4	–		
Linear shrinkage (%)	–	1	–		≤ 3

Source: TMR (2021a).

The requirements of MRTS04 for Class A2 fill material are summarised in Table 3.4. The Cu value of all samples was higher than the minimum requirement of 5, and the values for WPI were considerably below the maximum limit for G1-50 °C due to the limited portion of plastic fines within the samples. While The Atterberg limits were only determined for G1-50 °C, it was reasonable to assume that the WPI for G1-ambient, and G1-105 °C was below the maximum specified value of 1200. As such, the RAP samples could be used as a Class A2 fill material for the construction of the core section of embankments (≤ 10 m) with zoned cross-section, or embankments with homogenous cross-section, height of ≤ 3 m, and batters ≤ 1V:4H. However, due to the lack of knowledge on risk of settlement and potential loss of stability (as no previous trials have been done in Australia), for applications of embankment construction where heights range from 1 m to 10 m, it is suggested that the compactability, shear strength and compressibility of RAP should be investigated.

RAP could also be used as fill material in subgrade treatments as well as backfill applications since all materials pass the 25 mm sieve. According to MRTS04, fill materials used in embankments, subgrade treatments and backfills shall have a minimum 4-day soaked CBR of 3% when tested at 97% standard compaction and optimum moisture. No information on the CBR of the tested samples was available though.

According to the *Pavement Design Supplement* (TMR 2021b), Type 2.4 and Type 2.5 materials shall be used as a granular fill for soft subgrade improvement. The liquid limit of G1-50 °C conformed with the requirement of MRTS05 for Type 2 material (liquid limit ≤ 40%), while the linear shrinkage was slightly lower than the lower limit (i.e. 1.5%). No information was available on other properties to evaluate their conformance with the requirements.

MRTS04 also allows Type 2.4 to be used as unbound granular drainage material in the construction of subgrades, provided that the material meets the PSD requirements summarised in Table 3.3. While the test portion passing the 4.75 mm sieve was within the PSD limits, the PSD for the coarse fraction (retained on the 4.75 mm sieve) was outside the limits. In addition, sufficient information was not available on other engineering properties of the materials to check the conformance with a Type 2.4 material.

3.3.2 Second RAP Sample (G2)

The PSDs of the RAP samples from the second local Queensland supplier (G2 samples) are presented in Table 3.5 and

Figure 3.2.

The PSD curves for the G2 RAP samples were generally within the gradation limits of the Type 2.5 material, except for the fine portion passing the 0.6 mm sieve that were slightly below the lower limit. Similar to what was observed for the G1 sample, the materials dried at higher temperatures for PSD analysis, i.e. 50 °C and 105 °C, tended to have lower fine contents (passing the 75 µm sieve). Although the linear shrinkage of the G2 samples was not available, given the low fine contents (< 2%), the samples were considered to be suitable as free-draining backfill materials based on the maximum particle size and the portion of the aggregates passing the 0.15 mm sieve. The PSD of the G2 RAP samples did not meet the requirements of Table 3.5 for bedding materials and 20 mm nominal bedding and drainage materials.

The requirements of MRTS04 for Class A2 fill material are summarised in Table 3.6. The Cu values of the G2 samples were higher than the minimum requirement, and the information on the PI of the samples was not available. However, it can be assumed that the samples would have low PI values due to the coarse gradation and limited portion of plastic fines, and the WPI would be less than 1200. The RAP samples thus, could be used as a Class A2 fill material for the construction of the core section of embankments (≤ 10 m) with zoned cross-section, or embankments with homogenous cross-section, height of ≤ 3 m, and batters ≤1V:4H. RAP samples could also be used as fill materials in subgrade treatments as well as backfill applications since all materials pass the 25 mm sieve.

The CBR values were not available to assess the suitability of the G2 RAP samples as fill materials used in embankments, subgrade treatments and backfills, as detailed in MRTS04.

Table 3.5: PSD of RAP samples supplied from a local supplier in Queensland and requirements of MRTS04

Sieve size (mm)	Source			MRTS04 limits				
	G2-ambient	G2-50 °C oven	G2-105 °C oven	Well-graded bedding material	Bedding and drainage aggregate (20 mm nominal)	Granular fill (Type 2.4) (1)	Granular fill (Type 2.5) (1)	Unbound drainage material
	Passing (%)							
26.5	100	100	100	100		100	100	90–100
19	100	100	100		85–100	95–100	84–100	75–100
13.2	97	97	96			75–95	69–95	
9.5	84	80	79		25–55	60–90	56–90	50–65
6.7	68	64	64					
4.75	52	48	48			42–76	37–77	30–45
2.36	32	30	29	50–100	0–5	28–60	23–63	20–30
1.18	19	17	17					
0.6	11	10	9.4	20–90				
0.425	7.6	7.4	6.6			10–28	8–30	6–13
0.3	5	4.9	4.1					
0.15	2.4	2	1.4					
0.075	1.9	1.3	0.7	0–10		3–11	2–14	2–5

1. PSD requirements stated in MRTS05 (TMR 2022).
Source: TMR (2021a).

Figure 3.2: PSD curves of RAP samples supplied from a local supplier in Queensland

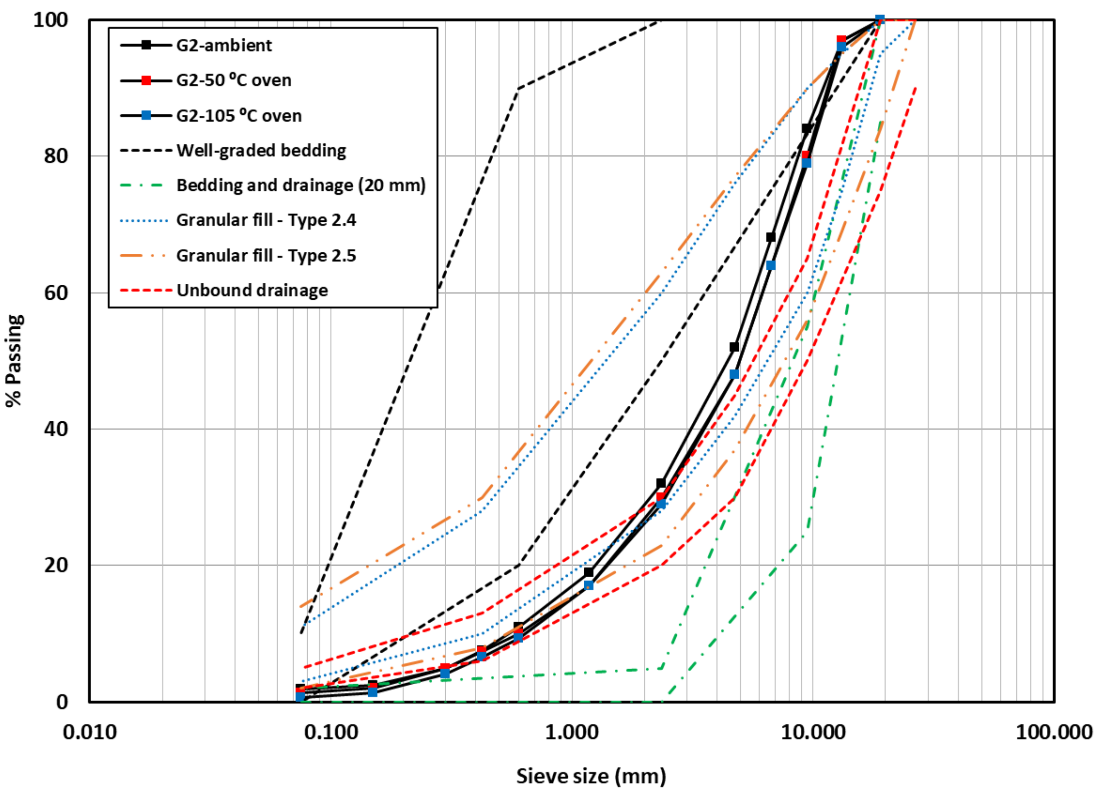


Table 3.6: Physical properties of RAP samples sourced from a local supplier in Queensland and requirements of MRTS04

Property	Source			MRTS04 limits	
	G2-ambient	G2-50 °C oven	G2-105 °C oven	Embankment fill (Class A2)	Free draining material
PSD parameters					
Maximum aggregate size (mm)	19	19	19		19
Passing 0.15 mm sieve (%)	2.4	2.0	1.4		≤ 5
D10	0.5	0.6	0.6		
D30	2.2	2.4	2.5		
D60	5.7	6.2	6.2		
Cc	1.5	1.5	1.5		
Cu	10.4	10.4	9.6	> 5	
Gravel content (%)	68	70	71		
Sand content (%)	30.1	28.7	28.3		
Fines content (%)	1.9	1.3	0.7		
Soil classification	GW	GW	GW		
WPI	–	–	–	< 1200	
Linear shrinkage (%)	–	–	–		≤ 3
Compaction properties					
OMC [1] (%) – Standard compaction	10.0				
MDD [2] (t/m^3) – Standard compaction	2.05				
Bitumen content					
Bitumen content (%)	3.20				

1. Optimum moisture content.
2. Maximum dry density.

Source: TMR (2021a).

3.4 Additional Mechanical Testing

3.4.1 Objective

The compressibility of embankment material has a significant impact on its serviceability and long-term performance. RAP particles contain a bitumen coating, which is sensitive to temperature and might exhibit significant compressibility, particularly at elevated temperatures. This can cause excessive settlements as well as reduced shear strength and adversely affect the structural performance of the road embankments (Soleimanbeigi & Edil 2015a, b). In unbound pavement layers, softening of the bitumen coating at elevated temperatures can cause excessive deformations and rutting, resulting in serviceability issues and cracking on the road surface (Ghorbani et al. 2020). Accordingly, several studies have been undertaken to investigate the compressibility, creep, and deformation properties of RAP used in road embankments.

Soleimanbeigi and Edil (2015a) investigated the compressibility of several types of recycled materials using one-dimensional compression tests and highlighted the higher compressibility of bituminous recycled materials compared to non-bituminous recycled materials. The results of their study also showed an increase in the compressibility of the bituminous recycled materials with a rise in the temperature. They observed an increase of 0.08% in the plastic strain of RAP per 1 °C increase in temperature. Ncube and Bobet (2021) identified the high amount of creep as the primary barrier to using RAP and suggested mixing RAP with other aggregates as well as stabilisation as potential solutions. Soleimanbeigi and Edil (2015b) reported that compacting RAP at elevated temperatures, reduces the compressibility of RAP, and samples compacted at higher temperatures had lower compressibility compared to those prepared at room temperature, when tested at the same high temperature.

In this project, additional testing was undertaken on RAP samples to characterise their shear strength and compressibility at a temperature higher than room temperature, as a worst-case scenario in terms of performance based on previous studies. For this aim, large-scale direct shear and one-dimensional consolidation tests were undertaken on RAP samples at 35 °C, with the samples being prepared at room temperature.

3.4.2 Methodology

Large-scale direct shear test

The shear strength properties of the RAP samples were investigated at elevated temperatures using a large direct shear test following the Australian testing method (AS 1289.6.2.2 2020). A multi-stage direct shear test was undertaken involving a consolidation stage under normal stresses of 50 kPa, 100 kPa, and 200 kPa, followed by a 10 mm shearing at each stage. The shear box included a top half which was fixed to the frame and a bottom half that moved relative to the top half along the horizontal shear failure plane. The horizontal and vertical displacements were recorded using 2 linear variable deformation transducers (LVDTs). The specimen dimensions were 300 mm x 300 mm, with a height of 150 mm, compacted using a hammer drill at the optimum moisture content and to relative dry density values of 95% MDD and 100% MDD. The compacted slabs were soaked in the water for 24 hours with a temperature of 35 °C before starting the test. A thermocouple was connected on one side of the bath and a pump on the other side to circulate the water through during the test to keep the temperature of the water constant at 35 °C.

The testing commenced with an initial consolidation under the constant normal stress of 50 kPa for 3 hours, followed by a shearing stage at a rate of 0.08 mm/min until the maximum horizontal displacement of 10 mm was reached. A low rate of shearing was selected to allow full dissipation of the pore pressure during shearing. Upon the completion of the first stage, the normal stress was increased to 100 kPa during consolidation, and shearing continued for a further 10 mm. The same procedure was repeated during the 3rd stage with a normal stress of 200 kPa. The recorded results including the normal and shear stresses were subsequently used for determining the shear strength properties of the RAP.

Large-scale oedometer test

A one-dimensional consolidation test was undertaken to evaluate the compressibility of the RAP at an elevated temperature of 35 °C following the Australian testing method (AS 1289.6.6.1 2020). For this aim, the system was equipped with a heater to maintain a constant test temperature of 35 °C. The samples were compacted at OMC to 95% MDD and 100% MDD in a cell with a diameter of 150 mm and height of 76 mm. The samples were subjected to increments of constant stresses from 6.25 kPa with a load increment ratio of 1 until reaching the maximum stress of 400 kPa, i.e. 6.25, 12.5, 25, 50, 100, 200 and 400 kPa. Samples were then subjected to unloading with subsequent applied stresses of 200 kPa and 50 kPa. Each loading stress was applied for a minimum of 24 hours, except the 100 kPa stress that was maintained on the specimen for 5 days.

3.4.3 Results and Discussion

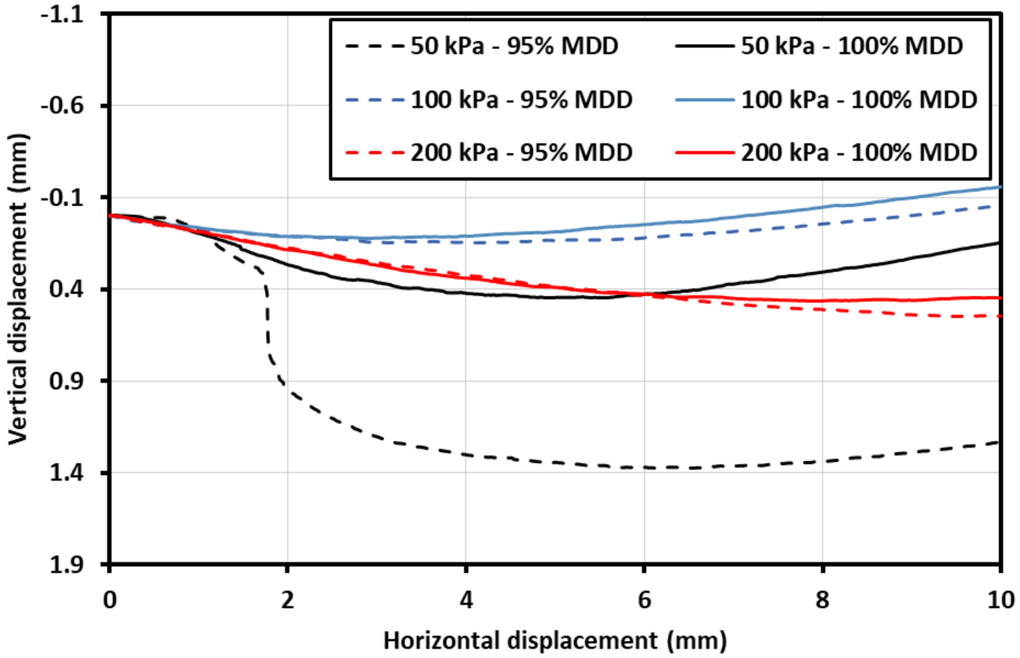
Large-scale direct shear test

The results from the large-scale direct shear testing of RAP sample against the degree of compaction is presented in Figure 3.3. Shear stress is observed to increase with increasing normal stress. The degree of compaction did not affect the shear strength notably, with similar values for cohesion and friction angle for the samples tested at 95% MDD to 100% MDD. However, at a normal stress of 50 kPa, the degree of compaction has a considerable influence on the dilation-compression behaviour. The shear stress of the

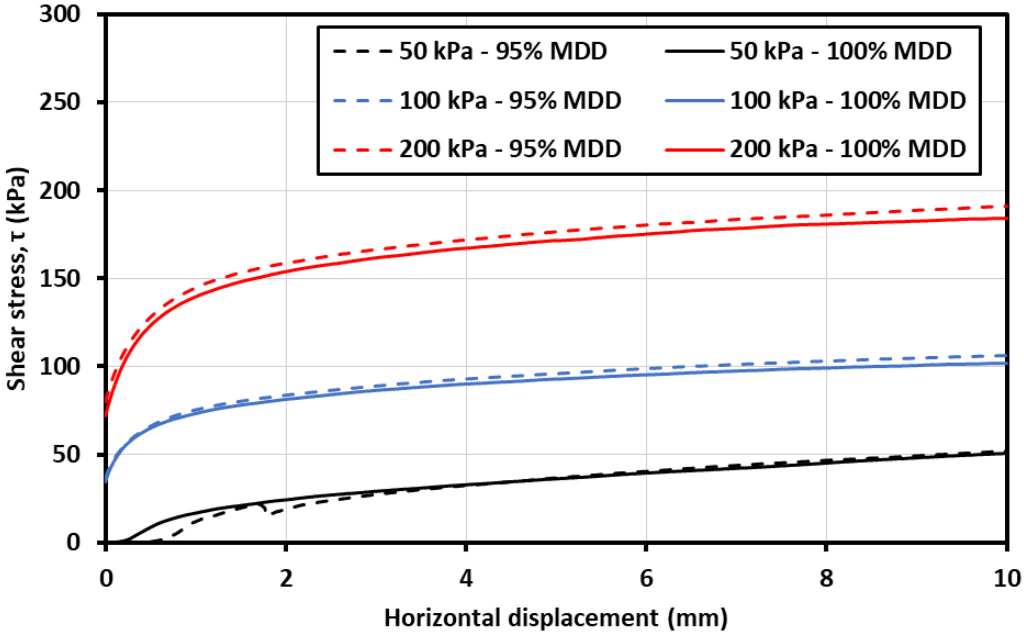
RAP samples does not reach a peak or residual shear stress value across the 10 mm shearing displacement.

Positive vertical displacement indicates compression during shearing while a negative vertical displacement indicates dilation. The RAP samples compacted to 100% MDD are observed to show greater dilation and lower compression at increased normal stresses. The results indicate that there is an initial compression of the RAP samples followed by dilation. At a normal stress of 50 kPa there is a significant initial compression, on the other hand, at a normal stress of 200 kPa there is a marginal dilative behaviour towards the 10 mm horizontal displacement.

Figure 3.3: Direct shear test results of RAP samples supplied from a local supplier in Queensland: a) horizontal displacement vs vertical displacement, b) shear stress vs horizontal displacement (without area correction)



a)

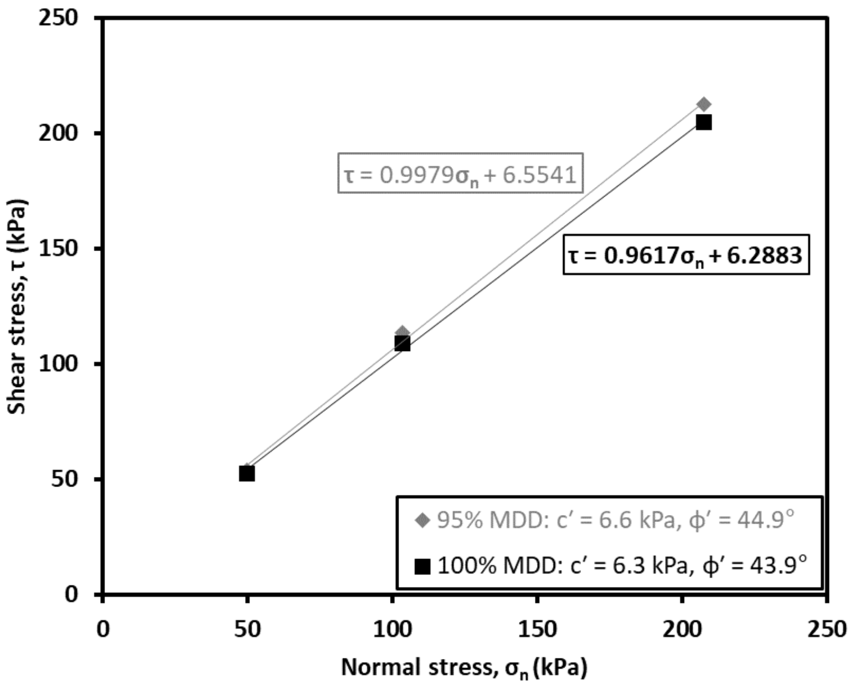


b)

Figure 3.4 shows the shear strength properties corrected for the area of the RAP samples based on the shear stress at 10 mm horizontal displacement, i.e. termination of the test. Results indicate that there is an insignificant change in cohesion and friction angle at 95% MDD (6.6 kPa and 44.9°) and 100% MDD (6.3 kPa and 43.9°). Compared to conventional granular material such as gravels that do not present any cohesion, the presence of negligible cohesion indicates there is bonding between aggregates in RAP materials, due to the presence of bituminous coating. Typically, the friction angles of dense to very dense sands and gravels have peaks ranging from 40 to 48° (Look 2007; Sivakugan & Das 2009).

Based on the results of large-scale direct shear testing, the residual bitumen content (3.2%) in the RAP sample did not have a detrimental impact on the shear strength properties, and the measured properties of RAP samples, in this project, would fulfil the requirements for use in earthwork applications typical in embankments.

Figure 3.4: Shear strength properties of RAP samples supplied from a local supplier in Queensland (with area correction)



Large-scale oedometer test

The results from oedometer testing of RAP samples are shown in Figure 3.5 and Figure 3.6. In clayey soils, with applying pressure, expulsion of water occurs over time, which is called consolidation. For a granular material, the vertical deformation caused by the applied pressure is settlement. By applying pressure on the RAP samples, a settlement was observed. In the oedometer test, since the lateral deformation is constrained, the observed settlement denotes the compressibility of the RAP sample. The results indicate that the compressibility is highly stress-dependent and the degree of compaction has a significant impact on compressibility.

Figure 3.5 depicts the relation between the void ratio and applied pressure for the tested RAP samples, and Figure 3.6 presents the variation of settlement against time. Compared to conventional materials, RAP has a high compressibility derived from the deformation of the binder coating on loading (Soleimanbeigi & Edil 2015a). The results show that the magnitudes of the void ratios are greater for the RAP samples compacted at 95% MDD compared to 100% MDD, as expected. Moreover, the reduction in the void ratio at 100 kPa was 43% and 21% when the RAP samples were compacted at 95% and 100% MDD, respectively. This means that, as anticipated, samples compacted at 95% MDD experienced much more settlement compared to those compacted at 100% MDD, when subjected to increments of applied pressure from 50 kPa to 100 kPa.

Hence, it is recommended that RAP samples are compacted at compaction degrees more than 95% MDD on site.

Under both compaction degrees, when samples were unloaded to 50 kPa, the void ratio values returned back to the corresponding void ratio of 50 kPa loading (Figure 3.5), whereas the settlement was only reversed insignificantly (Figure 3.6). Void ratio is defined as the volume of voids (i.e. water and air) in a sample to the volume of solids (i.e. aggregate particles) of that sample. The bituminous coating of RAP aggregates is considered in the solid part, although it is deformable under loading or unloading. With a constant total volume (i.e. volume of voids plus volume of solids), this deformability may cause changes in the volume of voids in the sample (while the volume of solids is constant), and accordingly, change the void ratio. The settlement though, is mainly reliant on the skeleton of the sample, i.e. the aggregates. As such, after unloading, while there was not much recovery of settlement observed, the deformability of the bituminous coating could have changed the void ratio. This may explain the discrepancy between the extent of recovery of the void ratio and settlement by unloading.

Figure 3.6 shows that an increase in the degree of compaction from 95% to 100% substantially reduces settlement at applied pressures greater than 50 kPa, although the duration of the loading seemed not to affect the settlement much. This could indicate that the previously reported compressibility over time, i.e. creep, for RAP materials could be mitigated by exposing the material to higher temperatures, for instance, by planning the construction for warmer months of the year. Soleimanbeigi and Edil (2015b) had previously reported that temperature-conditioning of RAP, that is compacting at elevated temperatures, reduces the compressibility of RAP. They recommended the construction of embankments using RAP to be planned for warmer seasons.

Although a relatively large settlement of RAP at applied pressures higher than 50 kPa (increasing from 50 kPa to 100 kPa) was observed, this was an immediate settlement under loading, and no creep behaviour was observed even after 5 days of applied pressure. More testing is in progress to further assess the compressibility of RAP and confirm the results. Until the results are obtained, it is recommended that RAP should be used in embankments less than 3 m in height. Further testing, for instance under longer loading times and/or different temperatures, is also recommended for further investigation and understanding the compressibility behaviour of RAP.

Figure 3.5: Compressibility of RAP samples supplied from a local supplier in Queensland: variation of void ratio against applied pressure in consolidation test

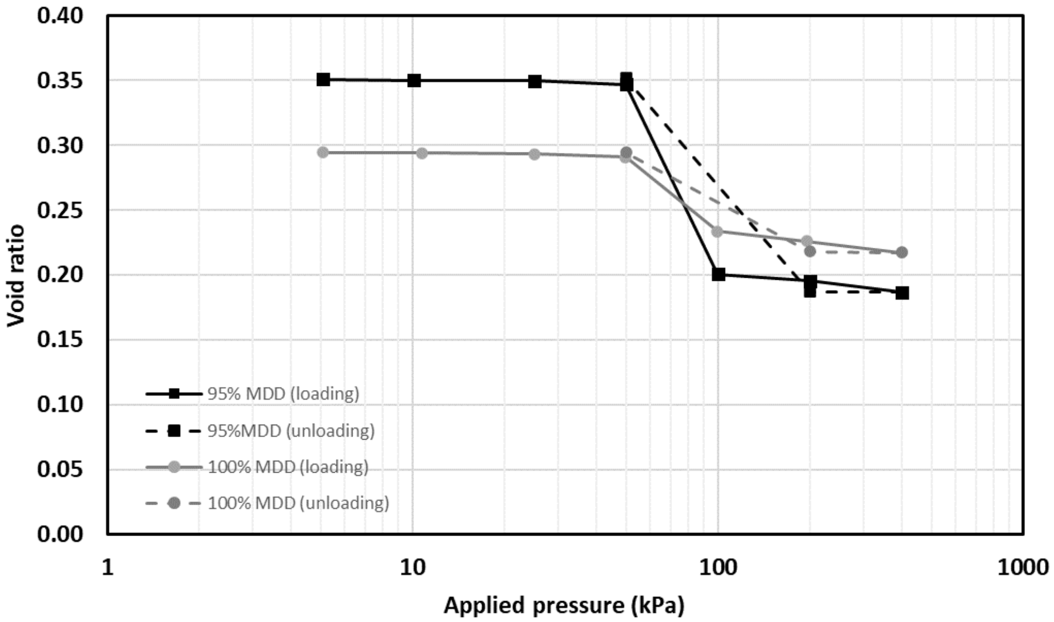


Figure 3.6: Compressibility of RAP samples supplied from a local supplier in Queensland: variation of settlement against duration of applied pressure in consolidation test

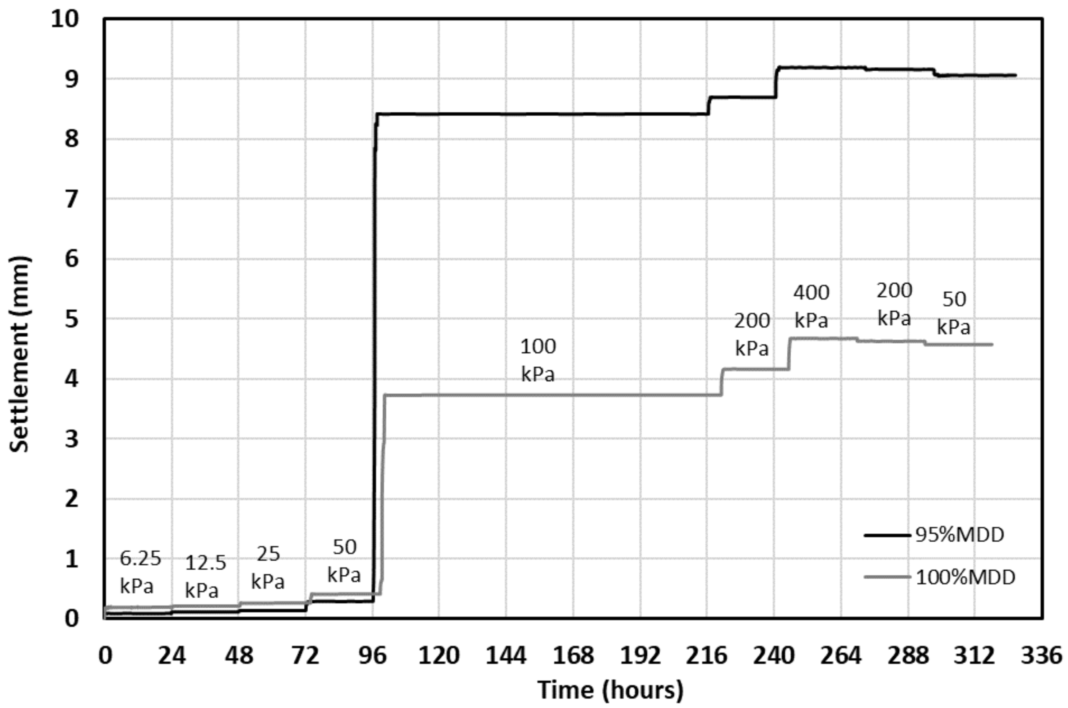


Table 3.7 presents the suitability of the investigated RAP for earthwork and drainage applications.

Table 3.7: Suitability of the investigated RAP for earthwork and drainage applications

Application		Sample no.	
		G1	G2
Embankments	Class A1 earth fill material	x	x
	Class A2 earth fill material	✓	✓
	Class B, C and D earth fill material	x	x
Subgrade	Fill material (used within 1.5 m below subgrade level)	✓	✓
	Granular fill for subgrade improvement	✓	✓
	Unbound drainage material	x	x
Backfill	Earth backfill material	✓	✓
	Free draining granular material	✓	✓
	Bedding material and drainage (WG)	x	x
	Bedding and drainage (20 mm nominal)	x	x
	Bedding and drainage (10 mm nominal)	x	x
Note		No information available on the CBR of the samples.	

x = not suitable, ✓ = suitable, WG = well-graded.

4 Coal Combustion Products

4.1 General

Coal combustion products (CCP) are generated in coal-fired power stations. The combustion of coal in the boiler produces BA and FA in the range of 10–30% and 70–90%, respectively (Abdullah et al. 2019). While there is an established use of CCP, particularly FA as a binder additive for modified and stabilised pavement layers throughout Australia, there remains potential to increase the usage of BA in road embankments, particularly in earth fill and drainage applications. To this end, this section evaluates the suitability of CCP as an embankment fill and drainage material through laboratory testing.

The details of the assessment program for environmental assessments and engineering characterisation of CCP are presented in Table 4.1 and

Table 4.2, respectively.

Table 4.1: Environmental assessment of CCP

Test/assessment	Number of tests/samples
Total concentrations of contaminants (TCC)	12
SQP assessment	✓

Table 4.2: Experimental testing for assessment of physical and mechanical properties of CCP

Test	Number of tests/samples
Particle size distribution (AS 1289.3.6.1)	19
Atterberg limits (AS 1289.3.9.1, AS 1289.3.2.1, AS 1289.3.3.2)	19
Emerson class number (AS 1289.3.8.1)	14
Maximum dry density and optimum moisture content under standard compactive effort (AS 1289.5.1.1)	9
California bearing ratio (AS 1289.6.1.1)	5
Direct shear (AS 1289.6.2.2)	5
pH (AS 1289.4.3.1)	5
Pinhole dispersion classification (AS 1289.3.8.3)	10
Permeability – falling head (AS 1289.6.7.2) (1)	5
Unconsolidated undrained (UU) triaxial (AS 1289.6.4.1)	5
Consolidated undrained (CU) triaxial (AS 1289.6.4.2)	5
One dimensional consolidation (AS 1289.6.6.1) (2)	5

1. On remoulded samples at 100% standard MDD.
2. On undisturbed samples.

Initially, 9 CCP samples were sourced from 5 different locations from a Queensland power station (Power Station A) for the experimental characterisation. Results of physical and mechanical testing are presented in Section 4.3.1. In a second stage and to broaden the investigation, CCP samples, including fly ash and bottom ash and their blends, from another 5 power stations (Power Stations B to F) in Queensland were procured (Table 4.3). Results of testing on these samples are presented in Section 4.3.2.

Table 4.3: Sources of additional CCP samples

Site	Product
Power Station B	Bottom ash as produced unprocessed.
	Fly ash from the dry storage area.
Power Station C	Bottom ash as produced unprocessed.
	Fly ash from the dry storage area.
Power Station D	Bottom ash as produced unprocessed.
	Fly ash from the dry storage area.
Power Station E	Bottom ash as produced unprocessed.
	Fly ash from the dry storage area.
Power Station F	Bottom ash as produced unprocessed.
	Fly ash from the wet storage area.

4.2 Health, Safety and Environmental Risk Assessment

This section outlines the advice and conclusions provided by the SQP in relation to the use of CCP in earthwork and drainage applications. The report is included in Appendix C.

The overall objectives of the technical review presented in this report are to provide general advice on the suitability, in terms of health, safety and the environment, to use CCP as earthworks and/or pavement material for civil construction.

More specifically the technical review provides the following:

- historic and background data provided by industry
- available literature on the use of CCP for earthworks and pavements
- the current EoW code provisions for ‘bound’ and ‘unbound’ use
- testing data for CCP proposed to be used (data provided by TMR).

The CCP samples from 7 different power stations collected in Queensland were tested and analysed. These samples were supplied by the power stations and have been assumed to relate to the stored or stockpiled materials. As detailed in Appendix C, the samples were analysed for a range of total recoverable hydrocarbons (TRH), volatile organics, organochlorine pesticides, organophosphorus pesticides, polychlorinated biphenyls (PCBs), acid herbicides, semivolatile organics, cyanide, fluoride, polycyclic aromatic hydrocarbons (PAHs), heavy metals and PFAS. The samples were also analysed for dioxins and furans and polybrominated diphenyl ethers (PBDEs).

The risk assessment undertaken focused on the use of CCP for road construction activities only. As taken from the SQP report (Appendix C), based on the available information the following can be concluded:

- Workers involved in the handling of unbound CCP should utilise PPE detailed in the safety data sheets (SDS) for these materials. Where the activities have the potential to result in the generation of dust, PPE should include respiratory protection in compliance with the SDS.
- Workers involved in the cutting of bound materials that include CCP (e.g. concrete) where dust may be generated (i.e. dry cutting) should wear respiratory protection in compliance with the relevant SDS.
- The above requirements (for workers) remain unchanged from the requirements that apply to workers using and handling conventional unbound aggregate material.
- CCP material sources from most power stations evaluated comply with the criteria detailed in the EoW code for bound and unbound applications as proposed. The concentration of boron reported in fly ash materials from Power Station E exceeded the criteria in the EoW code and hence further sampling and testing of fly ash materials from the station is recommended to determine if these materials are compliant with the requirements of the code.

- Further review of the CCP data, for all chemicals detected, has not identified any risk issues of concern, in relation to human health or the environment where the material is used in compliance with the EoW code. Further consultation with Department of Environment and Science is recommended to assess the potential to review the EoW code requirements for the use of CCPs in waterways.
- Where the material may be removed from the project area in future works, the concentrations present in the CCP are below the criteria for regulated waste (i.e. material would not be considered regulated waste).

The assessment undertaken has considered the use of 100% CCP in unbound applications. This is conservative for the proposed use in engineering fill, embankment materials and pipe drainage within road corridors. In practice, it is likely that the CCP will be mixed with other fill materials which would further reduce the potential impacts (particularly to aquatic environments), however the conclusions presented above would not change.

4.3 Physical and Mechanical Properties

4.3.1 Power Station A

The engineering properties of assessed CCP samples from Power Station A are presented in Table 4.4. Samples were collected from different locations (Locations A to E). Except for Location E, 2 samples with different gradations (G1 and G2) were collected from each location. Accordingly, samples were named LXGY, X being the location and Y being the gradation number. For instance, LAG1 stands for CCP sample from Location A with gradation number 1.

The PSD of the CCP samples indicated that more than 90% of the particles from all 5 sampling locations passed through the 0.075 mm sieve (No. 200). With respect to the gradations and Atterberg limits, the CCP samples were classified as ML (silts with relatively low plasticity).

Table 4.4 also presents the requirements of MRTS04 (TMR 2021a) for Class A1 and A2 embankment fill materials. The liquid limit of the CCP samples ranged between 34% and 49%. The shrink-swell potential of the CCP samples was assessed based on the liquid limit and plasticity index (PI) using the criteria suggested by Charman (1978). The samples LAG2, LCG1, LDG1, LDG2, and LEG1 had medium swell-shrink ratings ($45 \le LL \le 55$), while other samples had low ratings ($LL < 45$). The PI ranged between 3% and 8% for all samples, indicating that the PI of the tested CCP samples did not comply with the requirements of MRTS04 (TMR 2021a), i.e. $PI \ge 7$, except for two samples that just met the requirement. The linear shrinkage of all samples was equal to 1%, indicating that the samples had low swell-shrink activity (Charman 1978).

The Emerson class testing was undertaken to provide an assessment of the dispersion of soil particles. Results indicated that all samples were classified as Class 8, exhibiting no slaking and swelling. However, the pinhole test results indicated that the CCP samples are highly dispersive, and accordingly, have low resistance to erosion, so are only suitable as a Class A2 material. It is advised that these materials should not be used in the outer zone of embankments as Class A1 material.

Accordingly, the CCP samples may be suitable for use as core zone material in zoned embankment construction. It is considered that CCP would not be suitable for use in homogeneous embankment construction, based on the low PI values and high susceptibility to erosion due to dispersive properties.

The compaction, California Bearing Ratio (CBR), and direct shear testing were undertaken on the CCP samples to determine the physical and shear strength properties. These tests were performed on the blends of the 2 samples from each location.

MRTS04 specifies a minimum 4-day soaked CBR value of 3% for the fill materials used in embankments, subgrade treatments and backfill. The CBR values for all CCP samples were well above the requirements, with LD (blend of LDG1 and LDG2) and LEG1 samples exhibiting higher CBR values compared to the other samples. Accordingly, the CCP samples may be suitable for fill material within 1.5 m below the subgrade, level, provided it can be enclosed and capped by earth fill that has more resistant to erosion, such as Class A1 or B materials,

In addition, the CCP samples may be suitable for use as backfill for subgrade treatments or to replace unsuitable material. The high angle of friction, low compressibility, and low unit weight of CCP samples make them potentially suitable for lightweight backfill materials. However, the CCP would not be suitable for applications where the material is exposed to moderate to high water flows, due to the susceptibility to erosion.

Table 4.4: **Engineering properties of CCP samples – Power Station A**

Property	Location A		Location B		Location C		Location D		Location E	MRTS04 limits	
	LAG1	LAG2	LBG1	LBG2	LCG1	LCG2	LDG1	LDG2	LEG1	Embankment fill (Class A1)	Embankment fill (Class A2)
%Passing 0.075 mm test sieve	92	94	94	95	97	95	97	96	98	≥ 15	
Coefficient of Uniformity (Cu)	NA	NA	NA	NA	NA	NA	NA	NA	NA		> 5
Emerson class number	8	8	8	8	8	8	8	8	8	> 3	> 3 [1]
WPI	485	485	500	300	500	297	800	500	700	< 1200	< 1200
Cone liquid limit (%)	39	48	40	34	47	35	49	48	48		
Linear shrinkage (%)	1	1	1	1	1	1	1	1	1		
Crumbling	No	No	No	No	No	No	No	No	No		
Curling	No	No	No	No	No	No	No	No	No		
Cracking	No	No	No	No	No	No	No	No	No		
Plastic limit (%)	34	43	35	31	42	32	41	43			
Plasticity index (%)	5	5	5	3	5	3	8	5	7	≥ 7	
OMC (%)	36		32		34		40		41.5		
MDD (t/m^3)	1.25		1.28		1.23		1.18		1.15		
CBR (%)	11		11		6		30		20		
Swell (%)	0		0.5		0		0		0		
Apparent cohesion (kPa)	9		6		7		6		2		
Friction angle (degrees)	40		37		36		38		40		
pH	9.7		9.5		9.3		9.2		9.4		
Pinhole dispersion classification	D1 highly dispersive		D1 highly dispersive		D1 highly dispersive		D2 dispersive		PD1 potentially dispersive		

1. For outer zone and upper zone materials as well as homogeneous cross-sections.

LAG1: CCP sample from Location A with gradation number 1.

NA: not available

4.3.2 Power Stations B to F

The particle size distributions of the additionally supplied CPP samples, from 5 power stations, are summarised in Table 4.5 and shown in

Figure 4.1 and Figure 4.2 for BA and FA, respectively. For FA samples, additional hydrometer analyses were conducted to determine the particle size distributions of particles smaller than 75 microns.

Generally, BA samples had coarser gradations, with 9% to 15% of the particles passing the 75 µm sieve. The FA samples were considered fine grained soils with 58–97% of the particles passing the 75 µm sieve. Results indicate that, except for Power Stations C-E at 0.075mm, the BA materials meet the gradation requirements of MRTS04 for drainage aggregate. Given the linear shrinkage for all BA samples was 0 (refer to Table 4.6), which is less than the maximum value of 6% specified by MRTS04, BA could be considered for backfill application as bedding and drainage aggregate; however, more testing is required to confirm this.

Table 4.5: Particle size distributions of additional CCP samples – power stations B to F

Sieve size (mm)	Source										MRTS04 limits
	Power Station B		Power Station C		Power Station D		Power Station E		Power Station F		Well-graded bedding and drainage [1]
	FA	BA	FA	BA	FA	BA	FA	BA	FA	BA	
	Passing (%)										
19	–	100	–	100	100	94	100	98	100	100	–
9.5	–	98	–	100	–	86	–	93	–	100	–
2.36	100	91	100	99	97	76	100	62	100	96	50–100
0.6	–	52	–	66	–	65	–	36	–	74	20–90
0.425	99	–	100	–	95	–	100	–	100	–	–
0.075	64	9	91	18	58	15	96	14	97	9	0–10

1. Well-graded aggregate requirements shall not apply to drainage aggregate in MRTS04.

Figure 4.1: PSD curves of BA samples from different power stations

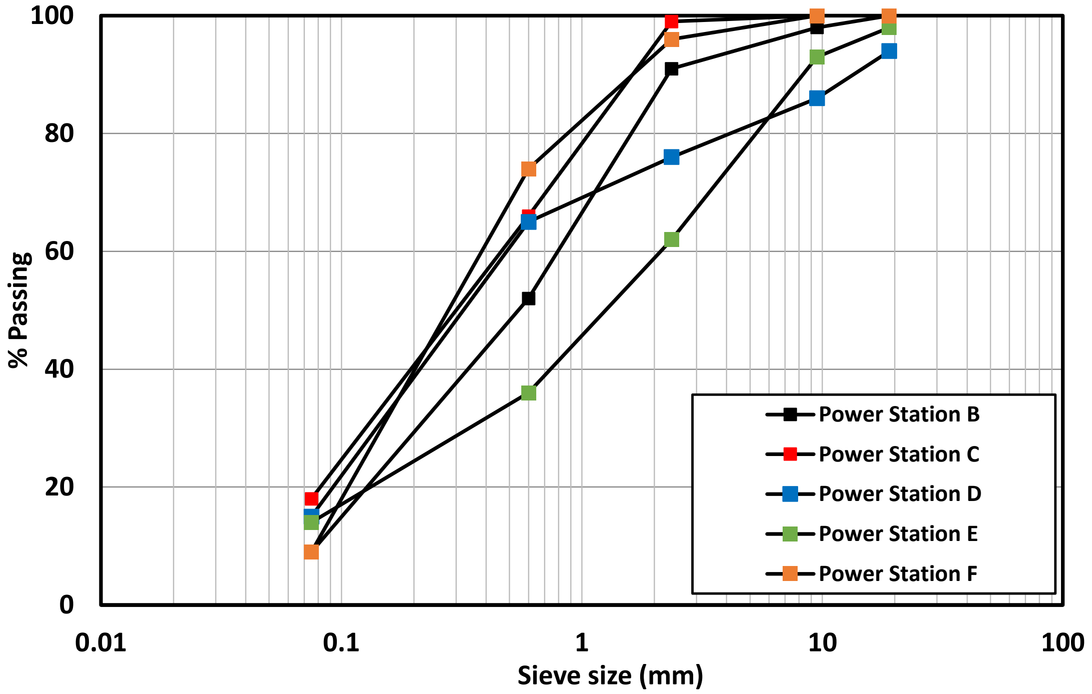


Figure 4.2: PSD curves of FA samples from power stations B to F

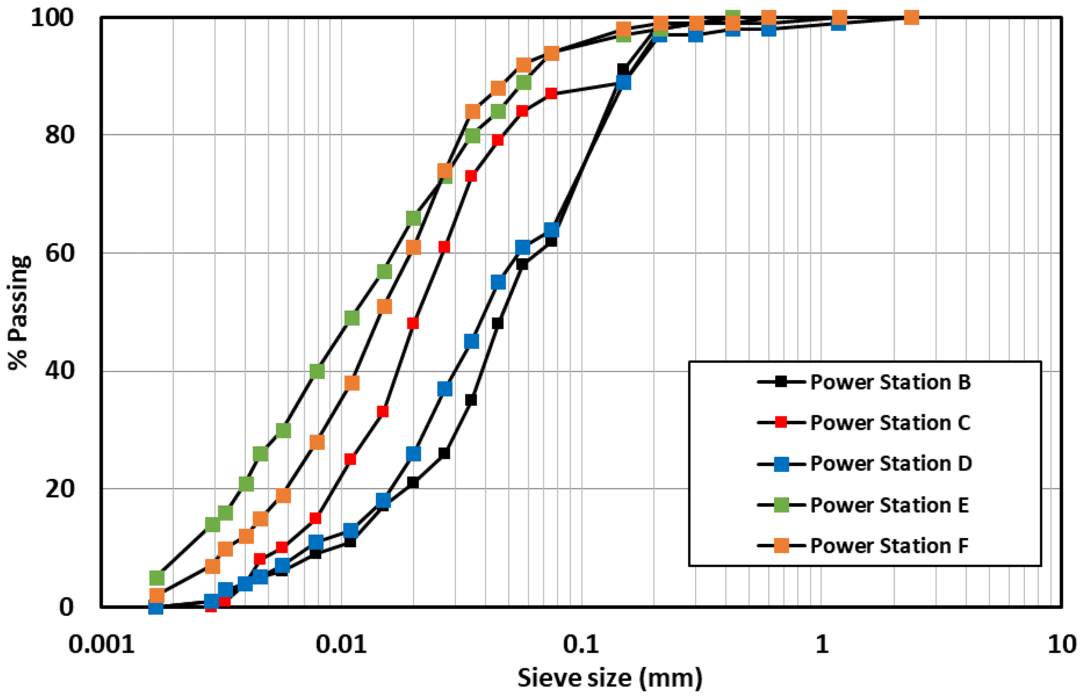


Table 4.6 summarises the other engineering properties of the CCP samples supplied from power stations B to F specified by MRTS04 for Class A1 and A2 embankment fill materials.

The liquid limit of the CCP samples ranged between 21% and 84%, with greater liquid limits (≥ 39%) typically reported in BA samples compared to the FA samples. The linear shrinkage of all the CCP samples was ≤ 0.5%, and the plasticity indices of all the FA samples were below 25 indicating that the samples have low swell-shrink activity (Charman 1978).

Generally, the FA samples were more suitable for embankments due to the finer gradations, i.e. larger proportion of particles passing the 75 µm sieve. Although the coefficient of uniformity (Cu) is used for classification of coarse-grained soils, D60 and D10 from hydrometer results were used to calculate Cu for FA samples. Except for one FA sample, all FA samples met the minimum Cu of 5 for a Class A2. The FA samples complied with the MRTS04 limits for an embankment material, except for the PI values for Class A1, which were considerably below the minimum requirement of 7%. Similarly, given the low PI values of the FA samples and the non-plastic nature of the BA samples, these products are likely to exhibit poor stability in embankments where Class A1 is to be used, and proper considerations and engineering controls are required for their use.

Results from Emerson class testing indicated that the FA samples were generally classified as Class 6, indicating complete slaking of the FA sample, which is above the minimum requirement (of 3) for both Class A1 and A2 embankment fill materials. Pinhole dispersion test results on FA samples, however, indicate that the tested materials are highly dispersive and not suitable to be used for outer zone, i.e. Class A1 material, due to their erodibility potential. Consideration could be given for the potential use of FA samples as Class A2 embankment fill materials in the construction of embankments with zoned cross-section.

Additional testing was undertaken to investigate the shear strength and compressibility of the FA samples supplied from different power stations. In particular, triaxial (CU and UU) and oedometer tests were conducted. Samples were prepared at 100% standard MDD and OMC. CU tests simulate load bearing situations that are encountered shortly after completing the initial compaction, while UU tests simulate stability analysis when a construction load is high. Both UU and CU triaxial tests were conducted at confining pressures of 50, 100 and 200 kPa.

Table 4.6: Engineering properties of additional CCP samples

Property	Source										MRTS04 limits	
	Power Station B		Power Station C		Power Station D		Power Station E		Power Station F			
	FA	BA	FA	BA	FA	BA	FA	BA	FA	BA	Embankment fill (Class A1)	Embankment fill (Class A2)
%Passing 0.075 mm test sieve	64	9	91	18	58	15	96	14	97	9	≥ 15	
Coefficient of Uniformity (Cu)	7.0	10.4	4.3	NA	7.2	NA	7.6	NA	6.1	5		> 5
Liquid limit (%)	30	55	26	80	50	84	21	47	47	70		
Plastic limit (%)	29	NT	24	NP	45	83	17	NP	44	NT		
Plasticity Index (%)	1	NT	2	NP	5	1	4	NP	3	NT	≥ 7	
WPI	99	NA	200	NA	475	NA	400	NA	300	99	< 1200	< 1200
Linear shrinkage (%)	0	0	0	0	0	0	0.5	0	0.5	0		
Maximum dry density – standard compaction (t/m³)	1.34	NA	1.28	NA	NA	NA	1.57	NA	1.02	NA		
Optimum moisture content – standard compaction (%)	22.5	NA	19	NA	NA	NA	16.5	NA	28	NA		
Permeability – falling head (m/sec)	8.4×10^{-8}	–	2.7×10^{-9}	–	8.3×10^{-8}	–	2.9×10^{-8}	–	1.6×10^{-7}	–		
Emerson class number	6	NA	6	NA	5	NA	6	NA	6	NA	> 3	> 3 (1)
Pinhole dispersion test												
Pinhole dispersion classification	D1	–	D1	–	D1	–	D1	–	D1	–		
Description	HD (2)	–	HD (2)	–	HD (2)	–	HD (2)	–	HD (2)	–		

1. For outer zone and upper zone materials as well as homogeneous cross-sections.
2. Highly dispersive.

NP: non-plastic; NA: not available; NT: not tested.

The shear strength properties of the CCP samples are summarised in Table 4.7. The shear strength properties including the cohesion and friction angle were determined for each stage of the triaxial tests. The friction angle of CCP compares with typical sand backfills which have a friction angle between 29° and 41° to 44° (Tsinidis et al. 2019) in both UU and CU test conditions and are hence considered to provide suitable stability for typical earthworks and embankments.

Table 4.7: Shear strength properties of FA samples

Test stage	Test parameter	Source				
		Power Station B	Power Station C	Power Station D	Power Station E	Power Station F
UU triaxial						
1 to 2	Cohesion (kPa)	30.2	51.6	18.1	140.5	69.3
	Friction (°)	39.1	38.7	37.5	34	29.2
2 to 3	Cohesion (kPa)	51.3	100.1	51.5	164.9	67.8
	Friction (°)	35.1	30.2	30.3	30.4	29.5
1 to 3	Cohesion (kPa)	40.8	75.3	34	154.4	68.4
	Friction (°)	36.4	33.2	32.8	31.5	29.4

Test stage	Test parameter	Source				
		Power Station B	Power Station C	Power Station D	Power Station E	Power Station F
CU triaxial						
1 to 2	Cohesion (kPa)	26.8	17.2	11.2	0.7	4.9
	Friction (°)	37.4	30.4	34.3	34.1	33.3
2 to 3	Cohesion (kPa)	39.3	11.6	24.8	2.9	8.6
	Friction (°)	36.3	31.4	32	33.9	32.3
1 to 3	Cohesion (kPa)	32.3	14.7	16.9	1.4	6.5
	Friction (°)	36.7	31	32.9	34	32.7

For the consolidation tests, the samples were subjected to increments of constant stresses from 6.25 kPa with a load increment ratio of 1 until reaching the maximum stress of 800 kPa, i.e. 6.25, 12.5, 25, 50, 100, 200, 400 and 800 kPa. Samples were then subjected to unloading with subsequent applied stresses of 200 kPa and 50 kPa. Each loading stress was applied for a minimum of 24 hours.

The consolidation behaviours of the FA samples are shown in Figure 4.3 and summarised in Table 4.8. The compression and swelling curves, as well as the wide range of void ratios, indicate a diverse behaviour between each CCP sample. The compression indices (Cc) of the CCP samples vary from 0.012 to 0.400, with the majority being in the range of 0.0005–0.05 for a sandy soil (Widodo & Ibrahim 2012), and the swelling indices (Cs) vary from 0.010 to 0.034, similarly reported for a sandy soil containing fly ash (Amiralian et al. 2012). The calculated permeability (k) values range from 9.60 x 10^{-11} m/s to 3.60 x 10^{-08} m/s, indicating these materials have permeability classification of 'very low' to 'practically impermeable' according to Head (1994). This may indicate that these materials should be used in the core zone of embankments.

Mesri (1973) classified the secondary compressibility of soils with a percentage of coefficient of secondary compression, Cα (%), of 0.2 as 'very low'. The results of Cα for all tested samples under various applied pressures were below 0.2 indicating that the tested CCPs have very low secondary compressibility.

Figure 4.3: Compressibility behaviour of the FA samples

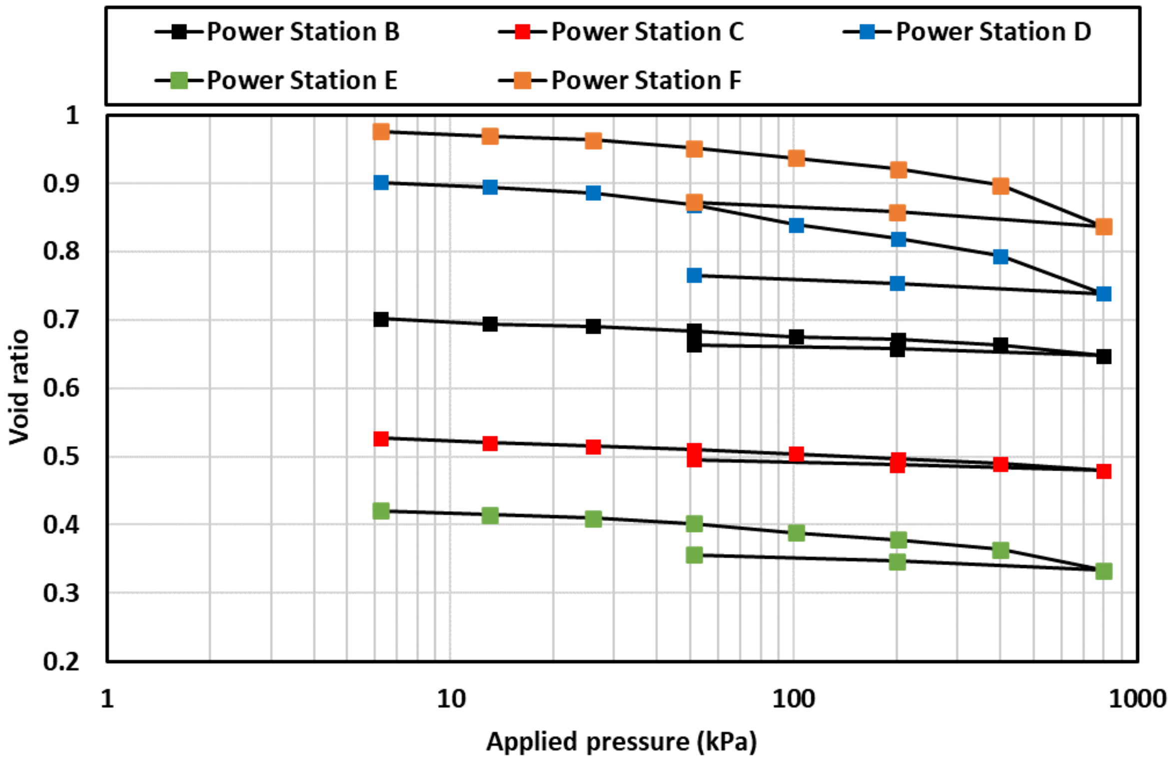


Table 4.8: Oedometer test results

Stage	Load (kPa)	Cc	Cs	k (m/s)	Cv (m^2/yr) t_{50}	Cv (m^2/yr) t_{90}	Ca (%)
Power Station B							
1	6.25–13	0.023	–	2.30E-08	191.17	118.2	0.034
2	13–26	0.012	–	2.00E-09	277.96	38.49	0.017
3	26–50	0.023	–	1.00E-09	284.92	20.41	0.034
4	50–100	0.03	–	7.30E-10	228.32	22.56	0.011
5	100–199	0.013	–	3.20E-10	121.28	45.86	0.021
6	199–401	0.027	–	2.70E-09	185.97	358.44	0.047
7	401–800	0.053	–	2.60E-09	217.17	351.79	0.048
8	800–200	–	0.017	1.60E-10	266.81	47.78	0.014
9	200–50	–	0.01	4.70E-10	179.77	61.88	0.023
Power Station C							
1	6.25–13	0.021	–	7.40E-10	291.78	3.61	0.041
2	13–26	0.017	–	1.70E-08	240.71	215.12	0.028
3	26–50	0.017	–	1.50E-09	198.02	36.85	0.036
4	50–100	0.02	–	6.60E-09	297.47	273.17	0.021
5	100–199	0.026	–	6.60E-10	269.59	41.82	0.062
6	199–401	0.023	–	2.60E-09	188.4	367.86	0.047
7	401–800	0.035	–	2.00E-09	230.69	362.95	0.047
8	800–200	–	0.015	1.60E-10	186.06	51.59	0.02
9	200–50	–	0.013	4.20E-09	208.32	375.88	0
Power Station D							
1	6.25–13	0.023	–	4.50E-09	277.82	25.24	0.015
2	13–26	0.028	–	1.20E-08	295.11	113.67	0.026
3	26–50	0.06	–	2.20E-09	241.99	18.49	0.02
4	50–100	0.098	–	3.60E-08	250.55	368.72	0.021
5	100–199	0.069	–	1.20E-09	180.66	35.65	0.08
6	199–401	0.085	–	7.60E-09	171.34	346.43	0.086
7	401–800	0.182	–	7.90E-09	162.61	332.65	0.066
8	800–200	–	0.025	1.40E-10	163.72	29.97	0.016
9	200–50	–	0.02	5.90E-10	187.4	41.57	0.039
Power Station E							
1	6.25–13	0.019	–	1.70E-08	146.55	87.63	0.023
2	13–26	0.016	–	2.60E-08	250.25	325.46	0.036
3	26–50	0.027	–	2.60E-09	250.26	37.5	0.053
4	50–100	0.046	–	1.30E-08	291.78	207.22	0.021
5	100–199	0.035	–	8.00E-10	248.73	34.15	0.074
6	199–401	0.049	–	5.80E-09	176.27	350.47	0.08
7	401–800	0.1	–	9.60E-11	176.62	5.61	0.043
8	800–200	–	0.022	2.00E-10	164.49	39.99	0.027
9	200–50	–	0.016	2.10E-10	277.23	14.48	0.032

Stage		Load (kPa)	Cc	Cs	k (m/s)	Cv (m²/yr) t_{50}	Cv (m²/yr) t_{90}	Ca (%)
	Power Station F							
1		6.25–13	0.02	–	7.10E-09	285.88	49.13	0.015
2		13–26	0.021	–	2.20E-09	271.07	29.08	0.025
3		26–50	0.4	–	3.50E-09	295.42	46.8	0.0031
4		50–100	0.047	–	4.00E-09	193.52	89.24	0.016
5		100–199	0.056	–	8.20E-10	248.36	30.63	0.068
6		199–401	0.079	–	6.90E-09	185.36	359.38	0.105
7		401–800	0.199	–	8.10E-09	263.35	330.43	0.033
8		800–200	–	0.034	2.30E-10	170.35	40.48	0.016
9		200–50	–	0.025	5.00E-10	262.72	29.41	0.043

Table 4.9: Suitability of the investigated CCP for earthwork and drainage applications

Sample no.		Application											
		Embankments			Subgrade			Backfill					Note
		Class A1 earth fill material	Class A2 earth fill material	Class B, C and D earth fill material	Fill material (used within 1.5 m below subgrade level)	Granular fill for subgrade improvement	Unbound drainage material	Earth backfill material	Free draining granular material	Bedding material and drainage (WG)	Bedding and drainage (20 mm nominal)	Bedding and drainage (10 mm nominal)	
P.S. A	LA G1	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	The PI value for some of the samples was slightly below the requirement.
	LA G2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LB G1	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LB G2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LC G1	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LC G2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LD G1	x	✓[1]	x	✓[2]	x	x	*	x	x	x	x	
	LD G2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LE G1	x	✓[1]	x	✓[2]	x	x	*	x	x	x	x	
P.S. B	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	No information available on the Emerson class number, PI, electrical and heat conductivity, and CBR of BA samples.
	BA	x	✓	x	*	x	x	*	x	*	x	x	
P.S. C	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	x	*	x	x	x	*	x	*	x	x	
P.S. D	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	x	*	x	x	x	*	x	*	x	x	

Sample no.		Application											
		Embankments			Subgrade			Backfill					Note
		Class A1 earth fill material	Class A2 earth fill material	Class B, C and D earth fill material	Fill material (used within 1.5 m below subgrade level)	Granular fill for subgrade improvement	Unbound drainage material	Earth backfill material	Free draining granular material	Bedding material and drainage (WG)	Bedding and drainage (20 mm nominal)	Bedding and drainage (10 mm nominal)	
P.S. E	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	x	x	x	x	x	x	x	*	x	x	
P.S. F	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	✓	x	*	x	x	*	x	*	x	x	

x = not suitable, ✓ = suitable, * = more information (e.g. PI, CBR and Emerson number) is required, WG = well-graded, P.S. = power station.

[1] Only in core zone of embankment, [2] when enclosed and capped by Class A1 or B earth fill

presents the suitability of the investigated CCP for earthwork and drainage applications. Classifications for embankment materials are based on current TMR specification MRTS04 for natural materials. While recycled materials may be used in the embankment applications, they may not be classified as per current MTRS04 classifications, e.g. Class A2 earth fill. The CCP materials are comparable with Embankment fill Class A2, in terms of strength and stability, but because of the potential for erodibility, these materials are recommended to be used when enclosed, i.e. only in core zone of embankment, and when enclosed and capped by Class A1 or B earth fill.

Table 4.9: Suitability of the investigated CCP for earthwork and drainage applications

Sample no.		Application											
		Embankments			Subgrade			Backfill					Note
		Class A1 earth fill material	Class A2 earth fill material	Class B, C and D earth fill material	Fill material (used within 1.5 m below subgrade level)	Granular fill for subgrade improvement	Unbound drainage material	Earth backfill material	Free draining granular material	Bedding material and drainage (WG)	Bedding and drainage (20 mm nominal)	Bedding and drainage (10 mm nominal)	
P.S. A	LAG1	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	The PI value for some of the samples was slightly below the requirement.
	LAG2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LBG1	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LBG2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LCG1	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LCG2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LDG1	x	✓[1]	x	✓[2]	x	x	*	x	x	x	x	
	LDG2	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	LEG1	x	✓[1]	x	✓[2]	x	x	*	x	x	x	x	
P.S. B	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	No information available on the Emerson class number, PI, electrical and heat conductivity, and CBR of BA samples.
	BA	x	✓	x	*	x	x	*	x	*	x	x	
P.S. C	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	x	*	x	x	x	*	x	*	x	x	
P.S. D	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	x	*	x	x	x	*	x	*	x	x	
P.S. E	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	x	x	x	x	x	x	x	*	x	x	
P.S. F	FA	x	✓[1]	x	✓[2]	x	x	x	x	x	x	x	
	BA	x	✓	x	*	x	x	*	x	*	x	x	

x = not suitable, ✓ = suitable, * = more information (e.g. PI, CBR and Emerson number) is required, WG = well-graded, P.S. = power station.

[1] Only in core zone of embankment, [2] when enclosed and capped by Class A1 or B earth fill

5 Recycled Crushed Glass

5.1 General

Glass cullet is recycled container glass (RCG) prior to processing, typically collected from the municipal waste stream (Austroads 2022a) and can be further processed through sorting, crushing etc. Typically, recycled glass fines (e.g. particle size up to 5 mm) can be used as a partial replacement of natural aggregates in unbound and bound pavement material applications. The allowable proportion varies depending on the materials type and application. There is a potential for the use of RCG in earthwork and drainage applications, which was investigated through a desktop study in Year 1 of the project. The summary of findings from Year 1 are presented in the following section.

5.2 Current Practices

Currently, MRTS04 permits the use of RCG for drainage applications, while the use of conventional and recycled materials is specified in MRTS05 (TMR 2022). Additionally, MRTS36 *Recycled Glass Aggregate* (TMR 2020) sets out the requirements of RCG used in asphalt, unbound granular road pavements, and earthwork applications.

MRTS04 states that free-draining granular material shall be a non-cohesive well-graded granular material comprising either sound sand and stone particles, RCG, or a blend of these materials, which do not break down under compaction, wetting or exposure to air. As such, RCG could be used as a free-draining granular material where it also complies with the requirements of MRTS36.

MRTS04 allows well-graded bedding material including RCG to be used for the foundation, bedding and haunch zone of drainage structures and services, given that the material meets the PSD and maximum shrinkage limit requirements.

Austroads in its ATS 3050 *Supply of Recycled Crushed Glass* (Austroads 2022b) allows the use of RCG up to 100% in some earthworks and drainage applications. Table 5.1 compares the TMR practice to other Australian states and territories and Austroads (Austroads 2022b) regarding the permissible use of RCG in earthwork and drainage applications.

Table 5.1: Comparison of permissible use of RCG in earthwork and drainage applications across Australian states and territories

Road agency	Application	Max allowable content (% by mass)
TMR	Sand and coarse sand for backfill	N/S
	Drainage structure bedding and haunch zone	N/S
	Free-draining granular material	N/S
Austroads	Bedding and haunch of drainage pipes, conduits, and services	100
	Side zone and backfill of drainage trenches	100
	Bedding for segmental or block paving	100
	Joint filling (i.e. filling the voids between individual segmental or block pavers)	100
	Drainage medium	100
	Embankment (core zone) fill	100
VicRoads	Type A, B and C fill	N/S
	Subsurface drainage and granular filter	100
DIPL	Bedding for drainage works	100

Road agency	Application	Max allowable content (% by mass)
MRWA	Embankment construction	20
TfNSW	Selected material zone	5
DIT	Select fill, general fill and bedding fill	–

Note: N/S = limit not specified.

6 Summary and Recommendations

The aim of this project is to evaluate the suitability of recycled materials including RCG, RCC, RAP, and CPP for earthworks and drainage applications. The environmental and engineering properties of selected recycled materials were investigated for potential use in embankments and drainage applications. The materials assessed have been sourced from various suppliers of waste products across Queensland and have been characterised through laboratory testing.

The findings of the project, to date, include the following:

Recycled crushed concrete (RCC)

- In relation to the chemical composition of RCC proposed to be used for pavements or drainage materials, there are no apparent risks of concern in relation to human health or the environment (terrestrial or aquatic).
- In relation to the pH of the RCC, it was concluded that there are no apparent risks of concern for RCC, where used in bound pavement materials or in compacted materials beneath sealed and unsealed surfaces. However, it is not considered appropriate to use RCC as a surface layer for unsealed roads. The pH of the leachate derived from RCC (where contact with rainfall may occur) would be buffered by soil, surface water and groundwater and the potential for adverse effects on aquatic ecosystems is considered to be low. Where RCC may be used for drainage, the SQP recommends that the pH of materials should be ≤ 9. Given this is impractical for RCC, the SQP recommends that RCC (with pH > 9) may be used for drainage provided the material is not used in areas closer than 30 m from a receiving waterway. More testing is required to ascertain the suitability of RCC for drainage applications.
- The obtained samples were initially intended to be assessed against the requirements for use in drainage applications, although suitability of their use in other earthwork applications was also investigated. The supplied RCC samples were single sized gravels or sands or well-graded sands. The former were generally suitable for usage as free-draining backfill materials behind the retaining walls, while the latter could potentially be used as bedding material in the foundation bedding zone of culverts and for bedding of pipes, conduits, and pits. Due to the favourable strength, shear, and deformation properties of the RCC, which is also well-established in the published literature, there is strong potential for its usage in other applications such as subgrade treatments or structural fills, provided that the gradation limits are met for the intended application.

Reclaimed asphalt pavement (RAP)

- There are no issues of concern in relation to risks to human health or the environment (terrestrial or aquatic) with the use of RAP in embankment materials, drainage lines or pavement materials.
- Two types of RAP, 1 profiled from a site in Queensland and 1 processed from a local Queensland supplier, were sourced for the laboratory characterisation. TMR prefers RAP to be reused in asphalt;, however, where RAP is not suitable for this end in asphalt (for example it may be mixed with other pavement or embankment materials), it may be considered for use in earthworks.. The supplied RAP samples were classified as well-graded gravel, and were found suitable for usage in embankments, subgrade treatments, and backfilling applications. The RAP samples had high shear strength properties. The primary concern with the use of RAP in embankments is the compressibility due to the softening of the bitumen particularly with elevated temperature, which might affect the long-term stability and serviceability of embankments.
  When the applied pressure was increased from 50 kPa to 100 kPa, at 35 °C, settlements of up to 8mm were observed. Although this was an immediate settlement under loading, and no creep behaviour was observed even after 5 days of applied pressure. More testing is in progress to further assess the compressibility RAP and confirm the results. Until the results are obtained, it is recommended that using RAP in embankments should be limited to heights of less than 3 m to avoid excessive settlement.

Coal combustion products (CCP)

- The assessment of risk to human health revealed that requirements (for workers) remain unchanged from the requirements that apply to workers using and handling conventional unbound aggregate material. Workers involved in the handling of unbound CCP should utilise personal protective equipment (PPE) detailed in the safety data sheets (SDS) for these materials. Where the activities have the potential to result in the generation of dust, PPE should include respiratory protection in compliance with the SDS. Workers involved in the cutting of bound materials that include CCP (e.g. concrete) where dust may be generated (i.e. dry cutting) should wear respiratory protection in compliance with the relevant SDS.

  Further review of the CCP data, for all chemicals detected, has not identified any issues of concern, in relation to human health or the environment where the material is used in compliance with the EoW code.

  Further consultation with Department of Environment and Science is recommended to assess the potential to review the EoW code requirements for the use of CCPs in waterways.
- CCP samples included blend of FA and BA (from ash pond), FA (from both dry and wet storage area) and BA (as produced unprocessed). The CCP samples were classified as silts with low plasticity for FA samples and silty sands for BA samples. Some CCP samples met the requirements for Class A2 fills, respectively and also as fill material (used within 1.5 m below subgrade level). The main concern regarding the use of CCP in embankments is the low plasticity, which might cause compactability and stability issues. Nonetheless, due to the high angle of friction, low compressibility, and low unit weight, CCP is considered suitable for use as a construction material for applications such as structural and non-structural fills.

  It is recommended that a blend of FA and BA is used in the core zone of embankments. Some of the CCP samples could potentially be used in backfill and bedding applications, although more information such as electrical and heat conductivity is required.

Table 6.1 presents the suitability of the investigated recycled materials for earthwork and drainage applications. This is based on using 100% of each material though, so where the requirements are not met, modifications, for instance through blending materials to amend gradation, would be a potential solution.

Table 6.1: Suitability of the investigated recycled materials for earthwork and drainage applications

Material		Application										
		Embankments [1]			Subgrade			Backfill				
		Class A1 earth fill material	Class A2 earth fill material	Class B, C and D earth fill material	Fill material (used within 1.5 m below subgrade level)	Granular fill for subgrade improvement	Unbound drainage material	Earth backfill material	Free draining granular material	Bedding material and drainage (WG)	Bedding and drainage (20 mm nominal)	Bedding and drainage (10 mm nominal)
RCC	20 mm nominal	x	x	x	x	x	x	x	√ F.T.	x	x	x
	10 mm nominal	x	x	x	x	x	x	x	√ F.T.	x	x	x
	Crusher dust	x	√	x	√	x	x	√	x	√	x	x
RAP		x	√	x	√	√	x	√	√	x	x	x
CCP	Blend of FA and BA (from ash pond)	x	√ [2] F.T.	x	√ [3] F.T.	x	x	x	x	x	x	x
	FA (from the dry storage area)	x	√ [2] F.T.	x	√ [3] F.T.	x	x	x	x	x	x	x
	FA (from the wet storage area)	x	√ [2] F.T.	x	√ [3] F.T.	x	x	x	x	x	x	x
	BA (as produced unprocessed)	x	*	x	*	x	x	*	x	*	x	x

x = not suitable, ✓ = suitable, * = more tests (e.g. PI, CBR and Emerson number) is required, F.T. = Field trial required, P.S = power station, WG = well-graded.

[1] These classifications are based on current TMR specification MRTS04 for natural materials. While recycled materials may be used in the embankment applications, they may not be classified as per current MTRS04 classifications, e.g. Class A2 earth fill.

[2] Only in core zone of embankment,

[3] When enclosed and capped by Class A1 or B earth fill

6.1 Recommendations

- It is well-established that RCC has sufficient shear and strength properties for usage in pavement road embankments. Results of assessments on the RCC samples, which were initially procured and intended to be assessed against the requirements for use in drainage applications, revealed that samples were mainly suitable to be used as a free-draining backfill material, bedding material, fill and backfill materials, depending on the gradation.
- RAP may be suitable for use as Class A2 earth fill material, earth backfill material, free-draining granular material and in subgrade applications. Results indicate that the residual binder in the RAP samples did not cause a creep behaviour. Although using RAP in embankments is recommended to be limited to heights of less than 3 m until further testings (in progress – Year 4 of O25) are completed.
- Some of the CCP samples met the requirements for Class A2 embankment fill, and fill material (used within 1.5 m below subgrade level). Based on the assessed mechanical properties, CCP can be used in the core zone of embankments as a blend of FA and BA.
- From an engineering perspective, shear and strength properties of RCG are similar to those of natural sand. In some fill (core zone of embankment), drainage and bedding applications, up to 100% RCG can be used.
- Conducting field trials can further inform the performance of the recycled materials in earth fill and drainage applications. However, it is recommended to identify options and applications where field trials and demonstration projects are required. Some applications, dependent on the case, could be implemented into specifications without field trials.

6.2 Future Research

The scope for potential future research includes further characterisation of recycled materials through laboratory testing and field trials, including:

- Carry out further laboratory testing to characterise CCP properties for use in earthwork and drainage applications. Tests could include CBR, electrical and heat conductivity, exchangeable sodium percentage and the sodium adsorption ratio and exchangeable cations.
- Conduct a field trial of RCC as a drainage material to assess the discharge of the water from placement in a trench.
- Conduct a field trial of CCP as an earth fill material to assess compatibility, stability, and durability.
- Extend the test results database by undertaking testing on additional samples.

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Appendix A Health, Safety and Environmental Risk Assessment: Recycled Crushed Concrete

Recycled Crushed Concrete in Road Infrastructure: Technical Review

Prepared for: Australian Road Research Board (ARRB) and Queensland Department of Transport and Main Roads

25 October 2022

EnRiskS

Document History and Status

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Limitations

Environmental Risk Sciences has prepared this report for the use of the Australian Road Research Board (ARRB) and the Queensland Department of Transport and Main Roads (TMR) in accordance with the usual care and thoroughness of the consulting profession. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report.

It is prepared in accordance with the scope of work and for the purpose outlined in the **Section 1** of this report.

The methodology adopted and sources of information used are outlined in this report. Environmental Risk Sciences has made no independent verification of this information beyond the agreed scope of works and assumes no responsibility for any inaccuracies or omissions. No indications were found that information provided for use in this assessment was false.

This report was prepared in September 2021, updated in February 2022 and finalised in October 2022. Environmental Risk Sciences disclaims responsibility for any changes that may have occurred after this time.

This report should be read in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. This report does not purport to give legal advice. Legal advice can only be given by qualified legal practitioners.

Table of Contents

Glossary of terms

BGL	Below Ground Level
COPC	Chemical of Potential Concern
CRC CARE	CRC for Contamination Assessment and Remediation of the Environment
CSM	Conceptual Site Model
HHRA	Human Health Risk Assessment
HSL	Health Screening Level
IMW	Intrusive Maintenance Worker
LNAPL	Light Non-aqueous Phase Liquid
LOR	Limit of Reporting
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NHMRC	National Health and Medical Research Council
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WHO	World Health Organisation

Executive summary

Environmental Risk Sciences Pty Ltd (enRiskS) has been engaged by the Australian Road Research Board (ARRB), on behalf of the Queensland Department of Transport and Main Roads (TMR) to undertake a technical review and provide advice in relation to the use of recycled crushed concrete in road infrastructure and in gravels used for pavement and drainage.

The proposed use of recycled crushed concrete in road infrastructure is part of a broader framework being considered in Queensland in relation to the use of recycled materials.

The objectives of the review undertaken and presented in this report are to determine if the proposed use of recycled crushed concrete in road infrastructure (i.e., pavements) and in drainage:

- has the potential cause impacts to human health
- has the potential cause impacts to the environment
- require any additional management measures for the use of the material.

ARRB has collected additional data to assist in characterising crushed concrete from various suppliers.

Based on the available information, including analysis of recycled crushed concrete samples from suppliers in Queensland, and the proposed use of recycled crushed concrete, the following can be concluded:

- the characteristics of recycled crushed concrete are consistent specifications for the use of these materials for pavements and drainage in NSW, Western Australia and South Australia
- the characteristics of recycled crushed concrete indicate the material is not considered to be regulated waste in Queensland
- in relation to the chemical composition of recycled crushed concrete proposed to be used for pavements or drainage materials there are no risk issues of concern in relation to human health or the environment (terrestrial or aquatic). Specifically:
    - concentrations detected in recycled crushed concrete are below criteria protective of risks to human health
    - measured leachate concentrations are below drinking water guidelines
    - where relevant the concentrations reported in recycled crushed concrete are not of concern to terrestrial environments
    - concentrations detected in recycled crushed concrete are not considered to be of concern in relation to aquatic environments
- in relation to the pH of recycled crushed concrete the review undertaken has concluded the following:
    - workers handling recycled crushed concrete (particularly fresh materials) should wear gloves and eye protection and other PPE as detailed on relevant safety data sheets for the product
    - there are no risk issues of concern for the general public who may come into direct contact with residual recycled crushed concrete materials or surface water runoff
    - there are no risk issues of concern for recycled crushed concrete where used in bound pavement materials or in compacted materials beneath sealed and unsealed surfaces

- it is not considered appropriate to use recycled crushed concrete as a surface layer for unsealed roads
- pH of the leachate would not result in any increased risk issues of concern for metals
- pH of leachate derived from recycled crushed concrete (where contact with rainfall may occur) would be buffered by soil, surface water and groundwater and the potential for adverse effects on aquatic ecosystems is considered to be low
- while no significant risks to human health or the environment have been identified, the following measures should be considered to minimise the potential for pH to impact on the offsite environment, where recycled crushed concrete may be used for drainage, the materials to be used should have a pH of ≤9. If the pH >9 it may be used for drainage provided the material is not used in areas closer than 30 m from a receiving waterway.

Section 1. Introduction

1.1 Background

Environmental Risk Sciences Pty Ltd (enRiskS) has been engaged by the Australian Road Research Board (ARRB), on behalf of the Queensland Department of Transport and Main Roads (TMR) to undertake a technical review and provide advice in relation to the use of recycled crushed concrete in road infrastructure and in gravels used for pavement and drainage.

The proposed use of recycled crushed concrete in road infrastructure is part of a broader framework being considered in Queensland in relation to the use of recycled materials.

The focus of this review relates to the nature and characteristics of the recycled crushed concrete, use in road infrastructure and drainage and exposures that may occur for workers, community or the environment.

1.2 Objectives and scope of works

The objectives of the review undertaken and presented in this report are to determine if the proposed use of recycled crushed concrete in road infrastructure (i.e., pavements) and in drainage:

- has the potential cause impacts to human health
- has the potential cause impacts to the environment
- require any additional management measures for the use of the material.

ARRB has collected additional data to assist in characterising crushed concrete from various suppliers.

This review has not provided an assessment of the engineering requirements or specifications relevant to the use of recycled crushed concrete as proposed. The focus of this review relates to the potential for harm to human health and the environment.

1.3 Methodology

This review has been undertaken in accordance with the following legislation and guidance (and associated references as relevant):

- *Environmental Protection Act 1994* and *Environmental Protection Regulation 2019*
- *Waste Reduction and Recycling Act 2011*
- National Environmental Protection Measure (NEPM) (NEPC 1999 amended 2013a, 1999 amended 2013b, 1999 amended 2013c, 1999 amended 2013d)
- enHealth, 2012. Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards (enHealth 2012)
- Queensland – Waste Reduction and Recycling Act 2011 and Waste Reduction and Recycling Regulation 2011
- Queensland Recycled Materials Environmental Assessment framework, Draft for Consultation (2015).

1.4 Qualification of author/SQP

This report has been prepared by Dr Jackie Wright, Director of enRiskS a Suitably Qualified Professional (SQP) for the assessment of harm to human health and the environment.

Section 2. Use of recycled crushed concrete

2.1 Use of recycled material in other jurisdictions

The use of recycled crushed concrete in road pavement and wells as within drainage materials has been approved and undertaken in a number of jurisdictions in Australia. The reuse of waste, or the use of recycled materials is a preferred activity to reduce the disposal of waste to landfill, consistent with the waste management hierarchy, shown below.

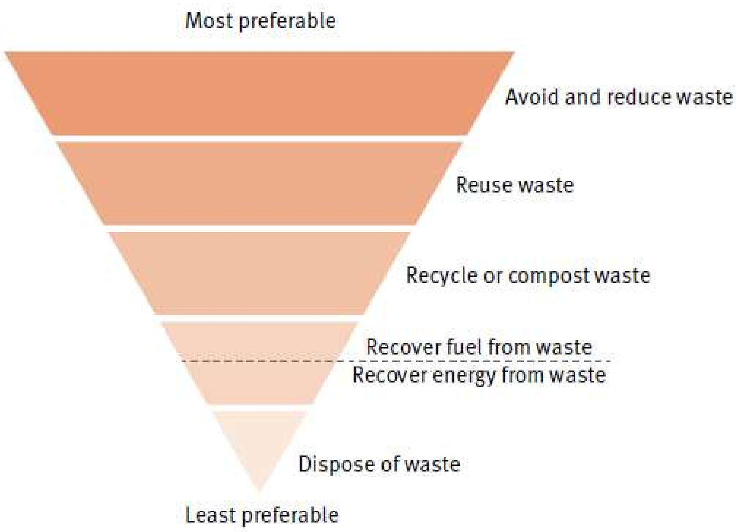


Figure 1: Waste and resource management hierarchy (Queensland Government 2019)

In NSW, the Department of Environment, Climate Change and Water (DECCW) provides a specification for the supply of recycled material for such uses (DECCW 2010). In addition, a Resource Recovery Order, "The recovered aggregate order 2014" and "The recovered aggregate exemption 2014" relate to the use of aggregate material comprising concrete, brick, ceramics, natural rock and asphalt for use as a road making material, or in building, landscaping or construction works. The Resource Recovery Order provides specifications for the characteristics of the materials that are suitable for reuse. DECCW (2010) indicates that crushed concrete may be suitable to comprise 100% of road base, fill, bedding material and drainage material.

In Victoria, VicRoads provides a technical note (TN 107, 2019) which indicates that the use of crushed concrete in road pavements has been well established in Victoria since the mid-1990's. No specifications in terms of chemical composition, is available for recycled crushed concrete in these applications.

In Western Australia the Roads to Reuse document (WA Government 2020) provides specifications for recycled materials that can be used in road base, which includes concrete. The document includes concentration limits for chemicals (and pH) in concrete-containing recycled road base product. For concrete-containing materials that have a pH > 9 the guidance states that these materials should not be used within 100 m of any wetland/watercourse or on land subject to flooding. The guideline does not allow for the use of concrete materials in drainage rock due to concerns in relation to pH. However guidelines, including concentrations limits are provided for materials where the pH sits between 6 and 9. Further guidance is provided in relation to recycled crushed concrete as road base (WA Government 2021), which references extensive research and long-term trials that demonstrate that the material is suitable for use as sub-base under full depth asphalt pavements. Crushed recycled concrete (27,000 tonnes) has been used in WA in the Kwinana Freeway Widening Project, delivered under the Roads to Reuse pilot program.

South Australia (DIT 2020; DPTI 2015) provides guidance on the use of recycled materials in road pavements. This includes reclaimed concrete blended/mixed with quarried materials and supplementary source materials that include brick, tile and asphalt. Where recycled aggregates are used in road pavement, they must comply with the quality requirements for the use and must not exceed 20% by mass of the total amount. The Master specification allows for reclaimed concrete to be mixed with quarried materials to produce recycled pavement material, stating that the 20% by mass relates to supplementary source materials such as brick, tile and asphalt. The basis of the 20% composition is not stated. Recycled aggregates are permitted to be used for pavement materials where it comprises inert material such as crushed concrete. These uses have been considered by DPTI (2015) and determined to be of low risk. Criteria as maximum concentrations that define waste fill including concrete materials are provided in this guidance.

In Queensland, Technical Standard MRTS35, Recycled Materials for Pavements was in use from 2010 (TMR 2010) and then updated in 2021 with Technical Specification MRTS05 Unbound Pavements to provide a single specification for recycled, quarried and natural pavement materials (TMR 2021). This standard permits up to 100% of Type 2 unbound materials to comprise reclaimed concrete, with general material comprising <70% recycled materials and recycled material blends comprising ≥ 70% recycled materials. Specifications are included for the use of recycled materials in base layers; however, it is noted that there are no restrictions on the use of recycled materials in other applications (e.g., non-trafficked shoulders, sub-cases, improved layers or subgrade treatments). The maximum pH of Type 2 materials containing recycled concrete in direct contact with galvanised or aluminium components is pH 11. There are no other limits relating to chemical concentrations or pH (in other situations) detailed in the standard. Other specifications include engineering specifications and limits for foreign materials.

Austroads provides guidance to the use of recycled materials in pavements (Austroads 2009 updated 2018). This includes the use of aggregates from recycled concrete. This document provides some guidelines on the characteristics of such materials including properties that relate to Class 1A and Class1B recycled crushed aggregate. Concentrations of metals and organics in these materials are required to be below relevant values from the contaminated land NEPM, noting that the guidance also states that authorities should develop their own policy documents for the use of recycled materials in consultation with state EPAs. The document indicates that blending coarse recycled concrete aggregates with natural aggregates at substitution rates below 30% is typical with no detriment to the (engineering) characteristics of the material.

Based on uses of recycled crushed concrete in other jurisdictions, **Table 1** presents a summary of the contaminant characteristics required to be met for the use of this material in pavements and/or drainage materials.

While some specifications include a wider range of chemicals, in general the concentrations adopted for key metals are similar across these jurisdictions. Guidelines from WA and SA include values for petroleum hydrocarbons, along with some additional metals and inorganics. The SA guidelines include values for a range of other organics.

Table 1: Summary of contaminant concentrations relevant for the use of recycled crushed concrete in Australia

Chemical or attribute	NSW (Resource Recovery Order) – Pavement and drainage*		WA (Roads to Reuse) – road base and drainage rock			SA, Waste Fill (DIT)
	Maximum average concentration for characterisation (mg/kg)	Absolute maximum concentration (mg/kg)	Recycled drainage materials (pH 6-9) (mg/kg)	Road base under asphalt (pH > 9) (mg/kg)		Maximum (mg/kg)
				Maximum average	Absolute maximum	
Mercury	0.5	1	1	0.5	1	1
Cadmium	0.5	1.5	1	0.5	1.5	3
Lead	75	150	200	75	150	300
Arsenic	20	40	20	20	40	20
Chromium (total)	60	120	75	60	120	400 Cr III 1 Cr VI
Copper	60	150	100	60	150	60
Nickel	40	80	60	40	80	60
Zinc	200	350	200	200	350	200
Antimony	--	--	--	10	20	NA
Barium	--	--	--	--	--	300
Beryllium	--	--	--	--	--	20
Cobalt	--	--	--	--	--	170
Manganese	--	--	--	--	--	500
Molybdenum	--	--	--	40	80	--
Selenium	--	--	--	2	4	--
Vanadium	--	--	--	25	50	--
Electrical conductivity	1.5 dS/m	3 dS/m	--	--	--	--
Benzene	--	--	1	--	--	1
Toluene	--	--	50	--	--	1.4
Ethylbenzene	--	--	100	--	--	3.1
Xylenes (total)	--	--	180	--	--	14
TRH C6-C10	--	--	100	--	--	65 (C6-C9)
TRH C10-C36	--	--	420	--	--	1000 (>C9)
PAHs	--	--	40	--	--	2
Aldrin/dieldrin	--	--	--	--	--	2
Chlordane	--	--	--	--	--	2
Cyanides	--	--	--	--	--	500
DDT	--	--	--	--	--	2
Heptachlor	--	--	--	--	--	2

Chemical or attribute	NSW (Resource Recovery Order) – Pavement and drainage*		WA (Roads to Reuse) – road base and drainage rock			SA, Waste Fill (DIT)
	Maximum average concentration for characterisation (mg/kg)	Absolute maximum concentration (mg/kg)	Recycled drainage materials (pH 6-9) (mg/kg)	Road base under asphalt (pH > 9) (mg/kg)		Maximum (mg/kg)
				Maximum average	Absolute maximum	
Phenolic compounds	--	--	--	--	--	0.5
pH	--	--	6 to 9	>9	>9	
Asbestos	0%	0%	Refer to guideline (WA Government 2020)			0%

* NSW Resource Recovery Order also includes criteria for the presence of metals, plaster and other materials (rubber, plastic, paper, cloth, paint, wood and other vegetable matter) in the recycled aggregate material to be used

2.2 Recycled crushed concrete as waste

Queensland has established guidelines relevant to the classification of regulated waste (DES 2019), as shown in **Table 2** for the chemicals detected in recycled crushed concrete. These should also be considered in the evaluation of potential issues associated with the use of recycled crushed concrete.

Table 2: Queensland waste guidelines

Chemicals and other attributes	Waste guidelines in QLD – Not regulated (mg/kg)
Mercury	<80
Cadmium	<90
Lead	<300
Arsenic	<300
Barium	<4,500
Boron	<20,000
Chromium (total)	<300 (Cr VI)
Copper	<220
Molybdenum	<117
Nickel	<1,200
Vanadium	<117
Zinc	<400
Aldrin and dieldrin	<10
Ethylbenzene	<17
Toluene	<1,470
Xylenes	<174
Petroleum hydrocarbons C6-C9	<950
Petroleum hydrocarbons C10-C36	<5,300

Refer to *Environmental Protection Regulation 2019*, Table 2 for guidelines relevant to other chemicals

2.3 Characteristics of recycled crushed concrete

2.3.1 General

Where recycled crushed concrete may be used for pavement or as drainage materials, it is relevant to consider the characteristics of the traditional materials used for these purposes. In relation to aggregates that may be used in pavements and for drainage, where recycled materials are not used, these materials would be derived from natural quarried materials. Similarly, beddings sands would be derived from natural materials (crushed quarry product, quarry pit material, river or dune sand). The characteristics of these materials would depend on the source location as naturally occurring elements vary in different geological areas. No data is available specific to the analysis of traditional materials that would be used in Queensland.

TMR provides technical specifications for the use of aggregate materials from a registered quarry. Where reclaimed or recycled concrete may be used, specifications relevant to unbound pavements (MRTS05) apply (also refer to **Section 2.1**). The specifications for these materials relate to material and engineering characteristics, not chemical composition.

MRTS05 for unbound pavement considers the use of recycled materials including recycled concrete, where the specification includes a maximum pH of 11 where recycled concrete is in direct contact with galvanised or aluminium components, and maximum percentages of foreign materials (noting that asbestos is not permitted). This specification does not include any maximum limits for metals or other chemicals in the materials.

2.3.2 Data from recycled crushed concrete suppliers in Queensland

TMR submitted crushed concrete samples from 3 suppliers, with 3 separate samples separated into different fraction sizes (dust, 10 mm and 20 mm), each split into 4 individual samples (A-D) submitted from each of these suppliers, for analysis. The materials sample from each supplier are as follows:

- Supplier 1 – material sampled from sales stockpile where the age of the materials (post crushing or storage time) is unknown
- Supplier 2 – material sampled directly from a stockpile under the belt of the crusher (i.e., the material is freshly crushed)
- Supplier 3 – material sampled from sales stockpile where the age of the materials (post crushing or storage time) is unknown.

Analysis of the samples collected included the following analytes:

- Total recoverable hydrocarbons (TRH)
- Volatile and semivolatile organics
- Organochlorine and organophosphorus pesticides
- Polychlorinated biphenyls (PCBs)
- Acid herbicides
- Cyanide (total), fluoride (total)
- Metals (antimony, arsenic, barium, beryllium, boron, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, silver, vanadium, zinc).

In addition, three of these samples were also analysed for the leaching of metals using the ASLP method. The samples selected for analysis included the sample where the highest level of metals was reported, and a representative sample selected from the other two suppliers.

Review of the analytical results indicates that the only chemicals detected in the materials analysed were TRH and some individual petroleum hydrocarbons (in some samples only), the pesticide dieldrin and some metals. **Table 3** presents a summary of the concentrations detected in the crushed concrete materials analysed. The table presents the data for each sample, with the maximum of the sub-sample A, B, C or D presented.

Table 4 presents the total and leachable concentrations reported, where the metal was detected in leachate. No other metals were detected in the leachate analysis (including antimony, arsenic, barium, beryllium, cadmium, copper, lead, mercury, molybdenum, nickel, selenium, silver and vanadium).

It should be noted that the leachate analysis reported the initial pH of the materials was between 10 and 11, consistent with concrete. The leachate analysis was conducted under neutral pH, with the leachate solution at pH 6.1. The final pH of the solution (post vigorous shaking for an extended period of time) was between 11 and 12, with no different reported between materials sampled from sales stockpiles and freshly crushed materials. While the ASLP method is not reflective of environmental conditions the analysis indicates that the material has the potential to result in an increase of the pH of infiltration water through the material. Additional pH data is discussed in **Section 2.3.3**.

Table 3: Summary of chemicals detected in recycled crushed concrete samples analysed

Analyte detected	Supplier 1# (maximum from sub-samples A-D) (mg/kg)			Supplier 2## (maximum from sub-samples A-D) (mg/kg)			Supplier 3# (maximum from sub-samples A-D) (mg/kg)		
	291	292	293*	305	306	307*	326	327	328*
TRH C10-C40	210	150	<100	260	<100	<100	250	<100	<100
Ethylbenzene	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	0.2	<0.1
Toluene	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	0.3	<0.1
Xylenes (total)	<0.3	<0.3	<0.3	0.5	<0.3	<0.3	<0.3	0.6	<0.3
Dieldrin	0.07	<0.05	<0.05	<0.05	<0.05	<0.05	0.12	0.06	<0.05
Arsenic	7.9	7.1	9.2	6.6	5.5	4.3	5.6	5.4	7.6
Barium	80	71	83	77	83	52	75	83	56
Boron	15	10	12	11	<10	10	<10	10	<10
Cadmium	<0.5	<0.5	<0.5	3.2	<0.5	<0.5	<0.5	<0.5	>0.5
Chromium	40	44	68	34	32	28	20	22	14
Copper	41	30	57	26	23	29	46	18	17
Lead	28	8.7	18	17	17	6.7	14	9.8	11
Nickel	16	19	26	16	13	12	12	11	12
Vanadium	38	39	49	35	36	27	31	31	25
Zinc	87	60	72	64	38	34	95	51	330

* Samples from which leachate testing was undertaken on a sub-sample as noted in **Table 4**

Materials sampled from sales stockpile of unknown age

Materials sampled were freshly crushed

Table 4: Summary of leachate data

Sample and analysis	Analyte detected in leachate	
	Boron	Zinc
328A – total (mg/kg)	<10	330
328A – leachate (mg/L)	0.06	0.03
307B – total (mg/kg)	10	34
307B – leachate (mg/L)	<0.05	<0.01
293D – total (mg/kg)	12	55
293D – leachate (mg/L)	<0.05	0.03

It should be noted that the maximum concentrations of chemicals reported in the recycled crushed concrete samples analysed, are generally below or within the range of maximums allowable in specifications adopted in NSW, Western Australia and South Australia in relation to the use of recycled concrete in pavement and aggregates as described in **Section 2.1** and below all criteria that defines regulated waste in Queensland (**Section 2.2**). **Table 5** presents a summary of the maximum concentrations reported in the recycled crushed concrete samples, with comparison against the minimum specification detailed in **Table 1** and the criteria for non-regulated waste from **Table 2**.

Table 5: Comparison of recycled crushed concrete results with available specifications and regulated waste guidelines

Analyte detected in recycled crushed concrete samples	Maximum detected from suppliers (mg/kg)	Range in specifications for use of material from NSW, WA and SA		Waste guidelines in QLD – Not regulated (mg/kg)
		Maximum average (mg/kg)	Absolute maximum (mg/kg)	
TRH C10-C40	260	--	420 to 1000	<5,300
Ethylbenzene	0.2	--	3.1 to 100	<17
Toluene	0.3	--	1.4 to 50	<1,470
Xylenes (total)	0.6	--	14 to 180	<174
Dieldrin	0.12	--	2	<10
Arsenic	9.2	20	20 to 40	<300
Barium	83	--	300	<4,500
Boron	15	--	--	<20,000
Cadmium	3.2	0.5	1 to 3	<90
Chromium	68	60	75 to 400	<300
Copper	57	60	60 to 150	<220
Lead	28	75	150 to 300	<300
Nickel	26	40	60 to 80	<1,200
Vanadium	49	25	50	<117
Zinc	330	200	200 to 350	<400

It is noted that the maximum concentration of cadmium detected exceeds the upper end of the range of maximums presented in the available specifications.

Cadmium was only detected on one occasion in one sample (from freshly crushed material) with the value of 3.2 mg/kg essentially equal to the upper end of the specifications of 3 mg/kg. This should not be considered an exceedance where sampling and analytical error is considered. It is noted that cadmium was not detected in leachate from the samples analysed (noting that the one sample where cadmium was detected was not analysed for leaching). In relation to future leaching from materials, where water may be in contact with the materials, the leaching potential will reflect average characteristics, not the maximum. Hence, based on the available data and consideration of the average concentrations in the material sampled, cadmium is unlikely to be of concern.

While the maximum concentration of zinc does not exceed the upper end of the range of specifications included in **Table 5**, the maximum sits at the upper end of the range. In addition, zinc was detected in leachate. The leachate analysis included the sample where the maximum zinc concentration was reported, with 330 mg/kg reported in soil and 0.03 mg/L reported in leachate. The soil-water partition coefficient (Kd) for this sample is 11,000. For the other samples analysed the Kd is approximately 1833 to >3400. All these values are significantly greater than the published Kd for zinc of 62 (USEPA 2021). This indicates that zinc, as reported in the recycled crushed concrete is not considered to be leachable in the environment (with the log Kd in the range 3.2 to 4, which is >3 and considered to have a low potential for leaching as detailed in the NEPM (NEPC 1999 amended 2013d)). The maximum concentration reported in leachate is less than 10 times higher than the default guideline for fresh and marine water quality (ANZG 2018) and hence where sufficient water was present to result in runoff, it is highly unlikely that zinc concentrations would be of concern to aquatic environments.

The specifications considered in **Table 5** are not specific to the protection of human health or the environment, which is further discussed in **Section 3**.

2.3.3 Additional data on the pH of leachate

The testing of recycled crushed concrete materials from Queensland suppliers (as detailed in **Section 2.3.2**) included some limited leachate testing using the ASLP method. This testing identified the pH of the leaching solution range from 10 to 11 at the start and 11 to 12 at the end of the test. The ASLP leach testing procedure involves the crushing of the material (to a maximum of 2.4 mm particle size), use of water at a set ratio of soil:water at a set pH (pH 4 was used in the tests) and vigorous shaking with the material for and extended period of time (16 hours). This method does not necessarily reflect leaching that can occur in-situ, particularly with the recycled crushed concrete as supplied, in particular the coarse materials that may be used in drainage (i.e., 10 mm and 20 mm).

To obtain a better understanding of the potential for water runoff from recycled crushed concrete to have elevated pH, 20 mm crushed concrete samples (as supplied – no further crushing undertaken) were sent to Envirolab Services for column leach tests. The testing involved 9 samples which comprised materials from 3 different samples [one from each of the suppliers] - BS21/293, BS21/307 and BS21/328. These samples were tested under 3 different conditions:

- unwashed (i.e. as received)
- twice washed
- wetted/washed.

In addition to the above, an additional two samples comprising no-fines (unwashed) crushed concrete also analysed.

The leach tests undertaken, and the results are summarised below.

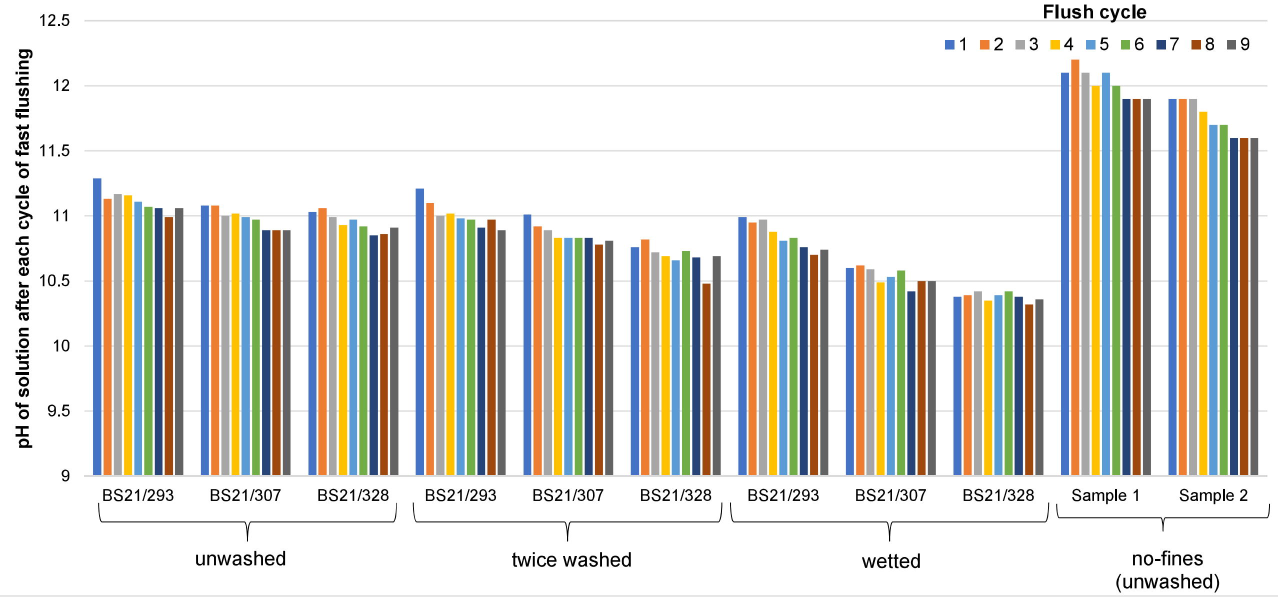
Stage 1 – Fast flushing

This work involved 9 cycles of fast flushing with approximately 2.3 to 2.4 L high purity water was undertaken through each column of crushed material. The pH of the water exiting the material (i.e. elutriate following each flush) was measured. The results are included in **Figure 2** providing a summary of the pH after each flush cycle for each sample analysed.

The data from this stage of testing indicates the following:

- following all flush tests, the pH of elutriate remained in the range 10.3 to 11.9
- with each flushing round, the pH of the elutriate generally decreased slightly, for all samples analysed
- the pH was highest for the no-fines crushed concrete samples analysed
- the pH of the materials tested that were twice washed were lower than the unwashed samples, and the materials that were wetted prior to the test, had a lower pH than all other samples.

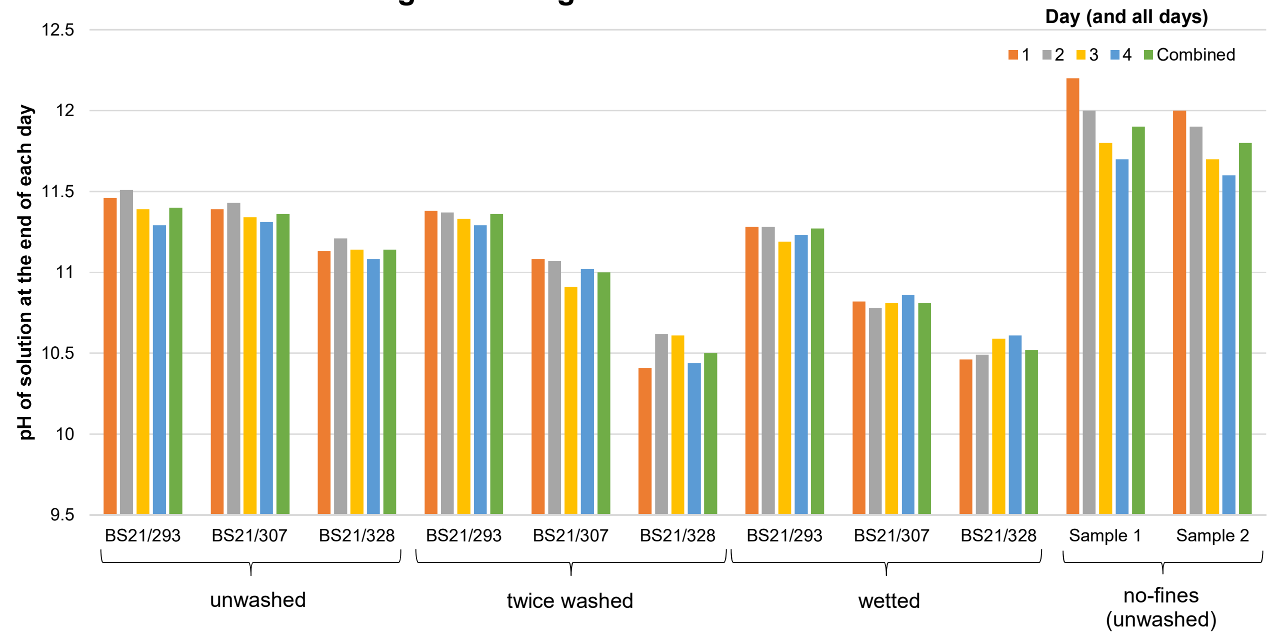
Figure 2: Stage 1 Leach Test Results



Stage 2 – Slow drip

This work involved further assessment of leaching from the material evaluated in Stage 1. The columns were sealed off to slow the movement of water through the material. The material was wetted with 1 L high purity water, after which a dip feed of high purity water was added at a rate of 7-9 mL/min. Elutriate collected over 24 hours was collected and measured at the same time each day, for 4 consecutive days. The results are included in **Figure 3** providing a summary of the pH after each day, as well as all days combined, for each sample analysed.

Figure 3: Stage 2 Leach Test Results



The data from this stage of testing indicates the following:

- the pH of elutriate following drip feeding of water remained in the range 10.4 to 11.9, which is similar to the range reported following the Stage 1 testing
- at the end of each day, the pH of the elutriate for many of the samples had no specific trend, with the pH varying over each day
- the pH of the no-fines (unwashed) materials was highest, noting that the pH generally decreased each day
- the pH of the materials tested as sample BS21/307 and BS21/328 that were twice washed or wetted prior to the test, had a lower pH than the other samples.

Overall, the wetted samples and in particular sample BS21/328 resulted in the lowest pH after the nine flushes during Stage 1 and reported lower levels of pH in Stage 2. Hence moistening the sample and leaving for 72 hrs gave lower pH eluates than two washes (where there was much more water contact with the material).

Section 3. Assessment of risks to human health and the environment

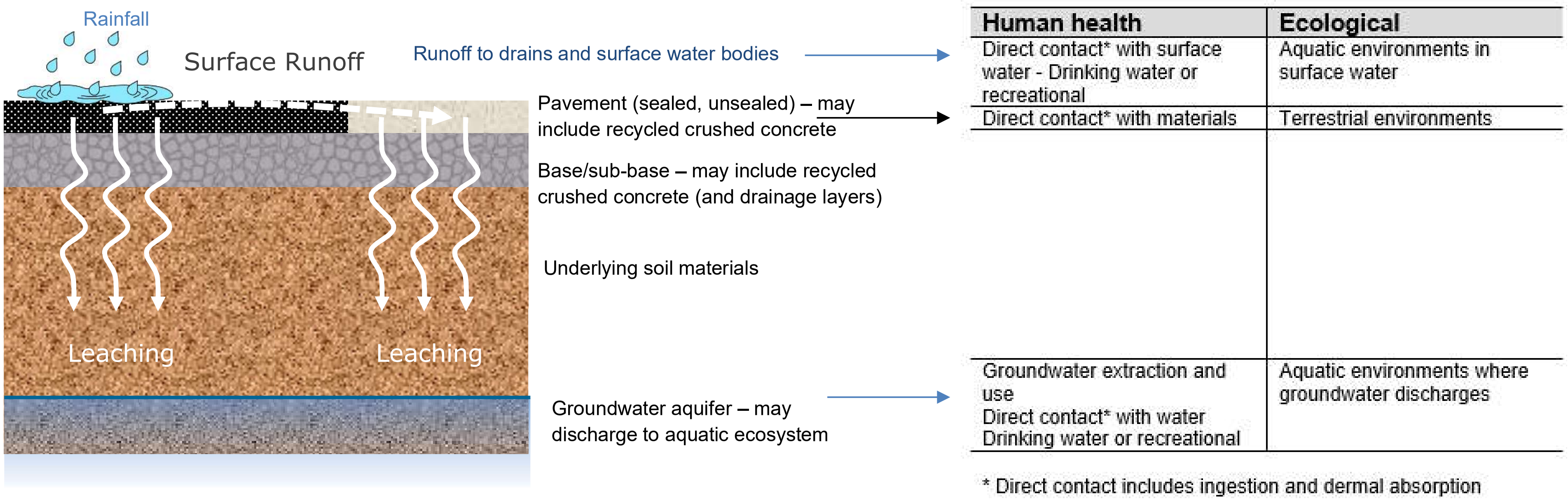
3.1 Potential for exposure

The focus of this review relates to consideration of potential risks to human health and the environment in relation to the use of recycled crushed concrete in pavement materials and in drainage.

In relation to the potential for exposure, the **Figures 1 and 2** provide diagrammatic conceptual site models relevant to the proposed use of this material. The figures include the mechanisms for contaminants to migrate from the materials (as proposed to be used) and the potential for exposure where human health and ecological risks may require further consideration.

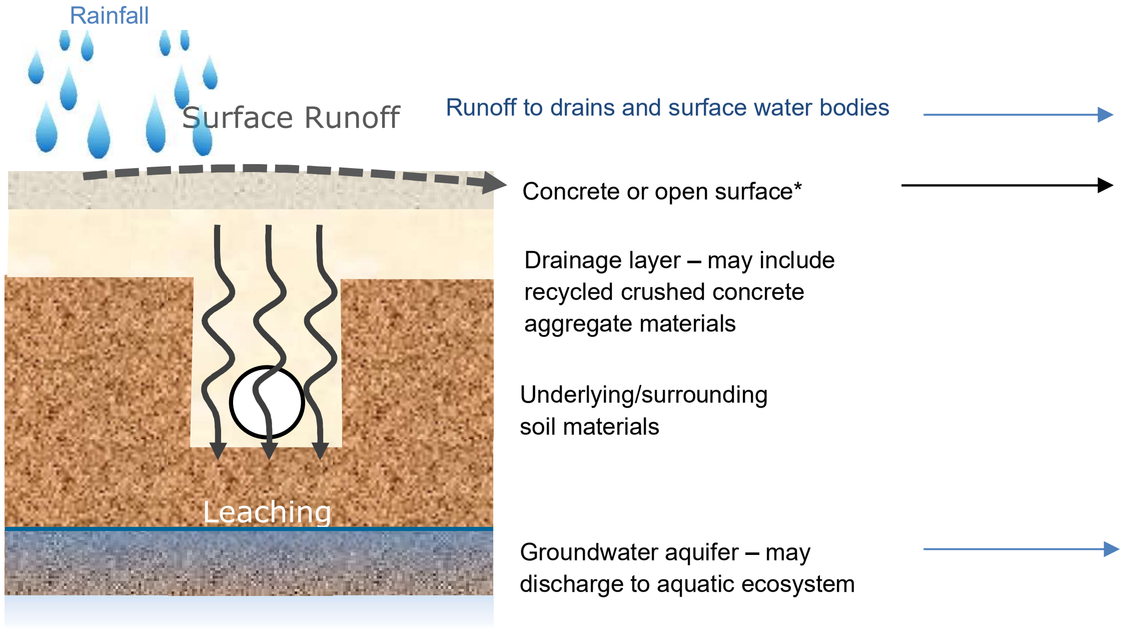
Where recycled crushed concrete is blended with other aggregates for these uses, these other materials would have their own unique properties that would be expected to be consistent with natural background.

For the purpose of this assessment the characteristics of recycled crushed concrete as presented in **Tables 3 and 4** have been considered. The pH of the material is also considered.



Note that where recycled crushed concrete is used in pavement application, the materials would be compacted resulting in a very limited potential for water to penetrate the materials and the leaching to be significant. This is further discussed in **Sections 3.2.3 and 3.3**.

Figure 1: Conceptual model – use of recycled crushed concrete in pavement materials



Human health	Ecological
Direct contact* with surface water - Drinking water or recreational	Aquatic environments in surface water
Direct contact* with materials	Terrestrial environments
Groundwater extraction and use Direct contact* with water Drinking water or recreational	Aquatic environments where groundwater discharges

* Direct contact includes ingestion and dermal absorption

* May include landscape areas

Figure 2: Conceptual model – use of recycled crushed concrete in drainage

3.2 Assessment of human health issues

3.2.1 Potential for exposure

In relation to potential risks to human health the pathways of exposure relevant to the use of recycled crushed concrete as proposed involve the following:

- Direct contact with recycled crushed concrete in roadways or pavements, where these materials are in an area accessible to workers and residents who may live directly adjacent to the locations where these materials may be used. This exposure relates to direct contact with chemicals that may be present in surface materials. Where materials are bound in asphalt or concrete, used at depth, placed beneath sealed surfaces there is no potential for direct contact with the materials to occur (refer to **Section 3.2.2**).
- Direct contact with chemicals that may have leached from the recycled crushed concrete used in pavement or for drainage that may directly runoff to surface water, where this water may be accessed for recreational uses or extracted for drinking water (refer to **Section 3.2.3**).
- Direct contact with chemicals that may have leached from the recycled crushed concrete as used, migrate to groundwater and groundwater is extracted and used for drinking water. Groundwater may also discharge to surface water where exposures via recreational use or drinking water may occur (refer to **Section 3.2.3**).

3.2.2 Direct contact with recycled crushed concrete materials

To assess the potential for the above exposures to be of concern, the maximum concentrations reported in recycled crushed concrete have been directly compared with guidelines that are based on the protection of human health for exposures by commercial/industrial workers and residents. These guidelines are available from the ASC NEPM (NEPC 1999 amended 2013a) and are protective of the following exposures, which are highly conservative in relation to likely exposures that may occur in areas where material is proposed to be used:

- Commercial/industrial workers – ingestion of soil and dust, dermal absorption of chemicals from contact with soil and dust and inhalation of dust, 8 hours per day for 240 days of the year for 30 years.
- Residents – ingestion of soil and dust, dermal absorption of chemicals from contact with soil and dust, inhalation of dust, ingestion of homegrown fruit and vegetables grown in soil (10% of intakes are from home produce).

Where guidelines are not available from the NEPM, they have been derived from CRC CARE (CRC CARE 2011) in relation to direct contact exposures with TRH, and the USEPA Regional Screening Levels (RSLs) for residential and industrial soil – which are derived on a similar basis as the NEPM guidelines.

Table 6 presents a comparison of the maximum concentrations reported against these health-based guidelines.

Table 6: Review of concentrations reported in recycled crushed concrete – Human health

Analyte detected in recycled crushed concrete samples	Maximum detected in material from suppliers (mg/kg)	Guidelines protective of human health (mg/kg)	
		Commercial/ industrial workers N (HIL-D)	Residents N (HIL-A)
TRH C10-C40*	260	62,00 to 120,000 C	3,300 to 6,300 C
Ethylbenzene	0.2	27,000 C	4,500 C
Toluene	0.3	99,000 C	14,000 C
Xylenes (total)	0.6	81,000 C	12,000 C
Dieldrin	0.12	45	6
Arsenic	9.2	300	100
Barium	83	220,000 U	15,000 U
Boron	15	300,000	4,500
Cadmium	3.2	900	20
Chromium	68	3600 (Cr VI)	100 (Cr VI)
Copper	57	240,000	6,000
Lead	28	1,500	300
Nickel	26	6,000	400
Vanadium	49	5,800 U	390 U
Zinc	330	400,000	7,400

* It is noted that TRH F2 (>C10-C16) is also considered to be volatile where there may be the potential for the inhalation of volatile TRH in air. For the proposed use of recycled crushed concrete, this would only be in outdoor areas where the NEPM (NEPC 1999 amended 2013a) indicates that the guideline protective of inhalation exposures in outdoor air is not limiting – this means that the saturated vapour concentration is lower than the vapour concentration that would result in unacceptable risks. Hence there are no vapour inhalation risk issues of concern, and the guidelines adopted relate to direct contact exposures only.

N = Health based guidelines as listed in the NEPM (NEPC 1999 amended 2013a), unless noted otherwise

C = CRC CARE guidelines (CRC CARE 2011) based on the protection of human health for direct contact exposures, the range presented for TRH reflects the values presented for the subfractions >C10-C16, >C16-C34 and >C34-C40

U = USEPA RSLs (USEPA 2021) for industrial or residential soil – protective of human health

Review of **Table 6** indicates that all concentrations reported in recycled crushed concrete are well below the conservative health-based guidelines that are protective of direct contact exposures by workers and residents. These guidelines are also protective of exposures that may occur for workers involved in handling these materials.

Another aspect of recycled crushed concrete relates to the pH of the material. pH issues relating to the use of recycled crushed concrete have been further addressed in **Section 4**.

Further review of potential risks related to the leaching of metals from recycled crushed concrete is presented in **Section 3.4**.

3.2.3 Leaching of chemicals from recycled crushed concrete and impacts on drinking water or recreational water quality

The available data indicates that the metals detected in the recycled crushed concrete are not very leachable. Only boron and zinc were detected in the leachate samples analysed.

Other chemicals such as petroleum hydrocarbons and dieldrin were not detected in many of the samples, and when detected, they were only reported just above the limit of reporting (i.e., only low concentrations detected).

Where recycled crushed concrete is used in pavement applications, the materials are required to be compacted (and in some cases bound) result in a very limited potential for water to penetrate the materials and for leaching to occur. It is therefore unlikely that leaching from recycled crushed concrete used in pavements would be significant. Leaching from recycled crushed concrete used in drainage may occur and requires further consideration.

To determine if there is the potential for chemicals that may leach from the recycled crushed concrete to impact on water quality, where used for drinking water or recreational water, the detected concentrations in leachate have been directly compared with drinking water guidelines. This approach does not take into account attenuation (which would be significant) between leaching from the material and migrating to and mixing in surface water and/or groundwater. Drinking water guidelines are conservative values that are also protective of recreational exposures.

Table 7: Review of leachate concentrations – Human health

Metals detected in leachate analysis	Maximum concentration detected (mg/L)	Drinking water guideline (mg/L) (NHMRC 2011 updated 2022)
Boron	0.06	4
Zinc	0.03	3 (aesthetic, also protective of health)

There are no concentrations reported in leachate that exceed drinking water guidelines.

Another aspect of recycled crushed concrete relates to the pH of the material. pH issues relating to the use of recycled crushed concrete have been further addressed in **Section 4**.

3.3 Assessment of ecological issues

3.3.1 Potential for exposure

In relation to the potential for ecological impacts related to the proposed use of recycled crushed concrete the following issues are of relevance:

- Terrestrial ecosystems - Pavement materials are used for roads where the growth of plants is not desired. In the case of asphalt or concrete sealed surface, these materials would be compacted and would preclude the growth of plants, regardless of the inclusion of recycled crushed concrete in this material. Similarly, where recycled crushed concrete is used in unpaved materials, the growth of plants would be prevented. Where recycled crushed concrete is used in subsurface drainage, plant growth and terrestrial ecosystems are not relevant. Hence the focus of this review relates to the potential for harm in areas located adjacent to the pavement or roadway where the materials may be used.
- Aquatic ecosystems – This is of relevance where chemicals present in recycled crushed concrete leach and may impact on surface water quality and/or groundwater quality, and groundwater discharges to an aquatic environment (refer to **Section 3.4**).

3.3.2 Terrestrial ecosystems

In relation to potential impacts on adjacent terrestrial ecosystems, this would only relate to the presence of the materials that may have spilled or extend beyond the road or pavement. Where the recycled crushed concrete is bound in asphalt or concrete or used in pavements and compacted then there is no potential for ecological exposures and therefore no risk.

To assess the potential for recycled crushed concrete to be of concern to terrestrial ecosystems, maximum concentrations reported in the recycled crushed concrete samples have been compared with published ecological investigation levels (EILs), as presented in **Table 8**. The level of protection relevant to terrestrial ecosystems adjacent to roadways or paved areas is consistent with that adopted in the NEPM for open space and residential use. This relates to 80% species protection and is expected to be conservative for areas where recycled crushed concrete may be present (unbound) in soil.

Soil EILs from the NEPM (NEPC 1999 amended 2013a) have been adopted in this assessment. Where EILs are not available, guidelines available from CCME or RIVM, protective of agricultural or residential soil have been adopted. The NEPM EILs have been derived to also considered potential leaching and impacts on groundwater and aquatic ecosystems.

Table 8: Review recycled crushed concrete concentrations – Terrestrial ecosystems

Analyte detected in recycled crushed concrete samples	Maximum detected in material from suppliers (mg/kg)	Guidelines protective of ecological health (mg/kg)
TRH C10-C40*	260	120 to 5,600 ES
Ethylbenzene	0.2	70 to 125 ES
Toluene	0.3	85 to 105 ES
Xylenes (total)	0.6	45 to 105 ES
Dieldrin	0.12	4 R
Arsenic	9.2	100 E
Barium	83	500 C
Boron	15	3,100 R
Cadmium	3.2	10 C
Chromium	68	200 AA
Copper	57	100 AA
Lead	28	1100 E
Nickel	26	35 AA
Vanadium	49	130 C
Zinc	330	310 AA

NEPM ecological guidelines

E = EIL

A = Added contaminant level (ACL) with the EIL based on background from QLD (low traffic volumes) + ACL calculated for CEC = 5 cmolc/kg, pH = 10, iron content = 5%, clay content = 1%

A = Aged contamination guideline (relevant to recycled crushed concrete)

ES = Ecological Screening Level for petroleum hydrocarbons

C = CCME guideline protective of residential soil (ecological)

R = RIVM intervention screening level for soil

Review of **Table 8** indicates the following:

- Where the maximum concentration reported is considered, zinc exceeds the adopted ecological guideline. It is noted that the guidelines are not specifically applicable to the maximum, with the average more representative of concentrations that may be relevant to terrestrial ecosystems, and where average concentrations are considered, these are below the ecological guideline. In addition, the adopted ecological guidelines are highly conservative as it is assumed that all the soil in large areas used for open space or recreational purposes is at the guideline levels – which would not be the case as the recycled material would only be present close to areas where used in pavements and drainage with limited potential for large areas or surface soil adjacent to these uses to include recycled crushed concrete. Where commercial/industrial guidelines are considered, the maximum concentrations are below these values.

- The concentrations reported for TRH are generally below the adopted ecological guidelines. The TRH guidelines relate to various subfractions of >C10-C40. Further review of the maximum concentration reported for these subfractions indicates that TRH >C10-C16 was not detected, TRH >C16-C34 was reported to be 110 mg/kg, which is below the ecological guideline for this fraction group of 300 to 1300 mg/kg (for fine and coarse soil), and TRH >C34-C40 was reported to be 150 mg/kg, below the ecological guideline of 280 to 560 mg/kg (for fine and coarse soil). It should also be noted that the guidelines adopted for TRH relate to the TRH being petroleum hydrocarbons. The guidelines are overly conservative for the assessment of TRH that comprises other, non-petroleum, compounds which is likely for recycled materials where biodegradation would result in the oxidation of petroleum products to a range of non-petroleum metabolites. On this basis the TRH detected is not considered to of concern to terrestrial ecosystems.

Another aspect of recycled crushed concrete relates to the pH of the material. pH issues relating to the use of recycled crushed concrete have been further addressed in **Section 4**.

3.3.3 Aquatic ecosystems

It is noted that the EILs and ESLs have been derived to also consider potential leaching and migration to groundwater (and protection of aquatic ecosystems). The potential for leaching to be of concern to any aquatic environment has also been further reviewed in **Section 3.4**.

3.4 Further review of potential risk issues

Where any material is used for paving (including concrete and asphalt) it will be compacted or bound such that the potential for water to penetrate/infiltrate the materials and for leachate to be present in runoff or infiltration water is very low. Where the material may be used for drainage, there is the potential for metals (and other contaminants if present) to leach and migrate to groundwater or surface water (where humans and aquatic ecosystems may be exposed).

This transport mechanism is not considered to be of concern where the characteristics of the materials used are consistent with what is considered to be clean fill or natural (or uncontaminated) materials. This is particularly relevant as metals (and inorganics) are naturally occurring within soil and rock, and hence there are concentrations that would be expected in materials such as soil, gravel, sand and crushed rock that are commonly used for pavement and drainage materials that are considered to be representative of naturally occurring materials. It is noted that the concept of naturally occurring requires consideration as there are numerous areas where mineralised rock/soil is present that may pose a risk to health and the environment. Hence some Australian jurisdictions have specifically defined the concentrations that are considered to be to be naturally occurring or clean fill, which typically excluded naturally mineralised areas.

Where the recycled crushed rock comprises characteristics consistent with clean fill or natural materials, the material is considered to be consistent with the characteristics of existing materials commonly used in roads and pavements, and of no concern to human health or the environment.

The clearest definitions of clean fill or natural materials are from Victoria, NSW and South Australia.

- EPA Victoria (EPA Victoria 2021) provides a definition of fill materials, commonly referred to as clean fill criteria. This provides concentrations of contaminants, below which are considered to not be contaminated and therefore not of concern to human health or the environment. The guidance also provides for review of the history of the material to determine if concentrations of metals above these criteria are derived from natural origins (where the material would not be considered contaminated). There is no requirement to test for leaching in relation to these materials.
- The NSW EPA provides criteria used to define excavated natural material (ENM) (NSW EPA 2014). This order provides the requirements that must be met by suppliers of excavated natural materials for use in fill or earthworks. The order provides characteristics of the material as a maximum average and absolute maximum concentrations. These criteria are considered to define clean fill in NSW and the material that complies with the ENM criteria is not considered to be contaminated and does not pose a risk to human health or the environment. Leach testing is not required for these materials.
- South Australia provides a standard for waste derived fill (SA EPA 2013). This standard provides the maximum concentrations of chemical substances that would meet the waste fill criteria. Concentrations in excess of the waste fill criteria require further assessment including consideration of leaching to the environment (noting that the standard also provides Intermediate Waste Criteria). The waste fill criteria relate to concentration of chemicals only. There is no requirement for leach testing of these materials.

It is acknowledged that the criteria established, as noted above, relate to soil (being clay, silt and/or sand), gravel and rock of naturally occurring materials. The South Australian standard allows for the inclusion of other inert mineralogical matter. These criteria are consistent with the characteristics of other natural materials commonly used in road applications, and if the characteristics of recycled crushed concrete has the potential to be of concern to the human health or the environment, when used in the same way as these other materials.

Queensland does not have a guideline on concentrations that comprise clean fill or natural (uncontaminated) materials. Schedule 19 of the *Environmental Protection Regulation 2019* defines "*clean earth*" as "*any natural substance found in the earth that is not contaminated with waste or a hazardous contaminant*". There are no criteria established in Queensland as to the concentrations of metals in these materials that is considered to be natural or uncontaminated. As noted in **Section 2.2** recycled crushed concrete is not considered to be regulated waste in Queensland.

Further assessment of soil (and rock) concentrations in Queensland that would be considered to be representative of natural background materials (precluding naturally mineralised areas) has been undertaken by Easterly Point Environmental (Salmon 2017). This review has considered the available data on background or natural soil concentrations in Queensland, along with guidance provided in the NEPM (NEPC 1999 amended 2013d, 1999 amended 2013a) to determine residual soil levels, which would be considered suitable for any use and are not considered to be of concern to human health or the environment.

Table 9 provides a review of the maximum concentrations reported in recycled crushed concrete against the available guidance from Victoria, NSW and SA in relation to the characteristics of natural materials or clean fill (i.e., uncontaminated material). The proposed residual soil levels for Queensland are also presented.

Table 9: Review of concentrations detected in recycled crushed concrete against criteria for natural materials or clean fill

Analyte detected in recycled crushed concrete samples	Maximum detected in material from suppliers (mg/kg)	**Criteria available for defining clean fill or natural materials** (not considered contaminated and not of concern to health or the environment) (mg/kg)				
		EPA Victoria – Clean fill	NSW EPA – Excavated Natural Material (ENM)		SA EPA – Waste derived fill	Queensland – suggested residual soil levels (based on background levels)
			Maximum average	Absolute maximum		
TRH C10-C40*	260	1000	250	500	1000	--
Ethylbenzene	0.2	7 (sum)	NA	25	3.1	--
Toluene	0.3		NA	65	1.4	--
Xylenes (total)	0.6		NA	15	14	--
Dieldrin	0.12	1 (OCPs)	--	--	2	--
Arsenic	9.2	20	20	40	20	50
Barium	83	--	--	--	300	--
Boron	15	--	--	--	--	--
Cadmium	3.2	3	0.5	1	3	4
Chromium [1]	68	-- Cr III 1 Cr VI	75	150	400 Cr III 1 Cr VI	50
Copper	57	100	100	200	60	200
Lead	28	300	50	100	300	60
Nickel	26	60	30	60	60	60
Vanadium	49	--	--	--	--	--
Zinc	330	200	150	300	200	400
pH	10-11	--	5 to 9	4.5 to 10	--	--

Notes

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

Review of **Table 9** indicates that in general the maximum concentrations reported in recycled crushed concrete would be considered naturally occurring or clean fill. There are a few analytes detected where the maximum exceeds the range of criteria presented. In relation to cadmium, this was only detected on one occasion and the detected concentration is essentially no different to the criteria of 3 mg/kg. For zinc, the maximum was only present in one sample, and it is noted that the zinc reported in this sample is not particularly leachable (refer to **Table 2** and discussion in **Section 2.3**) and hence would not be considered to be of concern. Where the characteristics of the recycled crushed concrete is consistent with natural or background materials, it should be considered suitable for the proposed use with no risk issues of concern for human health or the environment and there is no need to further consider leaching to and impacts on groundwater or surface water quality.

Another aspect of recycled crushed concrete relates to the pH of the material. pH issues relating to the use of recycled crushed concrete have been further addressed in **Section 4**.

3.5 Overview of human health and ecological risks

In relation to the chemical composition of recycled crushed concrete proposed to be used for pavements or drainage materials there are no risk issues of concern in relation to human health or the environment (terrestrial or aquatic).

Section 4. pH issues relating to recycled crushed concrete

4.1 General

One of the characteristics of recycled crushed characteristics that differs from natural materials or materials that would normally be classified as fill, is the pH. pH of concrete is high, with levels reported for materials typically pH 10 to 11 indicative of alkaline conditions.

4.2 Direct contact with recycled crushed concrete

In relation to human health, the only issues of concern relate to direct contact with soil and the potential for skin irritation. The natural pH of the surface of normal skin (the stratum corneum) is in the range 4.1 – 5.8 (95% interval with an arithmetic mean of 4.9) (Proksch 2018). The pH of skin is more neural in newborns, decreasing significantly in the first 2 months of life (Panther & Jacob 2015; Proksch 2018). Skin has a very good buffering capacity and hence direct contact and hence can resist alkaline aggression. Soap is an alkaline material (pH 9 approximately) which is well tolerated by people, as is direct contact with existing set concrete surfaces (Proksch 2018). The buffer capacity is reduced by repeated insults, for example, by washing out the buffer components with regular use of water and detergent. A low buffer capacity of the skin (and hence increased sensitivity to products such as soap and detergents) is reported for babies, aged individuals and diseased skin (Proksch 2018).

Fresh cement and the handling of concrete mixes, including wet concrete has a high potential for skin irritation and burns.

Once set and the upper surface of the concrete has undergone carbonation (refer to discussion below) the potential for concrete to result in skin irritation is low as the pH of the surface of the concrete is lower.

Crushed materials, however, have a higher surface area and skin irritation may occur when indirect contact with recycled crushed concrete. The fine particles, with the greatest surface area, pose the greatest risk for skin irritation as a result of direct contact with these materials, particularly freshly crushed materials. Where works relate to the use of recycled crushed concrete in drainage, the material proposed to be used are coarse, in the range 10 mm to 20 mm. Hence direct contact with dust or fine materials would be negligible for these works.

Workers regularly handling the materials should wear gloves and eye protection to prevent skin and eye irritation. Safety data sheets relevant to recycled crushed concrete materials should be followed by all workers handling the materials.

Where recycled crushed concrete is left on the ground surface and is exposed to air, the surface of the materials would be subject to carbonation and would be expected to be of less concern in relation to surface pH issues. Hence where some residual material may be present in an area where the public may come into contact with the materials over time, the potential for skin irritation is low.

Materials used for drainage, at depth, would not be accessible to the public for direct contact exposures.

4.3 Leaching

4.3.1 pH of leachate

To enable an assessment of the pH of leachate from crushed concrete it is first necessary to consider concrete production. Concrete is formed from a mixture of cement (or Portland cement), sand, coarser aggregates and water. The sand and aggregate, unless recycled materials themselves, tend to be relatively inert both physically and chemically (Jefferis 2019). The raw materials for cement production are a siliceous material such as clay or shale and a calcareous material such as limestone or chalk. These materials are fired in a kiln after which the clinker is ground, and calcium sulfate is added. This produces four principal minerals, tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite. On hydration the cements release calcium hydroxide that is strongly alkaline (with a pH of 12.6 at saturation) (Jefferis 2019).

The leachate produced from fresh concrete and recycled crushed concrete is highly alkaline. Experimental leaching tests of concrete and RCM described in literature produced high leachate pH values between pH 9 to 12, due to weathering of calcium hydroxide within the concrete material (Foy et al. 2019).

The ability of the environment to buffer the high leachate depends on a range of conditions.

Over time, concrete surfaces in contact with the atmosphere will carbonate, taking up atmospheric carbon dioxide (CO_2) during the process. During the process of carbonation, atmospheric CO_2 dissolves in water to create carbonic acid and enters pore space within the concrete. The dissolution process releases carbonate ions, which react with calcium ions to produce calcite ($CaCO_3$). The process occurs most rapidly at moderate humidity and is limited in low humidity due to a lack of water to dissolve the CO_2 and create carbonic acid and at high humidity (saturation) due to water filled pores preventing infiltration of carbonic acid. As the process requires CO_2 dissolved in water to enter pore space within the concrete, it is initiated at the surface and gradually penetrates the concrete surface with time. It is noted however that the process is limited and does not penetrate the full depth of concrete. Freshly exposed surfaces of old concrete (i.e., crushed material from demolition of old buildings and structures) therefore behaves as fresh concrete would and generates the high pH leachate. pH plumes are not considered to be an issue from mass concrete due to the relatively low surface area exposed. The difference with recycled crushed concrete is the amount of surface area available and therefore the much greater capacity for changes in pH in comparison to mass concrete (Foy et al. 2019).

Leachate pH decreases over time as recycled crushed concrete is weathered, as a result of the carbonation process. The rate at which recycled crushed concrete weathering can occur may be accelerated by exposing the material to air, as a result of the movement of atmospheric carbon dioxide through the materials (Foy et al. 2019; Jefferis 2019).

The volume of water that flows through the recycled crushed concrete also influences the pH of any leachate in the environment. The higher the water flow, the higher the dilution and the lower the pH of the leachate. In addition, it is noted that rainwater contains alkali reactive species (solutions of carbon dioxide and sulfur and nitrogen oxides from air). Reactions with these species on contact with the crushed materials would be rapid and occur at the site of initial contact, with the potential for neuralisation reducing significantly from the point of first contact (Jefferis 2019). The pH of leachate from crushed concrete materials that have been stockpiled is different to (generally lower) the pH of fresh crushed materials (Chen, J. & Brown 2012). The capacity of rainfall to neutralise the pH of recycled crushed concrete is limited particularly where large volumes of material is present.

4.3.2 Data on pH of leachate from crushed materials

To better understand the pH of leachate from materials, samples from Queensland suppliers were tested using ASLP (refer to **Section 2.3.2**) and flowthrough column tests as described in **Section 2.3.3**. All the leach tests reported pH levels in the range of 10.3 to 11.9 at the end of the tests. The flowthrough leach testing (Stage 1 and Stage 2) is considered more likely to be representative of field conditions. This testing identified that formerly stockpiled materials (BS21/328) that had been wetted and left for 72 hours resulted in the lowest level of pH in elutriate after 9 rapid water flushes and the pH during the drip feed test (Stage 2) remained lower. The pH of BS21/328 post testing was around 10.4. The other samples, in particular the stockpiled material in BS21/293 consistently reported pH in the range 10.7 to 11.5. The material tested that did not include fines (no-fines, unwashed) reported the highest pH, however the pH of these samples was observed to decrease over the tests completed.

The available data on the materials proposed to be used indicates that elevated pH in leachate or runoff is expected to occur, and requires consideration for the proposed uses.

4.3.3 Influence on metal leaching

For most metals, leaching is decreased from solid metals under alkaline conditions. This is observed in the available leachate data, where low levels of metals were detected in leachate from recycled crushed concrete samples, even under aggressive testing involved in the ASLP method. Hence the pH of the leachate from recycled crushed concrete is not considered to be a key issue in relation to the leaching of metals from the materials to the environment.

4.3.4 Use in pavement materials

Where recycled crushed concrete is used in pavement activities, the potential for water infiltration to occur, and leaching to be of importance is considered to be low. This is due to the following:

- binding of the recycled crushed concrete into new concrete would minimise the potential for high pH leachate to be generated by reducing surface area in contact with water (Foy et al. 2019)
- where the material is used under a sealed surface the potential for infiltration and leaching is negligible
- where the material is used under an unsealed but compacted surface the potential for infiltration and leaching is negligible.

4.3.5 Direct contact issues (human health)

The pH of leachate from recycled crushed concrete is a useful measure for understanding the potential for the material to influence the pH of runoff from such materials, there would not be exposure to leachate as it is measured in the laboratory. For the assessment of direct contact exposures, the pH of the runoff water is relevant and that would be lower than measured in leachate. As discussed above human skin has a significant capacity to buffer alkaline solutions, with pH up to around 10 being tolerated. pH levels in water runoff from areas where recycled crushed concrete is used is not expected to be greater than 10 (also refer to discussion below). Hence skin irritation is unlikely to be of concern.

4.3.6 Influence of soil and migration of alkaline pH in soil

Since this leachate will interact with a soil column beneath the area where it is placed (unbound and uncompacted) and groundwater, it is expected that pH will be neutralised by several factors such as soil acidity, carbonation in soil, groundwater dilution and carbonation in groundwater (Gupta 2017):

- the effect of soil acidity (in soil beneath where the recycled crushed concrete was used) was found minimal in laboratory experiments and results corroborated with the chemical modelling calculations on different soil acidities (Gupta 2017). However, blending recycled crushed concrete with soil may be a potential method to lower leachate pH. A study found that leachate pH decreased as the proportion of soil relative to recycled crushed concrete increased (Foy et al. 2019)
- effect of groundwater dilution was found to be significant (Gupta 2017). Hence there is limited evidence of pH issues relating to underlying groundwater systems
- it was observed that the leachate pH will be buffered or neutralised as a result of natural CO_2 values occurring in the soil and groundwater underneath the road base/material (Chen, Jiannan et al. 2020; Gupta 2017).

Soil has the capacity to buffer and neutralise high pH leachate. Soil with high clay content have been found to attenuate high pH leachate from road base materials. Clayey sands with CEC > 15.5 $cmol^+/kg$ have also been found to effectively attenuate high pH leachate through the dissolution of clay minerals (Chen, Jiannan et al. 2020).

The Michigan Department of Transportation (MDOT) has successfully used recycled crushed concrete as a base layer in highway pavements for several decades. However, MDOT had observed that some drainage water from roads with a recycled concrete base layer was very alkaline and created mineral deposits at drain outlets. Informal investigations showed that some drain discharge had pH levels above 10. Higher pH (>10) effluent renders the area around drainage outlets unsustainable for vegetation and aquatic life where the loss of vegetation results an associated increased risk of soil erosion (Bandara et al. 2020).

4.3.7 Potential for effects on the environment

If the pH of water is too high or too low, the organisms living within it will be adversely affected and will die. pH can also affect the solubility and toxicity of chemicals and heavy metals in the water (discussed above). The majority of aquatic creatures prefer a pH range of 6.5-9.0, though some can live in water with pH levels outside of this range.

ANZECC (ANZECC/ARMCANZ 2000) indicate that most natural freshwaters have a pH in the range 6.5 to 8, with the pH of marine waters is generally close to 8.2. The pH in water is controlled by the carbonate-bicarbonate buffer system, which is particularly strong in marine waters. Most waters have some capacity to buffer (or resist) changes in pH. This buffer capacity is often measured in terms of the alkalinity of the system. In most rivers, the buffer capacity is due, in the most part, to the presence of bicarbonate ions (HCO_3^-), contributed to the system mainly from the dissolution of rocks and soils within the catchment.

Changes to pH may affect the physiological functioning (e.g., enzymes, membrane processes) of biota. The majority of aquatic creatures prefer a pH range of 6.5-9.0, though some can live in water with pH levels outside of this range. Most effects evaluated in waters relate to lower pH conditions, where the dissolution or leaching or metals into the environment is important. Increases in pH may have effects, however are considered to be less serious (ANZECC/ARMCANZ 2000).

Figure 3: Aquatic pH levels with no effects and levels for potential effects[1]

In relation to runoff from roads where recycled crushed concrete is places, the research conducted by MDOT (Bandara et al. 2020) showed the alkalinity of leachate quickly dissipates within 100 feet (approximately 30 m) of a road drainage outlet as it likely becomes diluted and buffered by rainwater runoff. This distance is less than the buffer adopted in West Australian guidance of 100 m of any wetland/watercourse or on land subject to flooding (WA Government 2020).

The MDOT research identified that measures can be implemented to minimise the potential for alkaline runoff to be of concern to the environment (Bandara et al. 2020):

- use of materials and placement of road drainage outlets at least 30 m from receiving waters
- washing recycled crushed concrete to reduce fine particulates (which have the greatest surface area) - it is noted that the materials proposed to be used for drainage are coarse fractions of 10 mm and 20 mm with no fines, and the material specific leach testing indicates that wetting the material (not washing) is more likely to reduce pH of the leachate
- mixing recycled crushed concrete with other types of recycled aggregate
- controlling runoff from stockpiles of materials

[1] https://www.fondriest.com/environmental-measurements/parameters/water-quality/ph/

- use of bioswales/swales or bioretention trenches near the drainage outlets can mitigate problems associated with calcium-rich leachate from recycled crushed concrete bases. Bioswales can act as a filter for suspended particles and naturally reduce the high pH of the leachate
- minimise use in unsealed areas where mechanical movement would continue to crush the materials into smaller pieces exposing fresh surfaces, and where fine particulates and dust would be generated.

Most soil have a pH in the range of 3.5 – 10[2]. Natural soil pH depends on the rock from which the soil was formed (parent material) and the weathering processes that acted on it - for example climate, vegetation, topography and time. These processes tend to cause a lowering of pH (increase in acidity) over time. Some agricultural activities can also accelerate the acidification process [1]. Soil pH affects the amount of nutrients and chemicals that are soluble in soil water, and therefore the amount of nutrients available to plants. Some nutrients are more available under acid conditions while others are more available under alkaline conditions. Hence the presence of alkaline leachate may reduce the availability of some nutrients to some plant species.

Where surface soil pH is elevated as a result of leaching from recycled crushed concrete there may be the potential for some effects on terrestrial species, however this would be limited to areas where the materials are present, which is expected to be locations where plant growth is not desired.

4.4 Overview of human health and ecological risks

In relation to the pH of recycled crushed concrete the review undertaken has concluded the following:

- workers handling recycled crushed concrete (particularly fresh materials) should wear gloves and eye protection and other PPE as detailed on relevant safety data sheets for the product
- there are no risk issues of concern for the general public who may come into direct contact with residual recycled crushed concrete materials or surface water runoff
- there are no risk issues of concern for recycled crushed concrete where used in bound pavement materials
- it is not considered appropriate to use recycled crushed concrete as a surface layer for unsealed roads
- pH of the leachate would not result in any increased risk issues of concern for metals
- pH of leachate derived from recycled crushed concrete (where contact with rainfall may occur) would be buffered by soil, surface water and groundwater and the potential for adverse effects on aquatic ecosystems is considered to be low
- while no significant risks to human health or the environment have been identified, the following measures should be considered to minimise the potential for pH to impact on the offsite environment, where recycled crushed concrete may be used for drainage, the

[2] https://www.qld.gov.au/environment/land/management/soil/soil-properties/ph-levels, http://soilquality.org.au/factsheets/soil-acidity

materials to be used should have a pH of ≤9. If the pH >9 it may be used for drainage provided the material is not used in areas closer than 30 m from a receiving waterway.

Section 5. Advice and conclusions

This proposal relates to the proposed use of recycled crushed concrete in road pavements (including asphalt and concrete), as well use in drainage materials This assessment has specifically evaluated the potential for the use these materials to result in harm to human health or the environment.

Based on the available information, including analysis of recycled crushed concrete samples from suppliers in Queensland, and the proposed use of recycled crushed concrete, the following can be concluded:

- the characteristics of recycled crushed concrete are consistent specifications for the use of these materials for pavements and drainage in NSW, Western Australia and South Australia
- the characteristics of recycled crushed concrete indicate the material is not considered to be regulated waste in Queensland
- in relation to the chemical composition of recycled crushed concrete proposed to be used for pavements or drainage materials there are no risk issues of concern in relation to human health or the environment (terrestrial or aquatic). Specifically:
    - concentrations detected in recycled crushed concrete are below criteria protective of risks to human health
    - measured leachate concentrations are below drinking water guidelines
    - where relevant the concentrations reported in recycled crushed concrete are not of concern to terrestrial environments
    - concentrations detected in recycled crushed concrete are not considered to be of concern in relation to aquatic environments
- in relation to the pH of recycled crushed concrete the review undertaken has concluded the following:
    - workers handling recycled crushed concrete (particularly fresh materials) should wear gloves and eye protection and other PPE as detailed on relevant safety data sheets for the product
    - there are no risk issues of concern for the general public who may come into direct contact with residual recycled crushed concrete materials or surface water runoff
    - there are no risk issues of concern for recycled crushed concrete where used in bound pavement materials or in compacted materials beneath sealed and unsealed surfaces
    - it is not considered appropriate to use recycled crushed concrete as a surface layer for unsealed roads
    - pH of the leachate would not result in any increased risk issues of concern for metals
    - pH of leachate derived from recycled crushed concrete (where contact with rainfall may occur) would be buffered by soil, surface water and groundwater and the potential for adverse effects on aquatic ecosystems is considered to be low
    - while no significant risks to human health or the environment have been identified, the following measures should be considered to minimise the potential for pH to impact on the offsite environment, where recycled crushed concrete may be used for drainage, the materials to be used should have a pH ≤9. If the pH >9 it may be used

for drainage provided the material is not used in areas closer than 30 m from a receiving waterway.

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Appendix B Health, Safety and Environmental Risk Assessment: Reclaimed Asphalt Pavement

Reclaimed Asphalt Pavement in Road Infrastructure: Technical Review

Prepared for: Australian Road Research Board (ARRB) and Queensland Department of Transport and Main Roads

10 May 2022

EnRiskS

Document History and Status

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Limitations

Environmental Risk Sciences has prepared this report for the use of the Australian Road Research Board (ARRB) and the Queensland Department of Transport and Main Roads (TMR) in accordance with the usual care and thoroughness of the consulting profession. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report.

It is prepared in accordance with the scope of work and for the purpose outlined in the **Section 1** of this report.

The methodology adopted and sources of information used are outlined in this report. Environmental Risk Sciences has made no independent verification of this information beyond the agreed scope of works and assumes no responsibility for any inaccuracies or omissions. No indications were found that information provided for use in this assessment was false.

This report was prepared between March and May 2022. Environmental Risk Sciences disclaims responsibility for any changes that may have occurred after this time.

This report should be read in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. This report does not purport to give legal advice. Legal advice can only be given by qualified legal practitioners.

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Glossary of terms

ARRB	Australian Road Research Board
BGL	Below Ground Level
COPC	Chemical of Potential Concern
CRC CARE	CRC for Contamination Assessment and Remediation of the Environment
CSM	Conceptual Site Model
EIL	Ecological Investigation Level
ESL	Ecological Screening Level
HHRA	Human Health Risk Assessment
HIL	Health Investigation Level
HSL	Health Screening Level
IMW	Intrusive Maintenance Worker
LOR	Limit of Reporting
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NHMRC	National Health and Medical Research Council
NSW	New South Wales
PAH	Polycyclic aromatic hydrocarbon
RAP	Reclaimed asphalt pavement
SA	South Australia
SQP	Suitably Qualified Professional
TMR	Queensland Department of Transport and Main Roads
TRH	Total recoverable hydrocarbons
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WA	Western Australia
WHO	World Health Organization

Section 1. Introduction

1.1 Background

Environmental Risk Sciences Pty Ltd (enRiskS) has been engaged by the Australian Road Research Board (ARRB), on behalf of the Queensland Department of Transport and Main Roads (TMR) to undertake a technical review and provide advice in relation to the use of reclaimed asphalt pavement (RAP) in road infrastructure, specifically road embankments, drainage and road pavement.

The proposed use of RAP in road infrastructure is part of a broader framework being considered in Queensland in relation to the use of recycled materials.

The focus of this review relates to the nature and characteristics of the RAP, use in road infrastructure (specifically embankments and pavements) and exposures that may occur for workers, community or the environment.

1.2 Objectives and scope of works

The objectives of the review undertaken and presented in this report are to determine if the proposed use of RAP in embankments and road pavements:

- has the potential cause impacts to human health
- has the potential cause impacts to the environment
- require any additional management measures for the use of the material.

ARRB has collected additional data to assist in characterising RAP that may be used.

This review has not provided an assessment of the engineering requirements or specifications relevant to the use of RAP as proposed. The focus of this review relates to the potential for harm to human health and the environment.

It is noted that this assessment has only considered the use of RAP in road infrastructure, specifically for use in road corridors for fill in embankments, drainage and pavement (bound and unbound). This assessment has not considered the use of RAP in other locations.

1.3 Methodology

This review has been undertaken in accordance with the following legislation and guidance (and associated references as relevant):

- *Environmental Protection Act 1994* and *Environmental Protection Regulation 2019*
- *Waste Reduction and Recycling Act 2011*
- National Environmental Protection Measure (NEPM) (NEPC 1999 amended 2013d, 1999 amended 2013a, 1999 amended 2013b, 1999 amended 2013c)
- enHealth, 2012. Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards (enHealth 2012)
- Queensland – Waste Reduction and Recycling Act 2011 and Waste Reduction and Recycling Regulation 2011

- Queensland Recycled Materials Environmental Assessment framework, Draft for Consultation (2015).

1.4 Qualification of author/SQP

This report has been prepared by Dr Jackie Wright, Director of enRiskS a Suitably Qualified Professional (SQP) for the assessment of harm to human health and the environment.

Section 2. Use of reclaimed asphalt pavement

2.1 Use of recycled material in Australia

The use of RAP in road pavement has been approved and undertaken in a number of jurisdictions in Australia. The reuse of waste, or the use of recycled materials is a preferred activity to reduce the disposal of waste to landfill, consistent with the waste management hierarchy, shown below.

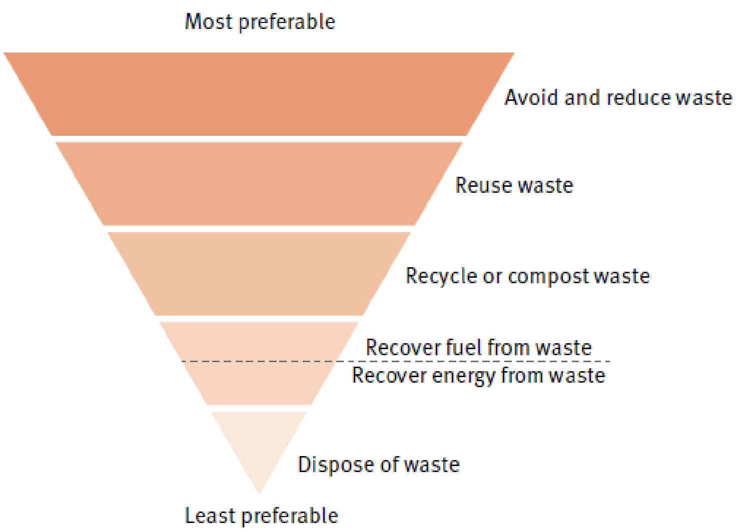


Figure 1: Waste and resource management hierarchy (Queensland Government 2019)

In NSW, the Department of Environment, Climate Change and Water (DECCW) provides a specification for the supply of recycled material for such uses (DECCW 2010). Resource Recovery Orders also apply to the use of RAP for a range of uses in NSW:

- "The recovered aggregate order 2014" and "The recovered aggregate exemption 2014" relate to the use of aggregate material comprising concrete, brick, ceramics, natural rock and asphalt for use as a road making material, or in building, landscaping or construction works. The Resource Recovery Order provides specifications for the characteristics of the materials that are suitable for reuse. In relation to RAP, this cannot contain coal tar. DECCW (2010) indicates that reclaimed asphalt blends (which do not contain coal tars) may be suitable to comprise 50% of road base, 50% of fill (particularly in roadways and beneath buildings), 20% of bedding material for paving and 5% of drainage material.
- "The reclaimed asphalt pavement order 2014" and "The reclaimed asphalt pavement exemption 2014" relate to the use of RAP for application to land for road maintenance activities, being use as a road base and sub-base, applied as a surface layer on road shoulders and unsealed roads, and use as an engineering fill an engineering material. The Resource Recovery Order and Exemption state that the RAP comprises an asphalt matrix which was previously used as an engineering material and must not contain a detectable quantity of coal tar or asbestos. No further material characteristics are defined in these documents.

In Victoria, VicRoads provides a technical note (TN 107, 2019) which indicates that the use of RAP in road pavements has been well established in Victoria since the early 2000's. No specifications in terms of chemical composition are available for RAP in these applications.

In Western Australia the Roads to Reuse document (WA Government 2020) provides specifications for recycled materials that can be used in road base, which may include RAP. The document includes concentration limits for chemicals (and pH) in a recycled road base product. Further guidance is provided in relation to the use of RAP as structural layers of asphalt pavement (WA Government 2021). This indicates tar up to 10% RAP can be incorporated into structural layers of full-depth asphalt pavements without additional mix design requirements. RAP is not permitted to be used in the wearing course (surface) asphalt for roads. RAP has been used in road projects including NorthLink 2 and NorthLink 3.

South Australia (DIT 2020; DPTI 2015) provides guidance on the use of recycled materials in road pavements. No recycled material is permitted to be included in asphalt aggregates used in road pavement. Waste Derived Fill (WDF) from Construction and Demolition Waste (C&D Waste) may include recycled bitumen. Criteria are included in this document as to what is acceptable in WDF (SA EPA 2013) which may be used for industrial purposes. The onus is on the supplier of WDF to demonstrate the material is fit for purpose and suitable for reuse, prior to transport and reuse.

The Queensland government provides an End of Waste Code for Recycled Aggregates (ENEW7604819) (Queensland Government 2021) under the Waste Reduction and Recycling Act 2011 (EoWC). This includes the use of recovered pavement material as a resource for engineering purposes in building, construction (which includes road and/or railway construction and maintenance) and/or landscaping applications. This EoWC does not provide any specifications for recycled aggregates addressed in the document, nor does the EoWC preclude the use of RAP in embankments or fill required to be used in road construction.

Queensland Transport and Main Roads (TMR), Technical Standard MRTS35, Recycled Materials for Pavements was in use from 2010 (TMR 2010) and then updated in 2021 with Technical Specification MRTS05 Unbound Pavements to provide a single specification for recycled, quarried and natural pavement materials (TMR 2021) and MRTS102 Reclaimed Asphalt Pavement Material setting out the requirements for the use of RAP in asphalt (TMR 2019).

MRTS05 permits up to 15% of Type 2 unbound materials to comprise RAP. Specifications are included for the use of recycled materials in base layers; however, it is noted that there are no restrictions on the use of recycled materials in other applications (e.g. non-trafficked shoulders, sub-cases, improved layers or subgrade treatments). There are no limits relating to chemical concentrations or pH relevant to RAP, other than noting that the RAP shall not contain tar binder and be free from contaminants such as clay, organic matter and other deleterious material.

MRTS102 provides technical specifications for RAP for use in asphalt. These specifications indicate that the RAP must be sources from asphalt and must not contain road base, concrete, coal tar, plastics, brick, timber, scrap rubber etc, and must be free from dust, clay, dirt and other deleterious matter.

TMR also provides technical specifications for the use of aggregate materials from a registered quarry. Where RAP may be used, specifications relevant to unbound pavements (MRTS05) apply (also refer to **Section 2.1**). The definition of RAP is "*asphalt that has been milled or excavated from existing pavements, or unused asphalt returning from jobsites. RAP used in unbound pavement material may also contain a small proportion of other materials (such as granular material or subgrade) that s picked up during milling or excavation*". This specification permits up to 45% of Type 2 unbound materials to comprise RAP. The specifications for these materials relate to material and engineering characteristics, not chemical composition.

Austroads provides guidance to the use of recycled materials in pavements (Austroads 2009 updated 2018). This includes the use of RAP in a bound base course and sub-base for intermediate layers in deep lift asphalt pavements, full depth bisemous residential streets, cycle paths and industrial surfacing. This document indicates that inclusion of up to 20% RAP in hot mix asphalt has little impact on the properties of the asphalt mix. The practical limit for RAP in hot mix asphalt is considered to be 40% to 50%. This document provides some guidelines on the characteristics of recycled materials used in pavements, but does not provide guidance on the use of RAP in fill materials. Concentrations of metals and organics in these materials are required to be below relevant values from the contaminated land NEPM, noting that the guidance also states that authorities should develop their own policy documents for the use of recycled materials in consultation with state EPAs.

Based on uses of RAP in other jurisdictions, **Table 1** presents a summary of the contaminant characteristics required to be met for the use of RAP in pavements.

While some specifications include a wider range of chemicals, in general the concentrations adopted for key metals are similar across these jurisdictions. Guidelines from NSW, WA and SA include values for petroleum hydrocarbons, along with some additional metals and inorganics. The SA guidelines include values for a range of other organics.

Table 1: Summary of contaminant concentrations relevant for the use of recycled crushed concrete in Australia

Chemical or attribute	NSW (Resource Recovery Order) – Pavement and drainage*		WA (Roads to Reuse) – road base and drainage rock**			SA, Waste Fill (DIT)
	Maximum average concentration for characterisation (mg/kg)	Absolute maximum concentration (mg/kg)	Recycled drainage materials (pH 6-9) (mg/kg)	Road base under asphalt (pH > 9) (mg/kg)		Maximum (mg/kg)
				Maximum average	Absolute maximum	
Mercury	0.5	1	1	0.5	1	1
Cadmium	0.5	1.5	1	0.5	1.5	3
Lead	75	150	200	75	150	300
Arsenic	20	40	20	20	40	20
Chromium (total)	60	120	75	60	120	400 Cr III 1 Cr VI
Copper	60	150	100	60	150	60
Nickel	40	80	60	40	80	60
Zinc	200	350	200	200	350	200
Antimony	--	--	--	10	20	NA
Barium	--	--	--	--	--	300
Beryllium	--	--	--	--	--	20
Cobalt	--	--	--	--	--	170
Manganese	--	--	--	--	--	500
Molybdenum	--	--	--	40	80	--
Selenium	--	--	--	2	4	--
Vanadium	--	--	--	25	50	--
Electrical conductivity	1.5 dS/m	3 dS/m	--	--	--	--
Benzene	--	--	1	--	--	1
Toluene	--	--	50	--	--	1.4
Ethylbenzene	--	--	100	--	--	3.1
Xylenes (total)	--	--	180	--	--	14
TRH C6-C10	--	--	100	--	--	65 (C6-C9)
TRH C10-C36	--	--	420	--	--	1000 (>C9)
PAHs	--	--	40	--	--	2
Aldrin/dieldrin	--	--	--	--	--	2
Chlordane	--	--	--	--	--	2
Cyanides	--	--	--	--	--	500
DDT	--	--	--	--	--	2
Heptachlor	--	--	--	--	--	2

Chemical or attribute	NSW (Resource Recovery Order) – Pavement and drainage*		WA (Roads to Reuse) – road base and drainage rock**			SA, Waste Fill (DIT)
	Maximum average concentration for characterisation (mg/kg)	Absolute maximum concentration (mg/kg)	Recycled drainage materials (pH 6-9) (mg/kg)	Road base under asphalt (pH > 9) (mg/kg)		Maximum (mg/kg)
				Maximum average	Absolute maximum	
Phenolic compounds	--	--	--	--	--	0.5
pH	--	--	6 to 9	>9	>9	
Asbestos	0%	0%	Refer to guideline (WA Government 2020)			0%

* NSW Resource Recovery Order also includes criteria for the presence of metals, plaster and other materials (rubber, plastic, paper, cloth, paint, wood and other vegetable matter) in the recycled aggregate material to be used

** Recycled road base cannot be used within the following locations within public drinking water source areas: Priority 1 (P1) areas; wellhead protection zones, reservoir protection zones.

2.2 RAP as waste

Queensland has established guidelines relevant to the classification of regulated waste (DES 2019), as shown in **Table 2** for the chemicals detected in RAP. These should also be considered in the evaluation of potential issues associated with the use of RAP.

Table 2: Queensland waste guidelines

Chemicals and other attributes	Waste guidelines in QLD – Not regulated (mg/kg)
Mercury	<80
Cadmium	<90
Lead	<300
Arsenic	<300
Barium	<4,500
Boron	<20,000
Chromium (total)	<300 (Cr VI)
Copper	<220
Molybdenum	<117
Nickel	<1,200
Vanadium	<117
Zinc	<400
Aldrin and dieldrin	<10
Organochlorine pesticides (total)	<50
Organophosphate pesticides (total)	<250
Benzene	<5
Toluene	<1,470
Ethylbenzene	<17
Xylenes	<174
Petroleum hydrocarbons C6-C9	<950
Petroleum hydrocarbons C10-C36	<5,300
PAHs	<300
Phenols (total)	<400,000

Refer to *Environmental Protection Regulation 2019*, Table 2 for guidelines relevant to other chemicals

It is noted that the reuse criteria for RAP from NSW, WA and SA (presented in **Table 1**) are lower than the Queensland guidelines relevant to determining regulated waste (noting that the guideline for xylenes is essentially the same in WA). Hence materials that met the WA or SA guidelines for reuse would not be classified as regulated waste in Queensland.

Section 3. Characteristics of RAP

3.1 General

Where RAP may be used in fill and pavements, it is relevant to consider the characteristics of the traditional materials used for these purposes.

Mineral aggregate and asphalt binder represent the two primary components of RAP, and each of these contributes to trace chemical concentrations. In addition, small amounts of other chemicals in RAP result from external sources, including road sealants, traffic markings, vehicle emissions, and wear of vehicle components. The two classes of chemicals most commonly investigated in asphalt and RAP studies are metals and polycyclic aromatic hydrocarbons (PAHs) (mainly due to the former use of coal tars in bitumen) (Spreadbury et al. 2021).

Asphalt binder (bitumen) is a petroleum product processed from crude oil and contains an assortment of hydrocarbons, including trace amounts of PAHs. Different asphalt binders exhibit a diverse suite of trace constituents depending on the petroleum source and manufacturing conditions. Asphalt mix designs may also incorporate additives, including softeners, rejuvenators, and emulsifiers, to provide desired binder and mixture characteristics to meet design climate and traffic conditions for longevity and for production technologies, such as cold/warm-mix asphalt (Spreadbury et al. 2021).

Aggregates, which dominate the mass of asphalt paving materials, can be sourced directly from mining operations or recycled materials/products. Where recycled materials are not used, these materials would be derived from natural quarried materials. The characteristics of these materials would depend on the source location as naturally occurring elements vary in different geological areas.

No data is available specific to the analysis of asphalt binder or aggregates that would be used in Queensland.

However, data is available from a range of published studies. These predominantly relate to the presence of metals and PAHs in the RAP, as well as evaluation of the potential for metals and PAHs to leach from RAP. The review presented by Spreadbury et al (Spreadbury et al. 2021) provides a summary of data relevant to RAP, with comparison against data from traditional asphalts and aggregates used in pavements. As noted above the source of these materials is not the same, hence variation in the presence and concentration of metals and PAHs in these studies is expected. This study found the following:

- Overall, concentrations of metals reported in RAP and traditional materials are reported within similar ranges. Concentrations of lead may be elevated in RAP from older roadways influenced by historic use of leaded petrol. In general concentrations of metals were higher in weathered asphalt samples, compared with unweathered materials, however the variability in aggregate source cannot be ruled out as the basis for the observed differences.
- In relation to PAHs in RAP, higher levels of PAHs were reported in materials derived from older pavements and weathered materials, noting that oxidation of asphalt binders (to form PAHs) was faster and occurred to a greater extent at smaller particle sizes. It is noted that many of the studies reviewed included coal-tar based sealants have been more widely used in the US and Europe. This is not the case in Australia.

- In relation to leaching studies, the results from these are variable as the test methods differ in different studies. Most of the studies relate to laboratory-based batch or column leach tests. Data relating to the measurement of runoff or leaching from RAP stockpiles or materials reused in pavements is very limited. Higher levels of leaching were found in acidic leach tests such as TCLP (as would be expected).
- Many of the studies did not detect PAHs in leachate, however some metals were detected, particularly lead (from former use of leaded petrol), barium (from lubrication additives and crankcase oil) and chromium (from crankcase oil). Where PAHs were detected in leachate, these were primary from studies undertaken on materials in Europe, where the coal-tar based materials may be present. Review of leaching from asphalt road surfaces by the WHO did not detect PAHs in road runoff (WHO 2004).
- External contributions (brake pad dust, tire dust, vehicle leakage, fuels) are likely to be a dominant source of trace chemicals, as asphalt binder or newly prepared asphalt pavement has been observed to leach less than some reported RAP samples studied. The variability in the trace chemicals may also reflect the variability in source materials and additives used in different locations/quarries and jurisdictions. While the potential for leaching is low, RAP from older pavements has leached constituents to a greater extent than newer RAP (likely due to a higher proportion of external contaminants from road use).
- Conventionally used aggregates and binders have reported the leaching of some metals and PAHs in concentrations similar to RAP.
- The study considered potential risks to drinking water supplies (groundwater) and determined that leching from RAP is unlikely to contaminate underlying or adjacent water supplies. Hence it is unlikely that leaching of metals and PAHs from asphalt (including RAP) requires further assessment.

Given the variability in the data, particularly as a result of the nature of the source materials used in aggregate and binders, it is important to consider data relevant to RAP expected to be utilised in pavement materials in Queensland.

3.2 Data from suppliers in Queensland

TMR submitted three samples of RAP provided by Queensland suppliers for detailed chemical analysis. The analysis included the following:

- total recoverable hydrocarbons (TRH)
- volatile organics
- organochlorine pesticides (OCPs)
- organophosphorous pesticides (OPPs)
- polychlorinated biphenyls (PCBs)
- acid herbicides
- semivolatile organics (which include PAHs)
- cyanide, fluorine, pH
- metals (antimony, arsenic, barium, beryllium, boron, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, silver, vanadium, zinc)
- dioxins and furans
- polybrominated diphenyl ethers (PBDEs)

The analysis undertaken covered a large range of chemicals which may be present as a result of the long-term use of asphalt pavement materials.

3.3 Review of available data

Table 3 presents a summary of the concentrations detected in the RAP analysed. The table presents the data for each sample analysed. The only chemicals detected in the analysis of these samples are selected metals, TRH (which is expected given the asphalt nature of the samples) and minor detections of dioxins and furans. It is noted that PAHs were note detected in any of the RAP samples analysed.

Guidelines are available for the use of RAP and the identification of regulated waste in Queensland (refer to **Tables 1 and 2**). The maximum concentrations reported in the RAP samples analysed have been compared against these guidelines in **Table 4**.

Table 3: Chemicals detected in RAP

Chemical detected	Concentration reported in each sample analysed (mg/kg)		
	BS21/736	S01	S02
TRH F2 (>C10-C16 minus naphthalene)	<500	<500	53
TRH F3 (>C16-C34)	1200	1200	1600
TRH F4 (>C34-C40)	1800	1400	1300
TRH C10-C40	3000	2600	2953
Arsenic	11	5.6	7.8
Barium	37	200	120
Copper	23	87	67
Lead	5	6.7	7
Nickel	18	30	27
Vanadium	47	58	52
Zinc	42	47	44
pH	9.4	8.7	8.5
Dioxins and furans (WHO_{05} TEQ upper bound)	2.4 pg/g	2.6 pg/g	1.6 pg/g

Table 4: Comparison of RAP results with available specifications and regulated waste guidelines

Chemical detected	Maximum concentration reported from samples analysed (mg/kg)	Specifications for use of RAP (WA and SA) as maximum (mg/kg)	Waste guidelines in QLD – Not regulated (mg/kg)
TRH F2 (>C10-C16 minus naphthalene)	53 to <500	--	--
TRH F3 (>C16-C34)	1600	--	--
TRH F4 (>C34-C40)	1800	--	--
TRH C10-C40	3000	420 to 1000	<5,300
Arsenic	11	20	<300
Barium	200	--	<4,500
Copper	87	100	<220
Lead	7	200	<300
Nickel	30	60	<1,200
Vanadium	58	--	<117
Zinc	47	200	<400
pH	9.4	6 to 9	6.5 to 9
Dioxins and furans (WHO_{05} TEQ upper bound)	2.6 pg/g	--	--

Review of the **Tables 3 and 4** indicates that that the concentration of TRH C10-C40 exceeds guidelines for the use of RAP in Western Australia and South Australia. There are no guidelines specific to the presence of TRH in RAP in other jurisdictions. Further review of the concentrations reported is included in **Section 4**.

In relation to pH, the maximum reported pH exceeds the range relevant to the use of RAP in South Australia and Western Australia, as well as the Queensland Waste Guidelines. However, results of the other two samples are within the range relevant to these guidelines. The variability in pH is expected to reflect the materials present in the pavement material. Further review of the concentrations reported is included in **Section 4**.

Section 4. Assessment of risks to human health and the environment

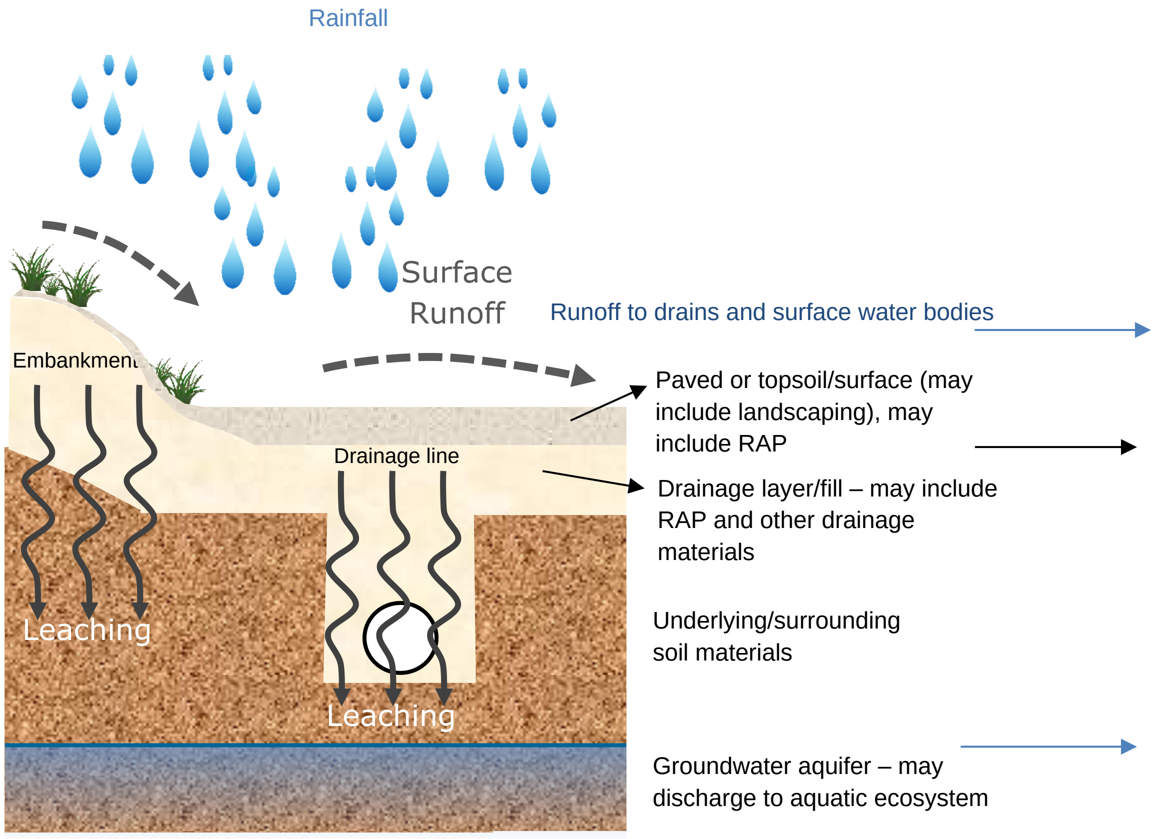
4.1 Potential for exposure

The focus of this review relates to consideration of potential risks to human health and the environment in relation to the use of RAP in fill/embankment materials, drainage and pavement materials.

In relation to the potential for exposure, the **Figures 1 and 2** provide diagrammatic conceptual site models relevant to the proposed use of this material in embankments and drainage materials and pavements. The figures include the mechanisms for contaminants to migrate from the materials (as proposed to be used) and the potential for exposure where human health and ecological risks may require further consideration.

Where RAP is blended with other aggregates and asphalt binders for use in pavements it is not expected that the inclusion of RAP would significantly change the chemical characteristics of the materials.

For the purpose of this assessment the characteristics of RAP as presented in **Tables 3 and 4** have been considered. The pH of the material is also considered.

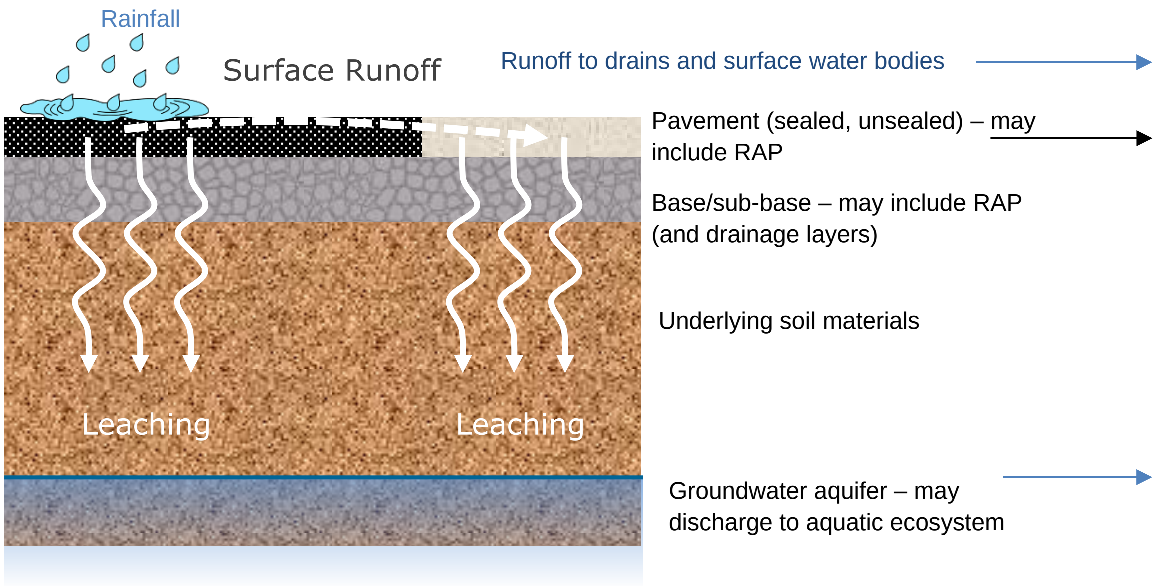


Human health	Ecological
Direct contact* with surface water or recreational use	Aquatic environments in surface water body
Direct contact* with materials at ground surface, or during maintenance works	Terrestrial environments in road corridor

Groundwater extraction and use for potable and non-potable uses	Aquatic environments where groundwater discharges
Direct contact* with water	

* Direct contact includes ingestion and dermal absorption

Figure 1: Conceptual model – use of RAP in embankment and drainage materials



Human health	Ecological
Direct contact* with surface water - Drinking water or recreational	Aquatic environments in surface water
Direct contact* with materials	Terrestrial environments
Groundwater extraction and use Direct contact* with water Drinking water or recreational	Aquatic environments where groundwater discharges

* Direct contact includes ingestion and dermal absorption

Note that where RAP is used in pavement application, the materials would be compacted resulting in a very limited potential for water to penetrate the materials and the leaching to be significant. This is further discussed in **Sections 4.3.2 and 4.3.3**.

Figure 2: Conceptual model – use of RAP in pavement materials

4.2 Assessment of human health issues

4.2.1 Potential for exposure

In relation to potential risks to human health the pathways of exposure relevant to the use of RAP as proposed involve the following:

- Direct contact with RAP in road corridors, where these materials are in an area accessible to workers and residents who may live directly adjacent to the locations where these materials may be used. This exposure relates to direct contact with chemicals that may be present in surface materials. Where materials are bound in asphalt, used at depth, placed beneath sealed surfaces there is no potential for direct contact with the materials to occur.
- Direct contact with chemicals that may have leached from RAP as proposed to be used that may directly runoff to surface water, where this water may be accessed for recreational uses or extracted for drinking water.
- Direct contact with chemicals that may have leached from the RAP as proposed to be used, migrate to groundwater and groundwater is extracted and used for drinking water. Groundwater may also discharge to surface water where exposures via recreational use or drinking water may occur.

4.2.2 Direct contact with RAP materials

To assess the potential for the above exposures to be of concern, the maximum concentrations reported in RAP have been directly compared with guidelines that are based on the protection of human health for exposures by commercial/industrial workers and residents. These guidelines are available from the ASC NEPM (NEPC 1999 amended 2013d) and are protective of the following exposures, which are highly conservative in relation to likely exposures that may occur in areas where material is proposed to be used:

- Commercial/industrial workers – ingestion of soil and dust, dermal absorption of chemicals from contact with soil and dust and inhalation of dust, 8 hours per day for 240 days of the year for 30 years.
- Residents – ingestion of soil and dust, dermal absorption of chemicals from contact with soil and dust, inhalation of dust, ingestion of homegrown fruit and vegetables grown in soil (10% of intakes are from home produce).

Where guidelines are not available from the NEPM, they have been derived from CRC CARE (CRC CARE 2011) in relation to direct contact exposures with TRH, and the USEPA Regional Screening Levels (RSLs) for residential and industrial soil – which are derived on a similar basis as the NEPM guidelines.

Table 5 presents a comparison of the maximum concentrations reported against these health-based guidelines.

Table 5: Review of concentrations reported in RAP – Human health

Chemical detected	Maximum concentration reported from samples analysed (mg/kg)	Guidelines protective of human health (mg/kg)	
		Commercial/ industrial workers [N] (HIL-D)	Residents [N] (HIL-A)
TRH F2 (>C10-C16 minus naphthalene) *	53 to <500	20,000 [C]	3,300 [C]
TRH F3 (>C16-C34)	1600	27,000 [C]	4,500 [C]
TRH F4 (>C34-C40)	1800	38,000 [C]	6,300 [C]
TRH C10-C40*	3000	62,00 to 120,000 [C]	3,300 to 6,300 [C]
Arsenic	11	300	100
Barium	200	220,000 [U]	15,000 [U]
Copper	87	240,000	6,000
Lead	7	1,500	300
Nickel	30	6,000	400
Vanadium	58	5,800 [U]	390 [U]
Zinc	47	400,000	7,400
Dioxins and furans (WHO_{05} TEQ upper bound)	2.6 pg/g	220 pg/g [U]	50 pg/g [U]

* It is noted that TRH F2 (>C10-C16) is also considered to be volatile where there may be the potential for the inhalation of volatile TRH in air. For the proposed use of RAP, this would only be in outdoor areas where the NEPM (NEPC 1999 amended 2013d) indicates that the guideline protective of inhalation exposures in outdoor air is not limiting – this means that the saturated vapour concentration is lower than the vapour concentration that would result in unacceptable risks. Hence there are no vapour inhalation risk issues of concern for use of these materials outdoors, and the guidelines adopted relate to direct contact exposures only.

N = Health based guidelines as listed in the NEPM (NEPC 1999 amended 2013d), unless noted otherwise

C = CRC CARE guidelines (CRC CARE 2011) based on the protection of human health for direct contact exposures, the range presented for TRH reflects the values presented for the subfractions >C10-C16, >C16-C34 and >C34-C40

U = USEPA RSLs (USEPA 2021) for industrial or residential soil – protective of human health

Review of **Table 6** indicates that all concentrations reported in RAP are well below the conservative health-based guidelines that are protective of direct contact exposures by workers and residents. These guidelines are also protective of exposures that may occur for workers involved in handling these materials.

<u>pH aspects</u>

In relation to human health, the only issues of concern relate to direct contact with soil and the potential for skin irritation. The natural pH of the surface of normal skin (the stratum corneum) is in the range 4.1 – 5.8 (95% interval with an arithmetic mean of 4.9) (Proksch 2018). The pH of skin is more neural in newborns, decreasing significantly in the first 2 months of life (Panther & Jacob 2015; Proksch 2018). Skin has a very good buffering capacity and hence direct contact and hence can resist alkaline aggression. Soap is an alkaline material (pH 9-11 approximately) which is well tolerated by people, as is direct contact with existing set concrete and asphalt surfaces (Proksch 2018). The buffer capacity is reduced by repeated insults, for example, by washing out the buffer components with regular use of water and detergent. A low buffer capacity of the skin (and hence increased sensitivity to products such as soap and detergents) is reported for babies, aged individuals and diseased skin (Proksch 2018).

Any contact with RAP, where used in embankment materials or pavements, would be expected to be negligible, or at most minimal and of short duration. Hence direct contact with RAP with may have pH in the range of 8 to 10 (refer to **Table 3**) would not be considered to be of concern.

4.3 Assessment of ecological issues

4.3.1 Potential for exposure

In relation to the potential for ecological impacts related to the proposed use of RAP the following issues are of relevance:

- Terrestrial ecosystems:
  - Pavement materials are used for roads where the growth of plants is not desired. In the case of asphalt sealed surfaces/pavements, these materials would be compacted and would preclude the growth of plants, regardless of the inclusion of RAP in this material.
  - Where RAP is used in unsealed pavements, the growth of plants would be prevented. Hence the focus of this review relates to the potential for harm in areas located adjacent to the pavement or roadway where the materials may be used.
  - For the use in drainage lines or embankment materials, where the RAP is placed at depth there is limited potential for contact with terrestrial environments. However, where RAP is accessible at the surface, some terrestrial environments may be present that require consideration.
- Aquatic ecosystems – This is of relevance where chemicals present in RAP leach and may impact on surface water quality and/or groundwater quality, and groundwater discharges to an aquatic environment (refer to **Sections 4.3.3 and 4.4**).

4.3.2 Terrestrial ecosystems

In relation to potential impacts on adjacent terrestrial ecosystems, this would only relate to the presence of the materials that may extend beyond the road or pavement, or where present at ground surface in an embankment along a road corridor. Where the RAP is bound in asphalt or concrete or used in pavements and compacted then there is no potential for ecological exposures and therefore no risk.

To assess the potential for RAP to be of concern to terrestrial ecosystems, maximum concentrations reported in the RAP samples analysed have been compared with published ecological investigation levels (EILs), as presented in **Table 7**. The level of protection relevant to terrestrial ecosystems adjacent to roadways (including in embankment materials) or paved areas is consistent with that adopted in the NEPM for commercial/industrial land use. This relates to 60% species protection and is expected to be conservative for areas where RAP may be present (unbound) in soil.

Soil EILs from the NEPM (NEPC 1999 amended 2013d) have been adopted in this assessment. Where EILs are not available, guidelines available from CCME or RIVM, protective of industrial soil have been adopted, where available. In the absence of guidelines for industrial soil (or equivalent level of species protection), residential/agricultural criteria have been adopted. The NEPM EILs have been derived to also considered potential leaching and impacts on groundwater and aquatic ecosystems.

Table 7: Review RAP concentrations – Terrestrial ecosystems

Chemical detected	Maximum concentration reported from samples analysed (mg/kg)	Guidelines protective of ecological health (mg/kg)
TRH F2 (>C10-C16 minus naphthalene)	53 to <500	170 ES
TRH F3 (>C16-C34)	1600	1,700 to 2,500 ES
TRH F4 (>C34-C40)	1800	3,300 to 6,600
TRH C10-C40	3000	170 to 6,600 ES
Arsenic	11	160 E
Barium	200	500 C
Copper	87	150 AA
Lead	7	1800 E
Nickel	30	60 AA
Vanadium	58	130 C
Zinc	47	440 AA
Dioxins and furans (WHO_{05} TEQ upper bound)	2.6 pg/g	220 pg/g UX

NEPM ecological guidelines
E = EIL
A = Added contaminant level (ACL) with the EIL based on background from QLD (low traffic volumes) + ACL calculated for CEC = 5 cmolc/kg, pH = 9, iron content = 5%, clay content = 1%
A = Aged contamination guideline (relevant to RAP)
ES = Ecological Screening Level for petroleum hydrocarbons
C = CCME guideline protective of residential soil (ecological)
R = RIVM intervention screening level for soil
UX = USEPA RSL for commercial/industrial soil adopted in the absence of a terrestrial guideline. Review of the available data indicates that guidelines that are protective of human health would also be protective of terrestrial health.

Review of **Table 7** indicates there are no exceedances of the screening level guidelines adopted for the protection of terrestrial ecosystems, as relevant to areas close to roadways, including embankments in road corridors, and pavements where RAP may be used.

pH aspects

Based on the data presented in **Table 3**, the pH of the RAP is expected to be in the range of 8 to 10. This is consistent with the range of pH for RAP materials reported in the literature (Hoppe et al. 2015).

Where these materials are bound in new pavement the pH of the RAP used in these materials is not expected to be relevant.

Where unbound RAP may be present, including where used in embankment materials, it is expected that the buffering capacity of soil in the area where the materials are utilised would address the elevated pH such that it would not be of concern to terrestrial species in areas located adjacent to or away from the area where the RAP would be used.

Should the pH of RAP be more elevated, at 11 or higher, this may result in impacts on terrestrial species, or aquatic species in the immediate vicinity (within 30 m) of location where RAP may be used (particular in drainage materials) (Bandara et al. 2020).

4.3.3 Aquatic ecosystems

It is noted that the EILs and ESLs have been derived to also consider potential leaching and migration to groundwater (and protection of aquatic ecosystems). The potential for leaching to be of concern to any aquatic environment has also been further reviewed in **Section 4.4**.

4.4 Further review of potential risk issues

Where any material is used for paving (including concrete and asphalt) it will be compacted or bound such that the potential for water to penetrate/infiltrate the materials and for leachate to be present in runoff or infiltration water is very low.

Where the material may be used in an area where drainage may occur (including in embankments), there is the potential for metals (and other contaminants if present) to leach and migrate to groundwater or surface water (where humans and aquatic ecosystems may be exposed).

This transport mechanism is not considered to be of concern where the characteristics of the materials used are consistent with what is considered to be clean fill or natural (or uncontaminated) materials. This is particularly relevant as metals (and inorganics) are naturally occurring within soil and rock, and hence there are concentrations that would be expected in materials such as soil, gravel, sand and crushed rock (including aggregate) that are commonly used for in pavements that are considered to be representative of naturally occurring materials. It is noted that the concept of naturally occurring requires consideration as there are numerous areas where mineralised rock/soil is present that may pose a risk to health and the environment. Hence some Australian jurisdictions have specifically defined the concentrations that are considered to be to be naturally occurring or clean fill, which typically excluded naturally mineralised areas.

Where the RAP comprises characteristics consistent with clean fill or natural materials, the material is considered to be consistent with the characteristics of existing materials commonly used in roads and pavements, and of no concern to human health or the environment.

The clearest definitions of clean fill or natural materials are from Victoria, NSW and South Australia.

- EPA Victoria (EPA Victoria 2021) provides a definition of fill materials, commonly referred to as clean fill criteria. This provides concentrations of contaminants, below which are considered to not be contaminated and therefore not of concern to human health or the environment. The guidance also provides for review of the history of the material to determine if concentrations of metals above these criteria are derived from natural origins (where the material would not be considered contaminated). There is no requirement to test for leaching in relation to these materials.
- The NSW EPA provides criteria used to define excavated natural material (ENM) (NSW EPA 2014). This order provides the requirements that must be met by suppliers of excavated natural materials for use in fill or earthworks. The order provides characteristics of the material as a maximum average and absolute maximum concentrations. These criteria are considered to define clean fill in NSW and the material that complies with the ENM criteria is not considered to be contaminated and does not pose a risk to human health or the environment. Leach testing is not required for these materials.
- South Australia provides a standard for waste derived fill (SA EPA 2013). This standard provides the maximum concentrations of chemical substances that would meet the waste fill

criteria. Concentrations in excess of the waste fill criteria require further assessment including consideration of leaching to the environment (noting that the standard also provides Intermediate Waste Criteria). The waste fill criteria relate to concentration of chemicals only. There is no requirement for leach testing of these materials.

It is acknowledged that the criteria established, as noted above, relate to soil (being clay, silt and/or sand), gravel and rock of naturally occurring materials. The South Australian standard allows for the inclusion of other inert mineralogical matter. These criteria are consistent with the characteristics of other natural materials commonly used in road applications, and if the characteristics of RAP has the potential to be of concern to the human health or the environment, when used in the same way as these other materials.

Queensland does not have a guideline on concentrations that comprise clean fill or natural (uncontaminated) materials. Schedule 19 of the *Environmental Protection Regulation 2019* defines "*clean earth*" as "*any natural substance found in the earth that is not contaminated with waste or a hazardous contaminant*". There are no criteria established in Queensland as to the concentrations of metals in these materials that is considered to be natural or uncontaminated.

Further assessment of soil (and rock) concentrations in Queensland that would be considered to be representative of natural background materials (precluding naturally mineralised areas) has been undertaken by Easterly Point Environmental (Salmon 2017). This review has considered the available data on background or natural soil concentrations in Queensland, along with guidance provided in the NEPM (NEPC 1999 amended 2013c, 1999 amended 2013d) to determine residual soil levels, which would be considered suitable for any use and are not considered to be of concern to human health or the environment.

Table 8 provides a review of the maximum concentrations reported in RAP against the available guidance from Victoria, NSW and SA in relation to the characteristics of natural materials or clean fill (i.e. uncontaminated material). The proposed residual soil levels for Queensland are also presented.

Table 8: Review of concentrations detected in RAP against criteria for natural materials or clean fill

Analyte detected in RAP samples	**Maximum concentration reported from samples analysed (mg/kg)**	**Criteria available for defining clean fill or natural materials** (not considered contaminated and not of concern to health or the environment) (mg/kg)				
		EPA Victoria – Clean fill	**NSW EPA – Excavated Natural Material (ENM)**		**SA EPA – Waste derived fill**	**Queensland – suggested residual soil levels (based on background levels)**
			Maximum average	**Absolute maximum**		
TRH C10-C40*	3000	1000	250	500	1000	--
Arsenic	11	20	20	40	20	50
Barium	200	--	--	--	300	--
Copper	87	100	100	200	60	200
Lead	7	300	50	100	300	60
Nickel	30	60	30	60	60	60
Vanadium	58	--	--	--	--	--
Zinc	47	200	150	300	200	400
Dioxins and furans (WHO_{05} TEQ upper bound)	2.6 pg/g	NA	NA	NA	NA	1 to 9.2 pg/g [1]
pH	9.4	--	5 to 9	4.5 to 10	--	--

Notes

1 – No background levels of dioxins and furans are recommended by Salmon 92017), however data reported in the National Dioxins Program (DEH 2004) included analysis of dioxins and furans in soil in various areas in Australia. In Queensland background levels of dioxins and furans were in the range 1 to 9.2 pg/g for urban soil and 0.56 to 10 pg/g for industrial soil. The range reported in the table relates to urban soil.

Review of **Table 8** indicates that with the exception of TRH, the maximum concentrations reported in RAP would be considered consistent with naturally occurring materials or clean fill.

In relation to TRH, this is expected to be elevated as RAP is derived from asphalt materials. The TRH reported in RAP is not expected to be different to that of asphalt. It is expected that the TRH present in RAP would be expected to be lower and of different composition to fresh asphalt, with older materials in RAP more likely to include weathered TRH comprising polar compounds and less petroleum TRH. PAHs were not detected in RAP, hence the TRH reported would not comprise any PAHs.

Asphalt is a mix of bitumen and aggregate. Bitumen is derived from petroleum oil and is a complex mixture of petroleum hydrocarbons (predominantly in the range C25+) (CONCAWE 1992; Franken et al. 1999). The exact chemical composition of asphalt is dependent on the chemical complexity of the original crude petroleum and the manufacturing process. Crude petroleum consists mainly of aliphatic compounds, cyclic alkanes, aromatic hydrocarbons, polycyclic aromatic compounds (PACs), and metals (e.g., iron, nickel, and vanadium). When petroleum hydrocarbons weather in the environment (as would be the case for heavy end hydrocarbons present in bitumen and asphalt) a range of polar metabolites are produced which are also present in the TRH analysis. These polar compounds are less toxic than the petroleum hydrocarbon compounds (CRC CARE 2013). Hence it is likely that TRH detected in RAP may reflect lower concentrations of petroleum hydrocarbons compounds and the presence of less toxic polar compounds. On this basis, the TRH detected is not expected to be of concern in relation to the environment where present in a road corridor, as used in pavements or embankments. Further TRH is not considered to be a useful measure or indicator of petroleum hydrocarbon contamination (Roinas 2015) for such materials where the characteristics of TRH reported may reflect natural organic matter and/or polar metabolites from the weathering of these materials. Aesthetically, the presence of RAP in embankments would be expected to be noticeable, which should be considered when utilising the materials in areas where the public may access and view embankments.

In addition to the above, review of RAP by the Virginia Department of Transport (VDOT)[1] and the US National Asphalt Pavement Association (NAPA)[2], where leaching of chemicals from RAP was considered, determined that RAP can be used as "clean fill" without undue environmental impacts.

4.5 Overview of human health and ecological risks

In relation to the chemical composition of RAP proposed to be used for pavements there are no risk issues of concern in relation to human health or the environment (terrestrial or aquatic).

[1] http://vtrc.virginiadot.org/rsb/RSB4.pdf

[2] https://www.asphaltpavement.org/uploads/documents/SR204-RAP_as_Clean_Fill.pdf

Section 5. Advice and conclusions

This proposal relates to the proposed use of RAP in road materials, including embankment materials, drainage lines and pavements. This assessment has specifically evaluated the potential for the use these materials to result in harm to human health or the environment. The assessment undertaken has focused on the use of RAP in road corridors only.

Based on the available information, including analysis of RAP samples from suppliers in Queensland, and the proposed use of RAP, the following can be concluded:

- No detectable concentrations of PAHs were reported in the RAP evaluated.
- Some metals were detected in RAP, however the concentrations reported are low and consistent with the characteristics expected for natural materials or clean fill, including gravel and sand commonly used in road applications, including embankments.
- The presence of TRH in RAP is expected to reflect some non-PAH hydrocarbons, but also natural organic matter and polar metabolites from the weathering of RAP.
- In addition to the above, there are no issues of concern in relation to risks to human health or the environment (terrestrial or aquatic), the use of RAP in embankment materials, drainage lines or pavement materials. This also includes stockpiled materials in road corridors.

The assessment undertaken has considered the use of 100% RAP in these applications. This is conservative for the proposed use in embankment materials, drainage and pavement materials within road corridors. Mixing of RAP with other fill or pavement materials for reuse in various road applications would not change the outcomes detailed above.

It is recommended that suppliers of RAP provide results of analysis of these materials (in relation to pH, metals, TRH and PAHs) to TMR to demonstrate the characteristics of the RAP provided remains consistent with the materials evaluated in this assessment. It is noted that RAP should not be used in drainage materials where the pH is 11 or higher.

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Appendix C Health, Safety and Environmental Risk Assessment: Coal Combustion Products

Reuse of coal combustion products in Queensland: Technical Review

Prepared for: Queensland Department of Transport and Main Roads

26 October 2022

EnRiskS

Document History and Status

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Limitations

Environmental Risk Sciences has prepared this report for the use of the Queensland Department of Transport and Main Roads (TMR) in accordance with the usual care and thoroughness of the consulting profession. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report.

It is prepared in accordance with the scope of work and for the purpose outlined in the **Section 1** of this report.

The methodology adopted and sources of information used are outlined in this report. Environmental Risk Sciences has made no independent verification of this information beyond the agreed scope of works and assumes no responsibility for any inaccuracies or omissions. No indications were found that information provided for use in this assessment was false.

This report was prepared between May and August 2022 and finalised on October 2022. Environmental Risk Sciences disclaims responsibility for any changes that may have occurred after this time.

This report should be read in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. This report does not purport to give legal advice. Legal advice can only be given by qualified legal practitioners.

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Glossary of terms

ACL	Added contaminant level
ADAA	Ash Development Association of Australia
ARRB	Australian Road Research Board
ASC NEPM	Assessment of Soil Contamination National Environment Protection Measure
CCP	Coal combustion product
CoPC	Chemical of Potential Concern
CRC CARE	CRC for Contamination Assessment and Remediation of the Environment
CSM	Conceptual Site Model
EIL	Ecological Investigation Level
EoW	End of Waste
ESL	Ecological Screening Level
GED	General environmental duty
HHRA	Human Health Risk Assessment
HIL	Health Investigation Level
HSL	Health Screening Level
LOR	Limit of reporting
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NHMRC	National Health and Medical Research Council
NSW	New South Wales
PAH	Polycyclic aromatic hydrocarbon
PBDE	Polybrominated diphenyl ether
PFAS	Per- and polyfluoroalkyl substances
PNEC	Predicted no effect concentration
PPE	Personal protective equipment
RRE	Resource Recovery Exemption
RRO	Resource Recovery Order
RSL	Regional Screening Level
SA	South Australia
SDS	Safety Data Sheet
SQP	Suitably Qualified Person
SSL	Soil Screening Level
TCLP	Toxicity Characteristic Leaching Procedure
TMR	Queensland Department of Transport and Main Roads
TRH	Total recoverable hydrocarbons
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WA	Western Australia
WDF	Waste Derived Fill
WHO	World Health Organization

Section 1. Introduction

1.1 Background

Environmental Risk Sciences Pty Ltd (enRiskS) has been engaged by the Queensland Department of Transport and Main Roads (TMR) to undertake a technical review and provide advice in relation to the proposed use of coal combustion products (CCP) from coal fired power stations in Queensland in earthworks and pavements.

The proposed use of CCP in road infrastructure is part of a broader framework being considered in Queensland in relation to the use of recycled materials.

In relation to the reuse of this material, an End of Waste Code (EoW code) on CCP provides limits for a range of chemical and physical characteristics in relation to the reuse of such materials in bound and unbound applications.

For the purpose of this report, and to be consistent with the EoW code, bound applications include asphalt, binder for road pavement stabilisation, cement products, cementitious mixes, ceramic products, concrete products, geopolymers, insulators, paints, coatings and adhesives, rigid and composite pavement structures, rubbers, varnishes, plastics, ceramics, ultra-light concrete and metal alloys.

Unbound applications include pipe bedding materials, sub-surface drainage, road pavement, base, sub-base and subgrade structures, selected layers which act as working platforms at the top of earthworks and engineered construction works. For the purpose of this assessment this includes earthworks such as embankment fill material.

The EoW code includes a range of conditions where the material cannot be used.

The focus of this review relates to the nature and characteristics of CCP, derived from Queensland power stations for use in bound and unbound applications in Queensland.

1.2 Objectives and scope of works

The overall objectives of the technical review presented in this report is to provide:

- general advice on the suitability, in terms of health, safety and the environment, to use CCP as earthworks and/or pavement material for civil construction.

More specifically the technical review provides the following:

- review of historic/background data provided by industry
- review available literature on the use of CCP for earthworks and pavements
- review of the current EoW code provisions for ‘bound’ and ‘unbound’ use
- review and use of testing data for CCP proposed to be used (data provided by TMR).

This review has not provided an assessment of the engineering requirements or specifications relevant to the use of CCP as proposed. The focus of this review relates to the potential for harm to human health and the environment.

It is noted that this assessment has only considered the use of CCP in bound and unbound road infrastructure, specifically for use in road corridors for fill in embankments, drainage and pavement. This assessment has not considered the use of CCP in other locations.

1.3 Methodology

This review has been undertaken in accordance with the following legislation and guidance (and associated references as relevant):

- *Environmental Protection Act 1994* and *Environmental Protection Regulation 2019*
- *Waste Reduction and Recycling Act 2011*
- National Environmental Protection Measure (NEPM) (NEPC 1999 amended 2013a, 1999 amended 2013b, 1999 amended 2013c, 1999 amended 2013d)
- enHealth, 2012. Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risks from Environmental Hazards (enHealth 2012)
- DES 2021, End of Waste Code, Coal Combustion Products (ENEW07359717) (DES 2021)
- Queensland – Waste Reduction and Recycling Act 2011 and Waste Reduction and Recycling Regulation 2011
- Queensland Recycled Materials Environmental Assessment framework, Draft for Consultation (2015).

1.4 Qualification of author/SQP

This report has been prepared by Dr Jackie Wright, Director of enRiskS a Suitably Qualified Person (SQP) for the assessment of harm to human health and the environment.

Section 2. Reuse of coal combustion products

2.1 Reuse of coal combustion products in Australia

The reuse of materials such as CCP from coal fired power stations has been approved and undertaken in a number of jurisdictions in Australia. The reuse of waste, or the use of recycled materials is a preferred activity to reduce the disposal of waste to landfill, consistent with the waste management hierarchy, shown below.

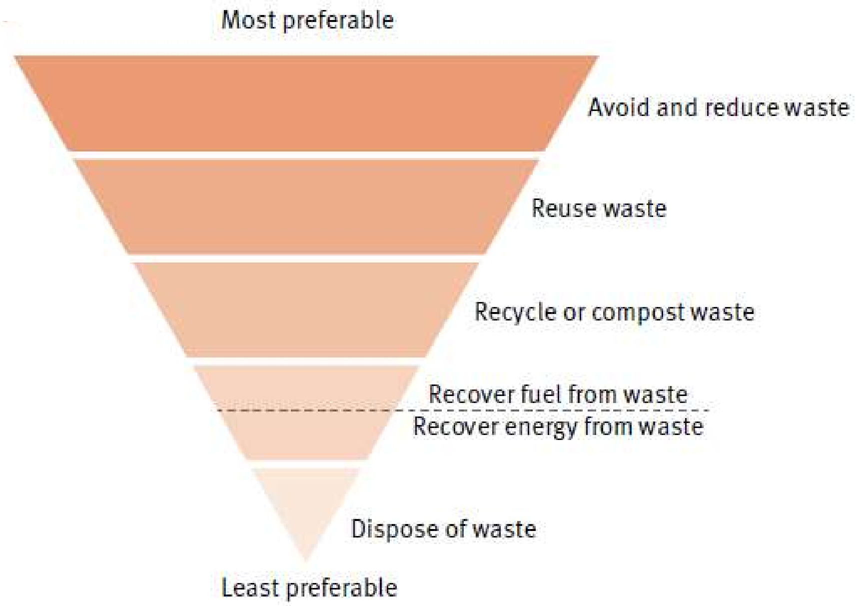


Figure 1: Waste and resource management hierarchy (Queensland Government 2019)

The reuse of ash in bound and unbound applications is permitted in NSW. The NSW EPA has established a Resource Recovery Order (RRO) and Resource Recovery Exemption (RRE) in relation to the reuse of coal ash: “The coal ash order 2014” and “The coal ash exemption 2014”. This allows for coal ash and coal ash blended with other materials to be applied to land as an engineering material. The material can be used as a soil amendment, in cement mixtures, in non-cement mixtures such as engineered fill, stabiliser, filter or drainage material or a sand substitute in a range of uses that include pipe bedding material, road pavement, base and sub-base structures, composite filler in asphalt. Non bound, or non-cementitious materials cannot be applied/used in or beneath water including groundwater. The RRO provides specifications (average and absolute maximum concentrations) for metals, electrical conductivity and pH (in non-cementitious mixes) for the reuse of such materials.

In Victoria, VicRoads provides a number of technical notes that relate to the inclusion of ash (more commonly fly ash) in cement materials. In addition, a case study was conducted by the Ash Development Association of Australia (ADAA) on the use of CCP in road base applications (including concrete and engineering fills) in Victoria. More generally, in relation to waste recycling and reuse, Publication 1825.1 (2021) outlines requirements under the *Environment Protection Act*

2017 and *Environment Protection Regulation 2021* for such activities. This legislation includes a general environmental duty (GED) to eliminate or reduce the risk of harm to people and the environment from pollution and waste.

In Western Australia the Roads to Reuse document (WA Government 2020) provides specifications for recycled materials that can be used in road base and drainage rock. The reuse materials addressed in this document does not include ash from any source. It is noted, however that fly ash is reused in concrete materials in Western Australia.

South Australia (DIT 2020; DPTI 2015) provides guidance on the use of recycled materials in road pavements. The guidance allows for the addition of fly ash to pavements (bound use), noting that fly ash is considered to be inert based on an extensive monitoring program conducted on behalf of the ADAA. Waste Derived Fill (WDF) has the potential to include mineralogically based homogeneous industrial residues. There is no specific definition of these residues that would preclude CCP, provided it met the criteria for reuse as WDF (SA EPA 2013) for industrial purposes. The onus is on the supplier of WDF to demonstrate the material is fit for purpose and suitable for reuse, prior to transport and reuse.

2.2 Queensland EoW Code

The Queensland EoW code for Coal Combustion Products (CCP) outlines when such materials can be considered to be a resource and is no longer a waste. Where the material is determined to be a resource, should it not be used in accordance with the conditions of the EoW code then it is deemed to be a waste again. Hence the conditions of use are important for compliance with the code.

The uses permitted under the EoW code are as follows:

- bound applications, limited to:
    - asphalt
    - binder for road stabilisation pavements
    - cement products
    - cementitious mixes
    - ceramic products
    - concrete products
    - geopolymers
    - insulators
    - paints, coatings and adhesives
    - rigid and composite pavements structures
    - rubbers
    - varnishes, plastics, ceramics, ultra-light concrete and metal alloys
- unbound applications on standard areas, as
    - pipe bedding materials
    - sub-surface drainage
    - road pavement, base, sub-base and subgrade structures
    - select layers which act as working platforms at the top of earthworks
    - engineered construction works (excluding filling of a void)
- The use in unbound applications must not use these materials:

  - below the groundwater table
  - within 50 m of a water supply bore
  - if the site of use (i.e. the location where the material is to be used) has pH greater than 8
  - if the resource is produced using biomass that contains, or is reasonably likely to contain, PFAS, then there are additional, more stringent, use restrictions as detailed in the code
- feedstock in the manufacture of a soil conditioner, soil product or in direct application to land (for naturally acidic soil).

For the use of unbound materials, the term "standard areas" is used. This means land that includes residential, parks, recreational playing fields, open spaces and commercial/industrial areas, excluding a facility and waters and the bed and banks of waters. "Waters" includes river, stream, lake, lagoon, pond, swamp, wetland, unconfined surface water, unconfined water, natural or artificial watercourse, bed and bank of any waters, dams, non-tidal or tidal waters (including the sea), stormwater channel, stormwater drain, roadside gutter, stormwater run-off, and groundwater and any part-thereof.

The EoW code provides limits for the reuse of these materials for various applications. These limits are listed in **Table 1**.

The EoW code also includes the general responsibilities that sit within the *Environment Protection Act 1994*, where Section 319 states there is a general environment duty. The duty relates to not conducting an activity that causes or is likely to cause environmental harm without taking all reasonable and practicable measures to prevent or minimise the harm. For the EoW code there is a requirement that the materials approved for use under the code are used in a manner that does not cause environmental harm.

It is implied that the use of CCP that complies with the limits presented in **Table 1** and complies with all other requirements of the EoW code would be meeting relevant obligations to prevent environmental harm.

Table 1: Resource quality limits – EoW code for CCP

Chemical or attribute	Total maximum concentration (mg/kg)		
	Bound applications	Unbound applications	Soil conditioner, soil product and direct land application
Arsenic	NS	20	20
Beryllium	NS	NS	60
Boron	NS	100	10
Cadmium	NS	1	1
Chromium (total)	NS	100	100
Chromium (III)	NS	NS	100
Chromium (VI)	NS	1.5	1
Cobalt	NS	100	100
Copper	NS	100	100
Lead	NS	50	50
Mercury	NS	1	10
Molybdenum	NS	NS	10
Nickel	NS	60	60
Selenium	NS	10	5
Zinc	NS	200	200
Electrical conductivity	NS	NS	10 (dS/m)
pH	NS	5 to 12.5 (pH units)	5 to 12.5 (pH units)
PFAS criteria relevant to a resource generated from the use of biosolids containing PFAS contamination			
Sum of PFOS and PFHxS	0.01	0.002	0.0002*
PFOA	0.02	0.004	0.0002*
PFOS (PFHxS not detected)	NS	0.001	0.0002*
PFHxS (PFOS not detected)	NS	0.003	0.0002*
PFBA, PFPeA, PFHxA	NS	0.001	0.0002*
Sum C9-C14 perfluoroalkyl carboxylic acids	NS	0.01	0.0002*
Perfluoroalkyl sulfonamides	NS	0.001	0.0002*
N:2 Fluorotelomer sulfonic acids	NS	0.004	0.0002*
Sum of PFAS	0.1	0.01	0.0002*

NS = not specified
* reflects the value presented or the limit of reporting (LOR), whichever is smaller

2.3 CCP as waste

In the event that the CCP is not used in accordance with the EoW code, or the materials are further removed following application, the material would be considered waste.

Queensland has established guidelines relevant to the classification of waste that is not determined to be regulated (DES 2019), as shown in **Table 2.** These should also be considered in the evaluation of potential issues associated with the long-term use of CCP.

Table 2: Queensland waste guidelines

Chemicals and other attributes	Waste guidelines in QLD – Not regulated (mg/kg)
Arsenic	<300
Barium	<4,500
Boron	<20,000
Cadmium	<90
Chromium (total)	<300 (Cr VI)
Copper	<220
Lead	<300
Mercury	<80
Molybdenum	<117
Nickel	<1,200
Vanadium	<117
Zinc	<400
Aldrin and dieldrin	<10
Organochlorine pesticides (total)	<50
Organophosphate pesticides (total)	<250
Benzene	<5
Toluene	<1,470
Ethylbenzene	<17
Xylenes	<174
Petroleum hydrocarbons C6-C9	<950
Petroleum hydrocarbons C10-C36	<5,300
PAHs	<300
Phenols (total)	<40,000

Refer to *Environmental Protection Regulation 2019*, Table 2 for guidelines relevant to other chemicals

It is noted that the criteria listed in the EoW code for CCP (**Table 1**) are lower than the Queensland guidelines relevant to determining whether waste requires regulation (noting that the guideline for xylenes is essentially the same in WA). Hence materials that met the EoW code criteria for reuse would not be classified as regulated waste in Queensland.

Section 3. Characteristics of CCP

3.1 General

Coal ash, or CCP is a general term to describe a range of products produced from burning coal in a coal-fired power station. These products include:

- fly ash, which is a very fine, powdery material comprised mostly of silica made from the burning of finely ground coal in a boiler
- bottom ash, is an incombustible product or unburned coal from the combustion process and comprises a course, angular ash particle that is too large to be carried up into the stacks so it forms at the bottom of the coal furnace
- boiler slag is molten bottom ash from slag tap and cyclone type furnaces that turns into pellets that have a smooth glassy appearance after being cooled with water
- other by-produces that include flue gas residues.

CCP mainly consists of silicate, carbonate, aluminate, ferrous materials and several of heavy metals and metalloids. The exact composition of the CCP is influenced by the type of furnace in which the coal is burned, the source and rank of the coal, actual operating conditions in the furnace and how the CCP is removed from the boiler station (wet or dry transport).

As by-products of a highly efficient and regulated industrial process in Australia, the ADAA states that CCP from various types of power stations will typically exhibit similar and consistent properties (particularly in relation to engineering properties).

When assessing the proposed reuse of CCP, the chemical characteristics of the material is of most importance, in particular the presence of trace metals and the potential presence of contaminants.

Coal fired power stations in Queensland combust black coal, typically sourced from coal resources from adjacent, neighbouring or nearby mines. None of the coal fired power stations from which CCP would be considered for reuse accept other waste that would include PFAS contamination. Hence PFAS are not considered to be a contaminant of concern for CCP, and the requirements in the EoW code for CCPs for PFAS do not apply and have not been further considered in this review.

3.2 Published data

As the characteristics of CCPs depends on the source of the coal and the operation of the power station, it is considered relevant to consider chemical characteristics of ash materials determined from Australian power stations. Limited data is publicly available, however the ADAA has provided the results of environmental testing completed on CCP in 2004, 2007 and 2008/2009.

The data presented relates to sampling of ash materials from power stations in NSW, Queensland, SA, WA and Victoria, and marketers of these materials in these states. Samples analysed included fly ash and bottom ash materials. The analysis included total concentrations for selected metals and leachate concentrations for metals, with selected samples also analysed for dioxins and furans.

The CCP samples were not collected from the surface of stockpiles as these were not considered representative. Samples were collected after removing approximately 0.2 m of surface material. All CCP samples were characterised as coarse (in accordance with AS 3582.1).

Tables 3 and 4 present a summary of the range of total concentrations (**Table 3**) and leachate concentration (**Table 4**) reported in the CCP samples analysed and reported by ADAA.

Table 3: Summary of concentrations reported in CCP by ADAA

Analyte reported	Concentrations reported (mg/kg)					
	2004 (range)		2007 (black coal) 95% UCl		2008/2009 (black coal) average	
	Bottom ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash
Number of samples analysed	4	7	26	26	11	22
Silver	--	--	0.1	0.1	ND	--
Arsenic	--	--	0.8	8.2	0.59	7.36
Boron	--	--	4.0	63	9.36	49.5
Barium	--	--	257.4	1157	111.36	271.5
Beryllium	--	--	0.6	5.1	0.55	2.07
Cadmium	<1	<1	0.1	0.2	ND	0.25
Cobalt	--	--	8.8	17.8	0.91	6.7
Chromium	--	--	3.9	18.3	2.36	10.55
Copper	--	--	6.4	22.7	4.18	18.45
Mercury	<0.1 to 2.1*	<0.1 to 0.5	ND	0.2	0.027	0.15
Molybdenum	--	--	2.3	15.2	0.64	6.95
Nickel	--	--	14.2	28.8	1.73	11.34
Lead	<1 to 8	<1 to 6	1.9	16.7	1.36	10.18
Antimony	--	--	0.5	1.1	--	--
Selenium	--	--	1.0	3.3	ND	4.05
Tin	--	--	2.4	3.0	ND	2.34
Zinc	--	--	7.1	64.8	4.86	44.55
Manganese	--	--	50.8	201.7	192.68	161.77
Dioxins and furans as TEQ	--	ND	NA	NA	NA	NA

* Reanalysis of the CCP sample where 2.1 mg/kg was reported (4 additional samples analysed) indicated concentrations in the range <0.1 to 0.5 mg/kg. The elevated level of 2.1 mg/kg could not be replicated.
-- Not analysed

ND = not detected

Table 4: Summary of leachate concentrations reported in CCP by ADAA

Analyte reported	Concentrations (mg/L)					
	2004 (range)		2007 (black coal) 95% UCI		2008/2009 (black coal) 95% UCI	
	Bottom ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash
Number of samples analysed	12	35	26	26	11	22
Silver	<0.1	<0.1	0.005	0.001	0.00058	0.00087
Arsenic	<0.1 – 0.2	<0.1 – 0.7	0.006	0.194	ND	0.02458
Boron	--	--	0.128	2.39	--	--
Barium	<1	<1 - 2	0.478	0.603	0.74	0.854
Beryllium	<0.1	<0.1	0.005	0.005	--	--
Cadmium	<0.1	<0.1	0.001	0.006	ND	0.00367
Cobalt	--	--	0.007	0.024	--	--
Chromium	<0.1	<0.1 – 0.5	0.025	0.069	ND	0.0467
Copper	<0.1 – 0.1	<0.1 – 0.4	0.03	0.203	ND	0.0558
Mercury	<0.01	<0.01	0.001	0.001	--	--
Molybdenum	--	--	0.01	0.242	--	--
Nickel	<0.1 – 0.1	<0.1 – 0.2	0.033	0.051	ND	0.0271
Lead	<0.1	<0.1	0.008	0.005	0.0075	--
Antimony	<0.1	<0.1	0.005	0.022	--	0.00667
Selenium	<0.1	<0.1 -0.2	0.01	0.07	ND	--
Tin	--	--	0.005	0.106	--	--
Zinc	<0.5 – 0.6	<0.5 – 0.6	0.101	0.196	0.043	0.187
Manganese	--	--	0.293	0.41	--	--
Thallium	<0.1 - 0.1	<0.1 - 0.1	--	--	ND	--

-- Not analysed

ND = not detected

In addition to the data presented in the above tables, analysis of CCP for radionuclides (ADAA 2009) determined that the levels reported in fly ash was similar to or not significantly higher than background, and bottom ash was consistent with background and would not be considered to be radioactive (particularly once used where the materials would be mixed with other products).

3.3 CCP sourced from Queensland Power Stations

In general fly ash and bottom ash predominantly comprises silicon dioxide, aluminium oxide, calcium oxide and iron oxide. The material includes some (variable) proportion of crystalline silica.

Bottom ash and fly ash (where relevant) data has been provided for samples collected from a number of power stations, as detailed in **Table 5**.

Table 5: Available data from power stations

Site	Product	Sample No.	Nominal composition
Power Station B	Bottom Ash as produced un-processed.	RH22-0077	100% Bottom Ash
	Fly Ash from the dry storage area.	RH22-0078	90% Fly Ash, 10% Bottom Ash
Power Station C	Bottom Ash as produced un-processed.	B21-663	100% Bottom Ash
	Fly Ash from the dry storage area	RH22-0088	90% Fly Ash, 10% Bottom Ash
Power Station D	Bottom Ash as produced un-processed.	BS21-662	100% Bottom Ash
	Fly Ash from the dry storage area.	RH22-0090	90% Fly Ash, 10% Bottom Ash
Power Station E	Bottom Ash as produced un-processed.	RH22-0091	100% Bottom Ash
	Fly Ash from the dry storage area.	RH22-0092	90% Fly Ash, 10% Bottom Ash
Power Station G	Bottom Ash as produced un-processed.	RH22-0093	100% Bottom Ash
Power Station F	Bottom Ash as produced un-processed.	BS21-664	100% Bottom Ash
	Fly Ash from the wet storage area.	RH22-0095	90% Fly Ash, 10% Bottom Ash
Power Station A	Bottom Ash as produced un-processed.	BS21-661	100% Bottom Ash
	CCP sampled from Stanwell in report 876936-S_report.pdf		90% Fly Ash, 10% Bottom Ash

These samples were supplied by the power stations and have been assumed to relate to stored or stockpiled materials. These samples were analysed for a range of total recoverable hydrocarbons (TRH), volatile organics, organochlorine pesticides, organophosphorus pesticides, polychlorinated biphenyls, acid herbicides, semivolatile organics, cyanide, fluoride, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), heavy metals and PFAS. These samples were also analysed for dioxins and furans and polybrominated diphenyl ethers (PBDEs).

These data are summarised in **Tables 6, 7 and 8**. It is noted that while the number of samples analysed is small, the concentrations reported in bottom ash and fly ask materials from these power stations is similar to the range of concentrations reported in CCP by ADAA (**Tables 3 and 4**), with the exception of barium in materials from Power Station A and boron from Power Station E.

Table 6: Summary of concentrations reported in bottom ash samples

Analyte	units	Concentration reported in bottom ash sample analysed from each power station (mg/kg)						
		Power Station B	Power Station C	Power Station D	Power Station E	Power Station G	Power Station F	Power Station A
TRH	mg/kg	nd	nd	d	nd	nd	nd	nd
Volatile organics, except	mg/kg	nd	nd	nd	nd	nd	nd	nd
Toluene	mg/kg	<0.1	<0.1	<0.1	<0.1	0.5	<0.1	<0.1
Organochlorine pesticides	mg/kg	nd	nd	nd	nd	nd	nd	nd
Organophosphorus pesticides	mg/kg	nd	nd	nd	nd	nd	nd	nd
Acid herbicides	mg/kg	nd	nd	nd	nd	nd	nd	nd
PCBs	mg/kg	nd	nd	nd	nd	nd	nd	nd
PAHs	mg/kg	nd	nd	nd	nd	nd	nd	nd
PFAS	µg/kg	nd	nd	nd	nd	nd	nd	nd
Cyanide	mg/kg	nd	nd	nd	nd	nd	nd	nd
Fluoride	mg/kg	nd	nd	nd	nd	nd	nd	nd
Semivolatile organics, except	mg/kg	nd	nd	nd	nd	nd	nd	nd
Di-n-butyl phthalate	mg/kg	<0.5	0.7	0.9	<0.5	<0.5	<0.5	1.0
Metals								
Antimony	mg/kg	<10	<10	<10	<10	<10	<10	<10
Arsenic	mg/kg	<2	<2	<2	2.0	11	<2	<2
Barium	mg/kg	18	330	250	42	19	<5	1500
Beryllium	mg/kg	<2	<2	<2	<2	2.7	<2	<2
Boron	mg/kg	<10	<10	22	36	16	<10	<10
Cadmium	mg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Copper	mg/kg	5.6	5.2	7.2	8.5	19	<5	16
Lead	mg/kg	<5	<5	<5	<5	21	<5	<5
Mercury	mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Molybdenum	mg/kg	<5	<5	<5	<5	8.6	<5	<5
Nickel	mg/kg	<5	<5	<5	9.0	7.6	<5	9.7
Selenium	mg/kg	<2	<2	<2	<2	<2	<2	<2
Silver	mg/kg	<2	<2	<2	<2	<2	<2	<2
Vanadium	mg/kg	<10	--	--	14	150	--	--
Zinc	mg/kg	<5	<5	6.5	8.1	73	<5	8.1
Dioxins, furans and PBDEs								
Dioxins and furans (as TEQ_{05}, upper bound)	pg/g (ng/kg)	1.2	1.2	1.8	16	4.1	1.2	1.7
PBDEs	ng/g (µg/kg)	nd	nd	nd	nd	nd	nd	nd

nd = not detected above the analytical limit of reporting (LOR), where a value is presented, it is <LOR

-- = not analysed

Table 7: Summary of concentrations reported in fly ash (CCP) samples

Analyte	units	Concentration reported in fly ash sample analysed from each power station (mg/kg)				
		Power Station B	Power Station C	Power Station D	Power Station E	Power Station F
TRH	mg/kg	nd	nd	nd	nd	nd
Volatile organics, except:	mg/kg	nd	nd	nd	nd	nd
Methylene chloride	mg/kg	<0.5	<0.5	1.5	<0.5	<0.5
Toluene	mg/kg	<0.1	<0.1	0.3	1.1	<0.1
Organochlorine pesticides	mg/kg	nd	nd	nd	nd	nd
Organophosphorus pesticides	mg/kg	nd	nd	nd	nd	nd
Acid herbicides	mg/kg	nd	nd	nd	nd	nd
PCBs	mg/kg	nd	nd	nd	nd	nd
PAHs	mg/kg	nd	nd	nd	nd	nd
PFAS	µg/kg	nd	nd	nd	nd	nd
Cyanide	mg/kg	nd	nd	nd	nd	nd
Fluoride	mg/kg	<100	<100	<100	180	<100
Semivolatile organics	mg/kg	nd	nd	nd	nd	nd
Metals						
Antimony	mg/kg	<10	<10	<10	<10	<10
Arsenic	mg/kg	2.9	11	4.5	10	7.8
Barium	mg/kg	130	260	230	70	9.4
Beryllium	mg/kg	<2	<2	<2	<2	<2
Boron	mg/kg	21	72	27	190	<10
Cadmium	mg/kg	<0.5	<0.5	<0.5	<0.5	<0.5
Copper	mg/kg	19	7.8	6.0	27	7.7
Lead	mg/kg	12	7.3	<5	<10	5.5
Mercury	mg/kg	0.2	<0.1	<0.1	<0.1	<0.1
Molybdenum	mg/kg	<5	<5	<5	<5	<5
Nickel	mg/kg	16	<5	<5	<13	<5
Selenium	mg/kg	<2	<2	<2	2.2	<2
Silver	mg/kg	<2	<2	<2	<2	<2
Vanadium	mg/kg	34	52	18	72	46
Zinc	mg/kg	34	27	15	18	33
Dioxins, furans and PBDEs						
Dioxins and furans (as TEQ_{05}, upper bound)	pg/g (ng/kg)	1.2	1.2	1.2	1.5	2.0
PBDEs	ng/g (µg/kg)	nd	nd	nd	nd	nd

nd = not detected above the analytical limit of reporting (LOR), where a value is presented, it is <LOR

Table 8: Summary of concentrations reported in Power Station A CCP

Analyte	units	Concentration reported in material	
		minimum	maximum
TRH	mg/kg	No TRH fractions detected in any sample analysed	
Volatile organics	mg/kg	No volatile chemicals detected in any sample analysed	
Organochlorine pesticides	mg/kg	No pesticides detected in any sample analysed	
Organophosphorus pesticides	mg/kg		
Acid herbicides	mg/kg		
PFAS	µg/kg	No PFAS compounds detected in any sample analysed	
Cyanide	mg/kg	Not detected in any sample analysed	
Fluoride	mg/kg	Not detected in any sample analysed	
Semivolatile organics	mg/kg	No semivolatile chemicals, including polycyclic aromatic hydrocarbons (PAHs) detected, with the exception of one detection of phthalate, as below	
Bis(2-ethylhezyl)phthalate	mg/kg	<0.5	4.2**
Metals			
Antimony	mg/kg	<10	<10
Arsenic	mg/kg	4.2	15
Barium	mg/kg	400	2200
Beryllium	mg/kg	<2	<2
Boron	mg/kg	13	21
Cadmium	mg/kg	<0.4	<0.4
Copper	mg/kg	31	44
Lead	mg/kg	6.5	11
Mercury	mg/kg	0.1	0.2
Molybdenum	mg/kg	<5	<5
Nickel	mg/kg	12	36
Selenium	mg/kg	<2	2.5
Silver	mg/kg	<2	<2
Vanadium	mg/kg	65	86
Zinc	mg/kg	19	35
Dioxins, furans and PBDEs			
Dioxins and furans (as TEQ_{05}, upper bound)	pg/g (ng/kg)	1.2	2.1*
PBDEs	ng/g (µg/kg)	No individual PBDEs detected	
pH			
Range of pH from materials testing	pH units	9.2	9.7

* It is noted that the maximum TEQ_{05} upper bound value reported was 52 pg/g, however this is from a sample where there were no detections of any individual dioxin or furan compound, however the analytical LOR was elevated, resulting in an elevated TEQ (where the LOR is adopted in the calculation)

** Bis(2-ethylhexyl)phthalate was detected in one sample. There are no sources of phthalates relevant to the production, handling and storage of CCP. The detection may be due to cross contamination during sampling or analysis.

Section 4. Assessment of risks to human health and the environment

4.1 Potential uses of CCP in road projects

Road projects that may be undertaken in Queensland would be expected to be located in a wide range of locations and areas, particularly in terms of proximity to environmental sensitive areas. These areas my include wetlands, floodplains, lagoons, creeks and rivers.

A road corridor, once constructed, does not have any significant terrestrial environment. However, land adjacent to road projects may include the presence of and/or habitats for threatened and endangered species.

The use of CCP in the construction of roadways needs to comply with the EoW code in relation to uses of unbound materials in or near waterways.

Where CCP is used in bound materials no additional consideration needs to be given in relation to proximity to groundwater or surface water features.

However, in relation to unbound applications where CCP may be used, compliance with the EoW code is important. The following review further considers potential risks to the environment, to determine if any additional measures may be required for this project, to protect the environment.

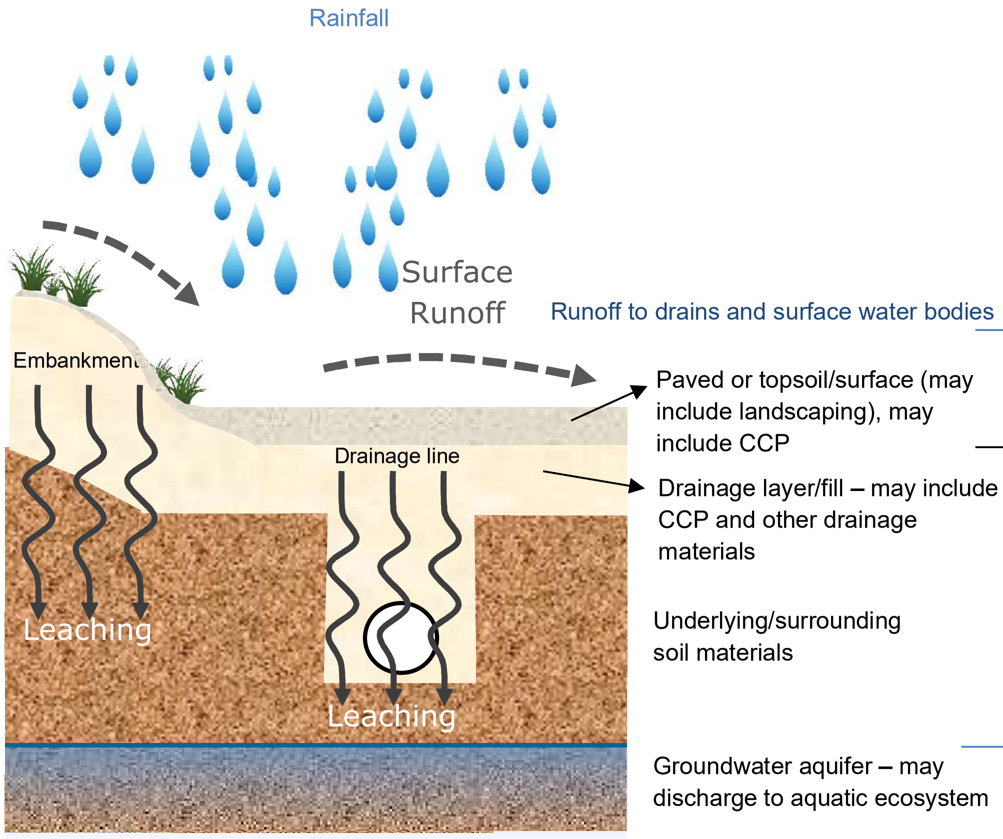
4.2 Potential for exposure

The focus of this review relates to consideration of potential risks to human health and the environment in relation to the use of CCP power stations in bound and unbound applications, including engineered fill, drainage and pavement materials.

In relation to the potential for exposure, the **Figures 2 and 3** provide diagrammatic conceptual site models relevant to the proposed use of this material as fill in embankments and drainage materials, and pavements. The figures include the mechanisms for contaminants to migrate from the materials (as proposed to be used) and the potential for exposure where human health and ecological risks may require further consideration.

Where CCP is used in a bound application, such as within concrete, the ash is expected to be bound and not available to people or the environment. The key issues of concern relate to the use of CCP in unbound materials.

For the purpose of this assessment the characteristics of CCP as detailed in **Section 3** have been considered. The pH of the material is also considered.

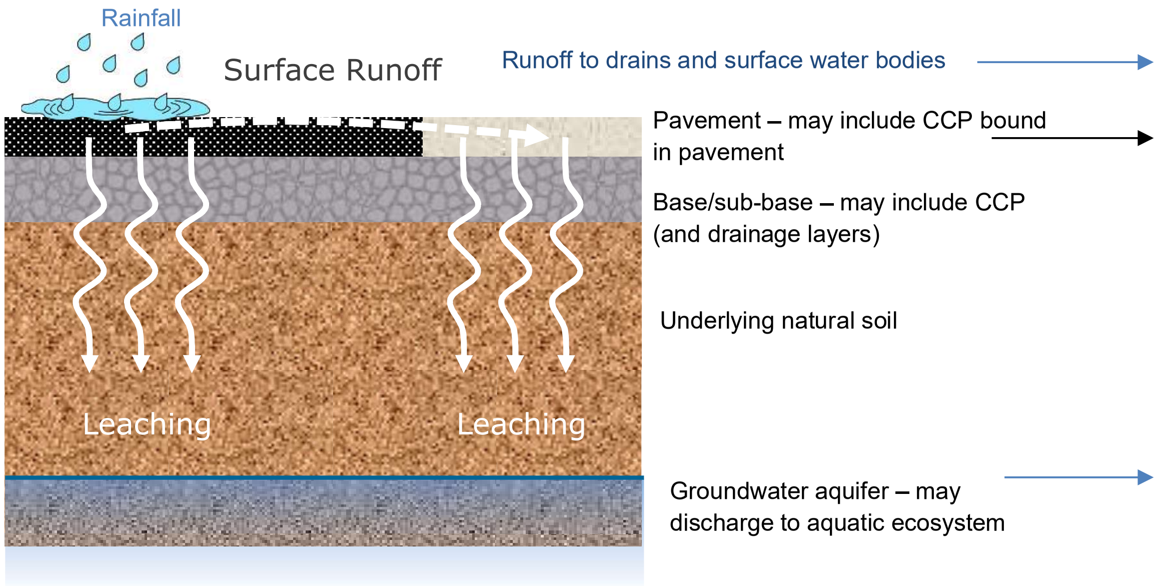


Human health	Ecological
Direct contact* with surface water or recreational use	Aquatic environments in surface water body
Direct contact* with materials at ground surface, or during maintenance works	Terrestrial environments in road corridor

Groundwater extraction and use for potable and non-potable uses	Aquatic environments where groundwater discharges
Direct contact* with water	

* Direct contact includes ingestion and dermal absorption

Figure 2: Conceptual model – use of CCP in embankment and drainage materials



Human health	Ecological
Direct contact* with surface water - Drinking water or recreational	Aquatic environments in surface water
Direct contact* with materials	Terrestrial environments
Groundwater extraction and use Direct contact* with water Drinking water or recreational	Aquatic environments where groundwater discharges

* Direct contact includes ingestion and dermal absorption

Figure 3: Conceptual model – use of CCP in pavement materials

4.3 Compliance with EoW code

For CCP materials derived from the power stations assessed, the first step in determining the suitability of these materials is to compare the concentrations reported with the criteria detailed in the EoW code for CCP. Compliance with these criteria would mean that the material is suitable for use as detailed in the EoW code and would not be of concern in relation to human health or the environment.

Table 9 presents a comparison of the maximum concentrations reported in CCP (as detailed in **Tables 6, 7 and 8**), with comparison against the EoW code criteria. For chromium and cobalt, the maximum concentration reported in CCP reported in the analysis conducted by ADAA (presented in **Table 3**) have been included as these metals were not reported in the analysis undertaken for this assessment. This comparison has not further considered PFAS, as the source of CCP does not include the combustion of materials which include PFAS contamination and PFAS was not detected in the analysis of CCP samples from any of the power stations.

Table 9: Review of concentrations in CCP with EoW code

Chemical or attribute	Maximum concentration reported in CCP from all power stations evaluated (mg/kg)	EoW code - Total maximum concentration (mg/kg)		
		Bound applications	Unbound applications	Soil conditioner, soil product and direct land application
Arsenic	15	NS	20	20
Beryllium	2.7	NS	NS	60
Boron	190	NS	100	10
Cadmium	<0.5	NS	1	1
Chromium (total)	18.3*	NS	100	100
Chromium (III)	--	NS	NS	100
Chromium (VI)	--	NS	1.5	1
Cobalt	17.8*	NS	100	100
Copper	44	NS	100	100
Lead	21	NS	50	50
Mercury	0.2	NS	1	10
Molybdenum	8.6	NS	NS	10
Nickel	36	NS	60	60
Selenium	2.5	NS	10	5
Zinc	73	NS	200	200
Electrical conductivity (dS/m)	--	NS	NS	10 (dS/m)
pH	9.2-9.7 (Power Station A data only)	NS	5 to 12.5 (pH units)	5 to 12.5 (pH units)

-- = not analysed in data provided
NS = not specified
* = maximum reported in CCP analysed by ADAA (refer to **Table 3**)

Review of **Table 9** indicates that for most of the analytes reported the maximum concentrations reported in CCP comply with criteria in the EoW code relevant to bound, unbound applications and use as a soil conditioner. The exception is boron. Boron only exceeds the EoW code criteria in the fly ash/CCP sample collected from Power Station E. All other samples of CCP from all other power stations are below the EoW code criteria for all uses.

Fly ash/CCP derived from Power Station E requires further testing of metals to determine if the material can meet the EoW code.

Not all the metals listed in the EoW code were reported in the analysis of the CCP samples collected. Any further sampling of CCP proposed to be used for bound or unbound applications should include analysis of chromium and cobalt.

It is noted that there are a number of other metals and some organics detected in CCP, for which there are no criteria listed in the EoW code. Hence further review of the detected concentrations has been undertaken to determine the potential risks to human health and the environment. Further review is presented in the following sections.

4.4 Assessment of human health issues

4.4.1 Potential for exposure

In relation to potential risks to human health the pathways of exposure relevant to the use of CCP in road applications include the following:

- Direct contact with CCP, and inhalation of dust derived from CCP where the material is being used in unbound applications by contractors or other workers. Such exposures relate to the use of CCP materials as provided from the power stations or mixed with other materials (fill/aggregate etc). These exposures are not relevant where CCP is bound. However, where a bound product such as concrete may be cut or ground up, there is the potential for dust to be generated. Depending on the proportion of CCP in these bound materials, inhalation of dust may be of importance and require management.
- Direct contact with CCP in road corridors, where these materials are in an area accessible to workers and residents who may live directly adjacent to the locations where these materials may be used for fill or drainage materials. This exposure relates to direct contact with chemicals that may be present in surface materials. Where CCP is used in bound applications, such as concrete and asphalt, or used at depth, placed beneath sealed surfaces there is no potential for direct contact with the materials to occur.
- Direct contact with chemicals that may have leached from CCP in unbound applications that may directly runoff to surface water, where this water may be accessed for recreational uses or extracted for drinking water.
- Direct contact with chemicals that may have leached from CCP in unbound applications and migrate to groundwater, where groundwater is extracted and used for drinking water. Groundwater may also discharge to surface water where exposures via recreational use or drinking water may occur.

4.4.2 Worker health

Based on the characteristics of CCP, and publicly available SDSs for fly ash and bottom ash, the material is classified as hazardous according to Safe Work Australia. This classification relates to skin and eye damage and irritation, respiratory irritation, carcinogenicity (related to the presence of crystalline silica) and repeated exposure toxicity. These exposures relate to skin and eye contact with the material and, more significantly, dust inhalation.

The CCP is stored at the power stations. The form of the material may vary from fine/sandy material to granular material that is loose or, in some cases compacted or solidified. The material would need to be removed from these stockpiles for use, which may result in the generation of dust and result in direct contact with the CCP.

To address these hazards a range of workplace management measures are outlined in SDS to eliminate or reduce exposure when directly handling the CCP. These workplace controls would be expected to include:

- only using the material outdoors
- wearing gloves, protective clothing, eye and face protection
- where an inhalation risk exists a Class P2 (particulate) respirator as required (i.e., where dust may be generated)
- washing after handling.

The requirements to wear a respirator relate to the presence and use of CCP as unbound material where dust has the potential to be generated during handling or use. The requirements should also relate to activities that result in the generation of dust from bound applications, such as grinding of concrete or other bound materials where CCP is used. These requirements are the same as applicable for the use of conventional quarry materials.

Where management measures are implemented in accordance with the SDS, risks to worker health would be mitigated.

4.4.3 Direct contact with CCP materials

To assess the potential for the above exposures to be of concern, the maximum concentrations reported in CCP have been directly compared with guidelines that are based on the protection of human health for exposures by commercial/industrial workers and residents. These guidelines are available from the ASC NEPM (NEPC 1999 amended 2013a) and are protective of the following exposures, which are highly conservative in relation to likely exposures that may occur in areas where material is proposed to be used:

- Commercial/industrial workers – ingestion of soil and dust, dermal absorption of chemicals from contact with soil and dust and inhalation of dust, 8 hours per day for 240 days of the year for 30 years.
- Residents – ingestion of soil and dust, dermal absorption of chemicals from contact with soil and dust, inhalation of dust, ingestion of homegrown fruit and vegetables grown in soil (10% of intakes are from home produce) all day, every day for 35 years.

Where guidelines are not available from the NEPM, they have been derived from CRC CARE (CRC CARE 2011) in relation to direct contact exposures with TRH, and the USEPA Regional Screening Levels (RSLs) for residential and industrial soil – which are derived on a similar basis as the NEPM guidelines. **Table 10** presents a comparison of the maximum concentrations reported against these health-based guidelines.

Review of **Table 10** indicates that all concentrations reported in CCP are well below the conservative health-based guidelines that are protective of long-term direct contact exposures by workers and residents. These guidelines are also protective of exposures that may occur for workers involved in handling these materials.

Table 10: Review of concentrations reported in CCP – Human health

Chemical detected in CCP samples from power stations evaluated	Maximum concentration reported from samples analysed (mg/kg)	Guidelines protective of human health (mg/kg)	
		Commercial/ industrial workers N (HIL-D)	Residents N (HIL-A)
Arsenic	15	300	100
Barium	2,200	220,000 U	15,000 U
Beryllium	2.7	500	60
Boron	190	300,000	4,500
Chromium VI	18.3*	3,600	100
Cobalt	17.8*	4,000	100
Copper	44	240,000	6,000
Lead	21	1,500	300
Mercury	0.2	730	40
Molybdenum	8.6	5,800 U	390 U
Nickel	36	6,000	400
Selenium	2.5	10,000	200
Vanadium	150	5,800 U	390 U
Zinc	73	400,000	7,400
Fluoride	180	47,000 U	3,100 U
Organics			
Methylene chloride	1.5	3,200 U	350 U
Toluene	1.1	99,000 N1	160
Bis(2-ethylhezyl)phthalate	4.2	1,600 U	390 U
Di-n-butyl phthalate	1.0	82,000 U	6,300 U
Dioxins and furans (WHO_{05} TEQ upper bound)	16 pg/g	220 pg/g U	50 pg/g U

N = Health based guidelines as listed in the NEPM (NEPC 1999 amended 2013a), unless noted otherwise

N1 = Health based guidelines protective of direct contact exposures (as vapour guidelines are not limiting) as detailed by CRC CARE (CRC CARE 2011)

U = USEPA RSLs (USEPA 2022) for industrial or residential soil – protective of human health (based on HI = 1 and cancer risk = 1 $x10^{-5}$)

* = maximum reported in CCP analysed by ADAA (refer to **Table 3**) and assuming that 100% of the chromium reported is chromium VI (which will not be the case as chromium is expected to be present in the environment as chromium III)

4.5 Assessment of ecological issues

4.5.1 Potential for exposure

In relation to the potential for ecological impacts related to the proposed use of CCP the following issues are of relevance:

- Terrestrial ecosystems:
  - Pavement materials are used for roads where the growth of plants is not desired. In the case of asphalt sealed surfaces/pavements, these materials would be compacted and would preclude the growth of plants, regardless of the inclusion of CCP in this material. CCP bound in materials such as concrete would not be available to the terrestrial environment.
  - Where CCP is used in unsealed pavements, the growth of plants would be prevented. Hence the focus of this review relates to the potential for harm in areas located adjacent to the pavement where the materials may be used.
  - For the use in drainage lines or engineered fill, where the CCP is placed at depth there is limited potential for contact with terrestrial environments. However, where

CCP is accessible at the surface, or included in soil amendments, some terrestrial environments may be present that require consideration.

- Aquatic ecosystems – This is of relevance where chemicals present in CCP leach and may impact on surface water quality and/or groundwater quality, and groundwater discharges to an aquatic environment (refer to **Sections 4.5.3 and 4.6**).

4.5.2 Terrestrial ecosystems

In relation to potential impacts on adjacent terrestrial ecosystems, this would only relate to the presence of the materials that may extend beyond the road or pavement, or where present at ground surface associated with the use of fill along a road corridor. Where the CCP is bound in asphalt or concrete or used in pavements and compacted then there is no potential for ecological exposures and therefore no risk.

To assess the potential for CCP to be of concern to terrestrial ecosystems, maximum concentrations reported in the CCP samples analysed have been compared with published ecological investigation levels (EILs), as presented in **Table 11**. The level of protection relevant to terrestrial ecosystems adjacent to roadways (including in embankment materials) or paved areas is consistent with that adopted in the NEPM for commercial/industrial land use. This relates to 60% species protection and is expected to be conservative for areas where CCP may be present (unbound) in soil.

Soil EILs from the NEPM (NEPC 1999 amended 2013a) have been adopted in this assessment. Where EILs are not available, guidelines available from CCME or RIVM, protective of commercial/industrial soil have been adopted, where available. In the absence of guidelines for industrial soil (or equivalent level of species protection), residential/agricultural criteria have been adopted, which may include ecological guidelines as established by ECHA. The NEPM EILs have been derived to also considered potential leaching and impacts on groundwater and aquatic ecosystems.

Table 11: Review of concentrations reported in CCP – Terrestrial ecosystems

Chemical detected in CCP samples from Power Station A	Maximum concentration reported from samples analysed (mg/kg)	Guidelines protective of ecological health (mg/kg)
Arsenic	15	160 [E]
Barium	2,200	2,000 [C]
Beryllium	2.7	8 [C]
Boron	190	36 [U]
Chromium III	18.3*	310 [A]
Chromium VI	NA	1.4 [C]
Cobalt	18.7*	300 [C]
Copper	44	150 [AA]
Lead	21	1,800 [E]
Mercury	0.2	24 [C]
Molybdenum	8.6	40 [C]
Nickel	36	60 [AA]
Selenium	2.5	2.9 [C]
Vanadium	150	330 [R]
Zinc	73	440 [AA]
Fluoride	180	200 [C]
Organics		
Methylene chloride	1.5	3.9 [R]
Toluene	1.1	135 [ES]
Bis(2-ethylhezyl)phthalate	4.2	60 [R]
Di-n-butyl phthalate	1.0	36 [R]
Dioxins and furans (WHO_{05} TEQ upper bound)	16 pg/g	220 pg/g [UX]

NEPM ecological guidelines

E = EIL

A = Added contaminant level (ACL) with the EIL based on background from QLD (low traffic volumes) + ACL calculated for CEC = 5 cmolc/kg, pH = 9, iron content = 5%, clay content = 1%

A = Aged contamination guideline (relevant to RAP)

ES = Ecological Screening Level for petroleum hydrocarbons

C = CCME guideline protective of commercial/industrial soil (ecological) or agricultural soil

R = RIVM intervention screening level for soil

UX = USEPA RSL for commercial/industrial soil adopted in the absence of a terrestrial guideline. Review of the available data indicates that guidelines that are protective of human health would also be protective of terrestrial health.

E = ECHA predicted no effect concentration (PNEC) for the chemical in soil, based on protection of terrestrial organisms.

U = USEPA Region 4 ecological guidelines, relevant to the protection of plants and soil invertebrates (most relevant for the areas where CCP may be utilised)

Review of **Table 11** indicates that with the exception of the maximum concentration reported for barium and boron there are no exceedances of the screening level guidelines adopted for the protection of terrestrial ecosystems, as relevant to areas close to roadways, including embankments in road corridors, and pavements where CCP may be used.

Additional review - Barium

In relation to barium, the maximum concentration reported of 2,200 mg/kg just exceeds the adopted screening level guideline of 2,000 mg/kg. The only exceedance of the guideline relates to the maximum concentration reported from the Power Station A. All other concentrations of barium are below this guideline. In relation to assessing potential ecological impacts the average concentration present in the environment is of most relevance. Given the minor exceedance noted,
the average concentration for materials sources from any one power station would be below the adopted guideline.

The screening level guideline adopted is the commercial/industrial soil guideline established by CCME, that is protective of human health and ecological aspects. Further review of this guideline indicates that it is dominated by the protection of human health with insufficient data available to address terrestrial health. Limited data is available for the assessment of terrestrial toxicity, however the USEPA Eco-SSLs indicates that a lower guideline of 330 mg/kg may be applicable for the protection of plants and soil invertebrates, where terrestrial environments are appliable.

This guideline, however, is based on very limited data and a conservative assessment approach. A more recent review of data (where more data is available) (Tindal 2007) indicates a guideline of 1,500 mg/kg for commercial/industrial settings is protective of soil invertebrates and plants. This guideline relates to soluble forms of barium in soil. The studies used to develop this guideline involved the use of highly soluble barium forms (100% soluble), which can be easily taken up into plants, microbes and animals.

The form of barium in CCP is unlikely to be soluble as the material is formed as a result of a combustion process. Testing of CCP by AADA included total concentrations and leachable concentrations (refer to **Tables 3 and 4**). For barium, in 2007, concentrations in bottom ash and fly ash were reported to be 257.4 and 1157 mg/kg, with the leachable concentrations reported to be 0.478 and 0.603 mg/L respectively.

This data indicates that the barium reported in CCP is poorly leachable and hence poorly soluble in the environment. The %barium leaching from the CCP is 0.05 to 0.2%, which is very low. If some allowance for variability was assumed and 1% was assumed leachable or soluble, this is very different to 100% for the soil guideline. Where the solubility of CCP is accounted for the screening guideline can be modified by a factor of at least 100, to get 150,000 mg/kg.

All concentrations of barium reported in CCP are well below the guideline of 150,000 mg/kg. Hence there are not ecological risk issues of concern in relation to the presence of barium in CCP, where the material may be used for unbound purposes within the scope of the EoW code.

Additional review - Boron

In relation to boron, the maximum concentration reported of 190 mg/kg just exceeds the adopted screening level guideline of 36 mg/kg. The only exceedances of the guideline relate to the maximum concentration reported from the Power Station E and the Power Station C (72 mg/kg reported). All other concentrations of boron are below this guideline.

The ecological guideline adopted in this assessment is based on the protection of plants, from the USEPA Region 4 screening tables. Boron is an essential micronutrient for plants and hence adverse effects occur as a result of deficiency as well as toxicity. Certain plants have mechanisms for a tolerance of elevated levels of boron in soil and water. In addition, some species of plants can be used to accumulate boron to specifically remediate soil. A more recent review by Alberta Canada (Aeppli 2016) identified a guideline of 7.9 mg/L of boron in soil solution as protective of plants and invertebrates in commercial/industrial settings.

Testing of CCP by AADA included total concentrations and leachable concentrations (refer to **Tables 3 and 4**). For boron, in 2007, concentrations in bottom ash and fly ash were reported to be 4 and 63 mg/kg, with the leachable concentrations reported to be 0.128 and 2.39 mg/L respectively.

This results in a soil/water partition coefficient of approximately 30. Based on a soil water criteria of 7.9 mg/L, and a soil water partition coefficient of 30, a soil guideline relevant to CCP of 237 mg/kg can be derived.

All concentrations of boron reported in CCP are below the guideline of 237 mg/kg. Hence there are not ecological risk issues of concern in relation to the presence of boron in CCP, where the material may be used for unbound purposes within the scope of the EoW code.

4.5.3 Aquatic ecosystems

It is noted that the EILs (including many of the other ecological guidelines) have been derived to also consider potential leaching and migration to groundwater (and protection of aquatic ecosystems). This means that where the total concentrations are below the soil guidelines (presented in **Table 11**) there would be no risk issues of concern in relation to leaching and impacts on aquatic ecosystems.

Limited data is available in relation to the potential for CCP materials from these power stations to leach to the environment. The range of concentrations reported from the power stations is generally consistent with the range reported by ADAA (**Tables 3 and 4**) hence the leachate data provided from analysis undertaken by ADAA has been considered to be generally representative of concentrations that may be present in leachate from CCP materials.

The leachate data relates to an acidic leach testing procedure (TCLP) which is conservative, as metals leach at a greater rate under acidic conditions which are very different to the pH of CCP which is alkaline (much less leachable). The testing procedure also involves grinding the material into smaller particles sizes and shaking the material with acidic solution for a significant period of time. These conditions are not representative of the natural environment where rainwater infiltration may occur.

The leachate concentration is not the concentration that could be in the environment following rainfall or contact with groundwater. The leachate concentration would be diluted in such a situation.

Further review of the leachable concentrations reported has been undertaken and presented in **Table 12**. The maximum concentration reported in leachate has been compared with drinking water guidelines, which are protective of human health, and guidelines based on the protection of aquatic ecosystems (fresh and marine water relevant to the area being evaluated). The level of protection has included 99% species protection to address areas of high ecological significance, if present adjacent to road corridors, and the default guidelines which comprise 95% species protection except where a chemical is bioaccumulative and a 99% species protection level is adopted. This comparison has only been undertaken for metals detected in leachate. Where leachable concentrations have not been detected, no further evaluation has been undertaken.

Table 12 also presents the level of dilution required for leachate concentrations (as the maximum reported) to be reduced to a level that meets the relevant guidelines.

Table 12: Review of leachate concentrations - CCP material

Analyte detected	Leachate concentration reported (TCLP) - maximum (mg/L)	Screening level guidelines (mg/L)			Dilution factor required to meet screening level guideline		
		Human health – Drinking water guidelines	Aquatic ecosystems (fresh/marine)[Z]		Human health	Aquatic ecosystems (fresh/marine)[Z]	
			Default guideline value	99% species protection		Default guideline value	99% species protection
Antimony	0.022	0.003 [A]	0.009	NA	7.3	2.4	--
Arsenic	0.7	0.01 [A]	0.013	0.0008	70	54	875
Barium	2	2 [A]	NA	NA	--	--	--
Beryllium	0.005	0.06 [A]	NA	NA	--	--	--
Boron	2.39	4 [A]	0.94	0.34	--	2.5	7
Cadmium	0.006	0.002 [A]	0.0002/ 0.0055	0.00006/ 0.0007	3	30/1.1	100/8.6
Cobalt	0.024	0.006 [U]	0.0014/ 0.001	NA/ 0.000005	4	17/24	--/4800
Chromium	0.5	0.05 [A]	0.001/ 0.0044	0.00001/ 0.00014	10	500/114	50000/3571
Copper	0.4	2 [A]	0.0014/ 0.0013	0.001/ 0.0003	--	286/308	400/1333
Lead	0.008	0.01 [A]	0.0034/ 0.0044	0.001/ 0.0022	--	2.4/1.8	8/3.6
Mercury	0.001	0.001 [A]	0.00006/ 0.0001 (B)	0.00006/ 0.0001	--	17/10	17/10
Manganese	0.41	0.5 [A]	1.9/0.08	1.2/0.08	--	--/3	--/3
Molybdenum	0.242	0.05 [A]	0.034	0.034	3	7	7
Nickel	0.2	0.02 [A]	0.011/ 0.070	0.008/ 0.007	10	20/2.9	25/29
Selenium	0.2	0.01 [A]	0.005 (B)	0.005	20	40	40
Silver	0.005	0.1 [A]	0.00005/ 0.0014	0.00002/ 0.0008	--	100/3.8	250/6.2
Tin	0.106	1.2 [U]	NA	NA	--	--	--
Thallium	0.1	0.0002 [U]	0.00003/ 0.017	NA	500	333/6.9	--
Zinc	0.6	6 [U]	0.008	0.0024/0.0033	--	75	250/182

* 95% species protection, except for bioaccumulative chemicals (B) where 99% relevant
A = Australian Drinking Water Guideline (NHMRC 2011 updated 2022)
U = USEPA RSL for tap water (USEPA 2022)
Z = 95% and 99% species protection values for fresh water quality (ANZG 2018), relevant to various different areas within the proposed construction corridor. The 99% species protection level is applicable to wetland areas of HES.

Review of **Table 12** indicates the following:

- The leachate results presented are considered highly conservative, overestimated, as these relate to acidic conditions. The pH of rainfall is neutral, hence concentrations in leachate in the environment would be significantly lower than presented in the table.
- In relation to human health:
  - maximum worst-case leachable concentrations of antimony, arsenic, cadmium, cobalt, chromium (assuming chromium VI), molybdenum, nickel, selenium and thallium exceed drinking water guidelines
  - the leachable concentrations are not what would be in any drinking water source, even where the material was placed near a drinking water source

- the EoW code does not allow the placement of CCP materials within 50 m of a drinking water source. Such as separation would result in dilution of any leachate from these materials to the point of exposure, such that a dilution factor of at least 20 (and more likely much greater) would be achieved. This level of dilution would result in concentrations that were below the drinking water guidelines for most contaminants except arsenic and thallium. Where the conservative factors detailed above are considered it is unlikely that concentrations that may reach a drinking water well would exceed the drinking water guidelines. Hence there are no risk issues of concern in relation to potential impacts to drinking water
- in relation to recreational water, the guidelines applicable are 10 times higher than drinking water (NHMRC 2008). Hence there would be no risk issues of concern in relation to impacts on recreational water quality.

- Maximum worst-case leachable concentrations for all the chemicals detected in leachate exceed guidelines that are protective of fresh and marine water quality. In terms of dilution required to meet the relevant water quality guidelines, the following is noted:
  - Where the CCP is used in compliance with the EoW code it cannot be placed in a groundwater aquifer or in a waterway, including a creek bed. Hence any leaching, should it occur from the CCP, would be well diluted prior to reaching an aquatic environment. In addition, the leachable concentration relevant to such a process is an average, rather than the maximum. For many of the metals evaluated in Table 12, concentrations in leachate are not detected in many of the samples analysed. The maximum reported has been considered further, which is highly conservative.
  - It should also be noted that metals are naturally occurring in many environments, including aquatic ecosystems, as a result of the natural geology. Any assessment of potential ecological risk issues would typically include an assessment of natural/ background conditions in conjunction with the guidelines. As the locations where CCP may be used are not known, background conditions cannot be addressed.
  - Where the material was not used in the vicinity of an area of high ecological significance (including wetlands) and the 95% species protection level applied (or 99% for bioaccumulative chemicals as noted in **Table 12**):
    - a dilution factor of up to 500 is required to reduce leachate concentrations for most chemicals to a level that complies with the relevant guidelines
    - dilution factors up to 50, and potentially up to 500 (where the conservative aspects detailed above are considered) are reasonable and would be expected to be achieved in relation to the migration of leachate from unbound material to an aquatic environment where the material was used in compliance with the EoW code.
  - Where the material was used in the vicinity of an area of high ecological significance (including wetlands) and the 99% species protection level applied:
    - a dilution factors of up to 250 are required to reduce leachate concentrations for most chemicals to a level that complies with the relevant guidelines
    - for chromium VI, based on the maximum leachate concentration a dilution of 50,000 is required, which is significant, however there are many aspects of this calculation that is overly conservative (as noted above and also assuming 100% of the chromium would be present as chromium VI, which will not be

the case as chromium VI will convert of chromium III in the environment, which is significantly less toxic)

- where the conservative factors applicable to the evaluation of leaching from CCP to the environment are considered, it is unlikely that concentrations in runoff entering aquatic waterways would exceed either background/existing conditions or the relevant guidelines.

It is noted that CCP is not permitted to be used in the vicinity of sensitive aquatic ecosystems. Hence the potential for impacts in these areas, where CCP is used in compliance with the EoW code is considered low.

Based on the above where CCP is used in compliance with the EoW code, it is unlikely that there would be any significant risk issues of concern in relation to aquatic environments.

Section 5. Conclusions

CCP derived from the power stations in Queensland is proposed to be used for bound and unbound road applications. Use of CCP for these purposes can be undertaken under the Queensland EoW code for Coal Combustion Products.

Data is available for CCP stored in stockpiles at a number of power stations. This data has been evaluated further to determine if the use these materials, in compliance with the EoW code, has the potential to result in harm to human health or the environment. The assessment undertaken has focused on the use of CCP for road construction activities only.

Based on the available information the following can be concluded:

- Workers involved in the handling of unbound CCP, should utilise personal protective equipment (PPE) detailed in the SDS for these materials. Where these activities have the potential to result in the generation of dust, PPE should include respiratory protection in compliance with the SDS.
- Workers involved in the cutting of bound materials that include CCP (e.g., concrete) where dust may be generated, should wear respiratory protection in compliance with the SDS. The above requirements (for workers) remain unchanged from requirements that apply to workers using and handling conventional unbound aggregate material.
- CCP materials sources from most power stations evaluated comply with the criteria detailed in the EoW code for bound and unbound applications as proposed. The concentration of boron reported in fly ash materials from Power Station E exceed the criteria in the EoW code and hence further sampling of fly ash materials from Power Station E is recommended to determine if these materials are compliant with the requirements of the EoW code.
- Further review of the CCP data, for all chemicals detected, has not identified any risk issues of concern, in relation to human health or the environment, including aquatic environments, where the material is used in compliance with the EoW code. Should the project require the use of CCP in areas defined as Waters under the EoW code, additional data (specifically ASLP or similar leach test data at a more appropriate pH, and a better understanding of background concentrations in the waterways where the material is proposed to be used) would need to be collected and an agreement obtained from DES for the use of the CCP in such areas.
- Where the material may be removed from the project area in future works, the concentrations presented in CCP are below the criteria for regulated waste (i.e., the material would not be considered regulated waste).

The assessment undertaken has considered the use of 100% CCP in unbound applications. This is conservative for the proposed use in engineering fill, embankment materials and pipe drainage within road corridors. Mixing of CCP with other fill materials would further reduce the potential for impacts (particularly to aquatic environments), however the conclusions presented above would not change.

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