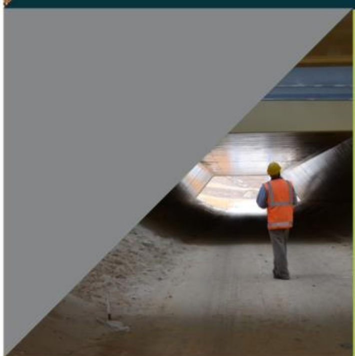
WARRIP

WESTERN AUSTRALIAN ROAD RESEARCH
AND INNOVATION PROGRAM

Implementing the Increased Use of Reclaimed Asphalt Pavement (RAP)

ELSABE VAN ASWEGEN
& LINCOLN LATTER



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mainroads
WESTERN AUSTRALIA

arrb

Implementing the Increased Use of Reclaimed Asphalt Pavement (RAP)

for Main Roads Western Australia

ABN 68 004 620 651

Victoria
80A Turner Street
Port Melbourne VIC 3207
Australia
P: +61 3 9881 1555
F: +61 3 9887 8104
info@arrb.com.au

Western Australia
191 Carr Place
Leederville WA 6007
Australia
P: +61 8 9227 3000
F: +61 8 9227 3030
arrb.wa@arrb.com.au

New South Wales
2-14 Mountain St
Ultimo NSW 2007
Australia
P: +61 2 9282 4444
F: +61 2 9280 4430
arrb.nsw@arrb.com.au

Queensland
21McLachlan Street
Fortitude Valley QLD 4006
Australia
P: +61 7 3260 3500
F: +61 7 3862 4699
arrb.qld@arrb.com.au

South Australia
Level 11,
101 Grenfell Street
Adelaide SA 5000
Australia
P: +61 8 7200 2659
F: +61 8 8223 7406
arrb.sa@arrb.com.au

	Reviewed
Project Leader	Elsabe van Aswegen
Quality Manager	Joe Grobler

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SUMMARY

Currently, Main Roads Specification 510 *Asphalt Intermediate Course* (Main Roads 2018b) allows the use of up to 10% recycled asphalt pavement (RAP) in structural asphalt mixes; however, Main Roads does not permit RAP use in the surface wearing course (Main Roads 2017b). These limits do not reflect the international state of practice and Main Roads would like to explore the feasibility and associated risk of incorporating higher RAP percentages in asphalt mixes.

The objective of this project was to translate the results and implement the findings from the Austroads project *Maximising the Use of Reclaimed Asphalt Pavement in Asphalt Mix Design* (Austroads 2016) into Main Roads asphalt specifications and the WA operating environment.

Review of literature

The literature reviewed indicates that the performance of asphalt mixes containing low proportions of RAP can be expected to be equivalent to mixes containing only virgin materials.

International studies have indicated that asphalt mixes exceeding 30% RAP contents may negatively impact the durability and fatigue performance of mixes, although this is not supported by some studies.

RAP management is an integral part of successfully using higher percentages of RAP. The management requirements specified by the various Australian road agencies generally cover aspects of sourcing, processing, stockpiling, proportioning, sampling and testing. It is noted that although there is a significant amount of commonality, some specifications are more prescriptive, which may be attributed to varying local materials, industry experience and individual agency requirements.

The review of international practice in relation to Main Roads showed that although relationships are evident between local and international practice, there are some aspects of international practice that differ significantly. This could be due to differences in design practice, test methods and industry experience and capability.

A review of available plant configurations and methods of incorporating RAP into asphalt mixes, showed that there is a vast range of existing options. Therefore, specifying maximum RAP contents based on the plant configuration/type may not be appropriate.

Managing variability in RAP

The main purpose of a management plan is to understand and reduce the extent of RAP variability used in asphalt mixes. To measure the variability of RAP in existing stockpiles stored at different WA asphalt suppliers, samples were obtained monthly, over a 12-month period during 2017. The results indicated a definite variability in processed RAP not only on a daily basis, but also on a month-to-month basis. This variation in the proportions of binder content, moisture content, particle size distribution and complex viscosity will require more diligence in monitoring the asphalt produced with RAP and adjusting the asphalt designs accordingly.

Draft Engineering Road Note 13B

A draft Engineering Road Note 13B (ERN 13B) was compiled that specifies the requirements for the design of intermediate course asphalt incorporating RAP. Changes were proposed for each of the specification documents that links to or is referenced in the draft ERN 13B. These are Specification 201 *Quality Systems* (Main Roads 2019), Specification 510 *Asphalt Intermediate Course* (Main Roads 2018b) and Specification 511 *Materials for Bituminous Treatments* (Main Roads 2017a).

RAP in Polymer Modified Binder (PMB) Asphalt Mixes

There are two issues with PMB and RAP:

1. When the RAP product itself contains a high level of polymer modification, and how this affects the performance of the new asphalt product into which the PMB RAP is introduced.
2. When RAP not containing PMB is added to a new asphalt mix containing PMB. The unmodified binder in the RAP may dilute the polymer content of the overall mix, potentially impacting on the performance of the mix.

The question about PMB and RAP became relevant, since Main Roads specifies PMB in the 14 mm intermediate course mix but does not allow RAP in PMB mixes. As a first step to evaluate the effect of RAP in new PMB asphalt, 10% and 20% RAP was added in a 14 mm dense graded asphalt, intermediate course mix. Specification 510 requires the binder to be an A15E PMB.

AGPT/T193 (2015), which was adopted in the draft ERN 13B, still needs to be verified for PMB, multigrade and hard penetration grade binders.

Conclusions of RAP in PMB Asphalt Mixes

Draft ERN 13B was followed for the for the limited RAP in PMB evaluation. The binder blend design method was used, but with no guidance on the viscosity limits that the blend viscosity should aim for when PMB binders are used in the blend.

The plant mix verification was simulated by extracting the binder after preparation of the three mixes to determine the complex viscosity. When the extracted binders' complex viscosities were used to calculate the blend viscosity, the calculation results compared well with the reported results.

Preparation of the three mixes proceeded in the laboratory, with the computing batch proportions based on the weight of the aggregate.

Moisture susceptibility results seem to indicate that the inclusion of RAP in the new PMB asphalt did not have a negative effect on the degree of stripping of the asphalt.

Flexural modulus results indicate that including RAP in the asphalt mix increase the stiffness. This may be beneficial in full-depth asphalt pavements.

However, the fatigue performance of the mixes that included RAP was less than the fatigue performance of the 0% RAP mix. The fatigue performance by the 10% and 20% RAP mixes appear similar, regardless of the difference in the percentage of RAP.

Recommendations

It is also recommended that the proposed draft ERN 13B should be used in a number of demonstration trials to refine the document, develop a data set for plant verifications of RAP mixes complex viscosity and to develop industry capability.

The RAP in PMB asphalt mix evaluation must be regarded as a first step to evaluate the effect of RAP in new PMB asphalt and further testing is required to verify these results.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

1.1 Background

Cocks et al. (2017) reports that in Western Australia (WA), local government used about 1.9 million cubic metres (3.8 million tonnes) of gravels and aggregate and Main Roads used about 1.4 million tonnes of gravels and aggregate for road construction in 2013. Construction and demolition material can potentially provide a portion of the total quantity of material required. However, the total amount of asphalt recycled in WA in 2012/13 was only 106 896 tonnes (Cocks et al. 2017). The use of reclaimed asphalt pavement (RAP) in asphalt mixes provides a vital basis for sustainable development, as well as direct economic and environmental benefits.

In WA, most of the road network comprises thin layers of asphalt on granular pavements. As a result, RAP quantities in WA are comparatively low, unlike other parts of the world that have had thick lift asphalt pavements for many years and their rehabilitation strategies require considerable depths of material to be removed. However, RAP does get collected in WA and is used by the asphalt suppliers on certain roads (Cocks et al. 2017).

In recent times, the asphalt suppliers have seen the financial benefits of using RAP and are now consciously stockpiling the product with a view of incorporating it in larger quantities in the future and as confidence in its use increases (Cocks et al. 2017). However, the recovery, storage, characterisation and documentation of RAP in WA is currently conducted in an ad hoc way.

Currently, Main Roads Specification 510, *Asphalt Intermediate Course* (2018b), allows the use of up to 10% RAP in structural asphalt mixes, however, Main Roads does not permit RAP use in the surface wearing course (Main Roads 2017b). These limits do not reflect the international state of practice and Main Roads would like to explore the feasibility and associated risk of incorporating higher RAP percentages in asphalt mixes.

There is a need to improve the background technical capacity and performance assessment of RAP mixes, to remove barriers to wider implementation without compromising the long-term performance of hot mix asphalt. This can be achieved by managing the associated risks on a technical basis, allowing for greater use of this valuable, but currently under-utilised resource.

1.2 Scope and Objectives

The objective of this project was to translate the results and implement the findings from Austroads project *Maximising the Use of Reclaimed Asphalt Pavement in Asphalt Mix Design* (Austroads 2016) into Main Roads WA asphalt specifications and the WA operating environment.

Austroads (2016) investigated the mix design requirements to provide guidance on the design and specification of asphalt mixes containing RAP to reduce the uncertainty surrounding its performance. The findings from this project resulted in the publication of AGPT/T193 (2015) *Design of Bituminous Binder Blends to a Specified Viscosity Value*, amongst other guidelines.

Austroads (2016) states that clear mix design guidelines, specifications and RAP management plans are needed to implement high RAP content mixes. The National Asset Centre of Excellence (NACoE) project *Implementing the Use of Reclaimed Asphalt Pavement (RAP) in TMR: Registered Dense-graded Asphalt Mixes (Year 1 – 2016/17)* (Yousefdoost, Rebbechi & Petho 2018) addresses the RAP management plan component. Appendix A of the report presents the outcomes of a literature review of international best practice in the management of RAP used in the manufacture of asphalt mixes containing RAP. Appendix B presents the outcomes of a literature review of international practices in the incorporation of RAP into new asphalt mixes using different types of asphalt plants. The type of asphalt plant available influences the amount of RAP that can be successfully included in an asphalt mix.

This project links to and builds on the above-mentioned projects.

The scope of the study included:

- evaluating the variability in metropolitan Perth RAP stockpiles and the impact of variability on the asphalt mix design process. Variability over time (months) and within a processed stockpile was assessed
- identifying best practice in RAP management that could be implemented in WA
- identifying plant requirements for successfully incorporating different RAP percentages
- investigating the applicability of AGPT/T193-15 using polymer modified binder (PMB) as the base binder through laboratory testing. The NACoE project makes comments with regard to PMBs but did not explore PMBs as a base binder explicitly
- developing specifications and supporting technical documentation for implementing higher percentages of RAP in the WA operating environment.

1.3 Structure of the Report

The structure and content of the report are as follows:

- Section 2 reviews current Australasian and broader international best practice in RAP management. The findings and recommendations from this section formed the basis for the development of specifications and supporting technical documentation.
- Section 3 reviews plant technology in terms of the methods of incorporating RAP into asphalt mixes during production. The capability of asphalt plants available in WA, specifically the Perth metropolitan area, where most plants are based, were reviewed. The findings and recommendations from this section formed the basis for the development of specifications and supporting technical documentation.
- Section 4 discusses the variability of RAP measured between three suppliers in the Perth metropolitan area during 2017, as well as the variability within a process stockpile measured over three days at a local supplier.
- Section 5 outlines the development of Main Roads RAP documentation, draft Engineering Road Note 13B. This document facilitates the use of higher RAP contents.
- Section 6 presents the results of the laboratory investigation on the performance of 10% and 20% RAP in PMB asphalt.
- Section 7 summarises the conclusions reached in this report.
- Section 8 discusses recommendations for refinement of draft documentation presented in this report and further work identified.

2 RAP MANAGEMENT PRACTICE

This section provides an overview of the existing documents and guidelines used by national and international road agencies in relation to the use and management of RAP.

2.1 Current Austroads Member Practice

The implementation of RAP in hot mix asphalt (HMA) mixes is well established in Australia and New Zealand, especially in metropolitan centres where a continuous supply has necessitated the development of management protocols. All Austroads member road agencies currently allow the use of RAP in the manufacture of HMA, although usage and management vary between jurisdictions.

The management of RAP is also referred to in the *Guide to Pavement Technology Part 4B: Asphalt* (Austroads 2014). Documents from the following Austroads member road agencies, the guide and relevant industry association were reviewed:

- Austroads
- Australian Asphalt Pavement Association (AAPA)
- Main Roads Western Australia (Main Roads)
- Roads and Maritime Services (RMS), New South Wales
- Department of Infrastructure, Planning and Logistics (DIPL), Northern Territory
- Queensland Department of Transport and Main Roads (TMR)
- Department of Planning, Transport and Infrastructure (DPTI), South Australia
- VicRoads, Victoria
- New Zealand Transport Agency (NZTA)

It should be noted that the specifications regarding RAP usage in Tasmania are based on VicRoads standard specifications and those used in the Australian Capital Territory (ACT) are based on RMS standard specifications. Therefore, Tasmania and ACT were not separately reviewed .

The following sections describe the RAP management practices outlined in the reviewed guidelines and documents, noting any unique aspects or practices that may be relevant to the update of Main Roads specifications.

2.1.1 Austroads

Guide to Pavement Technology Part 4B: Asphalt

Austroads (2014) contains guidance on RAP management practice. The source of RAP may be material reclaimed from asphalt surfaces or excavated road pavements. RAP materials should be crushed and screened to remove oversized particles and then fractionated into suitable sizes for asphalt production. Further separation of RAP into coarse and fine fractions assists in recombining materials to a grading target, especially for mixes containing more than 20% RAP or for gap graded mixes.

Although the addition of up to 15% RAP has little impact on the properties of dense grades asphalt (DGA) mixes with conventional binders, mixes exceeding 15% of the total mix may require binder grade adjustment to compensate for the stiffness of the aged RAP binder. RAP should be tested to ensure suitability for recycling. Typically, RAP testing is limited to particle size distribution (PSD) and binder content, although viscosity may be required where the binder grade needs to be adjusted to compensate for the aged RAP binder. Materials containing tar are not suitable due to the risk of fuming. Aggregates that are rounded or polished may only be suitable for basecourse applications.

RAP stockpile management should ensure:

- traceability is maintained, different sources, quality and sizes of RAP materials are kept separate
- consolidation of the stockpile is prevented
- moisture ingress is minimal, preferably by storing stockpiles undercover.

Maximising the Use of RAP in Asphalt Mix Design

Austroads (2016) was the final report of a three-year study which had aimed to maximise the use of RAP in new asphalt mixes and reduce the uncertainty surrounding the performance of asphalt mixes designed and constructed with RAP. The study included determining the characteristics of binder blends in RAP mixes, the performance of laboratory mixes containing varying percentages of RAP, and the validation of the design procedure for plant-produced mixes.

Furthermore, the report highlighted the importance of detailed RAP management plans, which should include, but not be limited to the following considerations:

- detailed plans for sourcing, processing, transport and storage of RAP
  - traceability of the source
  - ensuring it is free from deleterious materials, such as roadbase material, concrete, bricks, timber, dust, clay and dirt
  - processing and storage of the RAP at the processing site
  - determination of the maximum aggregate size and management of oversize material
  - handling and transportation from processing site to asphalt plant
  - handling and storage at the asphalt plant
- inspection and test plans for determining
  - binder content
  - grading
  - characterisation of RAP binder viscosity if mix contains > 15% RAP, at least once per 1000 tonnes of processed RAP
- binder blend viscosity, using AGPT/T193
- a strategy on how to incorporate RAP sources with changing RAP binder viscosities and/or binder contents.

Utilising the binder blend characterisation with an implemented RAP management plan and constant monitoring of stockpiles allows the asphalt manufacturer to produce an optimised asphalt mix, without adverse impact on performance.

2.1.2 AAPA

AAPA (2018) was published in June 2019. The document aligns with the Austroads work described in Section 2.1.1.

The management plan aims to set a standard for control of quality and consistency in the winning of RAP and the delivery of processed RAP for use in asphalt. The document generally covers the selection of suitable materials, reclaiming and processing, stockpiling, testing and delivery. Information regarding the incorporation and mix design of asphalt mixes containing RAP, including a worked example, is also included.

2.1.3 NACoE

Following the conclusion of the Austroads research program into maximising RAP usage, the Queensland Department of Transport and Main Roads (TMR) initiated a project under the NACoE research program with the aim of implementing the findings of the Austroads research into TMR specifications. The NACoE project proposed amendments to the current TMR specifications for the management of high RAP content asphalt mixes, which may have applicability to WA. These include (Yousefdoost, Rebbechi & Petho 2018):

- binder blends
  - contractors to document their process control procedures for the management of the binder blend in their quality plan
  - binder blend management based on the outcomes of Austroads (2016)
  - allowing the use of rejuvenating agents in asphalt mixes containing high RAP contents
- addressing the following issues
  - implementation of the contractor’s RAP management plan (including management of binder blend and visual monitoring of RAP for the presence of contaminants)
  - capability of the plant to produce conforming asphalt at RAP approval level requested
- RAP must be hard, sound and durable
- RAP must be visually checked for the presence of foreign materials
- contractor to nominate a binder content and production tolerance for the processed RAP
- periodically test the processed RAP for maximum density.

2.1.4 Comparison of Austroads Member Practice

A summary of the requirements specified by Austroads members regarding RAP management practice is presented in Table 2.1.

The requirements generally cover aspects of sourcing, processing, stockpiling, proportioning, sampling and testing. It is noted that although there is a significant amount of commonality, some of the specifications are more prescriptive, which may be attributed to varying local materials, industry experience and individual requirements.

General observations from the comparison between current Main Roads requirements and other Austroads member practice include:

- DIPL and VicRoads are the only jurisdictions that specify that RAP may only be sourced from milling or excavation of asphalt pavements.

- VicRoads is the only agency that does not specify that RAP must be a free-flowing material.
- NZTA is the only agency that does not specify the RAP source.
- TMR and RMS place requirements on the transportation of RAP from the processing site to the asphalt plant.
- Main Roads is the only agency that has requirements for the storage facilities for processed RAP.
- Main Roads, TMR and RMS require that RAP must maintain traceability.
- As a minimum, most agencies require processed RAP to be tested for PSD, bitumen and moisture content. Main Roads and VicRoads require sampling per 1000 tonnes, TMR per 500 tonnes and RMS daily.
- DPTI is the only SRA that specifies auditing.

The comparisons indicate that Main Roads requirements for RAP usage are generally in line with the other jurisdictions reviewed.

Table 2.1: Comparison of Austroads member practice

Criteria	AAPA	Main Roads	DPTI	DIPL	TMR	RMS	VicRoads	NZTA
Source	▪ Surplus asphalt plant mix ▪ Material obtained from milling or excavation of asphalt pavements	▪ Surplus asphalt plant mix ▪ Material reclaimed from asphalt wearing course or intermediate by cold planning	▪ Surplus asphalt plant mix ▪ Material obtained from milling or excavation of asphalt pavements	▪ Material obtained from milling or excavation of asphalt pavements	▪ Asphalt	▪ Asphalt	▪ Material obtained from milling or excavation of asphalt pavements	-
Processing/fractionating	▪ Free flowing and consistent in appearance, free from contaminants ▪ Blended, crushed and screened to single or multiple sizes (0/20 mm, 0/10 mm etc.) ▪ No segregation or contamination of processed RAP during transportation from processing site to asphalt plant	▪ Free flowing and consistent in appearance, free from contaminants ▪ Crushed and screened to produce 7 mm or 10 mm material with fines, 14 mm without fines, less than 2% passing 6.7 mm sieve	▪ Free flowing and consistent in appearance, free from contaminants ▪ Crushed and screened to maximum size of asphalt being produced	▪ Free flowing and consistent in appearance, free from contaminants ▪ Crushed and screened to maximum size of asphalt being produced	▪ Blended, crushed and screened to ensure 100% passing 26.5 mm sieve ▪ Free flowing, consistent PSD and minimal aggregate fracture, free from contaminants ▪ No segregation or contamination of processed RAP during transportation from processing site to asphalt plant	▪ Blended, crushed and screened to ensure 100% passing 26.5 mm sieve ▪ Free flowing, consistent PSD and minimal aggregate fracture, free from contaminants ▪ No segregation or contamination of processed RAP during transportation from processing site to asphalt plant	▪ Crushed and screened to maximum size of asphalt being produced, free from contaminants	▪ Free flowing and consistent in appearance, free from contaminants ▪ Crushed and screen to maximum size of asphalt being produced
Storage and stockpiling	▪ Separate stockpiles for processed/unprocessed RAP ▪ Processed RAP stockpile must not exceed 1000 tonnes ▪ Walled and covered where possible ▪ Floor of storage facility shall be sloped down to enhance drainage ▪ Stockpile shaped to reduce potential for segregation	▪ Separate stockpiles for processed/unprocessed RAP ▪ Processed RAP shall be stored under cover ▪ Floor of storage facility shall be concrete sloping down to a drain ▪ Processed RAP shall be maintained in lots, ensuring traceability	▪ Processed RAP of each size must be placed in separate stockpiles ▪ Processed RAP stockpiles must not exceed 1000 tonnes	▪ Processed RAP of each size must be placed in separate stockpiles	▪ Separate stockpiles for processed/unprocessed RAP ▪ Processed RAP stockpile must not exceed 1000 tonnes ▪ Stockpile at asphalt plant must not exceed 500 tonnes ▪ Processed RAP must be traceable to a designated stockpile	▪ Separate stockpiles for processed/unprocessed RAP ▪ Processed stockpile must not exceed 1000 tonnes ▪ Stockpile at asphalt plant must not exceed 500 tonnes ▪ Processed RAP must be traceable to a designated stockpile	▪ Mixes containing up to 10% contents above limits: – testing of multiple samples from processed RAP to match PSD and binder content data to registered asphalt mix design – statistical assessment of variability – once a stockpile is assessed for compliance, no further processed RAP shall be added	▪ Separate stockpiles for RAP
Inspection, test plans and auditing	▪ Minimum of 3 samples taken from each stockpile ▪ Processed RAP tested for PSD, bitumen content, maximum density and moisture content ▪ If rain of sufficient intensity to impact the moisture content of RAP occurs between when stockpile was tested and when RAP is to be used, moisture content must be retested	▪ RAP management plan detailing stockpiling, processing and testing is required ▪ Minimum of 3 samples/1000 tonnes in each of processed RAP ▪ Processed RAP tested for PSD, bitumen content and moisture content	▪ RAP management plan ▪ Indirect tensile strength testing on a daily production basis for mixes > 10% RAP ▪ Mixes > 10% RAP require RAP bitumen content and viscosity testing, may require rejuvenating agent to counteract hardening and produce a lower viscosity grade of bitumen ▪ Minimum of 1 kg sample/lot provided to DPTI	-	▪ Project quality plan detailing sampling, method and frequency is required ▪ RAP management plan to ensure homogenous distribution of aggregate and moisture control is required ▪ Processed RAP tested for PSD, bitumen content 1/500 tonnes ▪ Recovered binder viscosity of RAP tested 1/1000 tonnes (only if RAP binder exceeds 15% of total binder in the mix)	▪ Project quality plan detailing sampling, method and frequency is required ▪ RAP management plan to ensure homogenous distribution of aggregate and moisture control is required ▪ Processed RAP tested for PSD, bitumen content and moisture content daily	▪ RAP management plan (for mixes containing additional 10% RAP) ▪ Processed RAP tested for PSD, bitumen content and moisture content 1/1000 tonnes ▪ Processed RAP tested for unsound rock content and PSD on each production day, unless certification of specification compliance is received for delivery to mixing plant	▪ Project quality plan to monitor consistency grading, binder properties and incoming RAP if >15% RAP ▪ Processed RAP tested for PSD, bitumen content ▪ Processed RAP stockpile may be tested for minimum specific gravity if RAP is from different sources

2.2 Selected International Practice

A review of select international practice regarding RAP management and usage was undertaken.

2.2.1 Europe

The practice of using RAP in HMA and warm mix asphalt (WMA) production is well established in Europe. Table 2.2 shows figures released by the European Asphalt Pavement Association (EAPA) in 2016 detailing the use of RAP in HMA and WMA in Europe compared to the USA.

Table 2.2: Reuse and recycling rates of RAP in 2016, Europe compared to USA

Country	Available RAP (million tonnes)	% of available RAP used in				
		HMA and WMA production	Cold recycling	Unbound road layers	Other civil engineering applications	Landfill/ application unknown
Austria	1.40	40	No data	No data	No data	No data
Belgium	1.24	81	No data	No data	No data	No data
Czech Republic	1.80	17	30	20	10	23
Denmark	1.15	65	0	9	0	26
Finland	1.15	100	0	0	0	0
France	6.37	70	No data	No data	No data	No data
Germany	12.00	87	0	13	0	0
Great Britain	3.25	80	No data	No data	5	No data
Italy	9.00	20	30	20	0	30
Netherlands	4.43	71	11	0	0	18
Norway	1.11	37	0	63	0	0
Turkey	3.55	2	2	96	0	0
USA	74.20	94	0	4	1	1

Note: Countries without available RAP data and countries with less than 1 000 000 tonnes of available RAP were excluded from table.
Source: EAPA (2016).

European standard EN 13108-8:2016 *Bituminous Mixtures: Materials Specification, Reclaimed Asphalt* describes the required RAP documentation and management procedures. RAP must be derived from asphalt material, free from foreign materials and contaminants. Should the RAP contain any materials not derived from asphalt , the content and type must be documented. The RAP is then categorised according to the content and material type.

RAP stockpiles must also be tested for PSD, detailing the grading and sieve requirements. Furthermore, the RAP source, type, aggregate properties and homogeneity must be documented. Stockpiled RAP must maintain traceability and include the supplier, material designation and time and date of delivery.

The RAP binder type, properties and content must be determined and documented, indicating whether the binder is paving grade, hard grade, modified or if it contains any additional additives. Paving grade RAP binder can be classified according to the penetration, softening point or viscosity at 60 °C, in accordance with EN 13108-8. However, for binder that is not paving grade, a declaration of the nature and properties of the binder based on available information must be made to evaluate its suitability.

EN 13108-8 also outlines the required sampling and testing requirements. Processed RAP should be tested at a rate of one sample per 500 tonnes, rounded upwards with a minimum of five tests. Asphalt mixes containing low proportions of RAP (< 10% in surface courses, < 20% in binder courses or basecourses) may be tested at a reduced frequency of one sample per 2000 tonnes, and one sample per batch of feedstock.

Germany

The practice of using RAP in HMA and warm mix asphalt (WMA) production is well established in Europe. Table 2.2 shows figures released by the European Asphalt Pavement Association (EAPA) in 2016 detailing the use of RAP in HMA and WMA in Europe compared to the USA.

Table 2.2 shows that Germany is the highest producer of RAP in Europe, with approximately 87% of all RAP produced reused in HMA and WMA production. The management and production of RAP is covered in the German Asphalt Pavement Association Asphalt Guidelines *Recycling of Asphalt* (DAV 2011).

The RAP is typically produced through the selective milling of asphalt layers, where RAP recovered exclusively from wearing courses must be stored separately from material reclaimed from both asphalt wearing and asphalt binder courses. Asphalt reclaimed from stone mastic asphalt (SMA) and other special types of mixtures must also be stored separately. The reclaimed material must be crushed and screened to a homogenous material with a particle size no larger than the mix being produced. RAP stockpiles should maintain traceability and be stored dry, ideally in a warehouse.

Asphalt producers must develop a RAP management plan detailing stockpiling, testing and monitoring requirements, where the processed RAP is to be tested for PSD, RAP binder content and the ring-and-ball softening point. Sampling is required at a rate of one sample per 500 tonnes of stockpile.

Furthermore, the use of RAP in asphalt mixes, as well as the required performance testing is covered in the following two German specifications:

- *Technical Delivery Specification for Bituminous Mixtures for the Construction of Traffic Area Pavements* (FGSV 2013b)
  - allows use of RAP in all asphalt types with the exception of porous asphalt
  - regulates composition of mixes and quality requirements
  - requirements are universal, encompassing mixes containing RAP
  - softening point of an asphalt mix containing RAP has to meet the requirements of the binder specification in the tender.
- *Additional Terms of Contract and Guidelines for the Construction of Road Surfacing from Asphalt* (FGSV 2013a)
  - softening point (ring and ball) of a recovered binder from site control after paving is not allowed to exceed the softening point in the suitability test for the mix design.

2.2.2 Japan

Japanese RAP usage and management practice is outlined in NAPA (2015c) *High RAP Asphalt Pavements: Japan Practice: Lessons Learned*, developed from a US–industry study tour of Japan in 2014. Notably, approximately 99% of all Japanese RAP is recycled into new pavements, with mixes containing an average RAP proportion of 47% in 2013, primarily used in surfacing layers.

Effective RAP management practice, allowing Japan to consistently produce high RAP content mixes, includes the following key aspects:

- No restrictions are placed on the origin of the RAP.
- RAP is typically fractionated (although not required).
- Care is taken when crushing, screening and stockpiling to minimise the ingress of moisture and dust contents.
- Processed RAP stockpiles are kept covered and are stored on a paved surface, typically limiting stockpile moisture contents to between 1.5–2.0%.
- RAP is typically heated in a twin drum system (discussed in Section 3.1.1).
- RAP is required to meet the following criteria
  - binder content ≥ 3.8%
  - processed RAP percent passing 0.075 mm sieve ≤ 5%
  - recovered RAP binder must have a penetration > 20 penetration units (pu), or compacted RAP must have an indirect tensile (IDT) coefficient of < 1.70 MPa/mm.

2.2.3 South Africa

The estimated annual usage of RAP in South Africa in 2014 was 350 000 tonnes, 10% of the annual asphalt production rate (SABITA 2017). SABITA (2017) outlines the RAP management and usage best practice for South Africa.

RAP may be sourced from surplus plant mix or from material reclaimed from asphalt pavement layers. Crushing, screening and fractionating the RAP must produce a free–flowing material of uniform quality and free from contaminants. Although fractionating is recommended for all mixes containing RAP, mixes containing less than 15% binder replacement proportions may only require the removal of oversized lumps using a scalping screen.

RAP stockpile management is an important aspect of best practice and in South Africa the following recommendations are made:

- Unprocessed RAP stockpiles should be stored in arc-shaped uniformly layered stockpiles to improve uniformity.
- Processed RAP stockpiles should be stored in conical or small sloped piles to assist with water shedding and reduce stockpile consolidation
  - the stockpile base should be hardened and sloped to facilitate drainage and prevent ponding
  - ideally stored in an open-sided shed.
- Unprocessed RAP should be stored in separate stockpiles to processed RAP.

Sampling and testing requirements are also stated. It is recommended that RAP stockpiles are tested for moisture content daily, to ensure the moisture content does not exceed 0.5% as it may not be completely dried during the heating process. Additional quality control tests recommended for stockpiles include:

- binder content of RAP
- PSD of RAP aggregate
- bulk density of RAP aggregate

- agreed properties of RAP aggregate
- RAP binder properties (mixes > 15% binder replacement values).

2.2.4 United Kingdom

RAP usage and quality control requirements in the UK are outlined in the *Manual of Contract Documents for Highway Works: Volume 1 Specification for Highway Works Series 900: Road Pavements: Bituminous Bound Materials* (Highways Agency 2008). However, this does not cover RAP management practices.

RAP may be used in surfacing courses, binder courses, regulating courses and basecourses. It must be processed to a homogenous mixture with a maximum particle size of 32 mm. Asphalt mixes containing less than 10% RAP are tested similarly to traditional asphalt materials, however the RAP binder must be checked for penetration. Additionally, the penetration or softening point of the combined RAP and fresh binder must be calculated in accordance with EN 13108-1:2016 *Bituminous Mixtures: Material Specifications: Asphalt Concrete*. Cores of binder course and basecourse mixes containing more than 25% RAP must be tested for stiffness where compliance varies based on the grade of the virgin binder. Furthermore, Series 900 does not specify a maximum proportion of RAP.

To facilitate the routine additions of up 10% RAP in asphalt mixes, the Transport Research Laboratory (TRL) published the *Best Practice Guide for Recycling into Surface Course* (Carswell et al. 2010). This recommends practice in specifying, designing and producing RAP. Recommendations include:

- RAP intended for use in surface course mixes should be milled only from asphalt surface courses.
- RAP of different gradings and properties should be stored in separate stockpiles and transported separately to avoid contamination.
- Material reclaimed exclusively from the surface course should be stored in separate stockpiles to material reclaimed from multiple asphalt layers.
- Stockpiles should be stored in facilities to minimise contamination and moisture ingress.
- The maximum RAP content may be limited by plant capabilities.

2.2.5 United States of America

The USA is recognised as a leader in asphalt recycling, producing approximately 74 million tonnes of asphalt in 2016, of which 94% was recycled in HMA and WMA mixes (EAPA 2016). The RAP usage and management practices in the USA are similar to Australia in that each state jurisdiction has developed its own guidelines and specifications. As a result, practice varies between jurisdictions. Prominent publications that summarise current practice in the USA include:

- *Reclaimed Asphalt Pavement Management: Best Practices* (West 2010).
- *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice* (FHWA 2011).
- *Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content* (West, Willis & Marasteanu 2013).
- *Asphalt Pavement Industry Survey on Recycled Materials and Warm-mix Asphalt Usage 2015* (NAPA 2015a).
- *Best Practices for RAP and RAS Management* (NAPA 2015b).

Key information in these publications is summarised in the following sections.

Source

RAP is typically obtained from milling full-depth asphalt pavements and surplus asphalt plant mix, but may also be sourced from full-depth asphalt pavement demolition. When RAP is obtained from multiple sources, it is important that the RAP management plan considers when to keep a new source separate and when to combine the RAP obtained from different sources. Furthermore, RAP must be free from deleterious materials (FHWA 2011).

It may be beneficial to selectively mill the asphalt layers, where RAP recovered from surface layers is obtained separately to RAP from intermediate layers. This may be advantageous for wearing course mixes containing RAP where higher-quality, polish-resistant aggregates are desired, or where courses may contain unsuitable materials for RAP, such as slag (NAPA 2015b).

Processing and fractionating

Producing consistent RAP materials that meet applicable standards and may be used in high proportions requires processing, typically consisting of crushing and screening. Screening is used to separate RAP into discrete sizes and remove oversized particles. If desired, the screen may be used to fractionate the RAP into coarse and fine stockpiles, improving the control and consistency of RAP proportioning (FHWA 2011). Furthermore, crushing may be used to improve the consistency of RAP from different sources. However, it is important to select the crusher type, settings and techniques to avoid the excessive breakdown of aggregate particles, as this will increase the fines content (NAPA 2015b).

Storage and stockpiling

Requirements for RAP stockpiling vary between US jurisdictions. Generally, unprocessed and processed RAP must be stored in separate stockpiles. Best practice regarding stockpiles aims to minimise the risk of contamination, moisture ingress and segregation through (NAPA 2015b):

- storing unprocessed RAP in arc-shaped, uniformly layered stockpiles to improve uniformity
- storing processed RAP in conical, small sloped stockpiles to improve drainage and reduce stockpile consolidation
- storing stockpiles on paved, sloped surfaces to facilitate drainage and minimise segregation
- preferably storing RAP undercover to minimise moisture content fluctuations
- providing separate stockpiles based on the RAP source, sizes, quality of the material and the properties of the RAP binder.

Inspection, test plans and auditing

NAPA (2015b) recommends that to obtain the required consistency and properties of RAP stockpiles, a well-executed RAP sampling and testing plan should be developed. Best practice regarding the sampling and testing frequency of RAP stockpiles is to conduct at least one test per 1000 tons. Furthermore, to ensure stockpile consistency is undertaken using a representative statistical distribution, a minimum of 10 tests should be performed. Typical quality control tests include:

- binder content of the RAP
- PSD of the RAP aggregate
- bulk specific gravity of the RAP aggregate
- agreed properties of the RAP aggregate
- RAP binder properties (mixes > 15% binder replacement values).

The application of the design mix, as well as the proportion of RAP contents may require additional testing. For example, mixes used in a surface layer may require tests to evaluate the aggregate mineralogical composition or polishing characteristics (NAPA 2015b).

West (2010) highlighted that some state departments of transportation only allow traceable source RAP in their mixes, and RAP obtained from specific projects or pavement types. However, it was noted that by allowing only traceable source RAP in mixes hinders the use of RAP to its full potential, suggesting that the quality of RAP should be verified with routine testing as part of the quality control and mix design process.

2.2.6 Comparison of Main Roads and International Practice

A summary of the requirements specified in the international documentation regarding RAP management practice is presented in Table 2.3. International practices generally address the same criteria as Main Roads current specifications, although there is significant diversity in some respects. General observations from the comparison between current Main Roads requirements and international practice include:

- Main Roads specified source of RAP is generally in agreement with the international practices reviewed. However, the notable difference is Japan, where there are no restrictions placed on RAP origins.
- Germany and the UK recommend that asphalt material should be selectively milled, separating material reclaimed from wearing courses and other asphalt courses.
- Fractionating the processed RAP is recommended in Japan, South Africa and the USA. Additionally, South Africa specifies different processing practice for mixes containing more or less than 15% RAP proportions (by binder replacement).
- The UK recommends that RAP with different gradings and properties should be transported separately to avoid contamination.
- There is general agreement that best practice involves storing the processed RAP in a dry, covered area to minimise the risks of moisture ingress.
- Germany and the UK recommend storing material reclaimed exclusively from asphalt wearing courses separately to material reclaimed from multiple layers.
- Main Roads and European practice specify that RAP must be traceable.
- South Africa and the USA recommend best practice regarding the shape of unprocessed and processed RAP stockpiles.
- Testing of processed RAP generally includes PSD, RAP binder content and moisture content. Japan and the UK also include provision for penetration testing and Germany includes provision for softening point testing of RAP binder. South African specifications state that moisture content of RAP stockpiles should be checked daily.

In reviewing international practice in relation to Main Roads, it can be seen that although relationships are evident between local and international practice, there are some aspects of international practice that differ significantly. There are, however, several possible explanations. Differences in test methods and design practice, as well as industry experience and capability, may influence comparisons between international requirements.

Table 2.3: Comparison of Main Roads and international practice

Criteria	Main Roads	Germany	Japan	South Africa	UK	USA
Source	▪ Surplus asphalt plant mix ▪ Material reclaimed from asphalt wearing course or intermediate by cold planing	▪ Slabs of asphalt ▪ Selective milling of material reclaimed from asphalt courses	▪ No restrictions to RAP origin	▪ Surplus asphalt plant mix ▪ Material reclaimed from asphalt pavement layers	▪ Asphalt ▪ RAP intended for surface courses should be milled only from surface course[2]	▪ Surplus asphalt plant mix ▪ Material reclaimed from asphalt courses
Processing/fractionating	▪ Free flowing and consistent in appearance, free from contaminants ▪ Crushed and screened to produce 7 mm or 10 mm material with fines, 14 mm without fines, less than 2% passing 6.7 mm sieve	▪ Homogenous material ▪ Crushed and screened to maximum size of asphalt being produced	▪ Crushed and screened to minus 13 to 5 mm and minus 5 mm sizes ▪ RAP is commonly fractionated, and the plants are equipped with multiple RAP feed bins (although not required)	▪ Free flowing material of uniform quality, free from contaminants ▪ Mixes < 15% (binder replacement), crushed, screened and fractionated (optional) to appropriate size, oversized lumps removed ▪ Mixes > 15% (binder replacement), crushed, screened and fractionated to a sieve size one smaller than maximum aggregate used in mix	▪ Homogenously mixed ▪ Crushed to a maximum size of 32 mm ▪ RAP with different gradings and properties should be transported separately[2]	▪ Free from contaminants ▪ Crushed and screened to separate sizes for control and consistency ▪ Fractionating is recommended for control and consistency of RAP proportioning
Storage and stockpiling	▪ Separate stockpiles for processed/unprocessed RAP ▪ Processed RAP shall be stored under cover ▪ Floor of storage facility shall be concrete sloping down to a drain ▪ Processed RAP shall be maintained in lots, ensuring traceability	▪ Separate storage of material reclaimed exclusively from asphalt wearing courses and material reclaimed from asphalt wearing courses and asphalt binder courses ▪ Stored dry to reduce moisture content of stockpile, ideally in a warehouse ▪ Processed RAP shall be traceable[1]	▪ Stockpiles are covered and located on a paved surface ▪ Storage bins are kept covered	▪ Separate stockpiles for processed/unprocessed RAP ▪ Unprocessed RAP stored in arc-shaped uniformly layered stockpiles ▪ Processed RAP stored in conical or small, low-sloped piles ▪ Floor of storage facility shall be hardened and sloped for drainage ▪ Should be stored in open-sided shed	▪ Separate storage areas for each classification of RAP[2] ▪ Separate RAP stockpiles for RAP obtained from surface course, RAP obtained from multiple layers[2] ▪ Storage facilities minimise contamination and moisture ingress[2]	▪ Separate stockpiles for processed/unprocessed RAP ▪ Unprocessed RAP stored in arc-shaped uniformly layered stockpiles ▪ Processed RAP stored in conical or small, low sloped piles ▪ Separate stockpiles based on category of RAP ▪ Stored under to reduce moisture ingress ▪ Floor of storage facility shall be constructed on appropriate surfaces to prevent contamination
Inspection, test plans and auditing	▪ RAP management plan detailing stockpiling, processing and testing is required ▪ Minimum of 3 samples/1000 tonnes in each of processed RAP ▪ Processed RAP tested for PSD, bitumen content and moisture content	▪ RAP management plan detailing stockpiling, testing and monitoring ▪ Processed RAP tested for PSD, bitumen content and softening point 1/500 tonnes ▪ RAP binder type, properties and content must be documented[1]	▪ RAP binder properties tested for stiffness ▪ RAP tested for minimum binder content, penetration (or indirect tensile test) and fines content	▪ Processed RAP tested for PSD, binder content, moisture content, bulk density of RAP, properties for aggregate recovered from RAP ▪ Mixes > 15% (binder replacement) require RAP binder properties and RAP aggregate properties ▪ Moisture content of RAP checked daily	▪ Testing in accordance with traditional asphalt materials ▪ RAP binder tested for penetration and calculation of properties of combined binder (with fresh bitumen) ▪ Mixes > 10% require additional testing ▪ Mixes > 25% in basecourse or binder course require additional stiffness testing	▪ RAP sampling and testing plan is required ▪ Testing in accordance with traditional asphalt materials ▪ Processed RAP tested for PSD, binder content, bulk specific gravity, RAP aggregate properties and RAP binder properties at a minimum of 1/1000 tons (minimum 10 tests) ▪ Additional tests and frequency vary with RAP category and RAP content in mix

2.3 Current Practice and Limitations in WA

Consultation with representatives from three selected asphalt producers in the Perth metropolitan area were undertaken during April 2018. This was to gain a better understanding of the current RAP management and production processes, as well as to identify any limitations which may impact increased usage of RAP.

2.3.1 Current Practice

The current practice of local suppliers is summarised in Table 2.4, based on similar criteria listed in Table 2.1 and Table 2.3.

Table 2.4: Comparison of local Perth suppliers' current practice

Criteria	Supplier A	Supplier B	Supplier C
Source	▪ Removed asphalt pavement, plant surplus or site returns	▪ Removed asphalt pavement, plant surplus or site returns	▪ Only plant surplus or site returns
Processing/fractionating	▪ Screener operates with 10 mm and 14 mm screens to generate screen material classified as fine (< 10 mm) and oversize (> 14 mm). Oversize materials are crushed to minimise fracture of aggregate particles and then rescreened	▪ Crushed and screened to produce 10 mm material with fines	▪ Crushed and screened to produce 14 mm material with fines
Storage and stockpiling	▪ Processed RAP stored in a covered bay with capacity to hold 500 tonnes, bay has concrete sidewall and roof and is clearly identified as processed RAP storage	▪ Separate stockpiles for processed/unprocessed RAP ▪ Processed RAP stored under cover ▪ Approximately 70 000 tonnes unprocessed RAP ▪ Floor of storage facility sloping down to a drain ▪ Constructing new undercover stockpile areas with concrete floor sloping down to a drain	▪ Separate stockpiles for processed/unprocessed RAP ▪ Processed RAP not stored under cover ▪ Floor of storage facility sloping down to a drain
Maximum proportions	▪ Between 10-15% RAP by mass of total in local government wearing courses	▪ Up to 10% RAP by mass in local government wearing courses	▪ Up to 10% RAP by mass in local government wearing courses
Inspection, test plans and auditing	▪ Samples of processed RAP are collected and tested for moisture content, binder content and PSD for every 1000 tonnes of processed RAP	▪ Samples of processed RAP are collected and tested for moisture content, binder content and PSD for every 1000 tonnes of processed RAP	▪ Samples of processed RAP are collected and tested for moisture content, binder content and PSD for every 1000 tonnes of processed RAP
Documentation	▪ Generic national RAP management plan	▪ Site-specific RAP management plan	▪ Generic national RAP management plan

Criteria	Supplier A	Supplier B	Supplier C
Comments/opinions	▪ Relax envelope on nominal size required by Main Roads	▪ Increase use in wearing courses. Eastern states have included up to 20% without rejuvenators added	▪ Use 10 to 15% RAP in wearing courses ▪ Alternative to binder blend method, because test frequency high at every 1000 tonnes, if looking at high RAP content

2.3.2 Limitations

The major limitation that was identified in the consultations was the consistent sourcing of sufficient RAP quantities. As most of the road network in WA is comprised of thin layers of asphalt on granular pavement (Cocks et al. 2017), the quantities of RAP may not be adequate to consistently produce mixes containing RAP contents greater than 20%. Notably, Supplier C primarily sources its RAP from project returns or plant waste, rather than the milling of existing asphalt pavements, thus significantly limiting quantities. The estimated quantities of RAP processed by each of the local suppliers in 2017 was approximately:

- 25 000 tonnes by Supplier A
- 11 700 tonnes by Supplier B
- 6000 tonnes by Supplier C.

All suppliers indicated that if the target quantities of RAP were to be increased, there would be a significant amount of upfront capital investment required to improve the plant and upgrade the laboratories to keep up with the required testing. Supplier A also indicated that the available land for stockpiling may need to be increased to handle the increased quantities and associated storage requirements.

2.4 Discussion

This section set out to review current documented practice both nationally and internationally regarding RAP management practice. The study identified that Main Roads requirements are generally in accordance with other Austroads member requirements. Furthermore, in comparison with international practice, it may be concluded that Main Roads requirements for RAP management, although there is commonality, vary considerably in some respects.

In reviewing international practice in relation to Main Roads, it can be seen that although relationships are evident between local and international practice, there are some aspects of international practice that differ significantly. There are, however, several possible explanations. Differences in test methods and design practice as well as industry experience and capability may influence comparisons with international requirements.

Consultation with local industry indicated that there may be limitations to increasing the required RAP quantities. The limitations are generally related to sourcing sufficient quantities, land required for stockpiling and the required capital investment to upgrade the plant and testing laboratories.

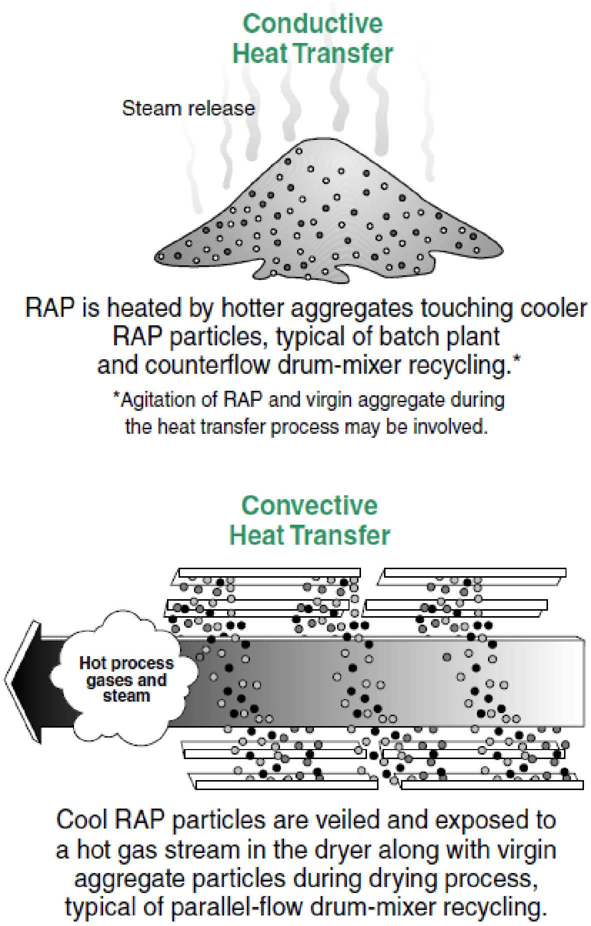
3 PLANT TECHNOLOGY AND REQUIREMENTS FOR THE PRODUCTION OF HIGH RAP CONTENT ASPHALT MIXES

3.1 Methods of Incorporating RAP into Asphalt Mixes

RAP can typically be added to asphalt mixes without the alteration of current plant technology. However, without specialised plant modifications the RAP content that can be added to the mix without compromising quality is typically 30% maximum (Arnold et al. 2012). There are generally two basic types of asphalt mixing plants available, batch mixing and continuous mixing . Furthermore, specialised plants capable of producing conforming asphalt mixes with high RAP contents (more than 50%) have also been developed, although they currently have limited use internationally.

Asphalt plants ordinarily heat RAP using two methods, conductive heat transfer or convective heat transfer as illustrated in Figure 3.1. Conductive heat transfer is common in batch mixing facilities while convective heating is typical of continuous mixing plants using parallel flow dryers. Section 3.1 discusses the different plant configurations as well as the associated heat transferal.

Figure 3.1: Conductive vs convective heat transfer



Source: NAPA (2007).

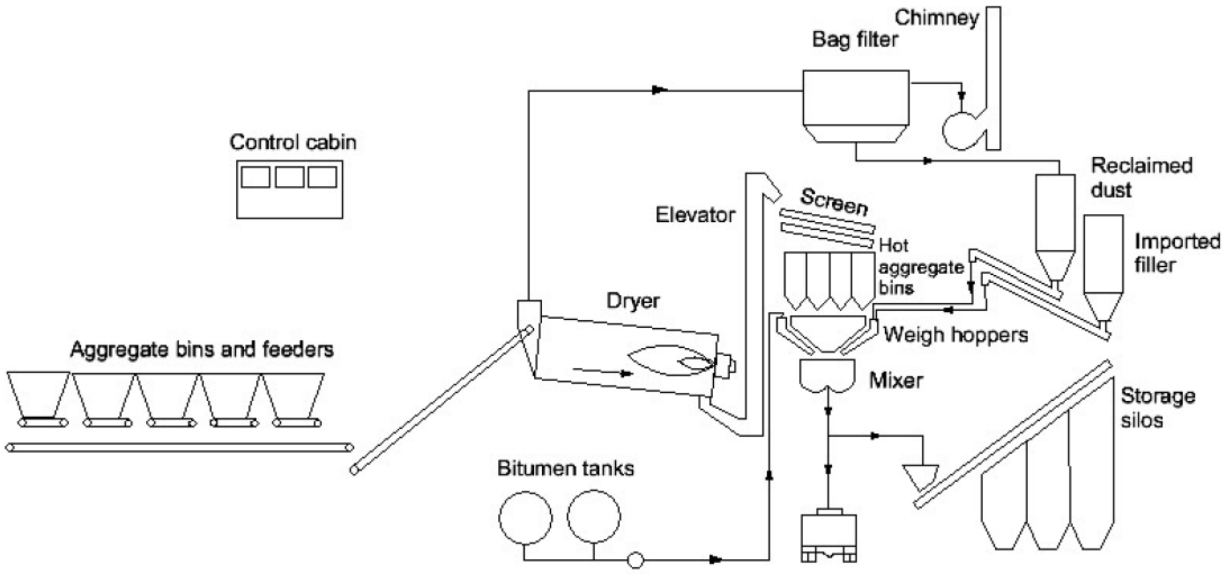
3.1.1 Batch Mixing Plants

In batch mixing plants, the aggregates and binder are weighed separately and mixed together in predetermined batch sizes in a pugmill mix chamber (AAPA 2010).

The typical batch plant mixing process, as represented by Figure 3.2 consists of the following:

1. aggregates are transferred using a conveyor from cold storage bins to a rotating dryer, where the aggregates are heated to the appropriate temperature for the mix type, typically 170 °C
2. the dry, heated aggregates are then elevated to a screen, where the hot aggregates are separated into various fractions
3. separated aggregates are then placed into hot storage bins
4. hot aggregates and filler are then weighed in a hopper, sprayed into the pugmill and wet mixed
5. asphalt mix is then discharged into trucks or transferred to hot storage.

Figure 3.2: Typical batch plant



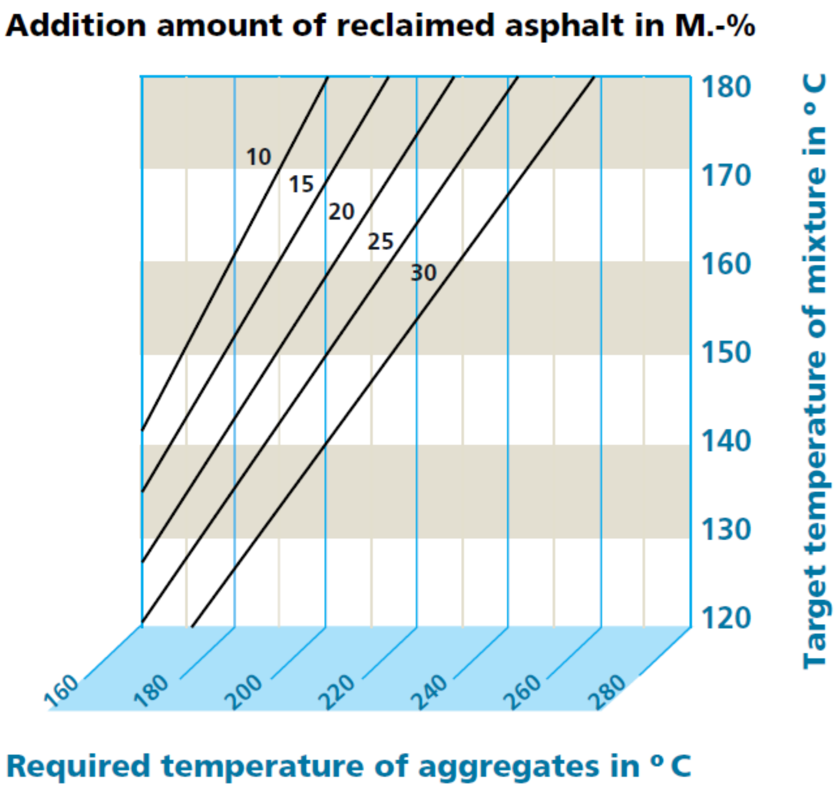
Source: Austroads (2014).

These plants have the advantage of flexibility in the ease of changing from one size of mix to another without wastage (AAPA 2010).

The most basic method for introducing RAP into new asphalt mixes is by adding cold, wet RAP to the weigh hopper in addition to the already superheated virgin aggregates. Heat is transferred from the superheated aggregates to the RAP. Direct heating of the RAP may cause damage to the binder properties/rheology due to excessive heat exposure.

In practice, the feasible RAP content that can be added to the mix is limited by the moisture content of the RAP, as the virgin aggregate has to be heated to an appropriate temperature to sufficiently dry the RAP material. DAV (2011) developed the values presented in Figure 3.3 and Table 3.1 for achieving moisture evaporation in the RAP based on the temperature of virgin aggregates and RAP content.

Figure 3.3: Required temperature of aggregates at specified mix temperatures varying with RAP content



Source: DAV (2011).

Table 3.1: Required temperature increase of virgin aggregates to remove moisture (grey areas to be avoided)

RAP content (%)	Moisture content of RAP (%)					
	1	2	3	4	5	6
	Required increase in virgin aggregate temperature (°C)					
10	4	8	12	16	20	24
15	6	12	18	24	30	36
20	8	16	24	32	40	48
25	10	20	30	40	50	60
30	12	14	-	-	-	-

Source: DAV (2011).

An alternative configuration to the batch plant mixing is to add the wet, cold RAP to the superheated aggregates via a cold feed bin directly into the hot elevator, where the heated aggregate is discharged from the dryer. The RAP mixes with the superheated virgin aggregate in the bucket elevator from which the combined aggregates are dropped into a pugmill where it is mixed with new binder. Typical RAP mix quantities can be as high as 30% (SABITA 2017).

Similar to the bucket elevator method, the proportion of RAP added to the mix can be increased to quantities of up to 40% with the addition of a heat transfer chamber (collar) on the dryer (DAV 2011). Heating occurs at the dryer through convective heat transfer, extending the heating time and reducing the amount of steam produced, thus allowing higher percentages of RAP to be introduced.

By introducing a separate (twin) drum dryer to the batch plant set-up, the RAP can be heated through convective heat transfer before being conveyed to a hot storage bin and transferred to the pugmill as a separate ingredient for mix production. Parallel flow dryers are typically used for the RAP dryer recycling technique. Steam and hydrocarbons from the convective heat transfer of the RAP are exhausted to the primary aggregate dryer where hydrocarbons are destroyed in the combustion area of the dryer. The percentages of RAP that can be added to the mix are primarily limited by the capability of the primary aggregate dryer to accept steam and hydrocarbon-laden gases from the RAP dryer (NAPA 2007). However, asphalt mixes containing as much as 80−100% have been produced using this method in Germany (DAV 2011). This particular configuration can be implemented in both a batching plant, and a continuous mixing plant.

3.1.2 Continuous Mixing Plants

Australian continuous mixing plants are primarily of the drum mixing plant configuration (Austroads 2014). Typical continuous drum mixing plants feed the aggregates into the burner end of the drum, where the mixing and coating of aggregates with binder occurs simultaneously in a revolving drum. Furthermore, there are two typical flow types of continuous mixing plants:

- Parallel flow – aggregates are fed into the drum at the burner end of the drum and bitumen is added near the outlet of the drum, farthest from the burner. Exhaust gases travel through the dryer in the same direction as the aggregates.
- Counter flow – typically utilise an extended burner to shield the bitumen and RAP from direct contact with the burner flame. Exhaust gases travel through the dryer against the flow of aggregates.

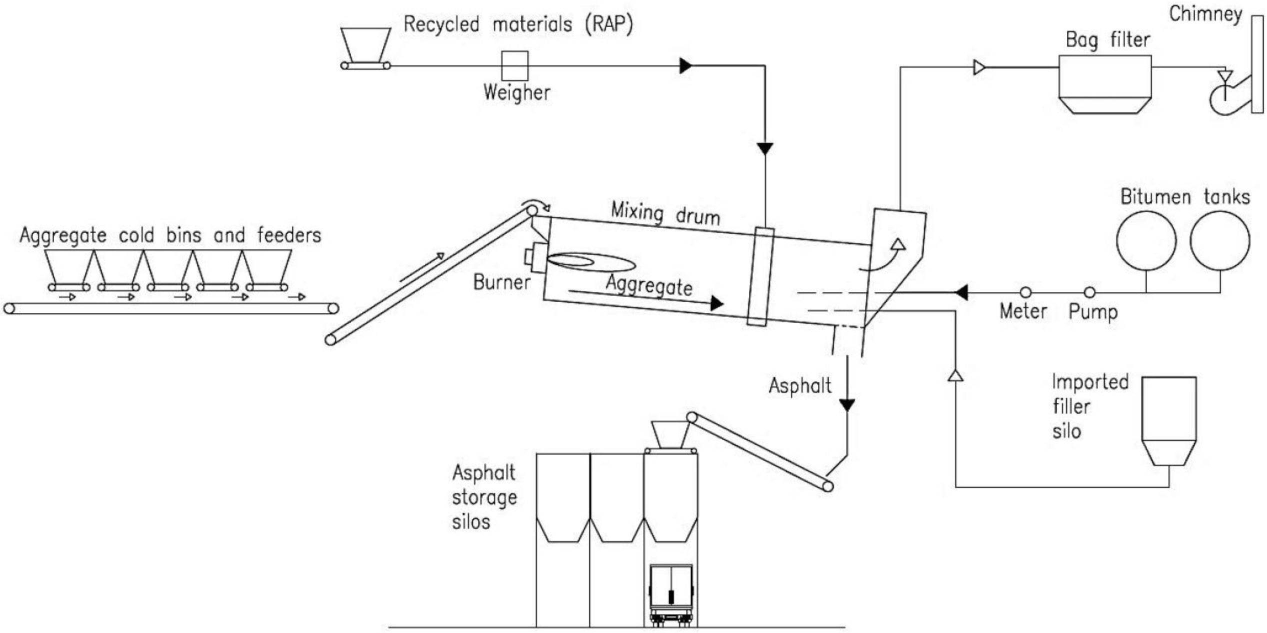
Compared to batch plants, continuous mixing plants do not further screen and recombine aggregates following heating and drying, thus eliminating the need for hot elevators, vibrating screens, hot aggregate storage bins and weigh hoppers (Austroads 2014).

Parallel Flow Mixers

The simplest configuration for a continuous mixing plant generally consists of a parallel flow drum mixer where RAP is fed into the drum from a cold feed bin via an inclined belt, in the same way that virgin aggregates are fed into the drum. The RAP is heated convectively on the burner side of the drum, where fresh binder is added at the discharge end of the dryer where the temperature is lower. Typical RAP content limits for this configuration are a maximum of 10% (SABITA 2017).

One of the most common approaches for introducing RAP into the mixing process is by equipping the parallel flow drum with a RAP collar, which enables RAP entry mid-drum away from the burner end, thus reducing damage to the RAP binder (Figure 3.4). However, the RAP proportions are still limited by the level of acceptable gaseous emissions and visible opacity limits (NAPA 2007). A maximum of 25% RAP is typically achievable using this configuration (SABITA 2017).

Figure 3.4: Typical parallel flow drum mixing plant (with RAP collar)



Source: Austroads (2014).

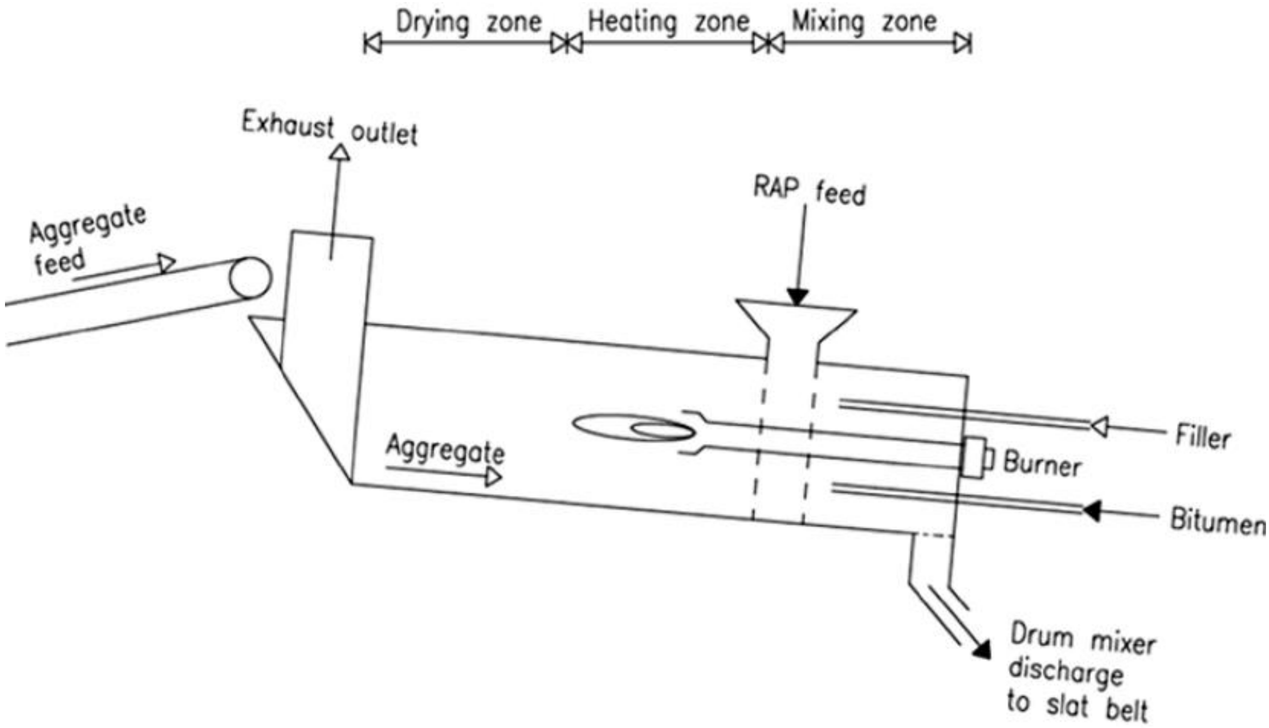
Continuous mixing plants may also use a separate rotating mixing drum or continuous pugmill, known as an after-mixer (coater) where the RAP can be introduced so all hydrocarbon, except for the burner fuel, can be kept from the process gas stream. The virgin aggregates are heated in the parallel flow dryer where the RAP is then heated conductively in the after-mixer (NAPA 2007). Maximum RAP proportions are limited by the physical space available in the mixing device, typically to approximately 30% (SABITA 2017).

The addition of an after-mixer to a parallel flow configuration with a RAP collar can increase the maximum RAP contents of the mix to 40% (SABITA 2017). The RAP is heated convectively in the same method as the RAP collar; however, as the binder is added in an isolated area, the hydrocarbon content in the process gases is reduced, thus increasing the acceptable RAP contents.

Counter Flow Mixers

Continuous mixing plants can change the dryer configuration to a counter flow drum mixing system, where the burner is located at the discharge end of the drum to isolate the mixing zone from the drying zone. The addition of RAP is typically achieved using a RAP collar, where heating occurs conductively with superheated aggregate in the vicinity of the hottest part of the dryer shell (Figure 3.5). RAP steam is exhausted directly into the aggregate dryer drum with the virgin aggregate steam. The design of this plant enables high proportions of RAP ranging from 30% (SABITA 2017) to 50% (Austroads 2014) to be used, as the RAP has a longer residence time with superheated virgin aggregates.

Figure 3.5: Typical counter flow drum mixing plant (with RAP collar)

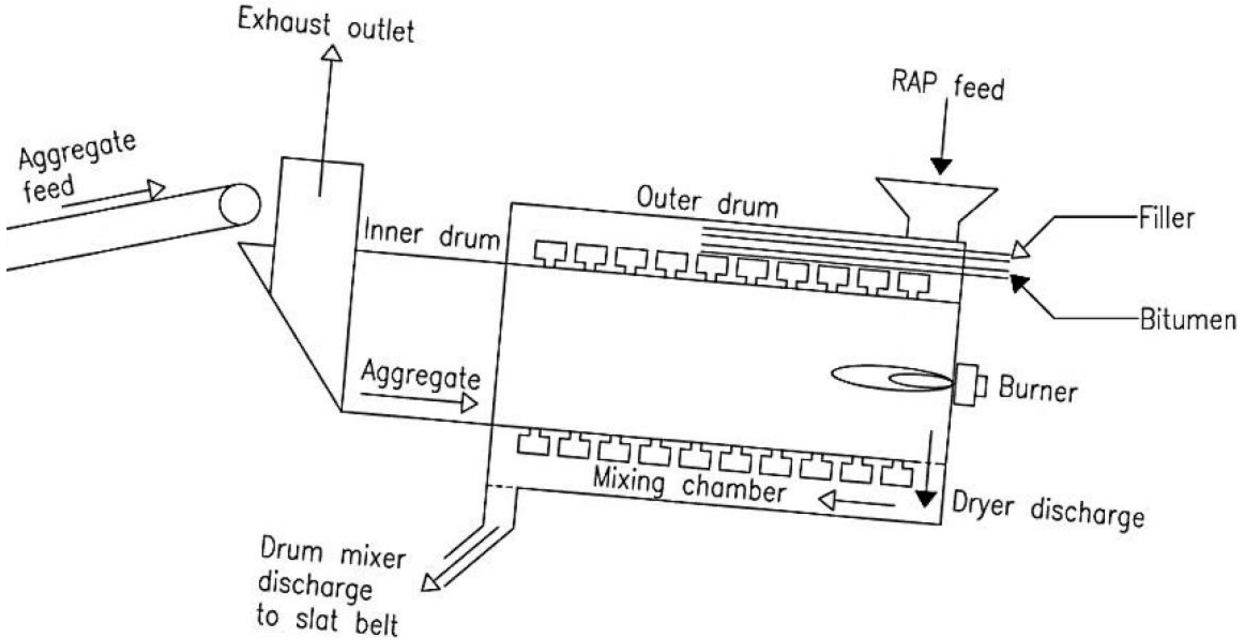


Source: Austroads (2014).

Alternatively, the RAP can be added to an after-mixer where it is heated conductively with the superheated virgin aggregates, similar to the parallel flow set-up with an after-mixer. The RAP content is limited by the length of the mixing device, typically to proportions of approximately 30%, with quantities up to 40% when used in combination with a RAP collar (SABITA 2017).

Double drum mixers comprise a counter flow dryer, with an inner drum where the virgin aggregates are dried and heated. The aggregates are then discharged to the outer drum for mixing, where the heated virgin aggregates, RAP, bitumen and filler are combined. The RAP is heated through conduction with the heated aggregates as well as the heat transfer from the combustion area of the drying shell. Although mixes containing up to 70% RAP (SABITA 2017) can be produced using this type of configuration, production is typically limited to approximately 30−40% RAP due to practical constraints (Austroads 2014). The principle of the double drum mixing system is illustrated in Figure 3.6.

Figure 3.6: Typical double drum mixer



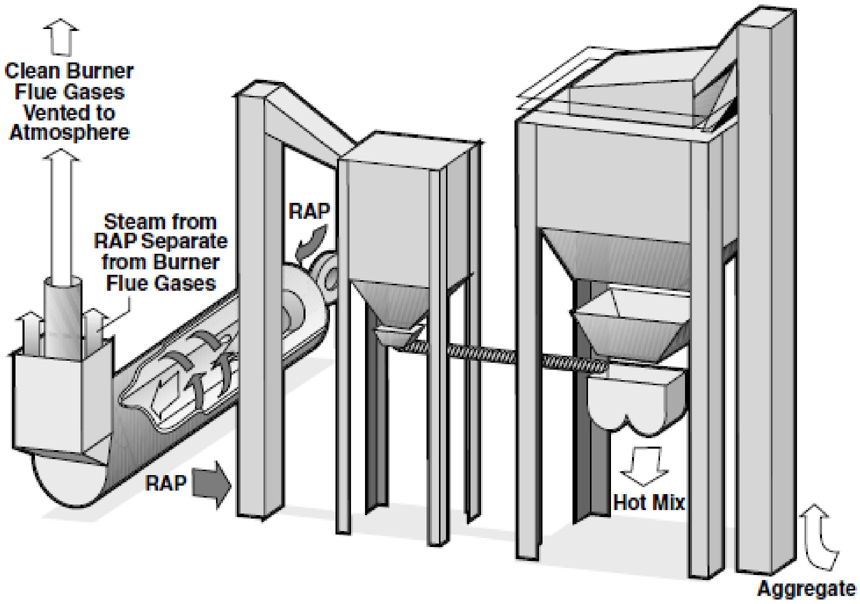
Source: Austroads (2014).

3.1.3 Specialised High RAP Content Plants

The practical RAP limit for conventional asphalt plants is typically around 50%; however, two highly specialised plants for producing mixes with high proportions of RAP have been developed overseas. These plants rely on an indirect heat transfer approach or microwave heat transfer technology.

The indirect heat transfer method heats RAP in a rotating dryer using conductive heat via flues or tubes that carry the burner exhaust gases through the dryer, resulting in little to no hydrocarbon vapour emissions (Figure 3.7). RAP recycling can reach levels of up to 100% using binder blends and rejuvenators. However, as RAP generally contains high fines content, gradation may limit the practical RAP content limits (NAPA 2007).

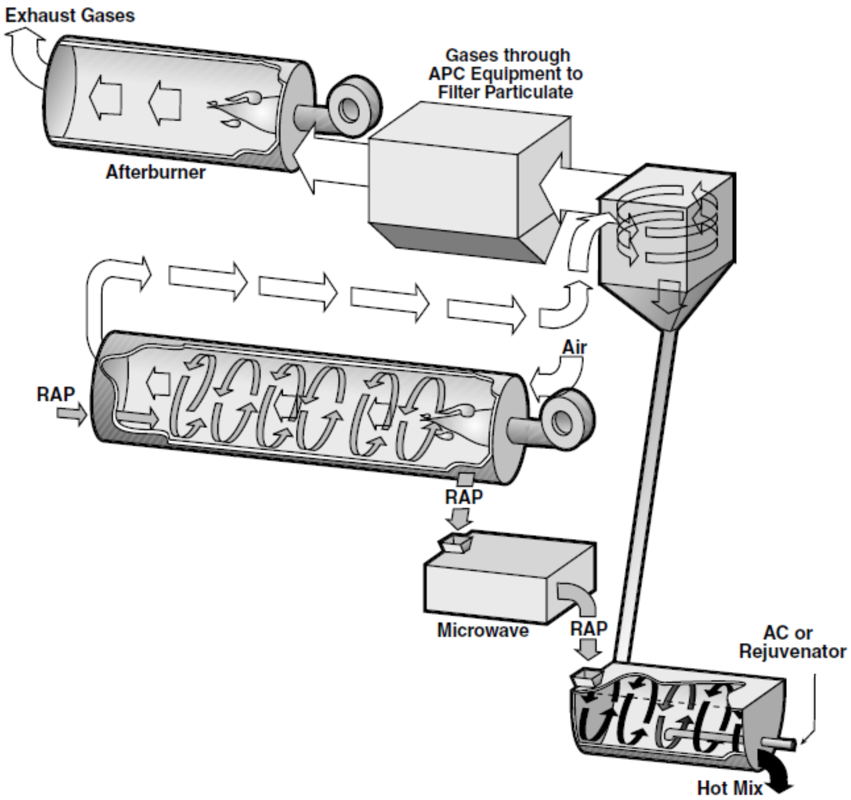
Figure 3.7: Indirect heat transfer approach



Source: NAPA (2007).

Microwave heat transfer technologies employ parallel or counter flow dryers to dry and heat the RAP to an elevated temperature, where it is then passed through a microwave heater to raise the RAP to paving temperatures. RAP is then combined with virgin aggregates, filler and binder in an after-mixer (Figure 3.8). Similar to indirect heat transfer, mixes may contain up to 100% RAP although this may be limited by achieving mix-compliant gradations (NAPA 2007).

Figure 3.8: Microwave heat transfer approach



Source: NAPA (2007).

3.1.4 Comparison between Different Plant Configurations

A summary of the method of RAP entering the asphalt mix, the RAP heating method and maximum RAP content that can be added to the mix for the assorted asphalt plant configurations is presented in Table 3.2.

Table 3.2: Typical maximum RAP content capabilities of different plant configurations

Type of mixing plant	Method of RAP entering mix	RAP heating method	Maximum RAP content (%)
Batch mixing plants			
▪ Weigh bucket	Weigh hopper via cold feed	Conductive – direct heating, mixing superheated virgin aggregates with cold, wet RAP	10–15
▪ Pugmill and bucket elevator	Bucket elevator via cold feed	Conductive – direct heating, mixing superheated virgin aggregates with cold, wet RAP	30
▪ Bucket elevator using heat transfer chamber (collar) on dryer	Bucket elevator via RAP collar	Convective – heated in heat transfer chamber (collar) on dryer	40
▪ RAP dryer recycling technique (twin drums)	Pugmill via separate hot storage bin and weigh hopper	Convective – heated in a typical parallel flow dryer	50-100

Type of mixing plant	Method of RAP entering mix	RAP heating method	Maximum RAP content (%)
Continuous mixing plants			
▪ Parallel flow with aggregate	Dryer drum via cold feed bin	Convective – heated in typical parallel flow dryer together with virgin aggregates	10
▪ Parallel flow with RAP collar	Mid-entry dryer drum via RAP collar	Convective – heating occurs in parallel flow dryer, in the middle of the drum	25
▪ Parallel flow with after-mixer/coater	Continuous rotating mixing drum via cold feed bins	Conductive – direct heating, mixing superheated virgin aggregates with cold, wet RAP	30
▪ Parallel flow with RAP collar and after-mixer/coater	Mid-entry dryer drum via RAP collar	Convective – heating occurs in parallel flow dryer, in the middle of the drum	40
▪ Counter flow with RAP collar	Mid-entry dryer drum via RAP collar	Conductive – direct heating, mixing superheated virgin aggregates with cold, wet RAP	30-50
▪ Counter flow with after-mixer	Continuous rotating mixing drum via cold feed bins	Conductive – direct heating, mixing superheated virgin aggregates with cold, wet RAP	30
▪ Counter flow with RAP collar and after-mixer	Dryer drum via RAP collar	Conductive – heated with virgin aggregate in the combustion area of the dryer	40
▪ Double drum mixer	Outer mixing shell via cold feed bins	Conductive – direct heating, mixing superheated virgin aggregates with cold, wet RAP, as well as heated drying shell	30–70
Specialised high RAP facilities			
▪ Indirect heat transfer	Batch or continuous mixing facility via rotating dryer	Conductive – heated in a rotating dryer via flues or tubes carrying burner exhaust gases through the dryer	100
▪ Microwave heat transfer	Continuous rotating mixing drum via microwave heater	Convective – heated using parallel flow or counter flow dryer to elevated temperatures then microwave heated to paving temperatures	100

3.2 Asphalt Plants Currently used in WA

Consultation with the main asphalt suppliers found that in Perth there are a variety of batch plants and drum plants. The suppliers indicated that the maximum RAP capabilities of each of the plants ranged from 10% to 30%. Therefore, there appears to be a significant limitation to the maximum RAP quantities these plants can produce.

3.3 Discussion

Based on the literature review of available plant configurations and methods of incorporating RAP into asphalt mixes, it is evident that there is a vast range of existing options. Some plants are configured to incorporate large proportions of RAP, although this may be limited by practical constraints. Therefore, the capability of the plant alone is not the sole factor in determining the maximum RAP content in an asphalt mix. The asphalt mix should still deliver the performance required, while containing RAP.

It is recommended that Main Roads adopts an outcome-based approach for determining the allowable RAP proportions for the suppliers' asphalt plants. This may be implemented by including a requirement for the suppliers to demonstrate that they are capable of producing conforming asphalt at the maximum RAP content to be adopted for the project. The technical evaluation could be undertaken as part of the asphalt mix design registration process.

4 TESTING AND EVALUATION OF RAP PROPERTY VARIATION IN WA STOCKPILES

The main purpose of a RAP management plan is to manage and limit the extent of RAP variability used in asphalt mixes. A test plan to evaluate the variability in properties of RAP stockpiles in WA formed part of the project. This section describes the testing and analysis undertaken as part of the test plan.

4.1 Variability of Processed RAP between Suppliers

To measure the variability of RAP in existing stockpiles stored at different WA asphalt suppliers, three suppliers in the Perth metropolitan area were approached to participate in the study. The suppliers would use RAP in asphalt mixes during the test period. The extent of WA sampling was limited to the Perth metropolitan area only, as the use of RAP in regional WA is relatively limited.

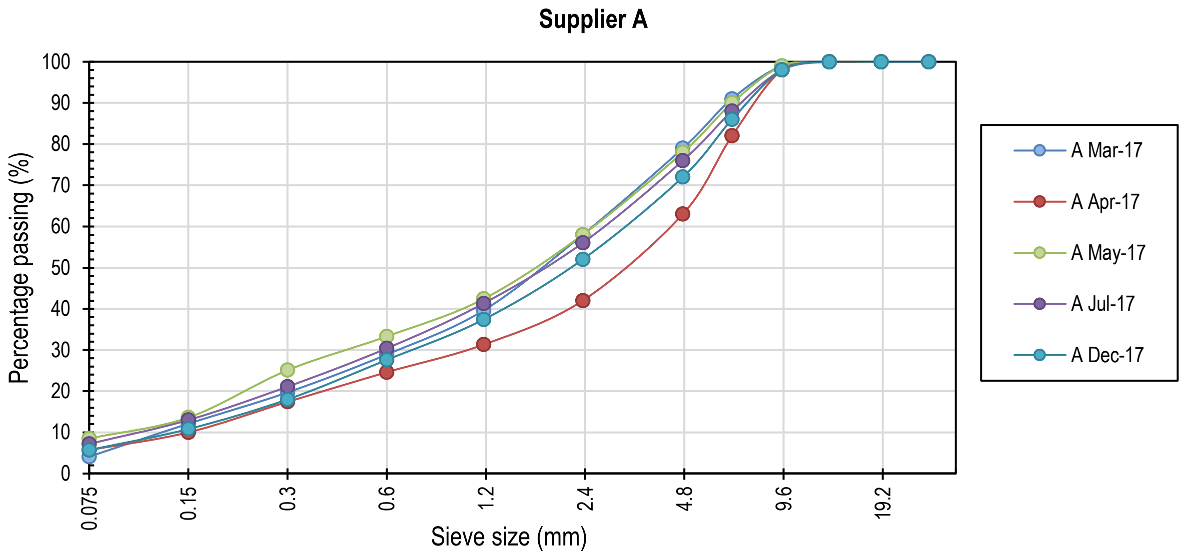
Samples were obtained monthly, over a 12-month period during 2017. A representative sample of RAP, from the stockpile of processed RAP in use for the specific month, sampled from a single sample point, was requested. If the supplier was not utilising processed RAP during the specific month, no sample was taken.

Suppliers provided the test results for the RAP sample's particle size distribution (PSD), binder content and moisture content. Binder extraction of the RAP sample and DSR testing on the extracted binder were conducted at the ARRB Vermont South Laboratory. The viscosity of the recovered binder was determined for temperatures between 50 ºC and 70 ºC using AGPT/T192 (2015).

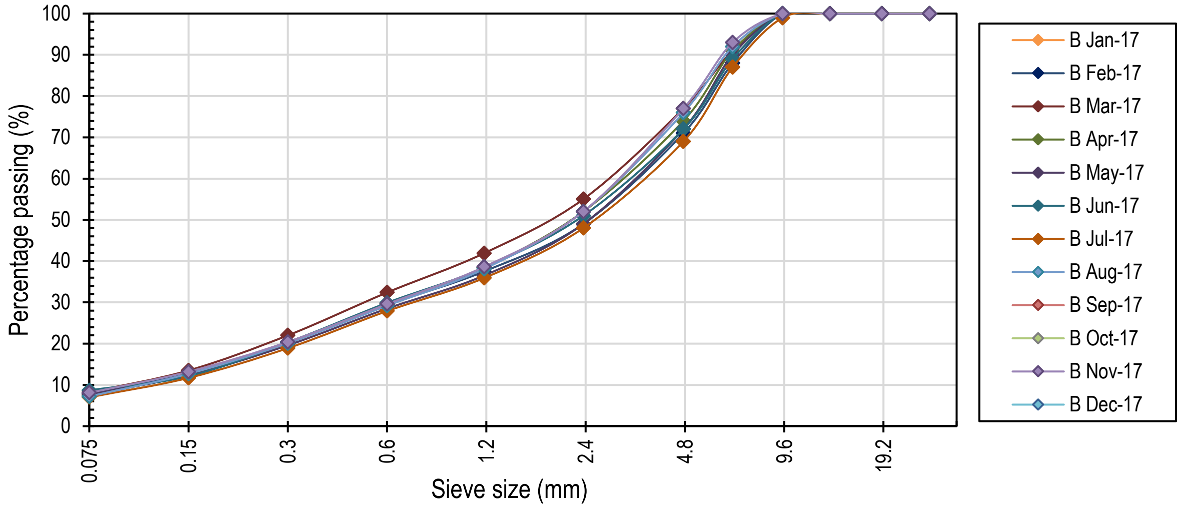
4.1.1 Particle Size Distribution

The PSD for the samples provided by the suppliers is depicted in Figure 4.1. Supplier A supplied limited samples during the 12-month period. All RAP was crushed and screened to pass the 9.5 mm sieve at between 95–100%.

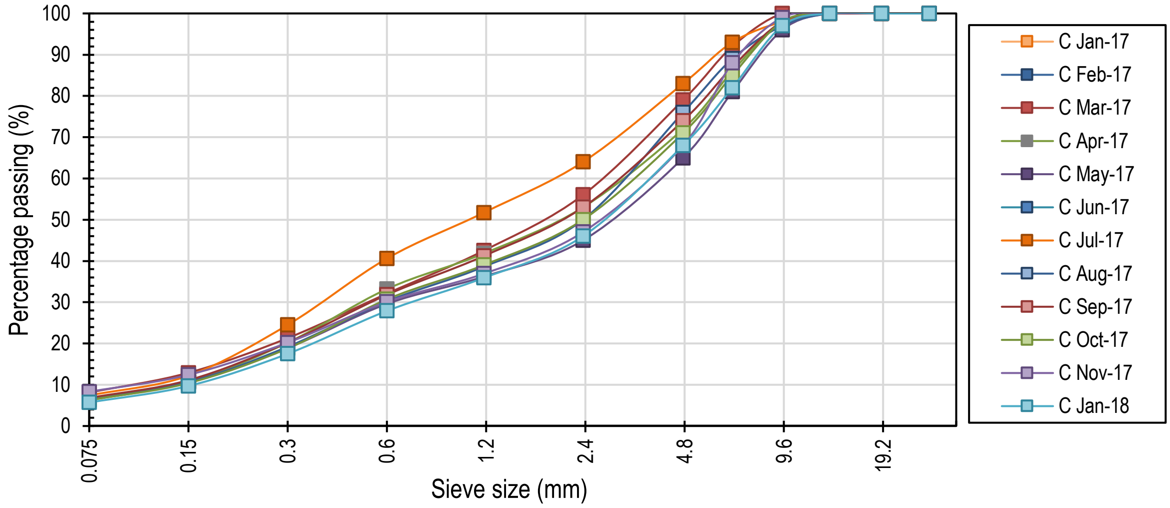
Figure 4.1: PSD of RAP samples from Perth Suppliers A, B and C



Supplier B


Percentage passing (%)
Sieve size (mm)
0.075
0.15
0.3
0.6
1.2
2.4
4.8
9.6
19.2
B Jan-17
B Feb-17
B Mar-17
B Apr-17
B May-17
B Jun-17
B Jul-17
B Aug-17
B Sep-17
B Oct-17
B Nov-17
B Dec-17

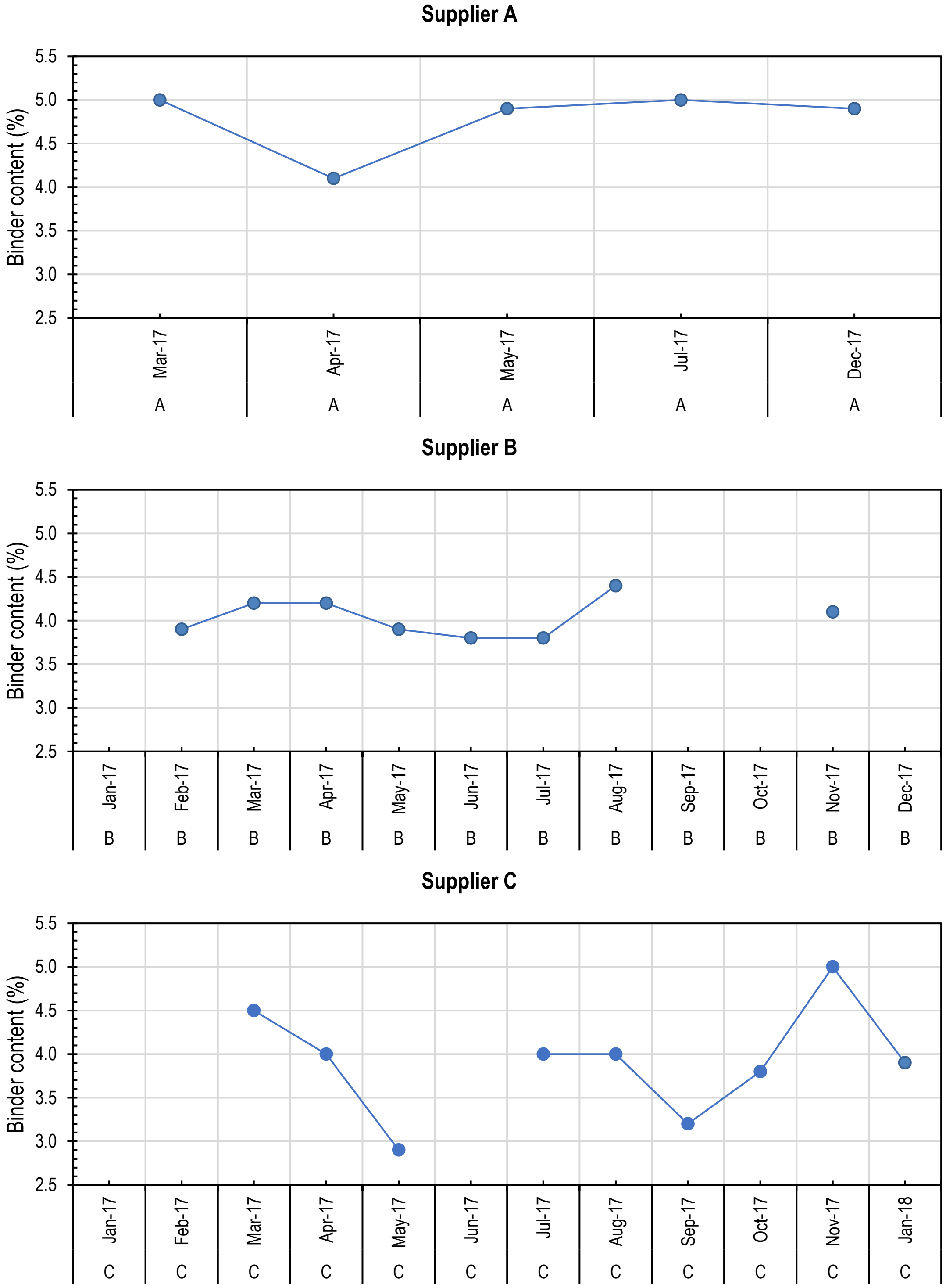
Supplier C


Percentage passing (%)
Sieve size (mm)
0.075
0.15
0.3
0.6
1.2
2.4
4.8
9.6
19.2
C Jan-17
C Feb-17
C Mar-17
C Apr-17
C May-17
C Jun-17
C Jul-17
C Aug-17
C Sep-17
C Oct-17
C Nov-17
C Jan-18

4.1.3 Binder Content

The binder content for the samples provided is depicted in Figure 4.2. The RAP binder content for Supplier C appears most variable, with binder contents between 2.9% and 5.0%. The RAP binder contents for Suppliers A and B show less variability and range between 3.8% and 5.0%.

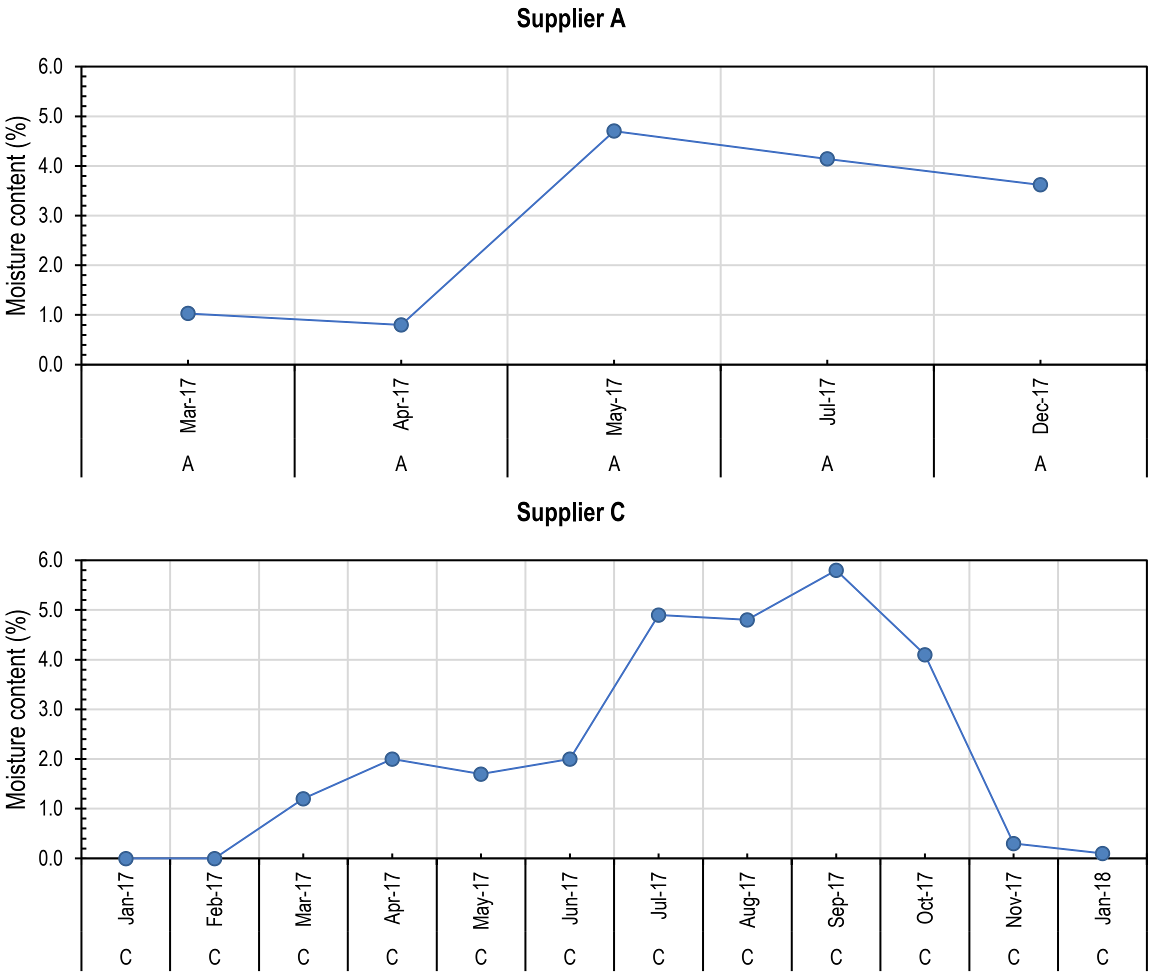
Figure 4.2: Binder content (%) of RAP samples from Perth Suppliers A, B and C



4.1.4 Moisture Content

The moisture contents are depicted in Figure 4.3. Supplier B did not report the moisture content of the samples provided. Supplier A reported RAP moisture content for May, July and December 2017 ranges between 3.6% and 4.7%. Supplier C moisture content indicates higher levels for the last six months of the supplied data, corresponding with the wet season in Perth, with a maximum moisture content of 5.8% in September 2017.

Figure 4.3: Moisture content (%) of RAP samples from Perth Suppliers A and C

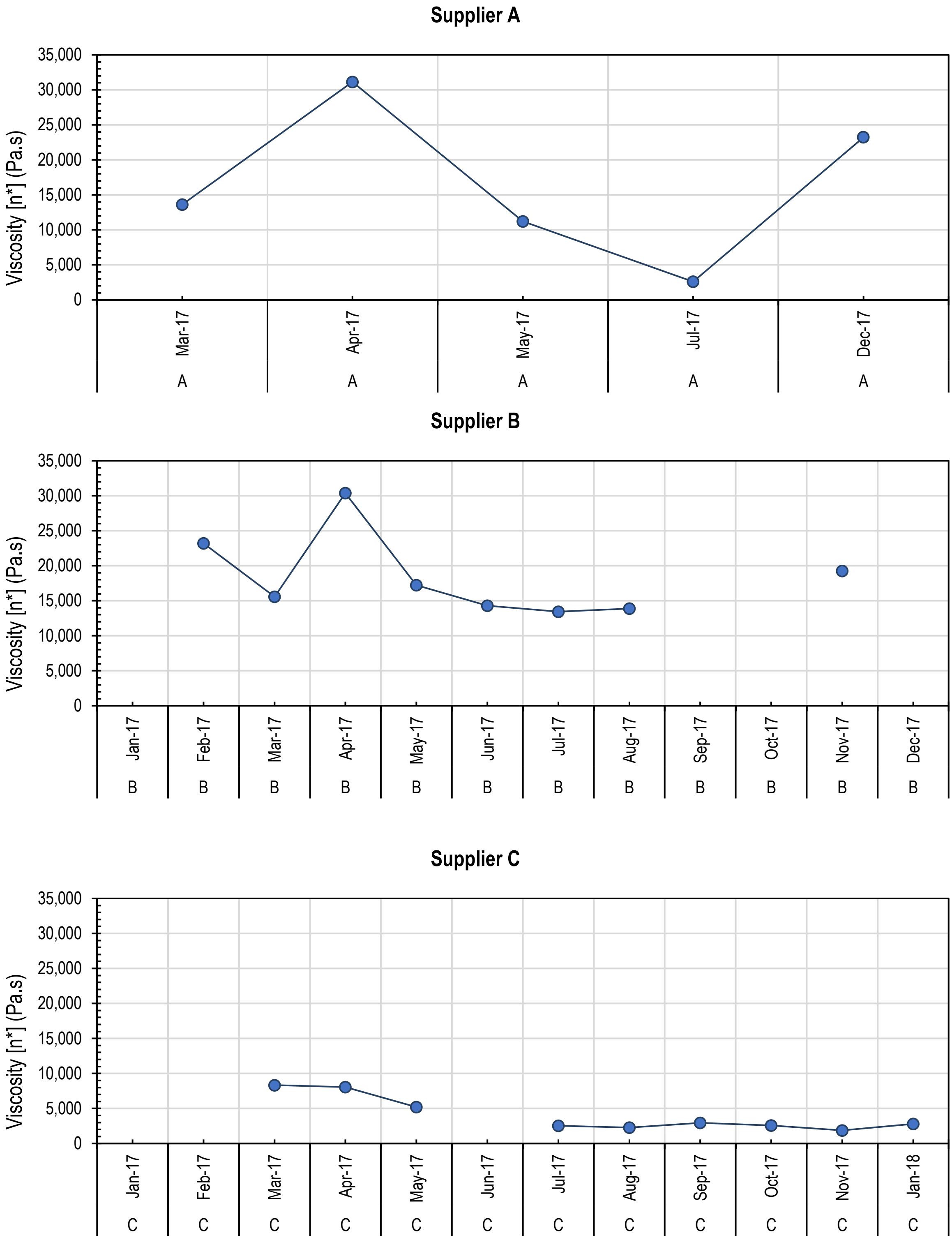


4.1.5 DSR Complex Viscosity (η)*

Following the recommendations in Austroads (2013), the results of DSR viscosity testing at 60 ºC and angular frequency of 1 rad/s is depicted in Figure 4.4 for comparison. The DSR viscosity test result at 60 ºC and angular frequency of 1 rad/s is considered similar to that of viscosity measured at the same temperature with the viscometer (Austroads 2013).

The variability in measured viscosity is considerable on a month-to-month basis, especially for Supplier A. The viscosity appears to remain constant for Supplier B between July and August 2017. Both Supplier A and B appear to have processed older material for RAP as the viscosity range is higher than for Supplier C, with a viscosity below 9000 Pa.s. Supplier C measured viscosity is less variable between July 2017 and January 2018. This correlates with the source of Supplier A and B RAP originating from projects and Supplier C RAP being plant returns only.

Figure 4.4: DSR complex viscosity (η*) of RAP samples from Perth Suppliers A, B and C



4.1.6 Impact of Variability on Binder Blend Proportions

In order to evaluate the impact of the variability measured and reported on in Section 5.1, the method outlined in AGPT/T193 (2015) was followed to calculate the proportions of a binder blend design. The proposed methodology relies on knowing the viscosity of each binder component, and then designing a suitable blend by using different percentages of each binder component as inputs into the blending equation to predict the target viscosity of the blended binder.

The blending formula is presented in Equation 1 (Austroads 2015):

$$VBI_i = \frac{3 + log\vartheta_i}{6 + \vartheta_i} \quad (1)$$

$$VBI_\beta = \sum_{i=1}^{n} x_i \cdot VBI_i$$

$$\mu = 10^{\left(\frac{3 \cdot VBI_\beta}{1 - VBI_\beta} - 3\right)}$$

where

ϑ_i	=	viscosity of i^{th} component (in Pa.s)
VBI_i	=	viscosity blending index of i^{th} component
VBI_β	=	viscosity blending index of the blend
x_i	=	volume fraction of i^{th} component
μ	=	viscosity of the blend (in Pa.s)

The aim of the binder blend design was to determine blend proportions, assuming the following:

- a 25% RAP content, with variable binder content
- target binder content of the asphalt mix containing RAP at 4.8%
- C320 virgin binder, with DSR complex viscosity of 490 Pa.s
- no low-viscosity oil added.

The blend should meet the DSR complex viscosity requirements for Austroads Class 600 bitumen (C600), i.e. approximately 980 Pa.s (± 55 Pa.s).

Table 4.1 summarises the results, based on the assumptions made and Equation 1. The viscosity of the blend for Supplier A and B achieves the target DSR complex viscosity of 980 Pa.s with variable success, with the lowest result at 738 Pa.s and the highest at 1066 Pa.s. Supplier Cs blend viscosities are generally lower averaging at approximately 671 Pa.s.

Table 4.1: Summary of binder blend design proportions per sample result

Assumptions:

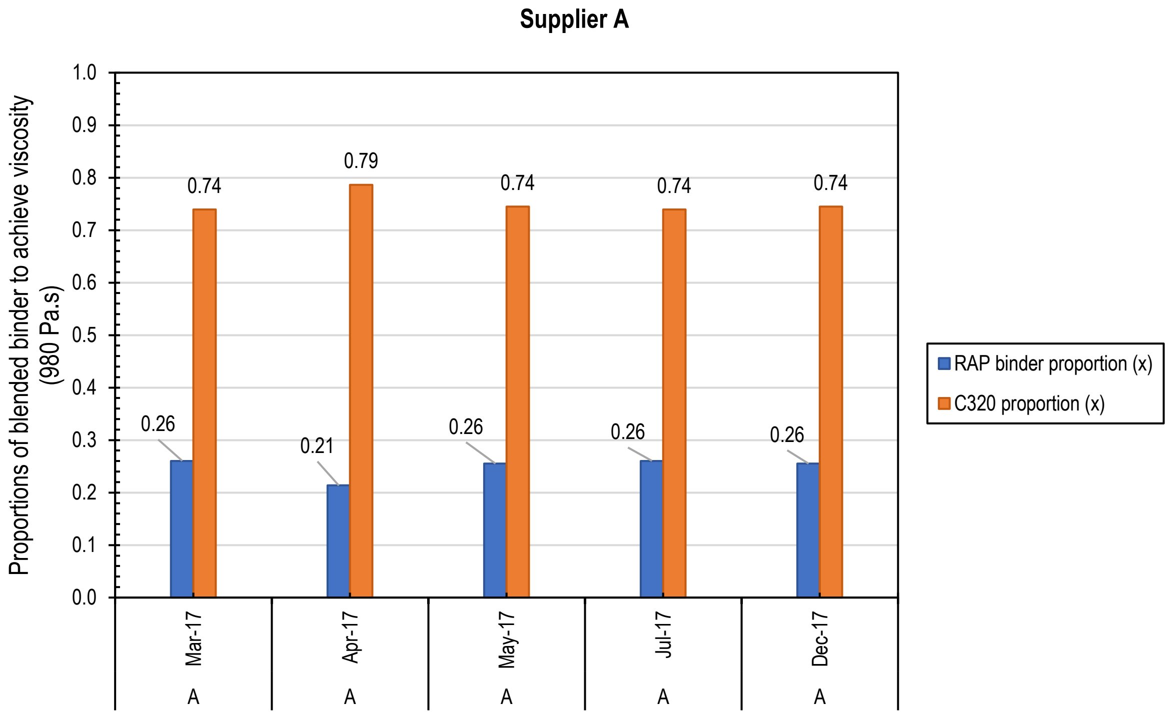
RAP in mix	25 %
Target binder of mix	4.8%

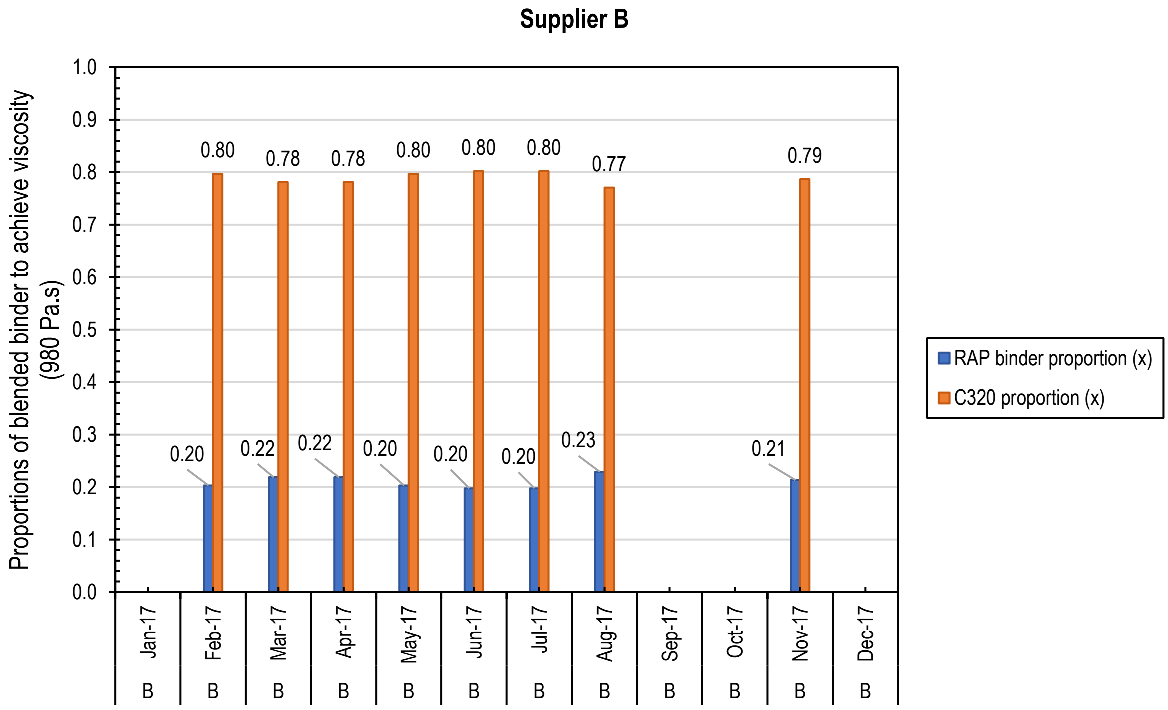
	Mean complex viscosity (Pa.s)	VBI (Pa.s)
C320	490	0.655

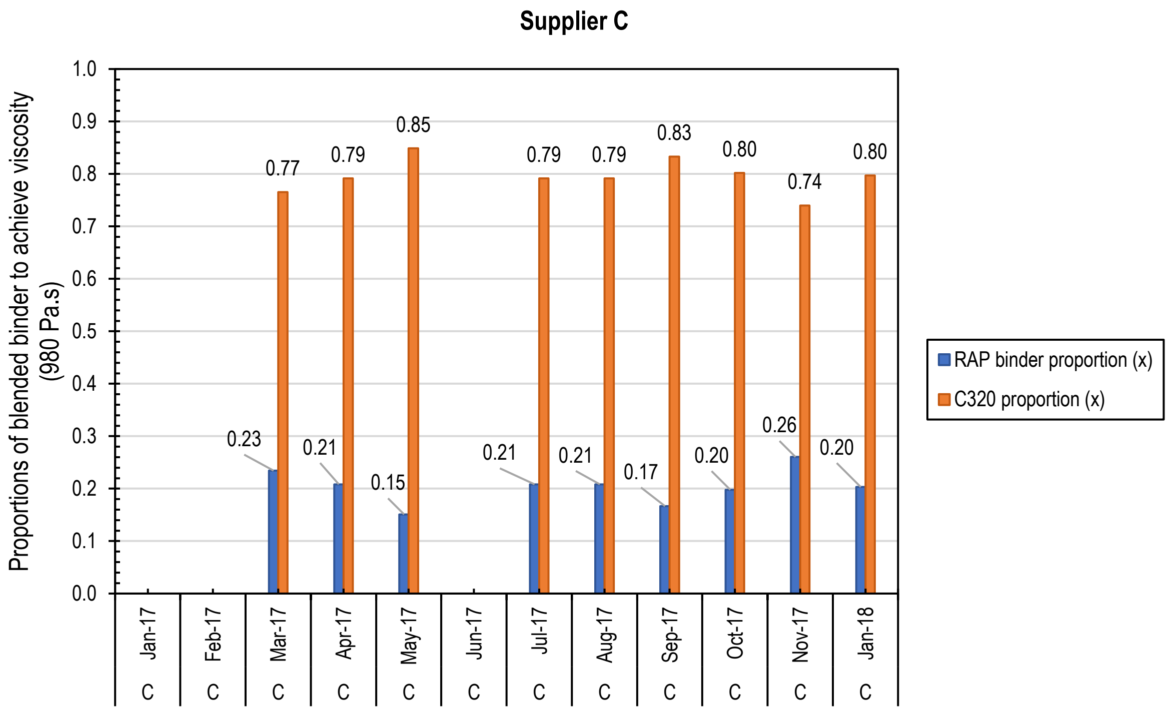
Supplier	Month sampled	RAP Binder content (%)	RAP binder proportion (x_{RAP})	ϑ_{RAP} (Pa.s)	VBI_{RAP} (Pa.s)	C320 proportion (x_{C320})	$VBI_{ß}$	μ (Pa.s)
A	Mar-17	5.00	0.260	13,630	0.704	0.740	0.668	1060
A	Apr-17	4.10	0.214	31,145	0.714	0.786	0.667	1050
A	May-17	4.90	0.255	11,205	0.701	0.745	0.667	1002
A	Jul-17	5.00	0.260	2,603	0.681	0.740	0.662	*738*
A	Dec-17	4.90	0.255	23,215	0.711	0.745	0.669	1159
B	Jan-17	No data	–	–	–	–	–	–
B	Feb-17	3.90	0.203	23,205	0.711	0.797	0.666	966
B	Mar-17	4.20	0.219	15,575	0.706	0.781	0.666	954
B	Apr-17	4.20	0.219	30,370	0.714	0.781	0.668	1066
B	May-17	3.90	0.203	17,240	0.707	0.797	0.665	*923*
B	Jun-17	3.80	0.198	14,305	0.705	0.802	0.665	*882*
B	Jul-17	3.80	0.198	13,440	0.704	0.802	0.664	*874*
B	Aug-17	4.40	0.229	13,880	0.704	0.771	0.666	966
B	Sep-17	No data	–	–	–	–	–	–
B	Oct-17	No data	–	–	–	–	–	–
B	Nov-17	4.10	0.214	19,265	0.708	0.786	0.666	972
B	Dec-17	No data	–	–	–	–	–	–
C	Jan-17	No data	–	–	–	–	–	–
C	Feb-17	No data	–	–	–	–	–	–
C	Mar-17	4.50	0.234	8,339	0.698	0.766	0.665	*892*
C	Apr-17	4.00	0.208	8,059	0.697	0.792	0.664	*828*
C	May-17	2.90	0.151	5,217	0.691	0.849	0.660	*678*
C	Jun-17	No data	–	–	–	–	–	–
C	Jul-17	4.00	0.208	2,541	0.681	0.792	0.660	*676*
C	Aug-17	4.00	0.208	2,259	0.679	0.792	0.660	*662*
C	Sep-17	3.20	0.167	2,956	0.683	0.833	0.660	*647*
C	Oct-17	3.80	0.198	2,581	0.681	0.802	0.660	*667*
C	Nov-17	5.00	0.260	1,871	0.676	0.740	0.660	*683*
C	Jan-18	3.90	0.203	2,802	0.682	0.797	0.660	*682*

Figure 4.5 illustrates the proportions of RAP binder and virgin binder, reported in Table 4.1, per supplier. The proportions calculated for Supplier A and B are fairly constant, while Supplier C appears to have more variability on a monthly basis. This variation in proportions will require more diligence in monitoring the asphalt produced with RAP and adjusting the asphalt designs accordingly.

Figure 4.5: Binder blend design proportions per sample per supplier







4.2 Variability of Processed RAP over a Period of Four Days

Supplier A conducted testing of RAP material sampled immediately after going through the crushing and screening process at the supplier's plant between 4 and 7 April 2017, in the morning and afternoon. The variability and impact of the variability on asphalt mix design is evaluated in this section.

The supplier noted that during operation, once there was sufficient processed RAP material, the RAP would be moved to the larger stockpile used in asphalt mixes or sold to subcontractors. The RAP is not used fresh after processing as evaluated in this section.

4.2.1 Variability in Test Results

Figure 4.6 depicts the PSD of the sampled RAP material, which is also summarised in Table 4.2. The range of percentage passing the sieve sizes 6.7 to 0.6 mm is between 11 and 22%. The tolerance on these sieve sizes is maximum ± 5% from the target grading.

Figure 4.6: PSD of RAP material sampled over four days from Supplier A

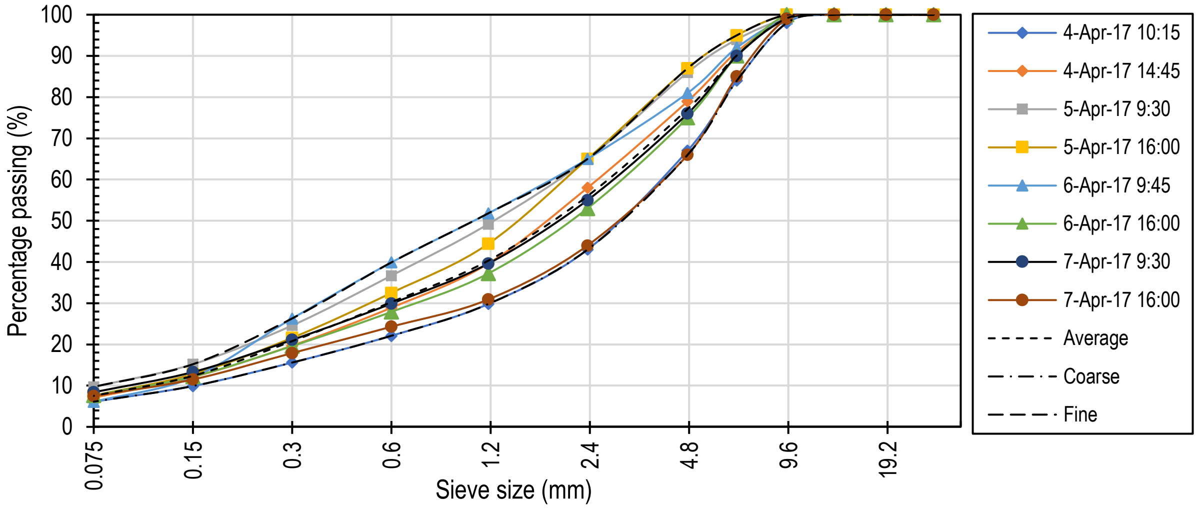
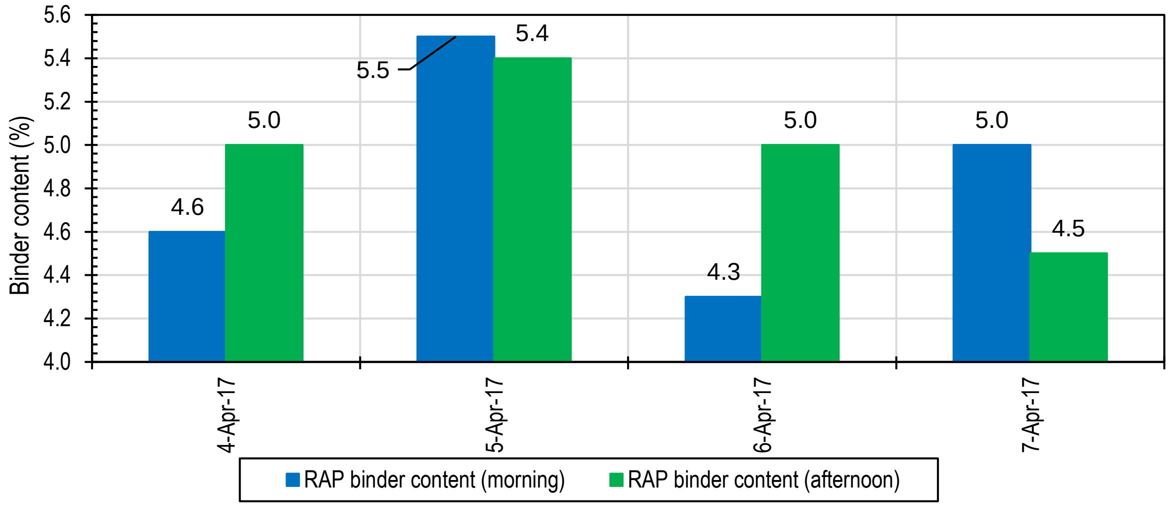


Table 4.2: PSD of RAP material sampled over four days from Supplier A

Date	4-Apr-17		5-Apr-17		6-Apr-17		7-Apr-17		Average	Minimum	Maximum	Range
Time	10:15	14:45	9:30	16:00	9:45	16:00	9:30	16:00				
Sieve size	Percentage passing (%)											
26.5	100	100	100	100	100	100	100	100	100	100	100	0
19	100	100	100	100	100	100	100	100	100	100	100	0
13.2	100	100	100	100	100	100	100	100	100	100	100	0
9.5	98	99	99	100	99	100	99	99	99	98	100	2
6.7	84	91	94	95	92	90	90	85	90	84	95	11
4.75	67	79	86	87	81	75	76	66	77	66	87	21
2.36	43	58	65	65	65	53	55	44	56	43	65	22
1.18	30	40	49	44	52	37	40	31	40	30	52	22
0.6	22	29	37	33	40	28	30	24	30	22	40	18
0.3	16	20	25	22	26	20	21	18	21	16	26	11
0.15	10	12	15	13	12	12	13	12	12	10	15	5
0.075	6.1	7.1	9.7	7.6	6.1	7.6	8.4	7.5	7.5	6.1	9.7	4

Figure 4.7 depicts the binder content of the sampled RAP material. The binder content varies between morning and afternoon sampling, with the largest difference on 6 April 2018 of 0.7%.

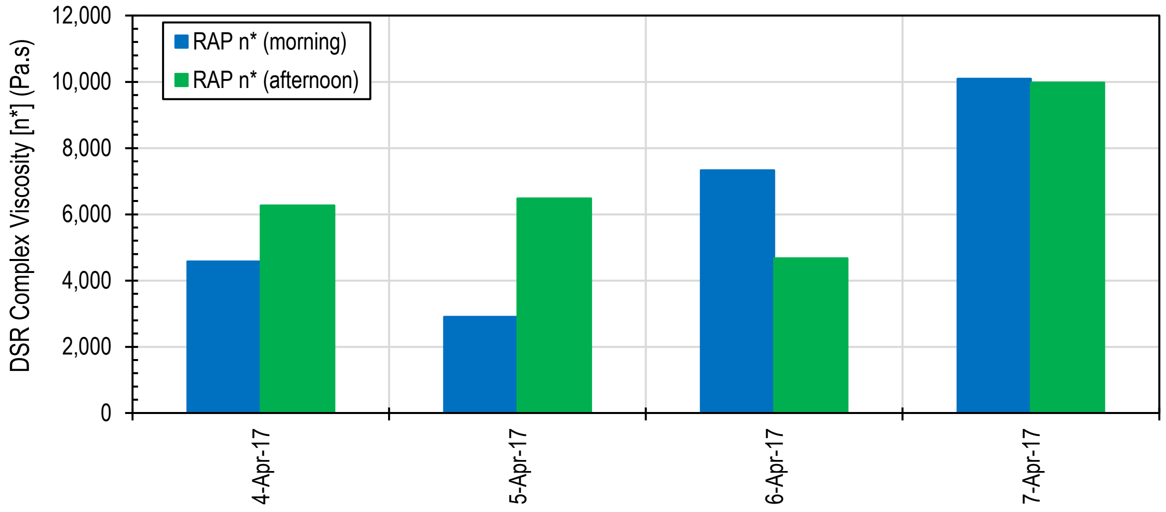
Figure 4.7: Binder content of RAP material sampled over four days from Supplier A



No moisture content data is available for these dates.

Figure 4.8 depicts the DSR complex viscosity of the sampled RAP material. The complex viscosity varies between morning and afternoon sampling, with the least difference in viscosity measured on 7 April 2017.

Figure 4.8: DSR complex viscosity of RAP material sampled over four days from Supplier A



4.2.2 Impact of Variability

At the time of sampling, Supplier A had a 25% RAP mix design in place. To evaluate the impact of the variability of the RAP, the design parameters were assumed as follows:

- RAP content 24.1%, with average binder content of 4.9% and average DSR complex viscosity of 6537 Pa.s
- target binder content of the asphalt mix containing RAP at 4.6%
- C320 virgin binder with DSR complex viscosity of 490 Pa.s

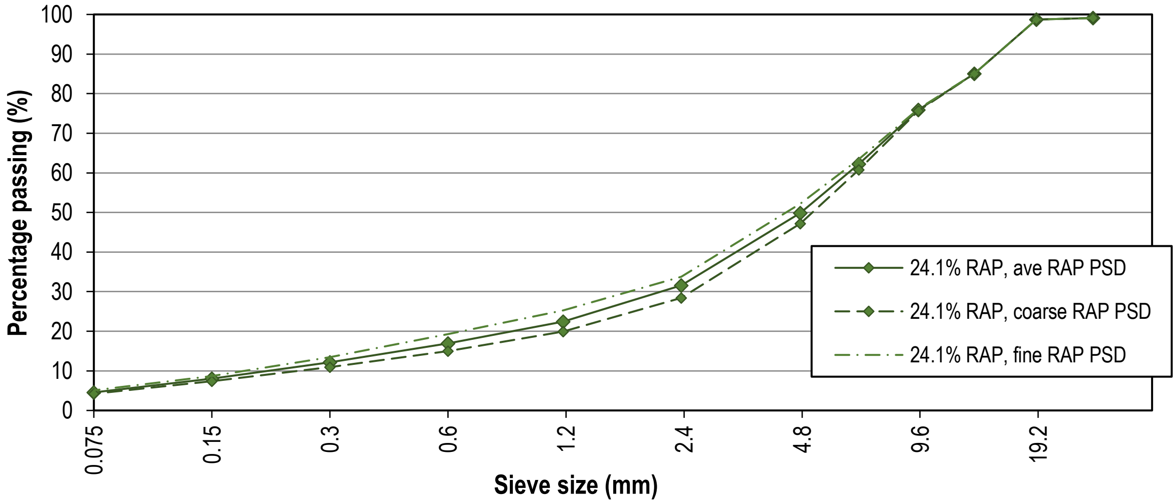
- C600 target DSR complex viscosity of 980 Pa.s
- no low-viscosity oil added
- aggregate fraction proportions as per the mix design.

Effect of variable PSD

Table 4.3 depicts the impact of using the average, most coarse and most fine RAP PSD in the asphalt mix, keeping all aggregate fraction proportions constant. The range of percentage passing the sieve size 4.75 to 0.6 mm is between 5.3 and 4.3%. Comparing the resulting PSDs to production tolerances (Main Roads 2018b), the impact of variable PSD for this example is negligible.

Table 4.3: Impact of variable RAP PSD on target asphalt PSD

	24.1% RAP, average RAP PSD	24.1% RAP, coarse RAP PSD	24.1% RAP, fine RAP PSD		Production tolerance
Sieve size (mm)	Percentage passing			Range	20 mm
26.5	99	99	99	0.0	
19	99	99	99	0.0	-3 +7
13.2	85	85	85	0.0	± 7.0
9.5	76	76	76	0.5	± 7.0
6.7	62	61	63	2.7	± 7.0
4.75	50	47	52	5.1	± 7.0
2.36	32	28	34	5.3	± 5.0
1.18	22	20	25	5.3	± 5.0
0.6	17	15	19	4.3	± 4.0
0.3	12	11	13	2.6	± 4.0
0.15	8	7	9	1.3	± 2.5
0.075	4.6	4.2	5.1	0.9	± 1.5



Effect of variable binder content

The target DSR complex viscosity of 980 Pa.s was almost achieved when the maximum RAP binder content was used. In this instance a 0.6% RAP binder content change from the average binder content, results in a 70 Pa.s binder blend viscosity change from the average blend viscosity.

Table 4.4 depicts the impact of using the average, minimum and maximum RAP binder content on the binder blend viscosity obtained for the asphalt mix, keeping all other variables constant. The binder blend viscosity ranges between 833 Pa.s and 971 Pa.s. The target DSR complex viscosity of 980 Pa.s was almost achieved when the maximum RAP binder content was used. In this instance a 0.6% RAP binder content change from the average binder content, results in a 70 Pa.s binder blend viscosity change from the average blend viscosity.

Table 4.4: Impact of variable RAP binder content on binder blend viscosity

RAP	24.1 %
Target binder of mix	4.6 %

	n* (Pa.s)	VBI (Pa.s)
C320	490	0.655
C600	980	0.666

RAP binder content (%)		RAP binder proportion (x)	RAP n* (Pa.s)	VBI_{RAP} (Pa.s)	C320 prop (x)	VBI_{B}	u (Pa.s)
Average	4.9	0.257	6537	0.694	0.743	0.665	900
Minimum	4.3	0.225	6537	0.694	0.775	0.664	833
Maximum	5.5	0.288	6537	0.694	0.712	0.666	971

Effect of variable DSR complex viscosity

Table 4.5 depicts the impact of using the average, minimum and maximum RAP DSR complex viscosity in the binder blend calculation of the asphalt mix, keeping all other variables constant. The binder blend viscosity range between 753 Pa.s and 987 Pa.s. This 234 Pa.s range results from a 4000 Pa.s range in RAP viscosity.

Table 4.5: Impact of variable RAP DSR complex viscosity on binder blend viscosity

RAP	24.1 %
Target binder of mix	4.6 %

	n* (Pa.s)	VBI (Pa.s)
C320	490	0.655
C600	980	0.666

RAP n* (Pa.s)		RAP Binder content (%) (x)	RAP binder proportion	VBI_{RAP} (Pa.s)	C320 prop (x)	VBI_{B}	u (Pa.s)
Average	6537	4.9	0.257	0.694	0.743	0.665	900
Minimum	2902	4.9	0.257	0.683	0.743	0.662	753
Maximum	10 090	4.9	0.257	0.700	0.743	0.666	987

4.3 Discussion

The analysis undertaken indicates that there is definite variability in processed RAP not only on a daily basis, but also on a month-to-month basis.

Differences in reported PSD over a 12-month period are significant for Supplier A and Supplier C, with the range on some sieve sizes more than 10%. The same range was observed over a four-day period of sampling from Supplier A. However, when the upper and lower extremes and average PSDs were used in an example mix with 24.1% RAP content, the resultant mixes were within the production tolerances of each sieve size.

The range of RAP binder content over a 12-month period was 0.9% (maximum) and over a four-day period 0.7% (maximum). This range is closer to the tolerance of 0.3% for binder content required (Main Roads 2018b). When the upper and lower extremes and average RAP binder contents were used in an example mix with 24.1% RAP content, the resultant binder blend viscosity of the mixes was within the 50 Pa.s tolerance for a C600 (Main Roads 2017a). (Note that Supplier C 12-month period RAP binder content results were not considered in this discussion due to the high variability, which was not reflected in the results for the other two suppliers).

RAP DSR complex viscosity varied over a 12-month period between 2500 Pa.s and 31 000 Pa.s. Over a four-day period the range was less, between 2900 Pa.s and 10 000 Pa.s. When the upper and lower extremes and average RAP DSR complex viscosity were used in an example mix with 24.1% RAP content, the resultant binder blend viscosity of the mixes was within the 50 Pa.s tolerance for a C600 (Main Roads 2017a).

The variability of results over a 12-month and four-day period indicates that RAP material is inherently variable. Although in this evaluation the variability did not lead to the assessed property being out of tolerance, it did indicate that with adoption of a RAP management plan and improved RAP management practices, the result can be considerably improved.

Feedback was given to the local asphalt industry during a workshop held in May 2018 at Main Roads. It was attended by approximately 20 representatives from asphalt suppliers, profiling companies and binder suppliers. The purpose was to convey the results of the RAP property testing and discuss the proposed way forward. During the workshop it was decided to proceed with the development of a technical guidance document, specification and implementation strategy.

5 DEVELOPMENT OF MAIN ROADS RAP DOCUMENTATION AND SPECIFICATIONS

5.1 Draft Engineering Road Note 13B – Asphalt Mix Design with RAP

5.1.1 Introduction

A draft Engineering Road Note 13B (ERN 13B) was compiled that specifies the requirements for the design of intermediate course asphalt incorporating RAP.

5.1.2 Asphalt Mix Design

Three levels of RAP use are outlined in the draft document, namely:

- Level 1 containing ≤ 10% RAP (MRWA current limit)
- Level 2 containing 11 to 25% RAP
- Level 3 containing 26 to 40% RAP.

At RAP Level 1 the asphalt manufacturer may include up to 10% RAP in 14 mm or 20 mm intermediate course asphalt mixes. This reflects the provision made in Specification 510.32.02 (Main Roads 2018b), with no additional asphalt mix design requirements applicable for RAP Level 1.

A design process is outlined in the draft document for RAP Level 2 and Level 3. RAP Level 2 or Level 3 is only applicable to 20 mm intermediate course asphalt manufactured with unmodified bitumen as the virgin binder.

5.1.3 Materials

The material requirements in the draft document can be summarised as follows:

Binder

- Bitumen may be a standard Austroads grade or be blended in line at the asphalt plant to a targeted viscosity.

RAP

- For RAP Level 2, the asphalt manufacturer must nominate a target PSD for the processed RAP.
- For RAP Level 3, the asphalt manufacturer must fractionate RAP into a coarse and fine fraction. The coarse fraction should consist of RAP with 100% retained on a 4.75mm sieve and a fine fraction where 100% of RAP should be passing a 4.75mm sieve.

Sand

- No natural sand is allowed in RAP Level 2 or Level 3 mixes.

Rejuvenating products

- No rejuvenating products or extender oils are in asphalt mixes containing RAP.

5.1.4 General

General requirements outlined in the draft document do not in essence differ from the standard Main Roads asphalt mix design requirements.

The main proposed change was to harmonise the method for determining bulk density of laboratory prepared specimens for the purpose of asphalt mix design with AS/NZS 2891.9.2 *Methods of Sampling and Testing Asphalt: Determination of Bulk Density of Compacted Asphalt: Presaturation Method.*

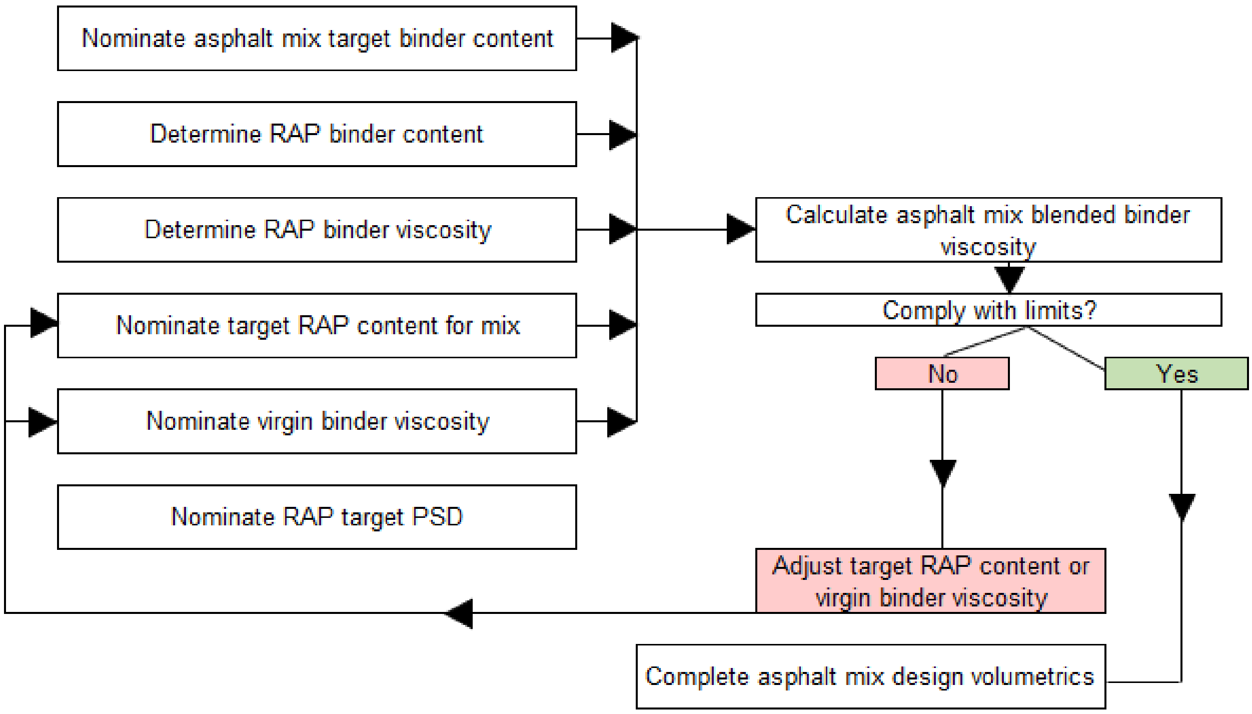
5.1.5 Design Criteria

Design criteria remains in accordance with Specification 510 (Main Roads 2018b).

5.1.6 Design Inputs

The asphalt mix design process and inputs for RAP Level 2 and 3 approved mixes are depicted in Figure 5.1.

Figure 5.1: Asphalt mix design process with RAP



RAP properties are determined as outlined in AGPT/T191 and AGPT/T192 .

5.1.7 Calculations

Calculations are as described in AGPT/T193 and should be used to determine the blended binder viscosity for RAP Level 2 and Level 3 approved mixes, with the unknown variable in the blend to be determined by the asphalt manufacturer. The unknown variable can be:

- the virgin binder viscosity or
- percentage of RAP (± 3%).

If the unknown variable is the percentage of RAP, guidance is given on the DSR viscosity that can be assumed for standard grades of bitumen (Table 5.1).

Table 5.1: Assumed viscosity for the virgin binder

Binder class	Viscosity (Pa.s)
C170	190 (1)
C240	240
C320	320
C450	450
C600	600

1 Median viscosity for C170 bitumen in WA is 190 Pa.s

The asphalt manufacturer may also blend the virgin binder at the asphalt plant to obtain the required viscosity to achieve the binder blend viscosity.

The variables must be adjusted to ensure that the blend viscosity complies with the specified binder viscosity range at the time of design and throughout production. C600 is generally specified as the binder for intermediate asphalt mixes in WA containing no RAP. The specified blended binder viscosity range is between 600 and 880 Pa.s. This target range was adopted from Queensland Department of Transport and Main Roads (2019b).

The draft document contains two worked examples and graphs that can be used as a first check when a standard grade of bitumen is considered for a particular RAP content.

5.1.8 Finalising Laboratory Design

In order to finalise the laboratory asphalt mix design process, guidance is given in terms of limits within which the laboratory mixes are produced, the average result for air voids and test results to be reported. Voids filled with mineral aggregate (VMA) and voids filled with binder (VFB) were added to the results to be reported.

For RAP Level 3 mixes, the additional action of preheating the RAP aggregate fractions before addition of binder to simulate the production process will be required.

5.1.9 Plant Mix Verification

The draft document requires suppliers to replicate the proposed asphalt mix design in a plant trial. At least 50 tonnes of the proposed mix should be manufactured and tested, amongst other, the asphalt binder should be recovered and tested to confirm the resulting viscosity of the blended mix.

5.1.10 Approval of Asphalt Mix Design

The complete asphalt mix design containing RAP at Level 2 or 3 contents must be submitted for approval. Only approved asphalt mix designs can be used on the Main Roads managed road network, as is the current practice in WA.

5.2 Draft Specification Updates

Three specification documents would be influenced by the content of Draft Engineering Road Note 13B. This section documents the changes that were proposed for specific clauses within each of the specification documents.

5.2.1 Specification 201 Quality Systems

Specification 201 *Quality Systems* (Main Roads 2019) sets out how the contractor must manage its obligations during construction through the implementation of an AS/NZS ISO 9001 compliant Quality Management System.

Table 5.2 reflects the Revision Register and Table 5.3 the changes proposed to existing or new clauses, highlighted in grey.

Table 5.2: Revision Register for Specification 201

Clause Number	Description of Revision	Authorised By	Issued Date
2.0 Minimum Testing Frequency – 2.2 Bituminous surfacing	Amended 'Bitumen Produced in Western Australia – Blending of Bitumens' to 'Bitumen Produced in Western Australia – Blending of Bitumens to Specified Grade'		
	Added 'Bitumen Produced in Western Australia – Blending of Bitumens to Target Viscosity for use of RAP'		

Table 5.3: Proposed new sub-clause under clause 2.2

PRODUCT/PROCESS	QUALITY VERIFICATION REQUIREMENT	MINIMUM TESTING FREQUENCY
2.2 BITUMINOUS SURFACING		
Bitumen Produced in Western Australia – Blending of Bitumens to Specified Grade	Tests in accordance with Specification 511	
	INITIAL BATCH: • Viscosity at 60 °C • Viscosity at 135 °C • Penetration at 25 °C • Viscosity of residue at 60 °C after RTFO test • Matter insoluble in toluene • Density at 15 °C • Flash point	1 test for initial batch for each binder class
	TRUCK LOADS: • Viscosity at 60 °C	1 test for each 5th load for each binder class
Bitumen Produced in Western Australia – Blending of Bitumens to Target Viscosity for use of RAP	Tests in accordance with Specification 511	
	EACH LOT OF PROCESSED RAP: • Viscosity at 60 °C	1 test for each lot for each bitumen at target viscosity

5.2.2 Specification 510 Asphalt Intermediate Course

Specification 510 *Asphalt Intermediate Course* (Main Roads 2018b) contains specifications related to the supply and application of 14 and 20 mm dense graded asphalt for the construction of an asphalt intermediate course.

Table 5.4 reflects the Revision Register and Table 5.5 the changes proposed to existing or new clauses, highlighted in grey.

Table 5.4: Revision Register for Specification 510

Clause Number	Description of Revision	Authorised By	Issued Date
Main Roads Standards	Added ERN 13B reference		
510.26.1	New clause referencing ERN 13B		
510.26.01.10	Rewording of clause		
510.26.05	Added ', including an asphalt mix design with RAP,'		

Clause Number	Description of Revision	Authorised By	Issued Date
510.30.1	Added clause on RAP Level 2 and RAP Level 3 binder		
510.32.1 – 5	Amended clause adding 1 to 5		

Table 5.5: Proposed new sub-clauses for Specification 510

ASPHALT MIX DESIGN **510.26 ASPHALT MIX DESIGN** 1. This clause specifies the requirements for the design of an asphalt mix for 14 mm and 20 mm asphalt intermediate course. Where RAP is to be included in 14 mm or 20 mm asphalt refer to Engineering Road Note 13B (ERN 13B) for asphalt mix design requirements. 510.26.01 GENERAL 1. The asphalt manufacturer shall be responsible for the development of an asphalt mix design and its approval by Main Roads. This clause specifies the properties and design process for nominal 14 mm and 20 mm asphalt.	
510.26.05 USE OF ASPHALT MIX DESIGN 2. **The Contractor shall provide proof to the Superintendent that the asphalt mix design, including an asphalt mix design with RAP, has been approved by the Principal before any asphalt is manufactured in accordance with that Approved Asphalt Mix Design and placed in the Works.** **510.27 – 510.29 NOT USED** **MANUFACTURE AND TRANSPORT** **510.30 RAP LEVEL 2 OR LEVEL 3 BLENDING** 3. The virgin binder viscosity or the amount of RAP shall be calculated in accordance with Section 4.5.2 of ERN 13B to ensure the viscosity of the asphalt binder meets the specified binder viscosity range (600 to 880 Pa.s). The amount of RAP shall remain within the limits of the Approved Asphalt Mix Design. This shall be done for each Lot of processed RAP.	***HOLD POINT***
510.32 MANUFACTURE OF ASPHALT 4. The quantities of coarse and fine aggregates, sand, mineral filler, adhesion agent, bitumen and RAP, when used, shall be accurately and positively controlled so as to produce the asphalt specified for use in the Works. The quantity of bitumen in the asphalt shall include that portion that comes from the use of RAP in the asphalt. 5. RAP, by mass of the total aggregate, may be used in the production of 14 mm or 20 mm asphalt. Where used, RAP shall be added as: a) RAP Level 1 – up to 10% RAP may be used and substituted for aggregates. Use of RAP Level 1 does not require an approved asphalt mix design; OR b) RAP Level 2 or RAP Level 3 – a nominated target amount of RAP may be used in accordance with an Approved Asphalt Mix Design. 6. The quantity of hydrated lime added as an adhesion agent shall be based on the total mass of aggregate and RAP. 7. Aggregates shall not be heated to a temperature in excess of 220 °C. 8. RAP shall not come into contact with hot virgin aggregates until the mixing stage. All fractions in a RAP Level 3 mix design shall be heated to a temperature greater than 100 °C prior to the mixing stage.	***Control*** ***Use of RAP*** ***Hydrated Lime*** ***Aggregate Temperature***

5.2.3 Specification 511 Materials for Bituminous Materials

Specification 511 *Materials for Bituminous Treatments* (Main Roads 2017a) specifies the supply and use of materials for sprayed bituminous surfacings and asphalt.

Table 5.6 reflects the Revision Register and Table 5.7 the changes proposed to existing or new clauses, highlighted in grey.

Table 5.6: Revision Register for Specification 511

Clause Number	Description of Revision	Authorised By	Issued Date
Main Roads Standards	Added ERN 13B reference		
511.06.01.2	Deleted reference to class. Now refers to Specified Grade		
511.06.01.3	New clause added – Blended Bitumen to Target Viscosity		
511.06.02.1	Added reference to Class 240 and Class 450		
511.09.01.1	Elaborated clause		
511.09.02.1 – 4	Added and reworded clauses		
511.09.03. 1, 2	Added and reworded clauses		
511.09.04	New clause regarding RAP Management Plan		

Table 5.7: Proposed new sub-clauses for Specification 511

PRODUCTS AND MATERIALS	
511.06 BITUMEN	
511.06.01 GENERAL	
2. Where bitumen is produced by the blending of a low and high viscosity bitumen the following process shall be completed to verify conformance of the blend formulation: • The Viscosity at 60 °C and other properties as required of the low and high viscosity bitumen shall be determined. • A blend formulation shall be determined to manufacture the specific class of bitumen. • The blend formulation shall be assigned a unique identifier. • A unique formulation shall be applicable to the batch of each of the two, or more, constituent materials used to manufacture the specific class of bitumen. • When a blend formulation is determined a laboratory or plant batch shall be manufactured. The batch shall be tested for all properties shown in Specification 201. Manufacture of the specific class of bitumen using the new blend formulation shall not be undertaken until testing confirms the blend complies to all specified requirements. • Bitumen manufactured using the blend formulation shall be sampled and tested for Viscosity at 60 °C at the frequency in Specification 201 QUALITY SYSTEMS. • When a batch of one of the constituent materials changes a new blend formulation shall be determined.	***Blended Bitumen to Specified Grade***
3. Where bitumen is produced by the blending of a low and high viscosity bitumen to obtain bitumen with a target viscosity for use with RAP Level 2 or Level 3 asphalt, the following process shall be completed to verify conformance of the blend formulation: • The Viscosity at 60 °C and other properties as required of the low and high viscosity bitumen shall be determined. • A blend formulation shall be determined to manufacture the bitumen at the target viscosity. The formulation shall be calculated for each Lot of processed RAP. • The blend formulation shall be assigned a unique identifier. • A unique formulation shall be applicable to the batch of each of the two, or more, constituent materials used to manufacture the bitumen at target viscosity.	***Blended Bitumen to Target Viscosity***

• When a blend formulation is determined a laboratory or plant batch shall be manufactured. The batch shall be tested for viscosity at 60 °C. Manufacture of the bitumen at target viscosity using the new blend formulation shall not be undertaken until testing confirms the blend viscosity (± 50 Pa.s). • Bitumen manufactured using the blend formulation shall be sampled and tested for Viscosity at 60 °C at the frequency in Specification 201 QUALITY SYSTEMS. • When a batch of one of the constituent materials changes a new blend formulation shall be determined. 511.06.02 PROPERTIES 4. Class 170, Class 320 and Class 600 bitumen shall conform to the properties shown in Table 511.1 at the time of manufacture and at any time until the bitumen is used. Class 240 and Class 450 bitumen shall conform to AS2008.	***Properties***
511.09 RECLAIMED ASPHALT PAVEMENT 511.09.01 PROPERTIES 5. RAP shall be obtained predominantly from material reclaimed from an asphalt wearing or intermediate course by cold planing but may contain small amounts of surplus asphalt from a plant or site returns. RAP shall be maintained in a separate stockpile prior to processing for use in asphalt. RAP shall not contain any of the following materials: a. Granular pavement materials, clay, soil or organic matter b. Bricks, concrete, glass or building materials c. Laterite asphalt, tar-based products, geotextile fabrics, raised pavement markers or road surface treatments such as high friction surfacings or coloured pavement markings. 511.09.02 PROCESSING AND STORAGE 6. Processed RAP shall be free flowing and consistent in appearance. Where the stored RAP is not free flowing it shall be screened and/or crushed again.	
7. At a minimum RAP shall be crushed and screened to produce a nominal 7 mm or 10 mm sized material incorporating fines with 100% of the material passing a 9.5 mm sieve. RAP material of a nominal 14 mm size may be crushed and screened but shall not incorporate fines. The processed 14 mm RAP shall have 100% of the material passing a 13.2 mm sieve and less than 2% of the material passing a 6.7 mm sieve.	***Size***
8. For RAP Level 3, RAP shall be crushed and screened into two fractions. A coarse fraction shall consist of RAP with 100% retained on a 4.75 mm sieve and a fine fraction shall have 100% of RAP passing a 4.75 mm sieve.	***Size Level 3***
9. All processed RAP shall be stored under cover until it is used in asphalt production. The storage facility must be covered on the top and at least three sides and not allow rainfall or other sources of moisture to wet the RAP after processing. The floor of the storage facility shall be concrete sloping down to a drain to allow removal of excess moisture. 511.09.03 STOCKPILE MANAGEMENT AND TESTING 10. Processed RAP shall be maintained in lots to ensure traceability. A minimum of three samples are to be taken for every 1000 tonne in each lot of processed RAP and tested for: a) Particle size distribution and bitumen content in accordance with WA 730.1 and moisture content in accordance with WA 212.1 or 212.2. b) Complex viscosity of the recovered RAP binder for RAP Level 2 and RAP Level 3 in accordance with AG:PT/T191 and AG:PT/T192.	***Storage Facility***
11. At RAP Level 2 and RAP Level 3 the particle size distribution and binder content of the RAP shall comply with the limits shown on the Approved Asphalt Mix Design certificate. 511.09.04 RAP MANAGEMENT PLAN	***PSD***
12. A RAP Management Plan (RMP) shall be prepared by the asphalt manufacturer. The RMP shall detail the following: a. The process commencing at the origin of the RAP, stockpiling prior to processing, processing, storage and testing. b. The capability of the plant to incorporate the specific RAP level.	***RAP Management Plan***

c. The process for manufacture of asphalt containing RAP.	

6 RAP IN POLYMER MODIFIED BINDER (PMB) ASPHALT MIX

6.1 PMB and RAP

Austroads (2015) cited the following two issues with PMB asphalt and RAP:

- When the RAP product itself contains a high level of polymer modification, and how this affects the performance of the new asphalt product into which the PMB RAP is introduced.
- When RAP not containing PMB is added to a new asphalt mix containing PMB. The unmodified binder in the RAP may dilute the polymer content of the overall mix, potentially impacting on the performance of the mix.

Literature on the issues mentioned is limited. Austroads (2015) reported on a study by Mohammad et al. (2003) which investigated issues with the re-use of an eight-year-old styrene-butadiene-styrene (SBS) modified binder. The study found that the polymer in the RAP source material had aged and degraded to such an extent that it would eventually disappear. The performance of mixes containing up to 60% of this type of RAP was tested and the results were as described in previous sections, with an increase in RAP content leading to a decrease in fatigue life, and an increase in rut resistance.

Kim et al. (2009) investigated the effect of different percentages of RAP on asphalt mixes containing PMB binder. Mixes containing 0, 15, 25 and 35% RAP were tested. Tests on blends of extracted RAP binder and PMB binder were also performed. The study showed that the RAP content did have a significant effect on the rutting and fatigue properties of the binder, as determined using the dynamic shear rheometer (DSR). However, this change in binder properties did not function as a performance indicator for the asphalt mix itself. The mixture performance in laboratory tests was similar for all different RAP contents.

Zhou et al (2018) suggested that 30% content of RAP can be used in surface layers without jeopardising pavement cracking performance if a virgin SBS modified binder and a suitable dosage of rejuvenator was used.

Singh, Girimath and Ashish (2018) conducted rheological investigations on extracted RAP binders. PMB (the specifics of the product were not disclosed) was blended with 0, 15, 25, and 40% of the two types of extracted RAP binders. The rutting and fatigue performance of PMB with varying percentages of RAP binders was evaluated using multiple stress creep recovery and linear amplitude sweep (LAS) tests, respectively. Although the addition of RAP binder to the PMB increased the stress sensitivity of the PMB-RAP binder blend, the stress sensitivity remained well within the critical limit. The result from the LAS test showed that the addition of RAP binder may adversely affect the fatigue resistivity of PMB. Overall, a change in performance of PMB was found to be dependent on the nature, source, and quantity of RAP binder.

Austroads (2015) in which the AGPT/T193 (2015) design methodology was developed, did not validate the impact of RAP on PMB, multigrade and hard penetration grade binders.

6.2 Austroads Member Practice

A summary of the proportions of RAP that may be added to PMB asphalt mixes as specified by Austroads members is presented in Table 6.1. General observations include:

- Main Roads is the only agency that limits intermediate and basecourse RAP content to less than 15% by mass.

- DPTI permits up to 50% RAP contents in non-wearing-course mixes without PMBs, the highest proportion of the agencies.
- None of the agencies permit the use of RAP in SMA or open grades asphalt (OGA).
- Additional testing requirements for mixes exceeding typical limits are specified by DPTI, TMR, RMS, VicRoads and NZTA.
- RMS and DPTI are the only agencies that allow RAP in PMB asphalt mixes but limited to 10% and 20% RAP respectively.

Table 6.1: Comparison of Austroads member RAP proportions in PMB asphalt mixes

Jurisdiction	RAP proportions in PMB asphalt mixes
AAPA	▪ Up to 15% RAP ▪ Mixes containing greater than 15% RAP only if concentrated PMB blend used
Main Roads	▪ Not permitted
DPTI	▪ Up to 20% for DGA levelling, intermediate or basecourse mixes using PMBs
DIPL	▪ Not stated
TMR	▪ Up to 15% RAP by mass in surfacing and other courses without additional requirements
RMS	▪ Up to 10% in surfacing and other courses containing PMBs
VicRoads	▪ Not permitted
New Zealand	▪ Up 15% in all DGA mixes without additional requirements, binder as specified ▪ Up to 30% in DGA mixes subject to selection of suitable binder grade or rejuvenator to correct binder viscosity, and additional performance testing and stockpile management plan

6.3 Selected International Practice

An overview of the proportions of RAP permitted in approved PMB mixes by the international road agencies reviewed is presented in Table 6.2. The following observations can be made:

- Germany and South Africa allow RAP in PMB asphalt mixes.
- In the UK, USA and Japan it is not clearly documented if allowed, but through performance-based specifications and penetration grade system it may be possible.

Table 6.2: Comparison of RAP proportions in PMB asphalt mixes

Jurisdiction	RAP proportions in PMB asphalt mixes
Main Roads	▪ Not permitted
Germany	▪ No specified restriction on PMB asphalt, smallest proportion determined from: – suitability of RAP for designated asphalt mix design – homogeneity of RAP – mechanical prerequisites of relevant asphalt plant ▪ Not permitted in porous mixes
Japan	▪ Not clear, however mixes containing RAP must meet mix design performance criteria
South Africa	▪ Limits imposed by virgin binder properties (with or without PMB) and final binder requirements to meet performance criteria and asphalt plant capabilities
UK	▪ Up to 10% RAP by mass of total aggregate in surface layers ▪ Mixes containing RAP must meet mix design performance criteria as mixes containing only virgin materials
USA	▪ Not clear, however performance grade (PG) system may allow modifiers

6.4 Evaluating the Influence of RAP in New PMB Asphalt Mixes

6.4.1 Methodology

A15E PMB is used within the Perth metropolitan area in surfacing and intermediate mixes to provide the following improvements in properties (Main Roads 2018a):

- better resistance to deformation (rutting)
- improved resistance to fatigue failure
- resistance to high stresses such as turning trucks.

The effect of adding 10% and 20% RAP into a dense graded mix was evaluated by comparing it to an approved mix containing A15E binder. This was done as a first step to evaluate the effect of RAP in new PMB asphalt.

A Main Roads approved 14 mm dense graded asphalt – intermediate course (14DGA-IC) mix design was selected. Specification 510 (2018b) requires the binder to be an A15E PMB. The approved mix has a design binder content of 4.8% ± 0.3%. Aggregate, A15E binder and RAP were sent to the ARRB Port Melbourne laboratory from Perth.

The supplied A15E binder was tested for compliance with AGPT/T190 (2019). The results are summarised in Table 6.3, with all properties within the specified limits of AGPT/T190 (2019).

Table 6.3: Properties of PMB modified binder, A15E

Binder property	Test method	Results	Limits for A15E	
			minimum	maximum
Viscosity at 165 °C (Pa.s)	AGPT/T111-06	0.762	–	0.9
Torsional recovery (%)	AGPT/T122-06	72	55	80
Softening point (°C)	AGPT/T131-	89	82	105
Consistency (Pa.s)	AGPT/T121-14	9061	5000	
Consistency 6% (Pa.s)	AGPT/T121-14	1300	To be reported	
Stiffness at 15 °C (kPa)	AGPT/T121-14	138	NA	
Stiffness at 25 °C (kPa)	AGPT/T121-14	21	–	30
Loss on heating (%)	AGPT/T103-06	0.1	–	0.6

The PSD and binder content of the RAP sample was determined. The binder was extracted using method AGPT/T191 (2015), with the resulting RAP binder content of 3.9%. The RAP PSD is reported in Table 6.4.

Table 6.4: PSD and binder content of RAP sample

Sieve size (mm)	Percentage passing (%)
26.5	100
19.0	100
13.2	100
9.5	100
6.7	86
4.75	71

Sieve size (mm)	Percentage passing (%)
2.36	51
1.18	38
0.600	31
0.300	22
0.150	16
0.075	11.8
Binder content (%)	3.9

Three laboratory-prepared mixes for further testing were produced, namely:

1. 14DGA-IC mix with 0% RAP content (0% RAP)
2. 14DGA-IC mix with 10% RAP content (10% RAP)
3. 14DGA-IC mix with 20% RAP content (20% RAP).

Table 6.5 summarises the PSD of the mixes.

Table 6.5: PSD of three laboratory-prepared mixes with proportion RAP

Sieve size (mm)	0% RAP	10% RAP	20% RAP
26.5	100	100	100
19.0	100	100	100
13.2	99	99	99
9.5	84	84	84
6.7	69	69	69
4.75	57	58	57
2.36	33	32	32
1.18	24	24	24
0.600	18	18	19
0.300	12	13	13
0.150	9	9	9
0.075	5.7	6.0	6.3

The following tests were conducted on the specimens to evaluate the effect of the RAP in new PMB asphalt:

1. Stripping potential of asphalt (AGPT/T232) to evaluate the moisture susceptibility of the mixes.
2. Flexural modulus (stiffness) (AGPT/T274) at 20 °C with loading frequencies of 0.1 Hz, 0.5 Hz, 1.0 Hz, 3.0 Hz, 5 Hz, 10 Hz, 15 Hz and 20 Hz. The method refers to a typical range of temperatures, namely 0 °C, 10 °C, 20 °C and 30 °C, but only one temperature was selected to provide a benchmark.
3. Flexural fatigue (AGPT/T274) at 20 °C and over three strain levels at 10 Hz. Only one temperature was selected to provide a benchmark. A reduced set of beams (9 instead of 18) was tested. A statistical analysis carried out as part of NACoE projects indicated that when

fitting a single model to asphalt fatigue results at different temperatures, it would be sufficient to test a minimum of 9 beams per temperature, over at least three strain levels (Denneman & Lam 2015; Denneman & Bryant 2016).

6.4.2 Binder Blend

The binder blend design method outlined in AGPT/T193 (2015) was followed, however, there is currently no guidance on the viscosity limits the blend viscosity should aim for when PMB binders are used in the blend. As noted in Section 6.1, Austroads (2015) did not validate PMB, multigrade and hard penetration grade binders using the binder blend design method.

The method in AGPT/192 (2015) was used to determine the complex viscosity for the A15E binder supplied and the extracted RAP binder. The A15E binder's complex viscosity resulted in 1660 Pa.s and the RAP binder's complex viscosity resulted in 14 200 Pa.s. The calculations are summarised in Table 6.6 and Table 6.7.

Table 6.6: Binder blend design for 10% RAP based on AGPT/T193

	RAP	Virgin binder	Blend
	RAP content = 10% RAP binder content = 3.9%	A15E	Blended mix's binder content = 4.8%
Viscosity:	Binder viscosity = 14 200 Pa.s	Binder viscosity = 1660	$\mu = 10^{\left(\frac{3VBI_\beta}{1-VBI_\beta}-3\right)}$ $\mu = 10^{\left(\frac{3(0.677)}{1-(0.677)}-3\right)}$ $\mu = 1947$
Volume fraction:	$x_{RAP} = \left(\frac{RAP\ content\ (\%)}{100}\right) \times \left(\frac{RAP\ binder\ content\ (\%)}{Asphalt\ mix\ binder\ content\ (\%)}\right)$ $x_{RAP} = \left(\frac{10}{100}\right) \times \left(\frac{3.9}{4.8}\right)$ $x_{RAP} = 0.08$	$x_{Blend} = x_{RAP} + x_{Virgin} = 1.0$ $x_{Virigin} = 1.0 - 0.08$ $x_{Virigin} = 0.92$	$x_{Blend} = x_{RAP} + x_{Virgin} = 1.0$
Viscosity index:	$VBI_{RAP} = \frac{3+\log(\vartheta_{RAP})}{6+\log(\vartheta_{RAP})}$ $VBI_{RAP} = \frac{3+\log(14{,}200)}{6+\log(14{,}200)}$ $VBI_{RAP} = 0.705$	$VBI_{Virgin} = \frac{3+\log(\vartheta_{Virgin})}{6+\log(\vartheta_{Virgin})}$ $VBI_{Virgin} = \frac{3+\log(1{,}660)}{6+\log(1{,}660)}$ $VBI_{Virgin} = 0.675$	$VBI_\beta = \sum_{i=1}^{n} x_i \times VBI_i$ $VBI_\beta = (0.08 \times 0.705) + (0.92 \times 0.675)$ $VBI_\beta = 0.677$

Table 6.7: Binder blend design for 20% RAP based on AGPT/T193

	RAP	Virgin binder	Blend
	RAP content = 20% RAP binder content = 3.9%	A15E	Blended mix's binder content = 4.8%
Viscosity:	Binder viscosity = 14 200 Pa.s	Binder viscosity = 1660	$\mu = 10^{\left(\frac{3VBI_\beta}{1-VBI_\beta}-3\right)}$ $\mu = 10^{\left(\frac{3(0.679)}{1-(0.679)}-3\right)}$ $\mu = 2290$
Volume fraction:	$x_{RAP} = \left(\frac{RAP\ content\ (\%)}{100}\right) \times \left(\frac{RAP\ binder\ content\ (\%)}{Asphalt\ mix\ binder\ content\ (\%)}\right)$ $x_{RAP} = \left(\frac{10}{100}\right) \times \left(\frac{3.9}{4.8}\right)$ $x_{RAP} = 0.16$	$x_{Blend} = x_{RAP} + x_{Virgin} = 1.0$ $x_{Virigin} = 1.0 - 0.16$ $x_{Virigin} = 0.84$	$x_{Blend} = x_{RAP} + x_{Virgin} = 1.0$

	RAP	Virgin binder	Blend
Viscosity index:	$VBI_{RAP} = \frac{3+\log(\vartheta_{RAP})}{6+\log(\vartheta_{RAP})}$ $VBI_{RAP} = \frac{3+\log(14{,}200)}{6+\log(14{,}200)}$ $VBI_{RAP} = 0.705$	$VBI_{Virgin} = \frac{3+\log(\vartheta_{Virgin})}{6+\log(\vartheta_{Virgin})}$ $VBI_{Virgin} = \frac{3+\log(1{,}660)}{6+\log(1{,}660)}$ $VBI_{Virgin} = 0.675$	$VBI_{\beta} = \sum_{i=1}^{n} x_i \times VBI_i$ $VBI_{\beta} = (0.16 \times 0.705) + (0.84 \times 0.675)$ $VBI_{\beta} = 0.679$

The plant mix verification was simulated by extracting the binder after preparation of the three mixes to determine the complex viscosity. The results are summarised in Table 6.8, showing the difference in calculated viscosity of 287 Pa.s between 0% RAP and 10% RAP and 343 Pa.s between 20% RAP and 10% RAP. This equates to a 17% and 18% difference between the results respectively.

The difference in verified blend viscosity was 400 Pa.s between 0% RAP and 10% RAP and 280 Pa.s between 20% RAP and 10% RAP. This equates to a 24% and 14% difference between the results respectively.

A 12% difference between results is allowed between laboratories. Therefore, firstly, the difference in viscosity can be considered outside of acceptable limits and secondly, the calculated and verified viscosity values are not comparable.

Table 6.8: Comparison between calculated and extracted binder viscosity

Mix	Calculated blend viscosity (Pa.s)	Percentage difference (%)	Mix verified blend viscosity (Pa.s)	Percentage difference (%)
0% RAP	1660		1660	
10% RAP	1947		2060	
20% RAP	2290		2340	
Difference: 0% RAP-10% RAP	287	17	400	24
Difference: 10% RAP-20% RAP	343	18	280	14

To prepare the three mixes, the laboratory batch was computed directly from the proportions based on the weight of the aggregate using Equation 2 and Equation 3 (NCHRP 2011):

$$M_{RAP} = \frac{M_{RAPAGG}}{(100 - Pb_{RAP})} \times 100 \qquad (2)$$

where

M_{RAP} = mass of RAP required for the laboratory batch (g)

M_{RAPAGG} = mass of RAP aggregate required for the laboratory batch (g)

Pb_{RAP} = RAP binder content (%)

The mass of binder provided by the RAP is then:

$$M_{RAPBinder} = \frac{Pb_{RAP}}{(100)} \times M_{RAP} \quad 3$$

where

$M_{RAPBinder}$ = mass of RAP binder for the laboratory batch (g)

M_{RAP} = mass of RAP for the laboratory batch (g)

Pb_{RAP} = RAP binder content (%)

These proportions and other volumetric properties of the mixes containing RAP are detailed in Table 6.9.

Table 6.9: Proportions and other volumetric properties of mixes containing RAP

% RAP	10% RAP	20% RAP
Maximum density (t/m^3)	2.502	2.505
Bulk density – compacted mix (t/m^3)	2.327	2.315
Average air voids (%) – TSR cores(1)	7.2	7.6
Average air voids (%) – fatigue beams(1)	4.9	5.0
Bitumen content		
Total mix mass (g)	18 172	18 172
Mass of aggregate (g)	17 300	17 300
Mass of binder (g)	872.0	872.0
Mass of RAP binder (g)	67.5 (equals 7.7% of 4.8%)	134.9 (equals 15.5% of 4.8%)
Mass of A15E binder (g)	804.5 (equals 92.3% of 4.8%)	737.1 (equals 84.5% of 4.8%)

1 Air voids reported are the average air voids of the samples tested.

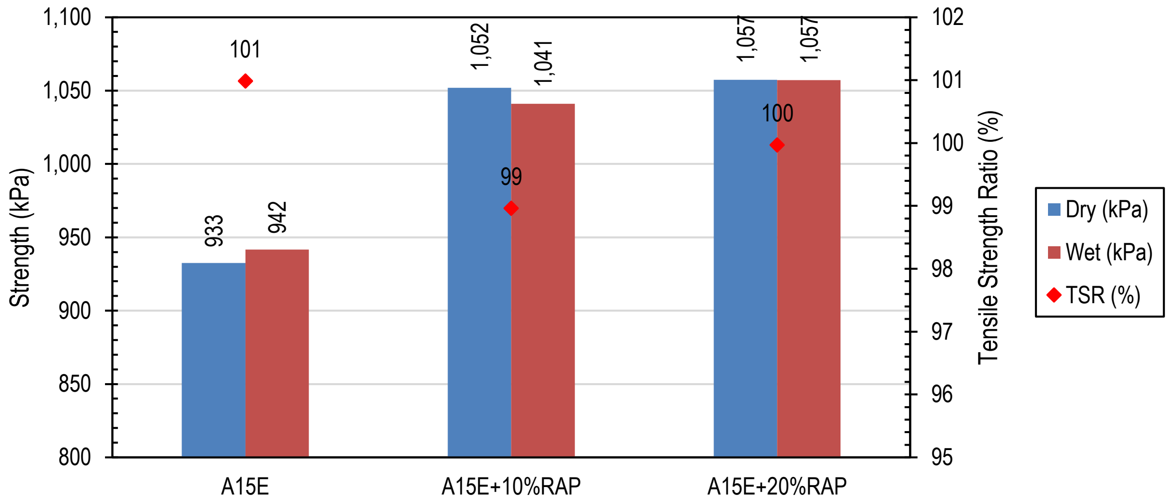
6.4.3 Moisture Susceptibility

The results of the moisture susceptibility testing are shown in Figure 6.1. The results adhere to Specification 510 (Main Roads 2018b) requirements with:

(a) the tensile strength ratio (TSR) greater or equal to 80%
(b) the dry strength greater than 850 kN
(c) the wet strength greater than 750 kN.

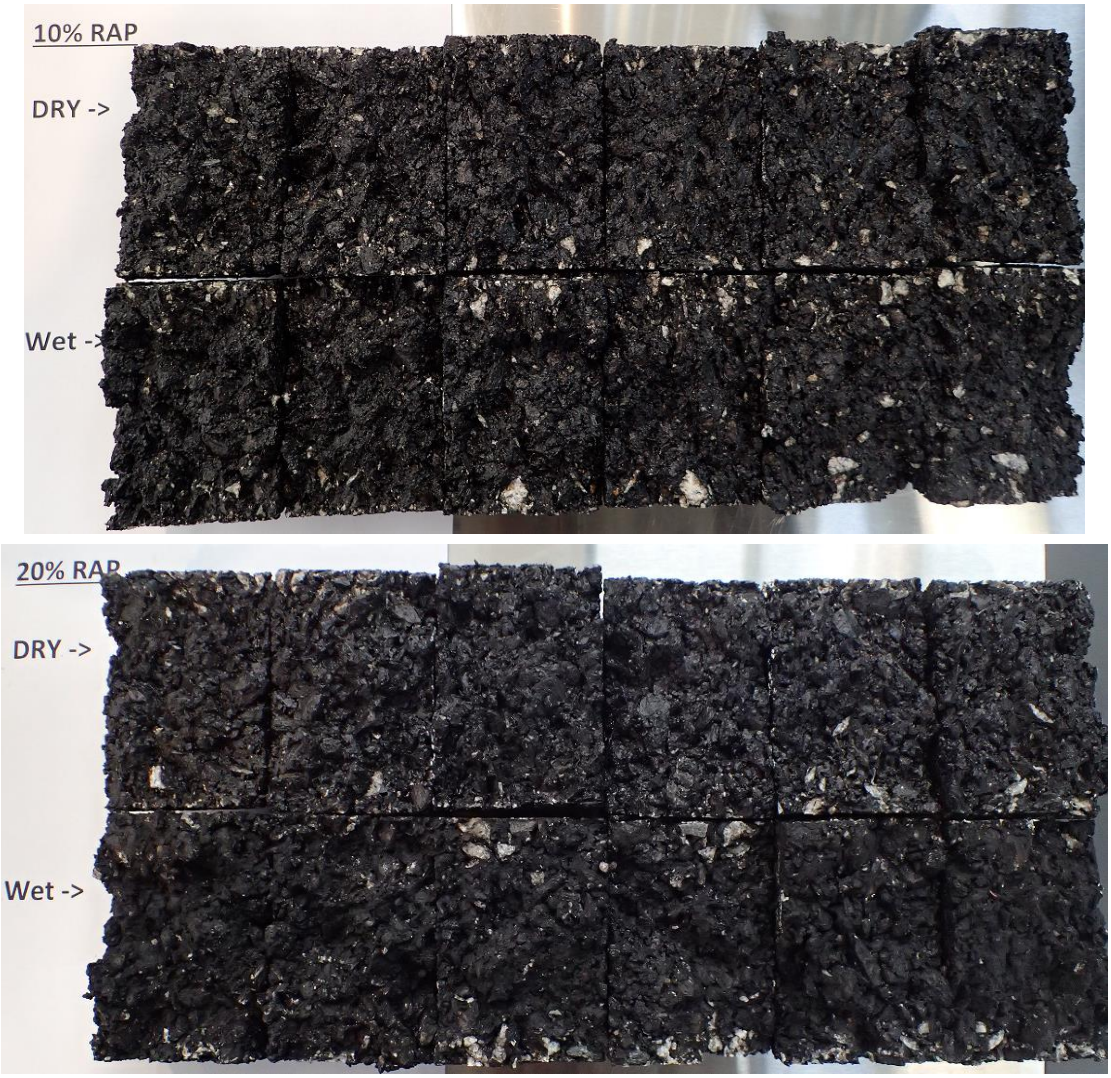
The results of the 10% and 20% RAP are almost identical for all three criteria. The strength results for the mixes with RAP are approximately 100 kPa more than the strength results for the mix with no RAP.

Figure 6.1: Moisture susceptibility results – tensile strength ratio (TSR)



Photographs of the three mixes after testing (Figure 6.2) show a minimal degree of stripping.

Figure 6.2: Visual assessment of the degree of stripping of three mixes

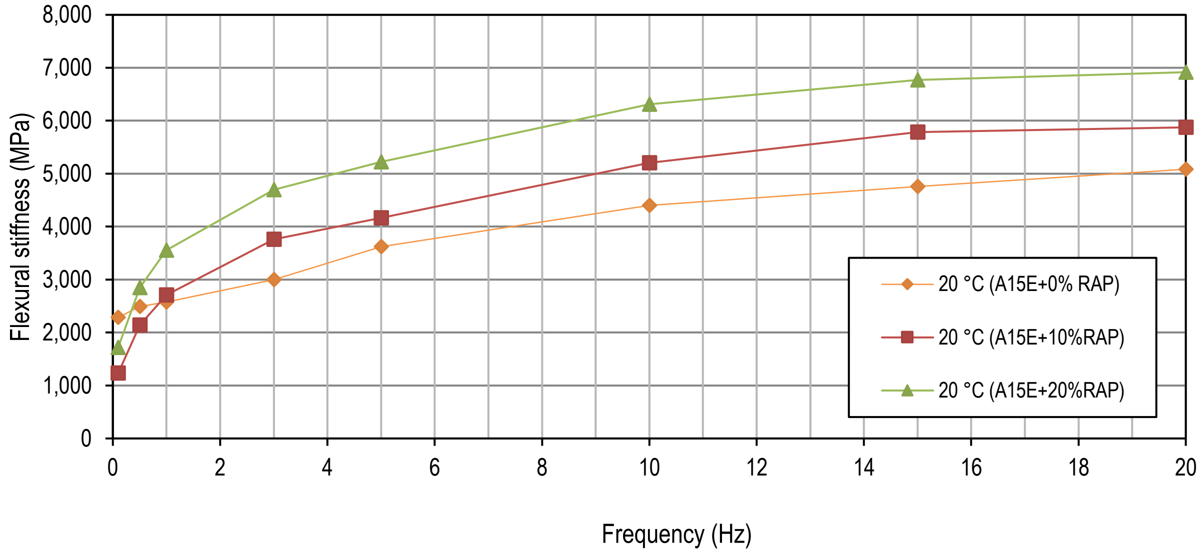


Based on these results, the inclusion of RAP in the new PMB asphalt does not appear to have a negative effect on moisture susceptibility.

6.4.4 Flexural Modulus (E)*

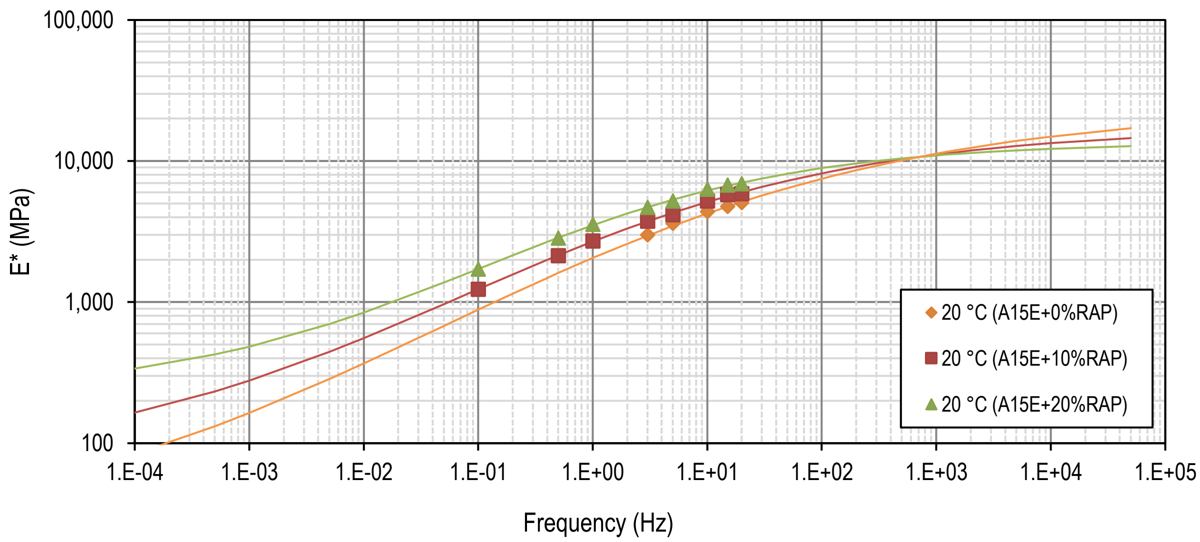
Figure 6.3 shows the frequency sweep (flexural) modulus results for the three asphalt mixes (0%, 10% and 20% RAP) at 20 °C. The mixes with RAP show an increased flexural modulus (E*). The 10% RAP mix shows an approximate 15% increase in flexural modulus and the 20% mix shows an approximate 45% increase in flexural modulus from the 0% RAP mix.

Figure 6.3: Flexural modulus (stiffness) at 20 °C



A complete flexural modulus master curve could not be produced because the mixes were tested only at 20 °C. However, 20 °C is the reference temperature (T_{ref}) to which all mean modulus test results obtained at different load frequencies for various temperatures are shifted to form a master curve. The resulting flexural modulus at 20 °C is shown in Figure 6.4 for the three mixes, with the lines representing the estimated shape of a master curve over a range of temperatures.

Figure 6.4: Flexural modulus results at 20 °C and estimated master curve shape



The estimated master curve regression coefficients are listed in Table 6.10.

Table 6.10: Estimated flexural master curve regression coefficients

Mix type	δ	α	β	γ	a	b	R^2	Temperature
0% RAP	1.2632	3.1254	-0.6444	-0.4903	5.339E-04	-0.1509	0.99	at 20 °C
10% RAP	1.8409	2.3956	-0.6768	-0.5893	5.339E-04	-0.1509	0.99	at 20 °C

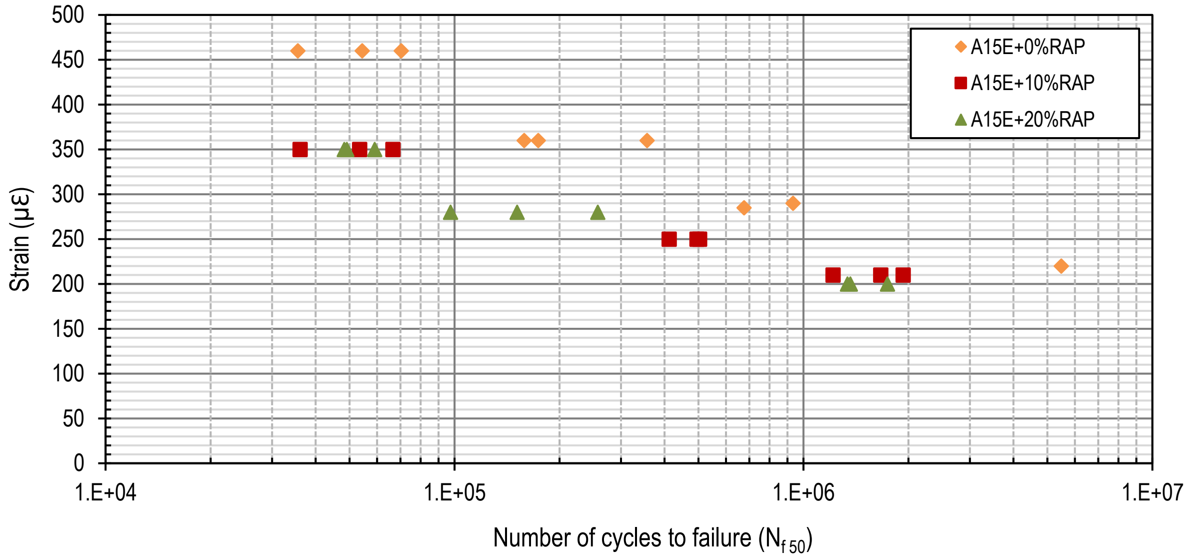
Mix type	δ	*α*	*β*	*γ*	a	b	R^2	Temperature
20% RAP	2.3487	1.7856	-0.7108	-0.7242	5.339E-04	-0.1509	0.99	at 20 °C

The results indicate that including RAP in the 14DGA-IG mix increases the stiffness. This may be beneficial in full-depth asphalt pavements.

6.4.5 Fatigue

Fatigue life is a key indicator of the field performance of asphalt materials. The fatigue performance of the three mixes was evaluated and the results are shown in Figure 6.5. The results appear to indicate similar fatigue performance by the 10% and 20% RAP mixes, both of which are less than the fatigue performance of the 0% RAP mix.

Figure 6.5: Strain level and loading cycles to failure



6.4.6 Conclusions

The binder blend design method outlined in AGPT/T193 (2015), which is adopted in the draft ERN 13B, needs to be verified for PMB, multigrade and hard penetration grade binders. For this limited evaluation, the binder blend design method was used, but with no guidance on the viscosity limits the blend viscosity should aim for when PMB binders are used in the blend.

The plant mix verification was simulated by extracting the binder after preparation of the three mixes to determine the complex viscosity. When the extracted binders' complex viscosities were used to calculate the blend viscosity, the calculation results compared well with the reported results.

Moisture susceptibility results seem to indicate that the inclusion of RAP in the new PMB asphalt did not have a negative effect on the degree of stripping of the asphalt.

Flexural modulus results indicated that including RAP in the 14DGA-IG mix increased the stiffness. This may be beneficial in full-depth asphalt pavements.

However, the fatigue performance of the mixes that included RAP was less than the fatigue performance of the 0% RAP mix. The fatigue performance of the 10% and 20% RAP mixes appear similar, regardless of the difference in percentage RAP.

It should be noted that this evaluation must be regarded as a first step to evaluate the effect of RAP in new PMB asphalt and further testing is required to verify these results.

7 CONCLUSIONS

The implementation of RAP in HMA mixes is well established in Australia and New Zealand, especially in metropolitan centres where a continuous supply of RAP has necessitated the development of management protocols. All Austroads member agencies currently allow the use of RAP in the manufacture of HMA, although usage and management practices vary between jurisdictions.

In reviewing international RAP management practice in relation to Main Roads, it can be seen that although relationships are evident between local and international practice, there are some aspects of international practice that differ significantly. There are, however, several possible explanations. Differences in test methods and design practice, as well as industry experience and capability may influence comparisons with international requirements.

Consultation with local industry indicated that there may be limitations to increasing the required RAP quantities. The limitations are generally related to sourcing sufficient RAP quantities, land required for stockpiling and the required capital investment to upgrade the plant and testing laboratories.

A review of available plant configurations and methods of incorporating RAP into asphalt mixes showed a vast range of existing options. Some plants are configured to incorporate large amounts of RAP, although this may be limited by practical constraints. Therefore, specifying maximum RAP contents based on the plant configuration/type may not be applicable.

The evaluation of local RAP stockpiles indicates that there is definite variability in processed RAP not only on a daily basis, but also on a month-to-month basis. This variation in proportions of binder content, moisture content, PSD and DSR complex viscosity will require more diligence in monitoring the asphalt produced with RAP and adjusting the asphalt designs accordingly. However, during a workshop with industry, it indicated that RAP management practices would be improved to match the requirements of guidance documents and specifications. It was therefore decided to proceed with the development of a technical guidance document, specification and implementation strategy.

A draft Engineering Road Note 13B (ERN 13B) was compiled and specifies the requirements for the design of intermediate course asphalt incorporating RAP. Specification 201 *Quality Systems* (Main Roads 2019), Specification 510 *Asphalt Intermediate Course* (Main Roads 2018b) and Specification 511 *Materials for Bituminous Treatments* (Main Roads 2017a) updates are proposed to tie in with draft ERN 13B.

Draft ERN 13B does not allow any RAP in PMB, OGA and SMA mixes. Austroads (2015) cited the following two issues with PMB and RAP:

1. When the RAP product itself contains a high level of polymer modification, and how this affects the performance of the new asphalt product into which the PMB RAP is introduced.
2. When RAP not containing PMB is added to a new asphalt mix containing PMB. The unmodified binder in the RAP may dilute the polymer content of the overall mix, potentially impacting on the performance of the mix.

Literature on the issues mentioned is limited. Austroads (2015) in which the AGPT/T193 (2015) design methodology was developed, did not validate PMB, multigrade and hard penetration grade binders.

A review of national practice indicates that RMS and DPTI are the only agencies that allow RAP in PMB asphalt mixes but limited to 10% and 20% RAP respectively. International practice generally includes additional testing requirements for such mixes.

The effect of adding 10% and 20% RAP into a 14 mm dense graded asphalt intermediate course (14DGA-IC) mix was evaluated. This was done as a first step to evaluate the effect of RAP in new PMB asphalt.

For this limited evaluation, the binder blend design method was used, but with no guidance on the viscosity limits the blend viscosity should aim for when PMB binders are used in the blend. The plant mix verification was simulated by extracting the binder after preparation of the three mixes to determine the complex viscosity. When the extracted binders' complex viscosities were used to calculate the blend viscosity, the calculation results compared well with the reported results.

Preparation of the three mixes proceeded in the laboratory, with the computing batch proportions based on the weight of the aggregate.

Moisture susceptibility results seem to indicate that the inclusion of RAP in the new PMB asphalt did not have a negative effect on the degree of stripping of the asphalt.

Flexural modulus results indicate that including RAP in the 14DGA-IG mix increases the stiffness. This may be beneficial in full-depth asphalt pavements.

However, the fatigue performance of the mixes that included RAP was less than that of the 0% RAP mix. The fatigue performance by the 10% and 20% RAP mixes appears similar, regardless of the difference in percentage RAP.

It should be noted that this evaluation must be regarded as a first step to evaluate the effect of RAP in new PMB asphalt and further testing is required to verify these results.

8 RECOMMENDATIONS

A draft ERN 13B was compiled and specifies the requirements for the design of intermediate course asphalt incorporating RAP. It is recommended that a number of demonstration trials are constructed using the draft ERN 13B to achieve the following:

1. determine if there is any refinement required within the document or other documents
2. develop a data set for the plant verification of RAP mixes complex viscosity
3. develop industry capability with the available plant.

Further work to evaluate the effect of RAP in new PMB asphalt is recommended. PMB asphalt mixes typically used in WA should be evaluated in a similar manner as reported in this report, but conducting flexural modulus and fatigue testing over the full temperature and strain range using the recommended number of samples. This will benchmark the effect of RAP on the mixes and develop a data set that may be used to develop limits for PMB blend viscosity.

REFERENCES

Arnold, JC, Noelting, M, Riebesehl, G & Denck, C 2012, 'Unlocking the full potential of reclaimed asphalt pavement (RAP): high quality asphalt courses incorporating more than 90% RAP: a case study', *Eurapsphalt & Eurobitume congress, 5th, 2012, Istanbul, Turkey,* European Asphalt Pavement Association, Brussels, Belgium.

Australian Asphalt Pavement Association 2010, *Asphalt mixing plants*, AAPA, Port Melbourne, Vic.

Australian Asphalt Pavement Association 2018, *Reclaimed asphalt pavement (RAP) management plan*, AAPA, Port Melbourne, Vic.

Austroads 2013, *Maximising the re-use of reclaimed asphalt pavement: binder blend characterisation,* AP-T245-13, Austroads, Sydney, NSW.

Austroads 2014, *Guide to pavement technology part 4B: asphalt,* AGPT04B-14, 2nd edn, Austroads, Sydney, NSW.

Austroads 2015, *Maximising the re-use of reclaimed asphalt pavement outcomes of year two: RAP mix design,* AP-T286-15, Austroads, Sydney, NSW.

Austroads 2016, *Maximising the use of reclaimed asphalt pavement in asphalt mix design: field validation,* AP-R517-16, Austroads, Sydney, NSW.

Bowering, RH 1991, 'Asphalt recycling in Australia: 1990', *Road rehabilitation workshop, 1991, Sydney, New South Wales*, Australian Road Research Board, Vermont South, Vic.

Carswell, I, Nicholls, J.C., Widyatmoko, I, Harris, J, and Taylor, R 2010, *Best practice guide for recycling into surface course*, Road Note RN43, Transport Research Laboratory (TRL), Berkshire, United Kingdom.

Cocks, G, Leek, C, Bondietti, M, Asadi, H, Deilami, S, Leach, R, Sicoe, M, Clayton, R, Keeley, R, Maekivi, C, 2017, 'The use of recycled materials for pavements in Western Australia', *Australian Geomechanics Journal*, vol. 52, no. 1, pp. 1-38.

Denneman, E & Bryant, P 2016, 'Development of mix specific modulus master curves and fatigue models for asphalt pavement design', *ARRB conference, 27th, 2016, Melbourne, Victoria*, ARRB Group, Vermont South, Vic, 12 pp.

Denneman, E & Lam, T 2015, 'Asphalt fatigue at Queensland temperatures: year 2 progress report', contract report 007177, ARRB Group, Vermont South, Vic.

Department of Planning, Transport and Infrastructure 2016, *Supply of asphalt,* specification R27, DPTI, Adelaide, SA.

Deutscher Asphaltverband e. V. 2011, *Recycling of asphalt,* Asphalt Guidelines, DAV, Bonn, Germany.

European Asphalt Pavement Association 2016, *Asphalt in figures 2016*, EAPA, Brussels, Belgium.

Federal Highway Administration 2011, *Reclaimed asphalt pavement in asphalt mixtures: state of the practice,* FHWA-HRT-11-021, FHWA, McLean, VA, USA.

Forschungsgesellschaft fur Straßen- und Verkehrswesen 2013a, *Technische Lieferbedingungen fuer Asphaltmischgut fuer den Bau von Verkehrsflaechenbefestigungen*, TL Asphalt-StB 07/13, Research Association for Roads and Transport (FGSV), (in German), Cologne, Germany.

Forschungsgesellschaft fur Straßen- und Verkehrswesen 2013b, *Zusatzliche Technische Vertagsbedingungen und Richtlinien fur den Bau von Verkehrsflachenbefestigungen aus Asphalt*, ZTV Asphalt-StB 07/13, Research Association for Roads and Transport (FGSV), (in German), Cologne, Germany.

Highways Agency 2008, *Manual of contract documents for highway works: volume 1 specification for highway works series 900: road pavements: bituminous bound materials,* MCHW vol. 1, series 900, Highways Agency, Surrey, UK.

Institute of Public Works Engineering Australasia & Australian Asphalt Pavement Association 2016, *Technical specification, tender form and schedule for supply and laying of asphalt road surfacing,* revision 4, IPWEA & AAPA, Perth, WA.

Kim, S, Sholar, GA, Byron, T & Kim, J 2009, 'Performance of polymer-modified asphalt mixture with reclaimed asphalt pavement', *Transportation Research Record*, no. 2126, pp. 109-14.

Main Roads Western Australia 2017a, *Materials for bituminous treatments,* specification 511, MRWA, Perth, WA.

Main Roads Western Australia 2017b, *Asphalt wearing course,* specification 504, MRWA, Perth, WA.

Main Roads Western Australia 2018a, *Bituminous surfacings guide part 1.1: selection of resurfacing treatments for metropolitan region,* MRWA, Perth, WA.

Main Roads Western Australia 2018b, *Asphalt intermediate course,* specification 510, MRWA, Perth, WA.

Main Roads Western Australia 2019, *Quality systems,* specification 201, MRWA, Perth, WA.

Mohammad, LN, Negulescu, II, Wu, Z, Daranga, C, Daly, DH & Abadie, C 2003, 'Investigation of the use of recycled polymer modified asphalt binder in asphalt concrete pavements', *Journal of the Association of Asphalt Paving Technologists*, vol. 72, pp. 551-94.

National Asphalt Pavement Association 2007, *Recycling hot mix asphalt pavements,* information series 123, NAPA, Lanham, MD, USA.

National Asphalt Pavement Association 2015a, *Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage 2015*, information series 138, NAPA, Lanham, MD, USA.

National Asphalt Pavement Association 2015b, *Best practices for RAP and RAS management,* quality improvement series 129, NAPA, Lanham, MD, USA.

National Asphalt Pavement Association 2015c, *High RAP asphalt pavements: Japan practice: lessons learned*, information series 139, NAPA, Lanham, MD, USA.

National Cooperative Highway Research Program 2011, *A manual for design of hot mix asphalt with commentary*, NCHRP report 673, NCHRP, Washington D.C., USA.

New Zealand Transport Agency 2014a, *Notes to the specification for dense graded and stone mastic asphalt,* M10 notes, NZTA, Wellington, NZ.

New Zealand Transport Agency 2014b, S*pecification for dense graded and stone mastic asphalt,* M10, NZTA, Wellington, NZ.

Northern Territory Department of Infrastructure, Planning and Logistics 2017, *Standard specification for roadworks,* DIPL, Darwin, NT.

Queensland Department of Transport and Main Roads 2017, *Asphalt pavements,* technical specification MRTS30, TMR, Brisbane, Qld.

Queensland Department of Transport and Main Roads 2019a, *Reclaimed asphalt pavement material,* technical specification MRTS102, TMR, Brisbane, Qld.

Queensland Department of Transport and Main Roads 2019b, *Use of high percentages of reclaimed asphalt pavement (RAP) material in dense graded asphalt,* technical note 183, TMR, Brisbane, Qld.

Roads and Maritime Services 2011, *Reclaimed asphalt pavement material,* QA specification 3153, RMS, Sydney, NSW.

Roads and Maritime Services 2013a, *Heavy duty dense graded asphalt,* QA specification R116, edn 8, rev 4, RMS, Sydney, NSW.

Roads and Maritime Services 2013b, *Light duty dense graded asphalt,* QA specification R117, RMS, Sydney, NSW.

Singh, D, Girimath, S & Ashish, PK 2018, ‘Performance evaluation of polymer-modified binder containing reclaimed asphalt pavement using multiple stress creep recovery and linear amplitude sweep tests’, *Journal of Materials in Civil Engineering*, vol. 30, no. 3.

Southern African Bitumen Association 2017, *Use of reclaimed asphalt in the production of asphalt,* TRH 21, SABITA, Pinelands, South Africa.

VicRoads 2017, *Hot mix asphalt,* section 407, VicRoads, Kew, Vic.

West, RC 2010, *Reclaimed asphalt pavement management: best practices,* National Center for Asphalt Technology, Auburn, AL, USA.

West, RC, Willis, RJ & Marasteanu, M 2013, *Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content,* National Cooperative Highway Research Program report 752, NCHRP, Washington, D.C., USA.

Yousefdoost, S, Rebbechi, J & Petho, L 2018, ‘Implementing the use of reclaimed asphalt pavement (RAP) in TMR: registered dense-graded asphalt mixes (Year 1 – 2016/17)’, P57 annual summary report, National Asset Centre of Excellence, Brisbane, Qld.

Zhou, Z, Gu, X, Ni, F & Jiang, Y 2018, “Cracking performance of laboratory-produced polymer modified asphalt mixture containing reclaimed asphalt pavement material: a multiscale analysis”, *Transportation Research Board annual meeting, 97th, Washington, D.C.*, TRB, Washington, D.C., USA.

<u>European Standards</u>

EN 13108-1:2016, *Bituminous mixtures: material specifications: asphalt concrete.*

EN 13108-8:2016, *Bituminous mixtures: material specifications: reclaimed asphalt.*

<u>Australian and New Zealand Standards</u>

AS/NZS 2891.9.2:2014, *Methods of sampling and testing asphalt: determination of bulk density of compacted asphalt: presaturation method.*

AS/NZS ISO 9001:2016, *Quality management systems: requirements.*

Austroads Test Methods

AGPT-T103-06, *Pre-treatment and loss on heating of bitumen multigrade and polymer binders (rolling thin film oven [RTFO] test).*

AGPT-T111-06, *Handling viscosity of polymer modified binders (brookfield thermosel).*

AGPT-T121-14, *Shear properties of polymer modified binders (ARRB elastometer).*

AGPT-T122-06, *Torsional recovery of polymer modified binders.*

AGPT-T131-06, *Softening point*.

AGPT-T190-19, *Specification framework for polymer modified binders.*

AGPT-T191-15, *Extractions of bituminous binder from asphalt.*

AGPT-T192-15, *Characterisation of the viscosity of Reclaimed Asphalt Pavement (RAP) binder using the Dynamic Shear Rheometer (DSR).*

AGPT-T193-15, *Design of bituminous binder blends to a specified viscosity value.*

AGPT-T232-07, *Stripping potential of asphalt: tensile strength ratio.*

AGPT-T274-16, *Characterisation of flexural stiffness and fatigue performance of bituminous mixes.*