

INTERIM TECHNICAL REPORT

P152: Increased Use of Reclaimed Asphalt Pavement Material (2024–2026)

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Summary

The use of reclaimed asphalt pavement (RAP) in asphalt has significant sustainability benefits. Queensland Department of Transport and Main Roads (TMR) currently allows up to 40% RAP in non-surfacing mixes. However, the quantity of RAP in EME2 mixes is limited to 15%, which is similar to current practice elsewhere in Australia. Given that EME2 has become the preferred mix type for basecourse asphalt in South East Queensland, the 15% RAP limit is a potential barrier to facilitating the use of more sustainable asphalt.

France allows up to 40% RAP in EME2, and so, there is an opportunity to increase the amount of RAP allowed in locally manufactured EME2. This multiyear project reviewed current French practices regarding the use of RAP in EME2 and investigated suitable RAP binder criteria based on local test methods for inclusion in TMR's technical specification MRTS32 *High Modulus Asphalt (EME2)*.

The first year of the project (2024–25) commenced with laboratory testing to investigate the development of suitable RAP binder criteria for EME2. This testing predominantly assessed whether a rotary evaporator method (ASTM D5404/D5404M) and a toluene solvent could be used to produce extracted RAP binders for testing. It was found that this method of binder extraction was not suitable for extracting very hard RAP binders as not all of the toluene solvent could be removed. The second year of the project (2025–26) completed the laboratory testing and assessed the correlation between dynamic shear rheometer (DSR) complex viscosity at 60 °C and 25 °C, penetration at 25 °C and softening point for 2 binders that were artificially aged in the laboratory using a pressure ageing vessel (PAV). Binders studied included a sample of unmodified C320 bitumen and an A15E polymer modified binder (PMB).

The study found strong correlations between some of the binder properties investigated. A single relationship to describe the correlation between complex viscosity at 60 °C and softening point could not be found for the 2 binders evaluated. A single relationship between complex viscosity at 60 °C and penetration at 25 °C was found for the bitumen and PMB tested. Such a single relationship is, however, not consistent with previous research, and further research would be required to confirm this. Importantly, a single relationship between complex viscosity at 25 °C and penetration at 25 °C was found for both binder types.

Considering the findings from the laboratory study, it is recommended that TMR considers a maximum complex viscosity at 25 °C and 1 rad/s of 15.5 MPa.s for the RAP binder in EME2 mixes containing up to 40% RAP. This is equivalent to the French penetration at 25 °C requirement of ≥ 5 (0.1 mm) for the RAP binder in high RAP content mixes.

The French softening point requirement of ≤ 77 °C for the RAP binder in these high RAP content mixes appears only to be suitable if the RAP is derived from unmodified bitumen and not necessarily highly

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The project team would like to acknowledge Fulton Hogan and the NTRO laboratory (including Shannon Malone, Elizabeth Woodall and Young Choi) for their contributions. modified PMBs such as A15E, given that these binders typically have softening point values greater than 77 °C even prior to any ageing occurring.

Contents

1	Introduction	1
1.1	Background	1
1.2	Project aim and objective.....	1
1.3	Report structure	1
2	RAP Binder Characterisation	2
2.1.1	French practice.....	2
2.1.2	Australian practice	3
3	Laboratory Investigation.....	5
3.1	Extraction of binder from RAP material	5
3.2	Laboratory ageing and testing of binder samples	6
3.3	Binder properties	10
3.3.1	Correlation between complex viscosity at 60 °C and softening point	10
3.3.2	Correlation between complex viscosity at 60 °C and penetration at 25 °C.....	11
3.3.3	Correlation between complex viscosity at 25 °C and penetration at 25 °C.....	12
3.3.4	Equivalent complex viscosity at 25 °C and 60 °C values.....	15
4	Conclusions and Recommendations	16
	References	18

Tables

Table 2.1:	RAP binder property limits in different European countries	2
Table 2.2:	Additional TMR requirements for EME2 containing > 15% RAP	4
Table 3.1:	RAP binder complex viscosity at 60 °C and 1 rad/s results	6
Table 3.2:	Binder conformance test results	7
Table 3.3:	C320 test results	8
Table 3.4:	A15E test results	8
Table 3.5:	Equivalent complex viscosity at 25 °C and 60 °C	15
Table 4.1:	Equivalent complex viscosity at 25 °C and 60 °C	17

Figures

Figure 3.1:	Complex viscosity at 60 °C versus PAV duration	9
Figure 3.2:	Penetration at 25 °C versus PAV duration	9
Figure 3.3:	Softening point versus PAV duration	10
Figure 3.4:	Complex viscosity at 60 °C versus softening point	11
Figure 3.5:	Complex viscosity at 60 °C and 1 rad/s versus penetration at 25 °C	12
Figure 3.6:	Complex viscosity at 60 °C and 10 rad/s versus penetration at 25 °C	12
Figure 3.7:	Complex viscosity at 25 °C versus penetration at 25 °C for C320 bitumen and A15E binders	13
Figure 3.8:	Correlation between complex viscosity at 25 °C and 1 rad/s and penetration at 25 °C for unmodified bitumen samples in Austroads project APT6154	14
Figure 3.9:	Complex viscosity at 25 °C and 1 rad/s versus penetration at 25 °C and 1 rad/s	14

1 Introduction

1.1 Background

The use of reclaimed asphalt pavement (RAP) material in new asphalt has significant sustainability benefits. Previous National Asset Centre of Excellence (NACOE) studies facilitated the increased use of RAP in Queensland Department of Transport and Main Roads (TMR) registered dense graded asphalt (DGA) mixes, and presently, technical specification MRTS30 *Asphalt Pavements* (MRTS30) allows up to 20% RAP in certain surfacing mixes and up to 40% RAP in non-surfacing mixes.

Since the introduction of EME2 high modulus asphalt to Queensland in 2014, it has become the preferred mix type for basecourse asphalt in South East Queensland (SEQ). At the time when the technology was transferred from France, it was nationally agreed to limit the amount of RAP in EME2 to 15%. This upper limit was also included in technical specification MRTS32 *High Modulus Asphalt (EME2)* (MRTS32). However, the 15% RAP upper limit is a potential barrier to using greater percentages of RAP on TMR's road network.

Notably, France (where EME2 originated from) allows up to 40% RAP in EME2 mixes, subject to additional control limits for the RAP material. In 2021, TMR (together with a local asphalt supplier) successfully trialled an EME2 mix with 30% RAP in the Metropolitan District. Since then, over 100,000 tonnes of EME2 containing 30% RAP and over 5,000 tonnes of EME2 containing 40% RAP have been supplied to projects in SEQ through TMR's non-standard asphalt mix design process.

There is, therefore, an opportunity to further improve the sustainability of asphalt pavements by reviewing and updating the maximum allowable RAP limit for EME2 in MRTS32. However, the additional RAP binder characterisation testing specified in France is an important consideration and requires further investigation prior to implementing these requirements in MRTS32. The methods used to characterise the RAP binder in France also differ from the methods currently used in Australia to characterise RAP binders. Adoption of the current French approach to the characterisation of RAP binder is, therefore, considered a significant impediment to the implementation of EME2 mixes with high RAP contents in Queensland.

1.2 Project aim and objective

The aim of this NACOE project was to improve the sustainability of EME2 by reviewing the maximum allowable RAP limit in MRTS32. The project objectives comprised:

- a desktop review of current RAP binder characterisation practices in Queensland and France
- a laboratory study to develop local control limits for RAP binders used in EME2
- a technical report documenting the study findings (this report).

Notably, the grading control requirements adopted in France for RAP used in EME2 was not considered in this report but will be investigated in future stages of the project.

1.3 Report structure

Section 1 of the report provides background information and the main objectives of the project. Section 2 provides a brief overview of current practice in France and Australia to characterise the RAP binder for asphalt mix design. Section 3 documents the laboratory investigation undertaken, followed by the study conclusions and recommendations in Section 4.

2 RAP Binder Characterisation

This section provides an overview of RAP binder characterisation practices in France and Australia.

When using RAP in new asphalt, it is generally assumed full blending occurs between the aged binder in RAP and the new (virgin) binder, resulting in a binder blend with properties representative of a mixture of the different binders. However, studies have shown that this assumption is not necessarily appropriate for all scenarios, and in some cases, no or limited blending occurs between the binders. Where no blending occurs, the RAP material is sometimes referred to as 'black rock' and the effect of the old binder should not be considered in the asphalt mix design (Austroads 2013).

The harder and more oxidised the RAP binder is, the less likely full blending between the binders will occur. For this reason, it is standard practice in several international jurisdictions to limit the hardness of the old binder in asphalt mixes containing higher percentages of RAP (refer to Table 2.1).

Table 2.1: RAP binder property limits in different European countries

Property	Belgium	France	Germany	Ireland	Poland	Portugal	Slovenia	UK
Penetration at 25 °C (0.1 mm)	> 10	≥ 5	> 15	> 15	> 15	> 15	–	> 15
Softening point (°C)	–	< 77	< 70	–	< 70	< 70	< 70	–

Source: Adapted from Ipavec et.al. (2012).

2.1.1 French practice

Standard French practice allows up to 40% RAP in basecourse asphalt, including EME2. The binder blend (i.e. combined virgin and RAP binder) for basecourse mixes containing greater than 20% RAP must conform to the design binder specification limits for penetration at 25 °C or softening point (Delorme et al. 2007).

The theoretical penetration at 25 °C and softening point of the binder blend is determined in accordance with Equation 1 and Equation 2, respectively.

$$\log_{10}(P) = a\log_{10}(P1) + b\log_{10}(P2) \quad 1$$

$$T_{R\&Bmix} = aT_{R\&B1} + bT_{R\&B2} \quad 2$$

where

- P = penetration at 25 °C of the binder blend (0.1 mm)
- a, b = proportion of the RAP binder and virgin binder, respectively, in the mix
- P1 = penetration at 25 °C of the recovered RAP binder (0.1 mm)
- P2 = penetration at 25 °C of the virgin binder (0.1 mm)
- T_{R&Bmix} = softening point of the binder blend (°C)
- T_{R&B1} = softening point of the recovered RAP binder (°C)
- T_{R&B2} = softening point of the virgin binder (°C)

The default recovered binder categories allowable for use in non-surface courses containing up to 10% RAP are:

- Grade P_{15} – indicates a RAP binder where the penetration at 25 °C of the individual RAP binder samples is at least 10 (0.1 mm) and the average value of all the RAP samples is ≥ 15 (0.1 mm); or

- Grade S_{70} – indicates a RAP binder where the softening point of the individual RAP binder samples is $\leq 77\text{ }^{\circ}\text{C}$ and the average value of all the RAP samples is $\leq 70\text{ }^{\circ}\text{C}$.

The default recovered binder categories allowable for use in non-surface courses containing up to 10% RAP are either of the following:

- Grade P_{15} – indicates a RAP binder where the penetration at $25\text{ }^{\circ}\text{C}$ of the individual RAP binder samples is at least 10 (0.1 mm) and the average value of all the RAP samples is ≥ 15 (0.1 mm).
- Grade S_{70} – indicates a RAP binder where the softening point of the individual RAP binder samples is $\leq 77\text{ }^{\circ}\text{C}$ and the average value of all the RAP samples is $\leq 70\text{ }^{\circ}\text{C}$.

RAP binders that do not meet the default requirements above can, however, still be used in wearing course mixes and at higher rates depending on specific circumstances. For these 'non-standard' RAP binders, P_{dec} or S_{dec} refers to the average penetration of softening point of the recovered binder.

The following additional requirements are specified for the RAP binder used in binder and basecourse mixes containing greater than 20% RAP (Delorme et al. 2007):

- The RAP binder content range must be $\leq 2\%$ or $\leq 1\%$ for mixes containing up to 30% and 40% RAP, respectively.
- The penetration at $25\text{ }^{\circ}\text{C}$ of the recovered RAP binder must be ≥ 5 (0.1 mm), or the softening point of the recovered RAP binder must be $\leq 77\text{ }^{\circ}\text{C}$ for mixes containing up to 30% RAP.
- The penetration at $25\text{ }^{\circ}\text{C}$ of the recovered RAP binder must be ≥ 5 (0.1 mm) and within a range of ≤ 15 (0.1 mm), or the softening point of the recovered RAP binder must be $\leq 77\text{ }^{\circ}\text{C}$ and within a range of $\leq 8\text{ }^{\circ}\text{C}$ for mixes containing up to 40% RAP.

It is worth noting that the differences between the European and Australian test methods will likely result in different softening point values. The European softening point method (EN 1427) requires the bath medium to be stirred during a softening point test, whereas the Australian softening point method (AS 2341.18) does not require the bath medium to be stirred (given AS 2341.18 was originally based on ASTM D36/D36M). The AS 2341.18 and ASTM D36/D36M methods yield softening point results that are generally around $1.5\text{ }^{\circ}\text{C}$ higher than those obtained using EN 1427 (Hunter et al. 2015).

2.1.2 Australian practice

The penetration at $25\text{ }^{\circ}\text{C}$ and softening point tests used in Europe (including France) require a relatively large binder sample and are, therefore, not necessarily practical for routine RAP binder characterisation testing. As a result, Australia has adopted the complex viscosity at $60\text{ }^{\circ}\text{C}$ and 1 rad/s parameter using the dynamic shear rheometer (DSR) to characterise recovered RAP binders. The testing is undertaken in accordance with Austroads test method ATM 192 and requires a significantly smaller binder sample compared to that needed for standard penetration and softening point tests.

TMR provides specific binder design requirements for DGA mixes containing $> 15\%$ RAP in MRTS30 and Technical Note 183 *Use of High Percentages of Reclaimed Asphalt Pavement Material in Dense Graded Asphalt* (TMR 2019). These requirements include one of the following:

- adjusting the virgin binder class (grade bump) for mixes containing up to 30% RAP
- varying the mix constituents (i.e. binder class, percentage of RAP, percentage of rejuvenating agent) for mixes containing up to 40% RAP.

When the option to vary the mix constituents is selected, the asphalt supplier must characterise the viscosity at $60\text{ }^{\circ}\text{C}$ of the virgin binder and the RAP binder in accordance with ATM 192. The binder blend is then designed to achieve the target binder viscosity at $60\text{ }^{\circ}\text{C}$ based on the viscosities and proportions of the individual binder components in accordance with Austroads test method AGPT/T193.

As noted in Section 1.1, MRTS32 currently limits the maximum percentage of RAP in EME2 to 15%. In addition, the RAP binder used in EME2 must have both of the following:

- minimum penetration at $25\text{ }^{\circ}\text{C}$ of 5 (0.1 mm)

- a maximum softening point of 79 °C.

To facilitate the increased use of RAP, TMR has also established non-standard mix design requirements for EME2 containing up to 40% RAP. The non-standard requirements include the additional control measures for the mix design and during production shown in Table 2.2.

Table 2.2: Additional TMR requirements for EME2 containing > 15% RAP

Stage	Requirements
Mix design	• RAP binder viscosity at 60 °C $\leq$ 42,000 Pa.s (mixes containing 16–30% RAP) • RAP binder viscosity at 60 °C within the range of 4,700–42,000 Pa.s (mixes containing 31–40% RAP) • Binder blend viscosity at 60 °C within the range of 6,800–30,000 Pa.s • Design binder content must not be less than standard EME2 mix design without any RAP • Testing of the non-standard mix design must demonstrate full compliance with the mix design and combined filler criteria in MRTS32
Asphalt manufacture	• RAP must be fractionated for mixes containing > 25% • RAP content in the production mix may vary by $\pm 5\%$ from the mix design but must not exceed the maximum allowable RAP content applicable to the asphalt plant's RAP Approval Level • Binder content and grading of the RAP must be determined at a minimum frequency of 1 test per 500 tonnes of RAP used • Viscosity at 60 °C of the RAP binder must be determined at a minimum frequency of 1 test per 1,000 tonnes of RAP used • The binder content of the RAP must not vary by more than $\pm 1\%$ from the nominated target value for mixes containing 16–30% RAP and more than $\pm 0.75\%$ for mixes containing 31–40% RAP • Viscosity at 60 °C of the RAP binder during production must be $\leq$ 42,000 Pa.s for mixes containing 16–30% RAP and within the range of 4,700–42,000 Pa.s for mixes containing 31–40% RAP • Viscosity of the binder blend must be within the range of 6,800–30,000 Pa.s

3 Laboratory Investigation

The laboratory investigation primarily aimed to examine the correlation between the complex viscosity and penetration at 25 °C, as well as the correlation between the complex viscosity and softening point of aged binders. Such correlations (if they exist) could then be used to develop local RAP binder specification limits for complex viscosity based on the French penetration at 25 °C or softening point criteria.

It was originally intended to investigate the correlation between penetration at 25 °C, softening point and complex viscosity at 60 °C of recovered binders from typical RAP samples in Queensland. Given the challenges associated with the recovery of relatively large quantities of binder from RAP material for laboratory testing (refer to Section 3.1), it was instead decided to test binder samples that were artificially aged in a pressure ageing vessel (PAV).

Section 3.1 of the report describes the results of the tests that were conducted on the recovered RAP binder samples during the first year of the project (2024–25). Sections 3.2 and 3.3 summarise the results that were obtained from fresh and PAV-aged binder samples during the second year of the project (2025–26).

3.1 Extraction of binder from RAP material

ATM 192 requires that the RAP binder be extracted for testing using the solvent extraction method in ATM 191. However, ATM 191 was originally designed to extract only small quantities of binder for DSR testing (i.e. typically 10 g of binder is extracted from 200 g of RAP). ATM 191 uses a toluene solvent to extract binder samples from asphalt.

Given the relatively large quantity of binder required for the penetration at 25 °C and softening point tests compared to complex viscosity testing, a significant number of extractions would have been required to complete the testing program. The ATM 191 extraction method was therefore not considered to be practical for this study, and it was therefore proposed to extract the binder using a rotary evaporation method, which produces a lot more binder sample for testing.

The rotary evaporation method used in the study followed the requirements of ASTM D5404/D5404M except that toluene was used for extraction instead of the solvents specified in the standard. Solvents specified in ASTM D5404/D5404M include trichloroethylene, methylene chloride and n-propyl bromide. These hazardous and potentially carcinogenic solvents are not commonly used in Australia due to health and safety concerns. Notably, ASTM D5404/D5404M yields significantly more binder than ATM 191 and was included as an acceptable extraction method in an earlier version of the Australian Flexible Pavement Association model specification for RAP.

Initial extractions were undertaken on RAP samples provided by an asphalt supplier using the ASTM D5404/D5404M rotary evaporation method with toluene. After extraction, the recovered binders physically appeared to be soft, which raised concerns about the appropriateness of the experimental method to extract highly oxidised, very hard RAP binders. The laboratory subsequently investigated whether using toluene was suitable to extract very hard RAP binders for characterisation testing.

This investigation included extracting the binder from:

- a control RAP sample sourced from Victoria (with a relatively low viscosity)
- one of the RAP samples supplied by a local asphalt supplier in Queensland (with a very high viscosity).

The extractions used both the ATM 191 and ASTM D5404/D5404M methods using a toluene solvent.

After extraction, the complex viscosity at 60 °C and 1 rad/s of the binders were determined in accordance with ATM 192, and the results are summarised in Table 3.1. Complex viscosity at 60 °C and 1 rad/s results were determined using the 2 brands of DSR owned by the National Transport Research Organisation (NTRO) laboratory (i.e. a TA Instruments Model AR1500ex and an Anton Paar Model MCR302).

Table 3.1: RAP binder complex viscosity at 60 °C and 1 rad/s results

Extraction method	DSR device	Complex viscosity at 60 °C and 1 rad/s (Pa.s)	
		Control Victorian RAP	Queensland RAP
ATM 191	TA Instruments	4,989	62,100
	Anton Paar	5,794	67,100
ASTM D5404/D5404M with toluene solvent	TA Instruments	4,929	18,100 18,200 ⁽¹⁾ 25,500 ⁽²⁾
	Anton Paar	5,457	21,900

1. Re-test.

2. A reduced pressure of 2 mbar was used at the end of the extraction process to try and remove more toluene from the sample.

The testing showed that the 2 different extraction methods resulted in extracted binders with similar complex viscosities at 60 °C and 1 rad/s for the control Victorian RAP with a lower viscosity, indicating that both methods were able to remove the solvent from this binder. However, the complex viscosities at 60 °C and 1 rad/s of the recovered binders that were extracted from the very hard Queensland RAP using ASTM D5404/D5404M and toluene (i.e. 18,100 Pa.s to 25,500 Pa.s) were much lower than the complex viscosity at 60 °C of the binder extracted using ATM 191 (i.e. 62,100 Pa.s to 67,100 Pa.s).

Similar complex viscosity at 60 °C results were obtained for both the control Victorian RAP binder and the Queensland RAP binder when measurements were conducted using the TA Instruments and Anton Paar DSRs.

The lower complex viscosity at 60 °C results obtained for the very hard Queensland RAP binder when ASTM D5404/D5404M was used with a toluene solvent suggests that the rotary evaporation method was unable to fully remove the solvent from this binder. This implies that the use of ASTM D5404/D5404M with a toluene solvent may not be suitable for extracting very hard RAP binders. The reason is likely to be a result of the higher boiling point (BP) of toluene (111 °C) compared to the other more hazardous solvents such as trichloroethylene (BP = 87 °C), methylene chloride (BP = 40 °C) and n-propyl bromide (BP = 71 °C) (Weast 1983) that are specified for use in ASTM D5404/D5404M. Solvents with higher boiling points are more difficult to remove from extracted binders than those with lower boiling points.

Considering the above, it was determined that the use of ASTM D5404/D5404M with a toluene solvent was not a suitable method for extracting very hard RAP binders for characterisation testing.

3.2 Laboratory ageing and testing of binder samples

Given the challenges associated with recovering large amounts of binder from RAP samples for the proposed laboratory testing, it was decided to artificially age a standard unmodified Class 320 (C320) bitumen and a polymer modified A15E binder in the laboratory. The purpose of the artificial ageing was to replicate the typical complex viscosity range of RAP binders in Queensland (i.e. approximately 4,000 Pa.s to 55,000 Pa.s), as well as the minimum penetration at 25 °C and maximum softening point limits in the French specification.

Table 3.2 lists the results of binder quality control conformance tests that were conducted on the samples of C320 bitumen and the A15E grade polymer modified binder (PMB) prior to PAV ageing. The C320 bitumen sample met all requirements of MRTS17 in terms of the tests that were performed. The A15E sample met all the point of manufacture requirements of MRTS18 in terms of the tests that were performed.

Table 3.2: Binder conformance test results

C320			A15E		
Property	Test method	Result	Property	Test method	Result
Viscosity at 60 °C (Pa.s)	AS/NZS 2341.2	339	Viscosity at 165 °C (Pa.s)	AS 2341.4	0.71
Viscosity at 135 °C (Pa.s)	AS 2341.4	0.52	Torsional recovery at 25 °C (%)	ATM 122	68
Penetration at 25 °C (0.1 mm)	AS 2341.12	47	Softening point (°C)	AS 2341.18	92.5
Viscosity at 60 °C after rolling thin film oven (RTFO) treatment (Pa.s)	AS/NZS 2341.10 and AS/NZS 2341.2	721	Consistency 6% at 60 °C (Pa.s)	ATM 121	1,378
Percentage increase in viscosity at 60 °C after RTFO treatment	AS/NZS 2341.10 and AS/NZS 2341.2	212	Stiffness at 25 °C (kPa)	ATM 121	19
			Stress ratio at 10 °C	AGPT/T125	2.60
			Segregation (%)	AGPT/T108	0.5

The laboratory ageing was undertaken in a PAV in accordance with Austroads test method AGPT/194 except that 50.0 ± 0.5 g of binder was added to the 140 mm dishes that were placed in the PAV, rather than the 15.6 ± 0.5 g of binder, which is stated in the AGPT/T194 method. The AGPT/T194 method was developed from the US AASHTO R28 PAV method, which is used to simulate the ageing of binders in asphalt but uses thinner binder films (i.e. 1.03 mm instead of 3.30 mm) to simulate the ageing of binders that occurs in sprayed seals.

Binder masses of 50.0 ± 0.5 g were added to the PAV dishes in the study to match the amount of binder added to the PAV dishes in AASHTO R28, which better replicates the ageing of binders in asphalt. At each of the 4 ageing times included in the study (i.e. 4, 5, 6 and 8 days), 5 dishes containing C320 bitumen and 5 dishes containing A15E were aged at the same time. This yielded between 200 and 250 g of each aged binder for testing.

The following tests were undertaken on the C320 bitumen and A15E binder samples that were aged in a PAV for 0 days, 4 days, 5 days, 6 days and 8 days, respectively:

- complex viscosity at 60 °C and 1 rad/s in accordance with Austroads test method ATM 192
- complex viscosity at 25 °C and 1 rad/s in accordance with a modified version of ATM 192
- complex viscosity at 25 °C and 60 °C, tested using a frequency of 10 rad/s, in accordance with a modified version of ATM 192
- penetration at 25 °C in accordance with test method AS 2341.12
- softening point in accordance with test method AS 2341.18.

The standard test procedure in ATM 192 requires the RAP binder to be tested at an oscillation frequency of 1 rad/s in the DSR. However, the European RAP rejuvenator assessment protocol was developed based on determining the complex viscosity of binders at 25 °C and 10 rad/s (Hugener et al. 2022). Both oscillation frequencies were therefore used for the DSR testing in this study.

The properties of the unaged (0 days PAV) and aged binder samples are summarised in Table 3.3 and Table 3.4. These tables also include the penetration index (PI) values obtained for each binder, which were calculated using Equation 3 (Hunter et al. 2015):

$$\text{penetration index} = \frac{1952 - 500 \log_{10}(\text{pen}) - 20SP}{50 \log_{10}(\text{pen}) - SP - 120} \quad 3$$

$$PI = \frac{1952 - 500 \log_{10}(\text{pen}) - 20SP}{50 \log_{10}(\text{pen}) - SP - 120}$$

where

pen = penetration at 25 °C result for the binder

SP = softening point result for the binder

Table 3.3: C320 test results

Property	PAV duration				
	0 days	4 days	5 days	6 days	8 days
Complex viscosity at 60 °C and 1 rad/s (Pa.s)	374	21,664	54,250	83,292	135,807
Complex viscosity at 60 °C and 10 rad/s (Pa.s)	358	12,123	24,668	34,647	50,877
Complex viscosity at 25 °C and 1 rad/s (Pa.s)	309,201	5,357,865	7,638,242	8,732,040	11,668,349
Complex viscosity at 25 °C and 10 rad/s (Pa.s)	181,607	1,416,426	1,788,990	1,959,020	2,387,360
Penetration at 25 °C (0.1 mm)	47.5	11.9	9.4	5.9	4.7
Softening point (°C)	53.6	77.0	84.5	88.5	96.0
PI	−0.5	0.9	1.4	1.2	1.7

Table 3.4: A15E test results

Property	PAV duration				
	0 days	4 days	5 days	6 days	8 days
Complex viscosity at 60 °C and 1 rad/s (Pa.s)	1,466	28,883	40,079	101,774	141,776
Complex viscosity at 60 °C and 10 rad/s (Pa.s)	536	9,575	12,844	32,522	41,023
Complex viscosity at 25 °C and 1 rad/s (Pa.s)	97,585	2,137,770	4,575,516	5,159,238	5,789,451
Complex viscosity at 25 °C and 10 rad/s (Pa.s)	47,106	571,770	1,005,890	1,117,518	1,208,814
Penetration at 25 °C (0.1 mm)	72.1	14.7	13.9	10.2	6.9
Softening point (°C)	92.5	98.5	105.0	103.5	116.0
PI	6.9	3.8	4.3	3.6	4.0

The C320 bitumen sample showed a penetration index value of −0.5 prior to PAV ageing, which is typical of PI values determined for Australian bitumens (−0.3 to −0.9). The PI value of the C320 bitumen became increasingly more positive as the PAV ageing time increased, indicating the binder rheological properties were becoming less sensitive to temperature and more like a multigrade bitumen, as the sample was aged.

The A15E binder sample showed a very high PI value of 6.9 prior to PAV ageing, indicating its rheological properties were much less sensitive to temperature than the C320 bitumen sample. For PAV ageing periods between 4 and 8 days, the PI of the A15E sample varied between 3.6 and 4.3. The changes in the PI value after ageing are probably influenced both by oxidation of the bitumen in the PMB (which would be expected to increase the PI value of the binder) and degradation of the polymer in the PMB (which would be expected to reduce the PI value of the binder). For each of the 5 ageing times studied, the A15E binder showed significantly higher PI values than the C320 bitumen sample. This indicated that the rheological properties of the A15E binder were much less sensitive to temperature than the C320 bitumen sample at all ageing times included in the study.

Figure 3.1, Figure 3.2 and Figure 3.3 show the effect of different PAV durations on the complex viscosity at 60 °C, penetration at 25 °C and softening point of the binders included in the study. As expected, the PAV duration had a significant effect on the properties of the binders. Also, adopting a maximum PAV duration of 8 days resulted in the binders having viscosity, penetration and softening point values within the range of interest for this study.

Figure 3.1: Complex viscosity at 60 °C versus PAV duration

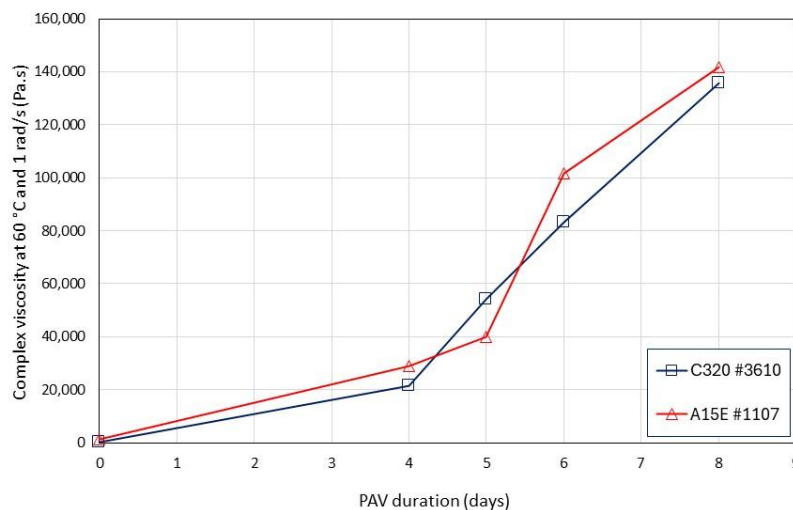


Figure 3.2: Penetration at 25 °C versus PAV duration

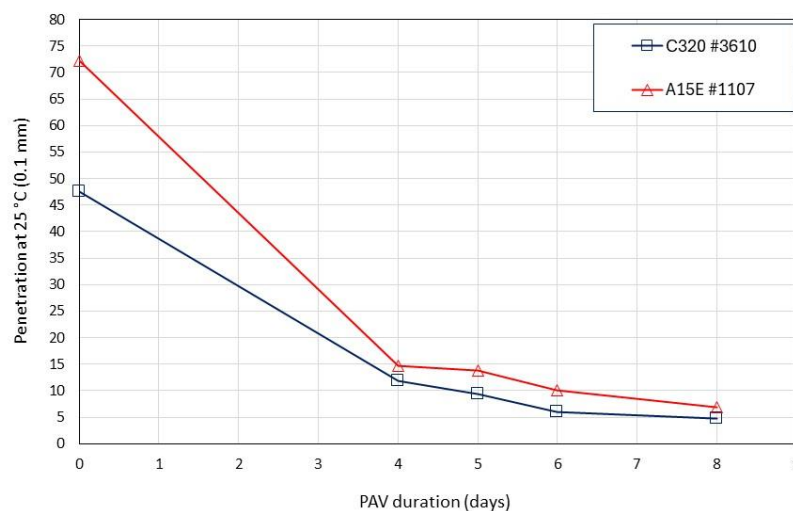
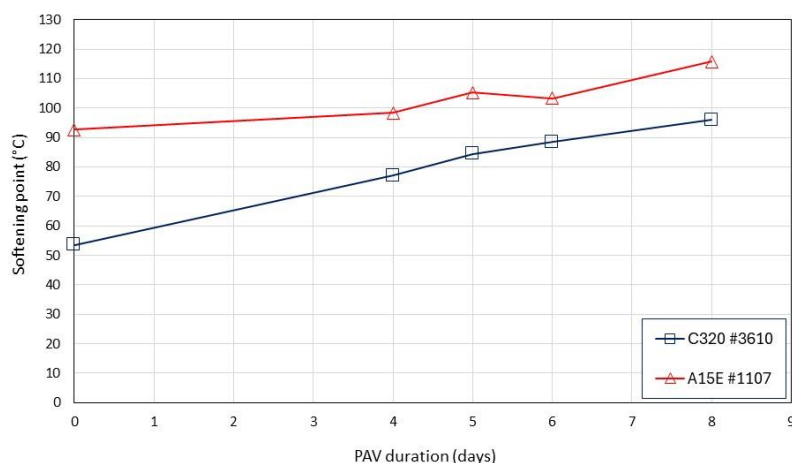


Figure 3.3: Softening point versus PAV duration



3.3 Binder properties

The correlations between complex viscosity, penetration at 25 °C and softening point of the unaged and laboratory-aged binders were investigated, and the findings are presented below.

3.3.1 Correlation between complex viscosity at 60 °C and softening point

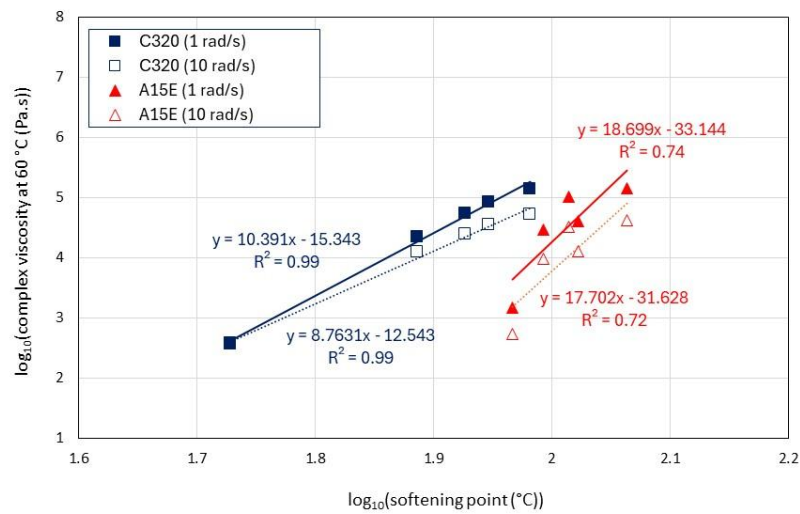
Figure 3.4 shows the correlation between the logarithm of complex viscosity at 60 °C (at 1 rad/s and 10 rad/s) versus the logarithm of softening point for both the C320 bitumen and A15E binders. There is a strong correlation between complex viscosity at 60 °C and softening point for the C320 bitumen sample at both oscillation frequencies used (R^2 values of 0.99), whereas the correlations between these test parameters are only fair (R^2 values of 0.74 and 0.72) for the A15E sample. There does not appear to be a single relationship for the C320 and A15E binders tested. The lack of a single relationship for both binders is most likely a reflection of the marked difference in PI values observed for the C320 bitumen and A15E binders after different ageing times as softening point results were obtained at significantly different temperatures (53.6 to 116.0 °C) than DSR test results (60 °C).

Based on the linear fit to the data shown in Figure 3.4, the equivalent complex viscosity at 60 °C and 1 rad/s for a softening point value of 78.5 °C (equivalent to 77 °C when determined using EN 1427) for the C320 bitumen sample is 22,256 Pa.s. This would correspond to a complex viscosity at 60 °C and 1 rad/s of 22 kPa.s if the result was rounded to the nearest kPa.s. Similarly, the equivalent viscosity at 60 °C and 1 rad/s for the A15E binder sample is 194 Pa.s.

It was noted in Section 2 that many European countries have minimum requirements for penetration at 25 °C and maximum requirements for softening point for extracted binders obtained from RAP to limit the presence of 'black rock' in high RAP content asphalt mixes that will not blend with any new (virgin) binder. Although the A15E binder had a softening point that was much greater than 78.5 °C prior to PAV ageing, this unaged binder would not likely act as black rock if it was included as part of a RAP mix, as unaged PMBs readily mix with other hot bituminous binders.

The European maximum requirements for softening point for extracted binders obtained from RAP therefore appear to be only suitable for limiting the amount of black rock in RAP that contains unmodified bitumen and are not suitable for limiting the amount of black rock in RAP containing highly modified PMBs such as A15E. The European RAP binder property limits included in Table 2.1 show that Belgium, Ireland and the UK only specify a minimum requirement for penetration at 25 °C, that is, there is no maximum softening point requirement for RAP in these 3 countries.

Figure 3.4: Complex viscosity at 60 °C versus softening point



3.3.2 Correlation between complex viscosity at 60 °C and penetration at 25 °C

Previous research by Heukelom (1969) found a correlation between penetration and viscosity at different temperatures. However, it is important to note that this correlation varies based on the temperature susceptibility of the binder (i.e. PI), which is influenced by the class and source of bitumen.

Figure 3.5 and Figure 3.6 show the correlation between the logarithm of complex viscosity at 60 °C and 1 and 10 rad/s, respectively, and penetration at 25 °C for the 2 binders tested. There appears to be a strong correlation between complex viscosity at 60 °C and penetration at 25 °C if the results obtained for both binders are considered. A single relationship between complex viscosity at 60 °C and penetration at 25 °C for the different binders was, however, unexpected and not consistent with the findings from previous research by Hunter et al. (2015) as the 2 binders showed very different PI results after each period of PAV ageing (see Table 3.3 and Table 3.4). The marked difference in PI values indicated that the rheological properties of the A15E binder were far less sensitive to changes in temperature than the rheological properties of the C320 bitumen sample. Given that the correlation between complex viscosity at 60 °C and penetration at 25 °C is expected to depend on the PI of the binder, a single relationship is not considered suitable given the range of different binder types that RAP materials are expected to contain. However, if such a relationship is desirable, further research would be required.

Figure 3.5: Complex viscosity at 60 °C and 1 rad/s versus penetration at 25 °C

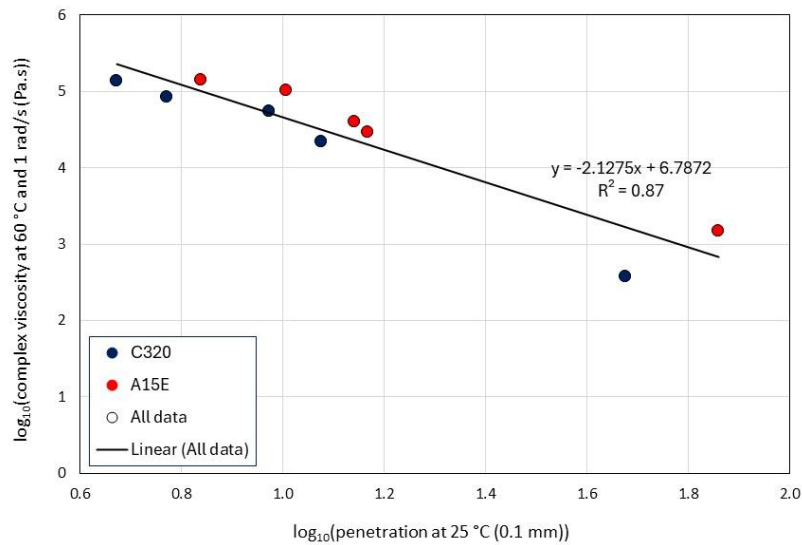
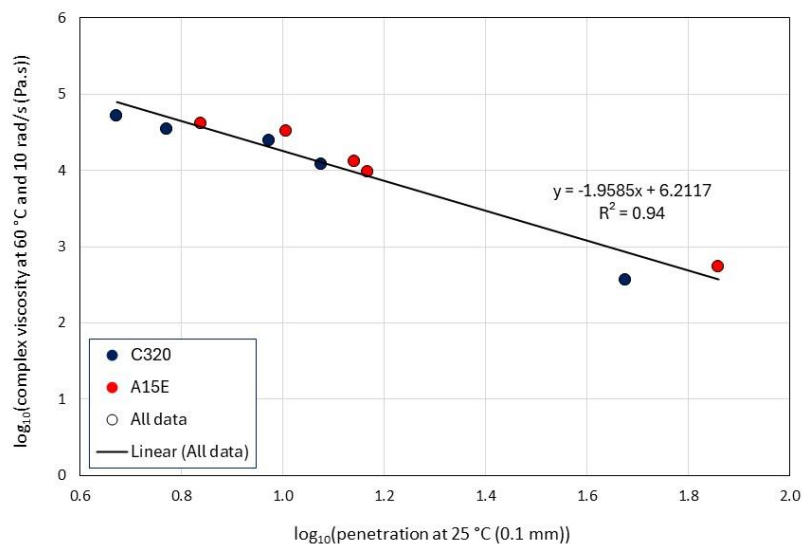


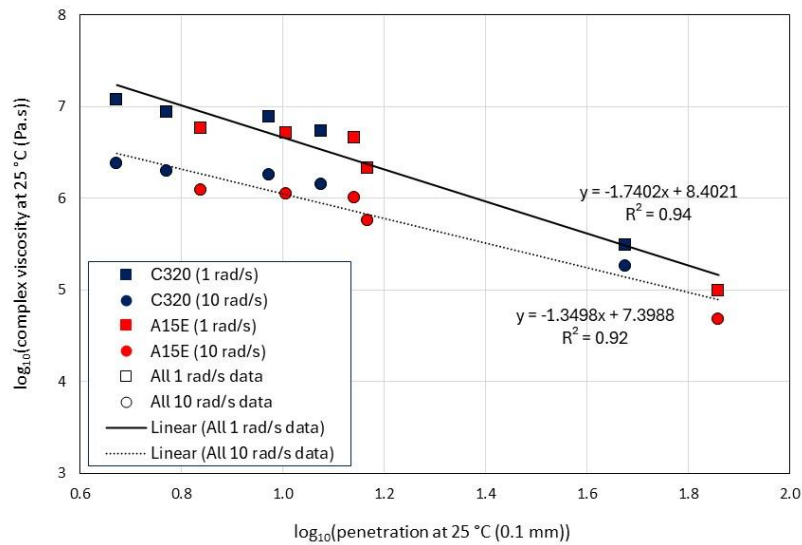
Figure 3.6: Complex viscosity at 60 °C and 10 rad/s versus penetration at 25 °C



3.3.3 Correlation between complex viscosity at 25 °C and penetration at 25 °C

Figure 3.7 shows the correlation between the logarithm of complex viscosity at 25 °C (at 1 rad/s and 10 rad/s) versus the logarithm of penetration at 25 °C for both the C320 bitumen and A15E binders. There appears to be a strong correlation between complex viscosity at 25 °C results at each tested frequency and penetration at 25 °C results when the data obtained for the C320 bitumen sample and the A15E binder are combined. The correlation coefficient (R^2) value obtained from the fit to the complex viscosity at 25 °C and 1 rad/s data (0.94) is slightly higher than that obtained from the fit to the complex viscosity at 25 °C at 10 rad/s data (0.92).

Figure 3.7: Complex viscosity at 25 °C versus penetration at 25 °C for C320 bitumen and A15E binders



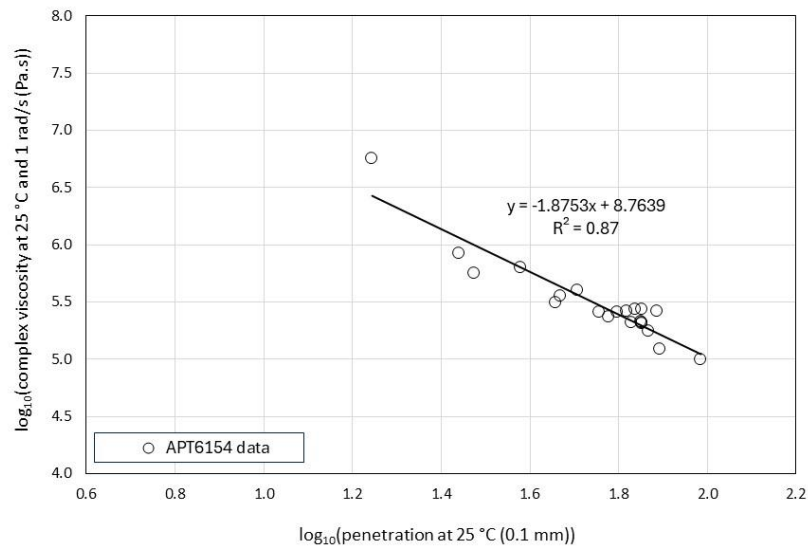
The results shown in Figure 3.7 appear to be consistent with research conducted in the 1950s and 1990s (van der Poel 1954; Gershkoff et al. 1997) and recent research conducted in Austroads project APT6154 *Laboratory Validation of the Rejuvenator Assessment Protocol*. APT6154 compared the results obtained in dynamic oscillatory rheological tests (which are equivalent to the DSR tests conducted in this study) and penetration tests, when both tests were conducted at the same temperature.

Studies conducted by van der Poel (1954) investigated the relationship between stiffness results obtained using dynamic oscillatory rheological tests. They found there was a direct correlation between stiffness results obtained using a test frequency of 2.5 rad/s and penetration results for a wide range of unmodified bitumen samples that displayed a range of PI values. Similarly, Gershkoff et al. (1997) found an excellent correlation ($R^2 = 0.97$) between complex modulus (G^*) results and penetration results for a wide range of unmodified bitumen samples and PMBs when DSR tests were conducted using a test frequency of 2.5 rad/s.

The results shown in Figure 3.7 appear to be consistent with these earlier studies of van der Poel and Gershkoff et al. In particular, there seems to be a slightly better correlation ($R^2 = 0.94$) between complex viscosity at 25 °C and 1 rad/s results and penetration at 25 °C results (which is closer to a test frequency of 2.5 rad/s) than the correlation observed between complex viscosity at 25 °C and 10 rad/s results and penetration at 25 °C results ($R^2 = 0.92$).

Austroads project APT6154 also found a strong correlation ($R^2 = 0.87$) between complex viscosity at 25 °C and 1 rad/s and penetration at 25 °C results for different unmodified bitumen samples. The dataset of APT6154 samples included 17 unaged bitumen samples, 3 bitumen samples subjected to rolling thin film oven (RTFO) treatment and 1 bitumen sample subjected to both RTFO and PAV treatment. The results obtained for the APT6154 binders are shown in Figure 3.8.

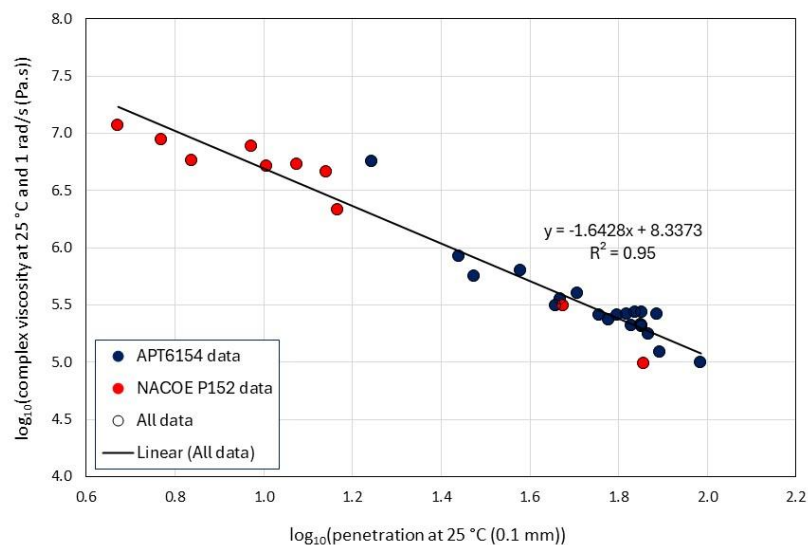
Figure 3.8: Correlation between complex viscosity at 25 °C and 1 rad/s and penetration at 25 °C for unmodified bitumen samples in Austroads project APT6154



Source: Austroads project APT6154.

Figure 3.9 shows the correlation between complex viscosity at 25 °C and 1 rad/s and penetration at 25 °C for the combined dataset obtained in NACOE project P152 and Austroads project APT6154. The combined results obtained in the 2 projects show a strong correlation ($R^2 = 0.95$) between the 2 test parameters.

Figure 3.9: Complex viscosity at 25 °C and 1 rad/s versus penetration at 25 °C and 1 rad/s



Source: NACOE P152 and APT6154 project data.

Based on the results of the study, the minimum penetration at 25 °C of 5 (0.1 mm) specified in France for RAP binders in asphalt mixes containing up to 40% RAP is equivalent to a complex viscosity at 25 °C and 1 rad/s of 15.5 MPa.s when using the relationship in Equation 4.

$$\log(\vartheta) = -1.643\log_{10}(\text{pen}) + 8.337$$

4

where

ϑ = complex viscosity at 25 °C and 1 rad/s (Pa.s)

pen = penetration at 25 °C (0.1 mm)

3.3.4 Equivalent complex viscosity at 25 °C and 60 °C values

The relationships presented in Section 3.3.2 and Section 3.3.3 were used to estimate the equivalent complex viscosity at 25 °C and 60 °C for a range of different penetration at 25 °C values, as shown in Table 3.5.

Table 3.5: Equivalent complex viscosity at 25 °C and 60 °C

Penetration at 25 °C (0.1 mm)	Complex viscosity at 25 °C and 1 rad/s (MPa.s)	Complex viscosity at 60 °C and 1 rad/s (kPa.s)
5	15.5	200
10	4.9	46
15	2.5	19
20	1.6	10
25	1.1	6.5

4 Conclusions and Recommendations

NACOE project P152 is a multiyear project aimed at facilitating the increased use of RAP in asphalt layers. The first phase of the project (documented in this report) was specifically focussed on aligning TMR's practice regarding the use of high percentages of RAP in EME2 with the practices originally developed in France.

The French specification allows up to 40% RAP in basecourse asphalt, including EME2. However, for mixes containing 30% or more RAP, the RAP binder must meet either of the following requirements:

- The penetration at 25 °C of the recovered RAP binder must be ≥ 5 (0.1 mm) and within a range of ≤ 15 (0.1 mm).
- The softening point of the recovered RAP binder must be ≤ 77 °C and within a range of ≤ 8 °C.

TMR's current technical specification MRTS32 limits the percentage of RAP in EME2 to 15%. Allowing higher percentages of RAP in locally manufactured EME2 should ideally include similar binder control limits to the French requirements to avoid excessively oxidised binders that may not adequately blend with the virgin binder during production. However, the penetration and softening point RAP binder tests specified in France require significantly larger amounts of recovered binder for testing compared to the standard complex viscosity test used in Australia. The larger binder sample requirements result in more time-consuming and expensive tests and are therefore considered an impediment to increasing the RAP content in local EME2 mixes. It is therefore desirable to develop equivalent RAP binder control limits for complex viscosity using a DSR in accordance with ATM 192.

Year 1 (2025–26) of the project investigated whether using the rotary evaporator method in ASTM D5404/D5404M and a toluene solvent could be used to produce relatively large extracted RAP binder samples for testing. It was found that this method of binder extraction was not suitable for extracting very hard RAP binders for characterisation testing as not all of the toluene could be removed from these binder types.

Year 2 (2025–26) of the project undertook laboratory testing to investigate the correlation between complex viscosity, penetration at 25 °C and softening point of 2 binders (i.e. C320 bitumen and A15E) that were artificially aged in the laboratory in a PAV. The study found the following:

- a strong correlation between complex viscosity at 60 °C and softening point for the C320 bitumen
- a fair correlation between complex viscosity at 60 °C and softening point for the A15E PMB
- a strong correlation between complex viscosity at 60 °C and penetration at 25 °C for both binders
- a strong correlation between complex viscosity at 25 °C and penetration at 25 °C for both binders.

A single relationship to describe the correlation between complex viscosity at 60 °C and softening point of both binders could not be found. Similarly, a single relationship between the complex viscosity at 60 °C and penetration at 25 °C does not appear to be appropriate given the difference in PI between the C320 bitumen and A15E binders. However, if a single relationship is desirable, it is recommended that further research be undertaken to determine if such a relationship exists across a range of different binders.

Notably, a single relationship between the complex viscosity at 25 °C and 1 rad/s and penetration at 25 °C was found when the results obtained for the C320 bitumen and A15E binders were compared. This relationship also held true when the results obtained in both NACOE project P152 and Austroads project APT6154 were combined to produce a larger dataset of results.

Based on the findings from the laboratory study, the equivalent viscosity at 25 °C and 60 °C shown in Table 4.1 were determined for the French penetration at 25 °C and softening point criteria.

Table 4.1: Equivalent complex viscosity at 25 °C and 60 °C

French criterion	Complex viscosity at 25 °C and 1 rad/s (MPa.s)	Complex viscosity at 60 °C and 1 rad/s (kPa.s)
Softening point ≤ 78.5 °C	Not determined	≤ 22
Penetration at 25 °C ≥ 5	≤ 15.5	≤ 200

Considering the findings from the laboratory study, it is recommended that TMR consider a maximum complex viscosity at 25 °C and 1 rad/s of 15.5 MPa.s for the RAP binder for EME2 mixes containing up to 40% RAP.

The French softening point requirement of ≤ 77 °C appears suitable for limiting the amount of 'black rock' in RAP derived from unmodified bitumen. However, this requirement does not appear suitable for highly modified PMBs such as A15E, given that these binders typically have softening point values greater than 77 °C even prior to any ageing occurring.

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