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Relationships Between Cutter Oil Properties and Sprayed Seal Performance

Relationships Between Cutter Oil Properties and Sprayed Seal Performance

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Abstract

This study investigated the relationship between cutter oil properties and sprayed seal performance so that this information could be used as a basis for updating Australian Standard 3568. AS 3568 specifies the properties of four different types of oils which can be used to reduce the viscosity of binders during sprayed seal construction. The standard has not been updated since 1999 and needs to be revised to be more performance-based so that it can include currently available commercial products.

During the study, seven commercially available oils were initially subjected to a range of currently specified AS 3568 tests. The results obtained for each oil were then compared to the results obtained in four different laboratory sprayed seal performance tests which were performed after each of the oils had been blended with a single sample of C170 bitumen. Correlations were found between the AS 3568-specified final boiling point and viscosity at 40 °C results obtained for each of the neat oils, and the results obtained in the laboratory performance tests.

A number of changes to AS 3568 have been proposed based on the results obtained in the study and input from the Austroads Bituminous Surfacings Working Group (BSWG).

Keywords

Cutter, cutter oil, high flash point cutter, flux oil, sprayed sealing, sprayed seal performance, Australian Standard.

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Edition 1.1 corrects the density property in Table 9.1 Proposed revised specification table for cutter oil and high flash point cutter.

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Summary

Cutter oils (cutters) are added to hot binders in Australia and New Zealand when sprayed seals are constructed at low temperatures in order to enhance the adhesion between binder and aggregate. Australian Standard AS 3568 *Oils for Reducing the Viscosity of Residual Bitumen for Pavements* is currently used by Australian jurisdictions either directly, or as a basis, for local specifications relating to the types of cutter oils used to reduce the viscosity of binders in sprayed seal construction. This standard, however, has not been updated since 1999 and specifies some materials which are no longer commercially available in the marketplace. The main aim of the study was to investigate the key properties of cutter oils which affect sprayed seal performance so that this information could be used as a basis for producing an updated version of AS 3568 which was more performance-based and allowed the use of currently available commercial oils.

A review of cutter oil specifications used by Austroads jurisdictions indicated that AS 3568 is used in New South Wales, Victoria and Tasmania to specify the properties of oils used to reduce the viscosity of binders during sprayed sealing. Other Austroads jurisdictions either use variants of AS 3568 or local specification documents to specify the properties of these oils due to local issues associated with the use of the current standard. AS 3568 currently includes specified requirements for cutter oil, high flash point cutter, flux oil and heavy flux oils. As heavy flux oil is no longer used by Austroads jurisdictions to reduce the viscosity of binders in sprayed seals, the specified requirements for this material could be removed from an updated version of AS 3568.

Investigations into the relationships between neat oil properties and sprayed seal performance were conducted by initially subjecting seven commercially available oils to a range of AS 3568-specified tests. The results obtained for each of the neat oils were then compared with those obtained in four different laboratory sprayed seal performance tests. Performance tests were conducted on mixtures which contained a single sample of C170 bitumen and various amounts of each oil. Laboratory sprayed seal performance tests investigated the stability/miscibility of each oil with C170 bitumen, the relative rates of oil loss over time from binder films containing different amounts of each oil, as well as the effects of the use of different oils on C170 bitumen viscosity reduction and initial aggregate wetting behaviour.

The results obtained in the study indicated that all seven oils were miscible with bitumen and did not separate out over time. Blends of C170 bitumen and each of the oils also showed very similar aggregate wetting performance when basalt aggregates were pushed into 2 mm binder films, immediately removed by hand, and the degree of binder coating on the aggregates was visually assessed as a function of test temperature. Investigations into the relative rates of oil loss from 2 mm binder films containing C170 bitumen and each oil indicated that there was a correlation between the AS 3568-specified final boiling point (FBP) results obtained for each oil and the fraction of oil retained in the binder films after the films were heated for 30 days at a constant temperature. The results obtained in viscosity at 40 °C tests on bitumen/oil blends which contained various concentrations of each oil showed that the viscosity of a bitumen/oil blend was dependent on the AS 3568-specified viscosity at 40 °C result obtained for each oil and the concentration of oil present in each blend.

A wide range of results was obtained for the different oils in AS 3568-specified aniline point and aromatic content tests. Even though this was the case, the results obtained for the neat oils in these tests did not correlate well with the results obtained in any of the performance tests. As the results obtained in aniline point and aromatic content tests do not appear to provide information about sprayed seal performance, these two test properties could be removed from an updated version of AS 3568.

Based on the results from the study, and input from Austroads Bituminous Surfacings Working Group (BSWG) members, several changes to AS 3568 have been proposed in this report. The main proposed changes involve removal of currently specified tests for cutter oil and high flash cutter which were found in the study to not provide information about sprayed seal performance, as well as specifying the properties of flux oil to meet the specification requirements for automotive diesel fuel. As Standards Australia approved a new project proposal to update AS 3568 on 14 November 2018, it could be revised in the very near future.

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1. Introduction

Cutter oils (cutters) are added to hot binders in Australia and New Zealand to enhance the adhesion between binder and aggregate when sprayed seals are constructed at low temperatures (i.e. when the pavement temperature is typically between 20 and 45 °C) (Austroads 2017a, 2018). When hot binders are used to construct sprayed seals, a thin film of binder is initially sprayed on the pavement. Shortly after the binder film is sprayed, aggregate is then applied to the road surface.

In the case of sprayed seals utilising Class 170 (C170) bitumen, cutter is recommended to be added to the binder during construction of a sprayed seal if the pavement temperature during construction is anticipated to be within the range of between about 20 and 45 °C (Austroads 2005, 2018). A guide to the amounts of cutter to be added when sprayed seals are constructed using hot bitumen is included in Austroads (2005). Austroads (2018) includes a guide to the cutter levels to be used when sprayed seals are constructed using hot polymer modified binders (PMBs). Both documents contain information about appropriate cutter levels to use as a function of the pavement temperature during construction and the traffic loading on the site.

Australian Standard AS 3568:1999 *Oils for Reducing the Viscosity of Residual Bitumen for Pavements* is used by Australian jurisdictions either directly, or as a basis, for local specifications relating to the types of cutter, flux and heavy flux oils to be used in sprayed seal construction. This standard, however, was last updated 20 years ago and specifies some materials which are no longer commercially available in the marketplace. Some of the test methods included in standard have also been superseded. Over the past decade, several cutters which do not meet the requirements of AS 3568 have also been found to perform satisfactorily during sprayed seal construction.

Evidence of non-conforming cutters performing satisfactorily in the field, combined with the fact that some of the test methods have been superseded, indicated that the current version of AS 3568 needs to be updated so that it is more performance-based, and reflects the use of materials which are currently commercially available. If AS 3568 was updated to be more performance-based and it reflected currently available products, it would be easier for Australian jurisdictions to directly adopt AS 3568 in their specification documents, rather than requiring some jurisdictions to maintain local specification documents.

The main aim of the research described in this report was to identify the key properties of cutters that affect sprayed seal performance so that this information could be used as a basis for producing an updated version of AS 3568. The information in the report includes a review of Australian jurisdiction and overseas specifications for oils used to reduce the viscosity of binders during the construction of sprayed seals (Section 2) as well as a review of previous research into the performance of cutters in sprayed seals (Section 3). Sections 4 to 8 of the report include the results of laboratory studies where the test properties of seven currently commercially-available oils were compared with their sprayed seal performance as assessed by a range of different laboratory tests. Laboratory performance tests were performed on blends containing C170 bitumen and each of the oils. Section 9 summarises the results obtained in the study and includes a number of proposed changes to AS 3568. Proposed changes to AS 3568 have been based on the results obtained in the study as well as input from Austroads Bituminous Surfacings Working Group (BSWG) members.

2. Cutter Specifications Used in Australia and Overseas

2.1 Australian Specifications for Oils Used to Reduce the Viscosity of Binders

This section reviews the specifications and test methods currently used in Australia for hydrocarbon oils/solvents that are used to reduce the viscosity of binders during sprayed sealing. Specified oils in Australia include cutter oil (cutter), high flash point cutter, flux oil and heavy flux oil. Section 2.1.1 lists current Australian Standard AS 3568 specification requirements, while Section 2.1.2 summarises specified requirements for different Australian jurisdictions and compares these requirements with AS 3568. Even though research was not generally conducted into the performance of flux oils or heavy flux oils in sprayed seals during the study, the specification requirements for these materials have been included in this section for completeness. Advice from jurisdiction members of the Austroads BSWG indicates that heavy flux oil is no longer used in sprayed seal construction (even though it is still referred to in some jurisdiction specification documents).

2.1.1 Current AS 3568 Specification Requirements and Associated Test Methods

Table 2.1 lists the specified properties for cutter oil, high flash point cutter and flux oil listed in the current version of AS 3568 as well as the associated test methods by which testing should be performed.

AS 3568 defines cutter oil to be a light petroleum distillate added to a binder during sprayed sealing to temporarily reduce its viscosity. Flux oil is defined as a petroleum distillate used to produce long-term reduction in the viscosity of a binder used in a sprayed seal. High flash point cutter is an oil similar to cutter oil except that it has a higher flash point (i.e. it is less flammable). Heavy flux oil is defined in AS 3568 as a petroleum residue which produces a long-term reduction in the viscosity of a binder.

In Table 2.1, aniline point, aromatic content and density at 15 °C are specified to reflect the difference in chemical composition of the different oils. Hydrocarbon solvents which show low results in aniline point tests (or high results in aromatic content tests) contain a larger proportion of aromatic hydrocarbons than aliphatic hydrocarbons. Density at 15 °C tests give an indication of the molecular weight of the hydrocarbons in the oils as hydrocarbon solvents containing chemicals with higher molecular weights generally have higher densities. The distillation properties in Table 2.1 give an indication of the relative volatility of the oils at different temperatures. Hydrocarbon solvents which contain higher molecular weight chemicals are generally less volatile than those containing lower molecular weight chemicals.

Flash point, fluidity and water content tests are included in AS 3568 primarily for handling purposes. Flash point tests are included in the specification as the *Australian Code for the Transport of Dangerous Goods by Road and Rail* (National Transport Commission 2018) indicates that liquids which have flash point results of 60 °C or lower in closed cup flash point tests, or 65.6 °C or lower in open cup flash point tests, need to be stored and transported as flammable (Class 3) materials if it cannot be shown by further testing that they will not sustain combustion. Liquids with flash points of 35 °C or less are always considered flammable (Class 3) materials. Fluidity is included primarily to ensure that the oils are not contaminated with particulate matter or other contaminants. Water content tests are included in AS 3568 primarily to ensure that hot binder does not foam when binder and oil are mixed.

An assessment of miscibility is included in Clause 4.3 of AS 3568 to ascertain whether the oil will suitably mix with bitumen. Miscibility requires one part by volume of the oil at ambient temperature to be mixed with one part by volume of bitumen at a temperature of 80 °C, and once the mixture cools to ambient temperature, no separation shall be observed after the mixture stands for one hour. Viscosity at 40 °C is specified in AS 3568 to ensure that the viscosity of a blend of oil and binder is in the appropriate viscosity range required for effective sprayed sealing.

Table 2.1: AS 3568 specification requirements for cutter oil, high flash point cutter and flux oil

Property	Requirements			Test method
	Cutter oil	High flash point cutter	Flux oil	
Aniline point (°C) or Aromatic content (% volume)	65 max. 15 min.	— 15 min.	75 max. 15 min.	ASTM D611 ASTM D1319
Density at 15 °C (kg/m ³)	775–830	780–840	790–880	ASTM D1298 or AS 2341.6
Distillation range Initial boiling point (IBP) (°C) % of original volume recovered at: 150 °C 200 °C 250 °C 300 °C 350 °C Final boiling point (FBP) (°C)	140 min. 10 max. 80 max. 80 min. — — 270 max.	140 min. 10 max. 80 max. 80 min. — — 270 max.	175–230 — 10 max. — 80 max. 80 min. —	ASTM D86
Flash point (°C) Abel closed cup apparatus Pensky-Martens closed cup	38 min. —	61.5 min. —	— 61.5 min.	AS 2106
Fluidity	Clean and free of particulate matter. Liquid at point of use.			—
Miscibility	Complete with no precipitation			AS 3568 Clause 4.3
Water content (% volume)	0.1 max.	0.1 max.	0.1 max.	AS 2341.9
Viscosity at 40 °C (mPa s)	2.0 max.	2.0 max.	1.6–4.6	ASTM D445

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Source: Adapted from AS 3568:1999.

Heavy flux oil has different requirements to those of flux oil, with some additional properties (i.e. sulphur/sediment content and pour point) as shown in Table 2.2.

AS 3568 was first published by Standards Australia in 1989 and was updated to the current version in 1999. AS 3568:1989 listed the same specified properties for cutter, flux and heavy flux oils as are listed in the 1999 version. The main changes between the 1989 and 1999 versions were that specified requirements for high flash point cutter were included in the standard, and small changes were made to the test methods listed in the document.

Table 2.2: AS 3568 specification requirements for heavy flux oil

Property	Requirements	Test method
Distillation range		ASTM D86
Initial boiling point (IBP) (°C)	190 min.	
Temperature at 50% recovery (°C)	320 min.	
Flash point (°C)		AS 2106
Pensky-Martens closed cup	61.5 min.	
Miscibility	Complete with no precipitation	AS 3568 Clause 4.3
Water content (% volume)	0.5 max.	AS 2341.9
Viscosity at 50 °C (mPa s)	45–90	ASTM D445
Sulphur content (% mass)	3.5 max	ASTM D1552
Sediment content (% mass)	0.15 max.	ASTM D473
Pour point (°C)	6 max.	ASTM D97

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Source: Adapted from AS 3568:1999.

Chester (1987) indicated that the specified properties included in the original version of AS 3568 for cutter and flux oils were a compromise between Australian jurisdiction specifications used at the time. The specified minimum aromatic content for cutter oil in the original version of AS 3568 was close to the average of individual jurisdiction requirements which were specified when the standard was drafted (i.e. 10 to 18% by volume minimum). The specified distillation ranges for cutter oil in the original version of AS 3568 were those specified by Roads and Maritime Services (Roads and Maritime) with the addition of initial boiling point (IBP) and final boiling point (FBP) requirements. Chester noted that some of the cutters which were commonly in use during the 1980s did not always meet the requirements of AS 3568.

2.1.2 Australian Jurisdiction Specifications for Oils to Reduce the Viscosity of Binders

The requirements for oils to reduce the viscosity of binders for sprayed sealing vary between Australian jurisdictions. Some jurisdictions specify compliance with the current version of AS 3568, whereas others require some variations from AS 3568, or have developed local specifications that differ significantly from AS 3568.

An overview of jurisdiction specifications is provided in Table 2.3. The comment ‘not used’ in the table indicates that the material is not specified in that jurisdiction to reduce the viscosity of binders. ‘Local specification’ indicates that the jurisdiction specifies properties which differ significantly from AS 3568. Jurisdictions have been listed in Table 2.3 in the order where the uppermost jurisdictions specify oils in terms of AS 3568. Jurisdictions listed lower in the table have specifications which progressively vary from AS 3568.

In New South Wales, Roads and Maritime Services (Roads and Maritime) specifies in QA Specification R106 (Roads and Maritime Services 2012) that cutter, high flash point cutter and flux oils need to conform to AS 3568. Heavy flux oil is not specified to be used to reduce the viscosity of binders.

In Victoria and Tasmania, Section 408 (VicRoads 2017) indicates that cutter oil, high flash point cutter and heavy flux oil need to comply with AS 3568. The document also indicates that other products, which do not meet AS 3568-specified requirements for these types of oils, can also be used subject to contractors providing evidence that the product has demonstrated satisfactory field performance for at least three years. Untried products are also allowed on a trial basis subject to approval by the superintendent. Flux oils are not used to reduce the viscosity of binders.

Table 2.3: Summary of Australian jurisdiction specifications for oils to reduce the viscosity of binders

Jurisdiction	Specification	Cutter oil	High flash point cutter	Flux oil	Heavy flux oil
NSW	QA Specification R106: <i>Sprayed Bituminous Surfacing (with Cutback Bitumen)</i> (Roads and Maritime Services 2012)	AS 3568	AS 3568	AS 3568	Not used
VIC/TAS	Section 408: <i>Sprayed Bituminous Surfacings</i> (VicRoads 2017)	AS 3568	AS 3568	Not used	AS 3568
NT	<i>Standard Specification for Roadworks</i> (Department of Infrastructure, Planning and Logistics 2017)	AS 3568 with variation	Not used	Not used	Not used
QLD	MRTS 19: <i>Cutter and Flux Oils</i> (Queensland Department of Transport and Main Roads 2017)	AS 3568 with variation	Not used	AS 3568 with variation	Not used
SA	Part R25: <i>Supply of Bituminous Materials</i> (Department of Planning, Transport and Infrastructure 2017)	AS 3568 with variation	Local specification	AS 3568	Not used
WA	Specification 511: <i>Materials for Bituminous Treatments</i> (Main Roads Western Australia 2017)	Local specification	Not used	Local specification	Not used

The Department of Infrastructure, Planning and Logistics (DIPL) in the Northern Territory overall specifies cutter oil as kerosene or 'Jet A1 aviation fuel' (Jet A1) which meets AS 3568, except that the FBP of the cutter is specified as 280 °C maximum (rather than 270 °C maximum (Table 2.1)) and flash point is to be determined with a Pensky-Martens closed cup tester as per AS 2106.2. High flash point cutter, flux oil and heavy flux oil are not specified to be used to reduce the viscosity of binders in this jurisdiction (Department of Infrastructure, Planning and Logistics 2017).

While an Abel closed cup apparatus is not specified in the Northern Territory for flash point tests on cutter oil (as per AS 3568), the test method quoted in this specification appears to reflect changes to the AS 2106 standard which occurred in 1999. AS 2106 was broken up into several different standards at this time which describe different methods of measuring the closed cup flash point of flammable liquids.

In Queensland, the Department of Transport and Main Roads (TMR) specifies cutter and flux oils to be used to reduce the viscosity of binders in a similar way to AS 3568 but there are several differences (Queensland Department of Transport and Main Roads 2017). Aniline point tests are not included as an option in Queensland specifications and there is no requirement to assess the fluidity of an oil. MRTS 19 also allows some local test methods to be used to characterise the properties of the oils, although most of these have either been withdrawn or are equivalent to AS 3568-specified test methods. Density at 15 °C tests are required to be conducted using a different test method than those included in AS 3568. Table 2.4 lists the specified test methods included in MRTS 19. Details which deviate from AS 3568 have been highlighted in the table. Similarly to the Northern Territory document, the Australian Standard test methods to be used to measure flash point have been updated to reflect changes to the AS 2106 standard. Density at 15 °C test results are also specified to be quoted in units of kg/litre in MRTS 19 (AS 3568 requires density at 15 °C results to be quoted in kg/m³).

Table 2.4: TMR specified test methods to characterise cutter and flux oils

Property	TMR test method
Aniline point (°C)	No requirement ⁽¹⁾
Aromatic content (% volume)	Q383 ⁽¹⁾ or ASTM D1319
Density at 15 °C (kg/litre ⁽¹⁾)	Q374 ⁽¹⁾
Distillation range	Q384 ^(1,2) or ASTM D86
Flash point (°C)	
Abel closed cup apparatus (for cutter oil)	Q381 ^(1,2) or AS/NZS 2106.1 ⁽¹⁾
Pensky-Martens closed cup (for flux oil)	Q382 ^(1,2) or AS 2106.2 ⁽¹⁾
Fluidity	No requirement ⁽¹⁾
Miscibility	Q385 ^(1,2)
Water content (% volume)	Q354 ^(1,2) or AS 2341.9
Viscosity at 40 °C (mPa s)	Q336 ^(1,2) or AS 2341.3 ⁽¹⁾

1 MRTS 19 specified test methods or measurement units which vary from AS 3568.

2 Test method now withdrawn or equivalent to the AS 3568-specified method.

Source: Queensland Department of Transport and Main Roads (2017).

The numerical specification limits for cutter oil in MRTS 19 are equivalent to those listed in AS 3568 except that the minimum allowed aromatic content is 10% by volume (instead of 15% by volume) and the FBP specification requirement is 280 °C maximum (rather than 270 °C maximum). The numerical specification limits for flux oil in Queensland specifications are equivalent to those listed in AS 3568. High flash point cutter and heavy flux oil are not specified to be used to reduce the viscosity of binders in Queensland.

In South Australia, the Department of Planning, Transport and Infrastructure (DPTI) specifies that cutter oil should be Jet A1 or kerosene which meets the requirements of AS 3568 except that the specified flash point of the material is 40 °C minimum (compared with 38 °C minimum in AS 3568) (Department of Planning, Transport and Infrastructure 2017). Flux oil used to reduce the viscosity of binders is required to meet AS 3568. Heavy flux oil is not used in South Australia to reduce the viscosity of binders.

The South Australian specification for high flash point cutter shows a number of differences from AS 3568 in terms of the specified properties in density at 15 °C, distillation range and viscosity at 40 °C tests. Due to this it has been classified as a local specification in Table 2.3. The other specified properties for high flash point cutter are the same as those listed in AS 3568.

As in the case of the Queensland specifications, the DPTI specification requires that density at 15 °C results on high flash point cutters need to be reported in kg/litre (rather than kg/m³). The range of specified density at 15 °C results in the South Australian specification are equivalent to those listed for the same type of material in AS 3568. DPTI also requires that density at 15 °C tests be performed using only AS 2341.6 (i.e. ASTM D1298 does not appear to be permitted). There are also differences in distillation range specified limits. Viscosity at 40 °C test results and specified limits are also expressed in terms of kinematic viscosity units (i.e. mm²/s) rather than in dynamic viscosity units (i.e. mPa s).

Table 2.5 shows the South Australian specified requirements for high flash point cutter in density at 15 °C, distillation range and viscosity at 40 °C tests which differ from those listed in AS 3568. Variations from AS 3568 have been highlighted in the table.

Table 2.5: DPTI specified properties for high flash point cutter which vary from those listed in AS 3568

Property	DPTI high flash point cutter requirement	DPTI test method
Density at 15 °C (kg/litre ⁽¹⁾)	0.78–0.84 ⁽²⁾	AS 2341.6
Distillation range		ASTM D86
Initial boiling point (IBP) (°C)	150 min. ⁽¹⁾	
% of original volume recovered at:		
150 °C	— ⁽¹⁾	
200 °C	80 max.	
250 °C	80 min.	
300 °C	—	
350 °C	—	
Final boiling point (FBP) (°C)	280 max. ⁽¹⁾	
Viscosity at 40 °C (mm ² /s ⁽¹⁾)	1.2–2.2 ⁽¹⁾	ASTM D445

1 Specified requirements which vary from AS 3568.

2 Equivalent to AS 3568 requirements if density at 15 °C is reported in kg/m³.

Source: Department of Planning, Transport and Infrastructure (2017).

Main Roads Western Australia (MRWA) essentially uses local specifications for cutter and flux oils which differ in many respects from the properties listed in AS 3568 (Main Roads Western Australia 2017). High flash point cutter and heavy flux oil are not specified to reduce the viscosity of binders in this jurisdiction.

The Western Australian specification for cutter oil indicates that suitable materials include oils that meet the requirements of Table 511.9 in WA Specification 511, as well as oils which have been certified to meet the requirements of Jet A1 aviation fuel (Joint Inspection Group 2016) if they are accompanied by a statement indicating that the Jet A1-certified oil has been denatured and supplied without change.

Table 511.9 specification properties do not include the option of conducting aniline point tests and an assessment of the fluidity of cutter oils is not required. There are also differences in specification limits for density at 15 °C, distillation range, flash point, water content and viscosity at 40 °C tests compared with the values listed in AS 3568. Distillation range test properties include a ‘temperature at 50% recovery’ specification limit which is not included in AS 3568. The miscibility requirement in Table 511.9 is similar to that in AS 3568 but not the same. Table 511.9 also requires density at 15 °C tests to be conducted using AS 2341.7 (instead of ASTM D1298 or AS 2341.6), viscosity at 40 °C results to be reported in terms of kinematic viscosity units (i.e. mm²/s) rather than dynamic viscosity units, and flash point tests to be conducted using a Pensky-Martens closed cup apparatus rather than an Abel closed cup apparatus.

Table 2.6 lists the requirements for cutter oil that are listed in Table 511.9 of the Western Australian specification documents. Variations from AS 3568 have been highlighted in the table.

The Western Australian specification for flux oil indicates that suitable materials include oils that meet the requirements of Table 511.10 in WA Specification 511, as well as oils which have been certified to meet the requirements of the Australian automotive diesel fuel specification (*Fuel Standard (Automotive Diesel) Amendment Determination 2009 (No. 1)*) if they are accompanied by a statement that the diesel has been supplied without change.

Table 511.10 specification properties do not require samples of flux oil to be subjected to aniline point, aromatic content or density at 15 °C tests, and an assessment of the fluidity of flux oil samples is not required. There are also differences in specification limits for distillation range, flash point, water content and viscosity at 40 °C tests compared with the values listed in AS 3568. As in the case of Table 511.9 specified properties, there is a specified requirement for the temperature at 50% recovery in distillation range tests and viscosity at 40 °C test results need to be expressed in terms of kinematic viscosity units (i.e. mm²/s). The miscibility requirement in Table 511.10 is again similar to the requirement in AS 3568 but it is not the same.

Table 2.6: Comparison of MRWA Table 511.9 cutter oil specification requirements with AS 3568

Property	MRWA cutter oil requirement	MRWA test method
Aniline point (°C)	No requirement*	—*
Aromatic content (% volume)	15 min.	ASTM D1319
Density at 15 °C (kg/m ³)	780–820*	AS 2341.7*
Distillation range		ASTM D86
Initial boiling point (IBP) (°C)	132–160*	
Final boiling point (FBP) (°C)	265 max.*	
Temperature at 50% recovery (°C)*	220 max.*	
Flash point (°C)		AS 2106
Pensky-Martens closed cup*	35 min.*	
Fluidity	No requirement*	—
Miscibility with equal parts of C170 bitumen*	No precipitation	—*
Water content (% volume)	0.05 max.*	AS 2341.9
Viscosity at 40 °C (mm ² /s*)	1.0–1.4*	ASTM D445

* Specified requirements which vary from AS 3568.

Source: Main Roads Western Australia (2017).

Table 2.7 lists the requirements for flux oil that are listed in Table 511.10 of Western Australian specification documents. Variations from AS 3568 have been highlighted in the table.

Table 2.7: Comparison of MRWA Table 511.10 flux oil specification requirements with AS 3568

Property	MRWA flux oil requirement	MRWA test method
Aniline point (°C) or Aromatic content (% volume)	No requirement*	—*
Density at 15 °C (kg/m ³)	No requirement*	—*
Distillation range		ASTM D86
Initial boiling point (IBP) (°C)	170–195*	
Final boiling point (FBP) (°C)	360–400*	
Temperature at 50% recovery (°C)*	250–290*	
Flash point (°C)		AS 2106
Pensky-Martens closed cup	65 min.*	
Fluidity	No requirement*	—*
Miscibility with equal parts of C170 bitumen*	No precipitation	—*
Water content (% volume)	0.05 max.*	AS 2341.9
Viscosity at 40 °C (mm ² /s*)	2.0–4.0*	ASTM D445

* Specified requirements which vary from AS 3568.

Source: Main Roads Western Australia (2017).

2.2 International Specifications for Oils Used to Reduce the Viscosity of Binders

A literature review was conducted into the specifications used in New Zealand, South Africa, USA and Europe for oils which are used to reduce the viscosity of binders during sprayed sealing. In the case of South Africa, USA and Europe, there are no stand-alone specifications for cutters or flux oils, however, the distillation properties of solvents used to reduce the viscosity of binders are indirectly specified in the cutback bitumen specifications associated with each region.

2.2.1 New Zealand

The New Zealand Transport Agency (NZTA) does not have a specification for cutter or flux oil used in the construction of initial seals. *Chipsealing in New Zealand* (Transit New Zealand 2005), however, states that for general sprayed sealing work, kerosene is used as cutter, and automotive diesel fuel (diesel) is used as flux oil. Kerosene used in sprayed sealing work typically meets specified requirements for Jet A1 aviation fuel (Joint Inspection Group 2016) and high flash point cutter is not commonly available (Robert Busutil, personal communication, June 2017).

In the New Zealand *Performance Based Specification for Reseals* (NZ Transport Agency 2012) document, flux oil to be used in reseals is specified to be diesel which complies with the *NZ Petroleum Products Specifications Regulations* (Petroleum Products Specifications Regulations 2002 (SR2002/210)). Alternative fluxing materials may also be considered for use upon demonstration that the oil will remain in the seal for at least the same time as diesel, and that use of the proposed added concentration to the binder will result in an equivalent viscosity at 60 °C reduction as when the specified quantity of diesel is added to the binder.

2.2.2 South Africa

In South Africa there is no specification for cutter or flux oils to be used to reduce the viscosity of binders in sprayed seal construction. There is, however, a specification (SABS Standards Division 2012) for three different grades of cutback bitumen which consist of blends of bitumen and kerosene. The South African cutback bitumen grades are classified in terms of their kinematic viscosity at 60 °C for reference purposes. Dynamic viscosity at 60 °C tests (with results quoted in mPa s), however, can also be used as field tests. Comparison of the dynamic viscosity at 60 °C limits in the South African cutback bitumen specification with the requirements of the analogous Australian specification (AS 2157) indicates that South African MC-10 and MC-30 grades are similar to Australian AMC00 and AMC0 cutback bitumen grades. The South African MC-300 grade has viscosity at 60 °C limits which overlap the specified limits for Australian AMC4 and AMC5 grades.

While South Africa does not directly specify the properties of cutters used in sprayed sealing, the South African cutback bitumen specification does require cutback bitumen samples to be subjected to distillation tests, and the percentage by volume of total distillate obtained at various temperatures is specified. These tests are effectively specifying the distillation properties of the cutter in the cutback bitumen in a similar way to AS 3568.

2.2.3 USA

The USA also does not have specifications for cutters or flux oils used to reduce the viscosity of bitumen but has a variety of different specifications for types of cutback bitumen made with various hydrocarbon oils/solvents. Cutback bitumens in the USA are classified into rapid-curing, medium-curing and slow-curing types depending on the type of solvent that is blended with bitumen. Each cutback bitumen type is then further separated into a number of cutback bitumen grades which are classified according to the kinematic viscosity at 60 °C of the binder.

There are four rapid-curing cutback bitumen grades specified in ASTM D2028/D2028M which are generally mixtures of bitumen and highly volatile solvents such as naphtha or automotive gasoline. Rapid-curing cutback bitumen is not typically used in Australia or New Zealand due to flammability concerns associated with its low flash point. Medium-curing cutback bitumens are mixtures of bitumen and solvents such as kerosene. There are five medium-curing grades specified in ASTM D2027/D2027M. These cutback bitumens are similar to those specified in Australia and include binder grades which have kinematic viscosity at 60 °C properties which are broadly equivalent to those specified for Australian AMC0 through to AMC4 cutback bitumen grades in AS 2157. There are four slow-curing cutback bitumen grades included in ASTM D2026/D2026M which are primarily mixtures of bitumen and a solvent such as diesel. This is generally equivalent to the practice of using diesel as flux oil in Australia.

As in the case of the South African cutback bitumen specification, the cutback bitumen grades specified in the USA include a requirement to subject the binders to distillation tests. In the case of rapid-curing and medium-curing cutback bitumen grades, the percentage by volume of total distillate obtained at various temperatures is specified which is effectively specifying the distillation properties of the solvents used to produce the cutback bitumens. Slow-curing cutback bitumen grades are required to be subjected to distillation tests, however, only the percentage by volume of total distillate obtained up to a distillation temperature of 360 °C is specified. This is broadly equivalent to determining the percentage by volume of solvent in the cutback bitumen, rather than determining the boiling point properties of the solvent which was added to the binder.

2.2.4 European Union

There are no European documents which specify the properties of oils which can be used to reduce the viscosity of binders during sprayed sealing. In the past, bitumen and PMBs were typically blended with kerosene to produce cutback binders for sprayed sealing; however, the use of these materials in Europe has significantly reduced over time (Hunter, Self & Read 2015).

Although cutback binders are now not commonly used in Europe, the specified properties of these materials are still contained in European Standard EN 15322. This document includes the specified properties of various cutback binder grades as well those specified for binder/oil blends which contain oils derived from plant-based materials. EN 15322 includes 11 cutback binder grades which are classified in terms of either dynamic viscosity at 60 °C or viscosity as measured at various temperatures (i.e. 25, 40 or 60 °C depending on the grade) using an efflux viscometer (EN 12846-2). EN 15322 includes cutback binder grades which are labelled from Class 0 thorough to Class 10. In terms of the four grades classified in terms of dynamic viscosity at 60 °C (i.e. Class 7 through to Class 10 grades), these grades have specified viscosity limits which are similar to those specified for AMC 5 through to AMC 7 grades in the Australian cutback bitumen specification (AS 2157).

EN 15322 requires that cutback binders of Classes 1 to 7 be subjected to distillation tests to determine the amount of oil which is present in the cutback binder. There are also specified limits for Class 2 to 6 cutback binders in terms of the percentage by volume of total distillate obtained at various temperatures. Like South African specification requirements, and US requirements for rapid-curing and medium-curing cutback bitumens, these requirements are essentially specifying the boiling point properties of the oil added to the binder in an analogous way to AS 3568.

2.3 Summary

Australian Standard AS 3568 was first published in 1989 and listed specified requirements for cutter, flux and heavy flux oils to be used to reduce the viscosity of binders during sprayed sealing. Specified requirements for cutter and flux oils were a compromise between Australian jurisdiction specifications used at the time. The current version of AS 3568 was revised in 1999 and included specification requirements for high flash point cutter and small changes to the specified test methods. While AS 3568 is used to specify the properties of oils used to reduce the viscosity of binders in New South Wales, Victoria and Tasmania, variants of AS 3568 or local specification documents are generally used to specify the properties of these oils in other Australian jurisdictions.

A review of overseas specification requirements for oils to reduce the viscosity of binders during sprayed sealing indicated that the properties of the oils are generally not directly specified in New Zealand, South Africa, USA or the European Union. New Zealand documents do however indicate that flux oil used in resealing should either meet New Zealand requirements for automotive diesel fuel or show essentially the same performance during sprayed sealing as diesel fuel. The properties of oils used to reduce the viscosity of binders are indirectly included in South African, USA and European cutback binder specifications. The only oil properties specified in these regions appear to relate to the distillation (i.e. boiling point) properties of the oils.

3. Previous Research into the Performance of Cutters in Sprayed Seals

3.1 Initial Research (1950s and 1960s)

Initial research into the performance of cutters in sprayed seals was performed by Dickinson (Dickinson 1961, 1984) in South Africa. This research involved monitoring the rate of temperature reduction that occurred when binders were sprayed on the road, as well as conducting field trials to investigate the factors which affected initial adhesion between binder and aggregate in sprayed seals. A series of tests was also performed in the laboratory to investigate the effects of humidity, aggregate type and the presence of dust on aggregates on the adhesion between binder and aggregate.

Dickinson monitored the rate of temperature reduction which occurred when hot binders were sprayed in the field and found that a cutback binder sprayed at 125 °C cooled to the pavement temperature (34 °C) within 2 minutes of application. Based on this result, he concluded that initial adhesion between binder and aggregate in a sprayed seal was very dependent on the temperature of the pavement.

A series of road trials was conducted on lightly trafficked roads (1200 vehicles/day) near Pretoria using neat 180-200 penetration grade bitumen (similar to Class 50 bitumen) and blends of 180-200 penetration grade bitumen and kerosene to investigate the effects of pavement temperature and binder viscosity on initial binder-aggregate adhesion. The bitumen/kerosene blends used had similar viscosity at 60 °C test results as an AMC4 grade cutback binder which is listed in the Australian cutback bitumen specification (AS 2157). If an AMC4 grade cutback binder is manufactured with C170 bitumen it typically contains of the order of 18 parts cutter (Queensland Department of Transport and Main Roads 2011). Even though the South African trials were conducted using a softer 180-200 penetration grade bitumen than C170 bitumen it is likely the cutback bitumens contained relatively high concentrations of cutter (> 10 parts). The pavement temperature was varied during the road trials by constructing seals at both sunrise and midday at various sites between February and September 1959. The degree of aggregate adhesion in each of the trials was assessed by an expert panel at least 48 hours after construction.

The results of the field trials indicated that satisfactory aggregate retention occurred for seals constructed using neat 180-200 bitumen if the viscosity of the bitumen at the pavement temperature was lower than about 300 000 Pa s during construction. If the viscosity of the bitumen was higher than this, good binder-aggregate adhesion did not occur. Dickinson concluded that the binders used in sprayed seals needed to have low enough viscosities when aggregate was applied to ensure that they were fluid enough to rapidly wet the aggregates. If the aggregates were sufficiently wetted by binder during construction, effective adhesion between binder and aggregate could then occur.

For cutback bitumen seals containing 180-200 grade bitumen and kerosene, satisfactory aggregate retention occurred when the viscosity of the cutback bitumen in the sprayer was lower than about 8000 Pa s at the pavement temperature. Dickinson concluded that a lower binder viscosity was necessary to effectively wet aggregates when a cutback binder was used as some of the cutter evaporated from the surface of the binder film present on the road surface prior to it being brought into contact with aggregate. This evaporation would increase the viscosity of the surface of the binder film.

Dickinson also conducted a series of laboratory tests to investigate the adhesion between aggregates and binder films containing either neat bitumen or blends of bitumen and kerosene. The bitumen/kerosene blends were similar to those used during the road trials. During these tests, 1 mm thick binder films were initially prepared on circular test trays. The films were then placed in a purpose-built cabinet where temperature and humidity could be controlled, and an excess of 8 mm aggregate was added to the top of the binder films. The aggregate was slightly compacted using a weighted plunger and the binder and aggregate were left in contact for various periods of time. After the required time period had passed, the test trays were removed from the cabinet and non-adhering aggregate was removed by placing the test trays on a mechanical vibrator for a set period of time. The mass of aggregate which had adhered to the binder films was then determined by weighing.

The results obtained in these experiments indicated that there was less aggregate adhesion to cutback bitumen films than neat bitumen films if the test conditions were chosen so that both films had the same viscosity at the temperature they were tested. This result agreed with trends observed during the road trials. Dickinson found that adhesion between binder and aggregate was not markedly affected by the humidity of the air above the binder films (in the humidity range between 0 and 82% at temperatures between 12 and 16 °C) and that there was less adhesion between binders and dusty aggregate than between binders and washed aggregate. Dickinson also found that the adhesion between binder and aggregate was only marginally affected by the source/geological type of the aggregate. Based on the results of field trials and laboratory tests, Dickinson concluded that the viscosity of the binder at the pavement temperature was the most important factor which affected initial adhesion between the binder and aggregate in sprayed seals.

3.2 Research Conducted Since the 1980s

A considerable amount of research was conducted in Australia and New Zealand during the 1980s and 1990s which compared the rates of evaporation of different types of cutters in sprayed seals. These studies included both road trials and laboratory studies. One of these studies (Chester 1987) also investigated the relative amounts of bitumen viscosity reduction which occurred when different cutters were blended with bitumen. During the late 1990s and 2010s, several Australian studies were conducted to determine the relationship between the complex viscosity of blends of polymer modified binders (PMBs) and selected cutters, and the degree of aggregate wetting that occurred when binder films and aggregate were brought into contact. These experiments were performed to provide information about the appropriate levels of cutter to be used when sprayed seals were constructed using PMBs.

While a considerable amount of research has been published by Australian and New Zealand authors in this area, no other published research was found by authors located in other countries other than the initial work conducted by Dickinson (Section 3.1). This likely reflects the common practice of using cutters for sprayed sealing in both countries and the overall significant contribution of sprayed seals to each country's road networks. Sprayed seals are constructed in Europe and the USA on only very low volume roads or they are used as a maintenance treatment (e.g. to increase the surface texture and skid resistance of an existing asphalt pavement or seal an existing road surface against the ingress of water) (Hunter, Self & Read 2015). Sprayed seals are also typically constructed in Europe and the USA using bituminous emulsions rather than hot binders which may contain cutter.

It was generally accepted in Australasia in the 1980s that the viscosity of binders used in sprayed sealing affected both the initial wetting of aggregates during sprayed seal construction (as noted by Dickinson) and the performance of sprayed seals over time (Chester 1986a). If the viscosity of the binder film in a sprayed seal was too low when the seal was subjected to traffic, then aggregate loss could occur over time as the binder would be too soft to effectively retain the aggregate. Flushing of the binder in the seal could also occur during periods of hot weather if the viscosity of the binder film was too low.

Before the 1980s, it was assumed that cutters would be lost from a sprayed seal within a few weeks after it was constructed, whereas flux oils would be retained in a sprayed seal for a considerable amount of time (i.e. years) (Chester 1986a). These assumptions are still quoted in the definitions for cutter oil and flux oil in AS 3568 (as noted in Section 2.1). Cutters were thought to be added to binders during sprayed seal construction to assist with aggregate wetting and initial aggregate reorientation when roads were constructed at low temperatures. The cutter was then assumed to evaporate over a relatively short period of time which increased the viscosity of the binder film. This ensured that aggregate loss or flushing did not occur when the sprayed seals were trafficked. Flux oils were thought to be materials which were retained in sprayed seals for extended periods and so their addition to binders would effectively produce binders in sprayed seals which were softer than conventional bitumen grades. Soft fluxed binders were thought to be appropriate for use in sprayed seals constructed on low-traffic roads.

Several studies were conducted in the 1980s and 1990s to investigate the rates of cutter and flux oil loss from sprayed seals as a result of initial studies by Donbavand (1984) which challenged the assumptions relating to the loss of cutter and flux oil from sprayed seals. Studies of the rate of cutter loss were predominantly performed due to concerns at the time that if the rate of cutter loss was not rapid, then the binders in these seals could remain soft for extended periods. This could lead to aggregate loss under traffic or flushing in hot weather.

Prior to the 1980s, a material referred to as 'power kerosene' was used as the standard cutter in sprayed sealing operations in Australia. During the 1980s, power kerosene was no longer manufactured locally and a material referred to as 'lighting kerosene' was used as a replacement (Chester 1986a). Lighting kerosene has very similar boiling point properties and aromatic content as the standard 'Jet A1' cutter which is now conventionally used in sprayed sealing applications. Power kerosene was more volatile and had a higher aromatic content than Jet A1.

3.2.1 Road Trials Investigating Cutter Loss Over Time

During the early 1980s, Donbavand (1984), developed a new experimental technique which could determine the concentration of cutter or flux oil in either a blend of bitumen and oil, or a field binder sample which was obtained by removing the binder present on aggregate particles which were collected from a constructed sprayed seal. The concentration of oil in the samples was determined by a thermogravimetric technique where the mass loss of volatiles was measured as a function of sample temperature. This technique allowed both the amount and type of oil present in a binder sample to be investigated.

Donbavand studied the loss of cutter in sprayed seals constructed using a blend of New Zealand 180-200 penetration grade bitumen and 3 parts lighting kerosene by testing binder samples obtained from two sampling sites in Pukehou (which is located on the eastern side of the north island). The results of these experiments indicated that 54% of the kerosene that was added to the sprayer remained in a seal 8 months after construction, and 43% remained 20 months after construction. These results did not agree with the assumption that cutter oils were lost from a sprayed seal within a few weeks.

Donbavand also investigated the rate of flux oil loss by sampling from a single site in Dunedin which was sprayed with a blend of 80-100 penetration grade bitumen (similar to C170 bitumen) and 8 parts diesel. Even though Dunedin experiences relatively cold temperatures (as it is located in the southern part of the south island), 7% of the 8 parts of diesel which was added to the sprayer (i.e. 0.56 parts of the originally added diesel) was lost from the seal 8 months after construction. Considering the relative coldness of the site, the observed result was not consistent with the assumption that flux oils would be retained in a sprayed seal for a considerable amount of time (i.e. years).

In response to the results obtained by Donbavand, Chester conducted a road trial in Coldstream, Victoria, which monitored the loss of three different cutters and one flux oil (diesel) over time (Chester 1986a, 1986b). Trial sections included a control section sprayed with neat C170 bitumen and trial sections sprayed with blends of C170 bitumen and 8 parts mineral turpentine, lighting kerosene and Mobil Pegasol R150. The trial section containing flux oil was sprayed using a blend which contained C170 bitumen and 4 parts diesel. Pegasol R150 was included in the trial as it represented a 'theoretical-type oil' which had a relatively narrow boiling point range (specified as 190–214 °C) and a very high aromatic content (typically 97% by volume). A narrow boiling point range material was included in the trial to represent a more chemically pure material than oils normally used in sprayed seal construction. Pegasol R150 was not conventionally used as a cutter in sprayed sealing operations.

The concentration of oil in each of the trial sections was determined as a function of time by taking aggregates from each section at different times after construction. The binder was manually scraped from the aggregates and then weighed. Binder samples were then heated in an oven for 48 hours at 100 °C under a vacuum of 90 kPa in order to evaporate the oil from the samples. The samples were then weighed after oven treatment to determine the concentration of oil present in the original samples.

The results obtained in the Coldstream trial appeared to mirror those obtained by Donbavand, as 40% of the lighting kerosene which was initially present on the road surface remained in the seal 7 months after construction. Seven months after construction, the concentrations of mineral turpentine and Pegasol R150 in the seal sections were 31% and 33%, respectively, of the initial cutter concentrations on the road surface. The concentration of flux oil in the diesel section was 60% of that initially present on the road surface 7 months after construction. The results obtained for the trial section containing diesel clearly indicated that flux oils were lost from a sprayed seal over time and it could not be assumed that they would be retained in a seal for years. This result appeared to indicate that flux oils would be better considered as slowly evaporating cutters.

During the period between 1987 and 1998 at least three additional road trials were conducted in Australia, and two additional road trials were conducted in New Zealand, to further investigate the rate of evaporation of cutters and flux oils from sprayed seals. Australian trials included a South Australian trial which monitored the loss of lighting kerosene from eight different sites in various regions of central South Australia (Glover 1989), and two trials in Victoria which monitored the rate of loss of two different cutters (lighting kerosene, Pegasol R150), a high flash point cutter (Shell Mexcut V) and a flux oil (diesel) from seals constructed in Port Campbell and Inverleigh (Meydan 1997, 1998). The Australian trials used C170 bitumen as the bituminous binder. Oil concentrations between 2 and 10 parts were added to the sprayer prior to construction of the seals.

The two New Zealand trials were conducted at Lower Hutt and Gracefield (which are located in the southern part of the north island). Both trials used 180–200 penetration grade bitumen as the bituminous binder. The trial at Lower Hutt monitored the rate of cutter loss from an initial blend that contained 10 parts lighting kerosene (Patrick 1987), while the trial at Gracefield monitored the rate of cutter loss from trial sections initially containing 5 and 10 parts lighting kerosene (Herrington & Ball 1994).

The results obtained in the trials conducted between 1987 and 1998 were all consistent with those obtained originally by Donbavand and Chester, in that they all showed that a significant percentage of the cutter added to a binder was present in a sprayed seal many months after construction. The results obtained for sections in the Port Campbell and Inverleigh trials where a fluxed binder was used also showed that a significant amount of diesel was lost from a sprayed seal over time (as only between 20 to 25% of the diesel that was initially present on the road surface was retained in the seals seven months after construction).

It was noted by several researchers (Patrick 1987; Glover 1989; Meydan 1998) that the actual rates of cutter and flux oil loss observed in trials conducted in the 1980s and 1990s were not the same at all sites. These differences were attributed to differences in the temperature conditions at each of the trial sites (i.e. greater rates of oil loss were observed at hotter sites than colder sites).

3.2.2 Investigations of Cutter Loss During Spraying

During four of the road trials described in Section 3.2.1, measurements were performed to determine the amount of cutter or flux oil which was lost when binders were sprayed on the road. These investigations compared the amount of oil added to a sprayer with either the amount of oil in the binder that was delivered from the sprayer jets, or the amount of oil in the binder just after it had been sprayed on the road. Table 3.1 summarises the results obtained in each of the trials and includes information about the oil type and concentration of oil in the sprayer, the binder temperature in the sprayer (if known), where the binder was sampled after spraying, and the percentage of oil which was retained and lost from the binder during spraying.

Table 3.1: Comparison of trials which investigated the amount of cutter or flux oil loss during spraying

Trial	Oil type and concentration in sprayer	Binder temperature in sprayer (°C)	Point at which binder was sampled after spraying	% of oil retained in binder after spraying	% of oil lost from binder during spraying
Coldstream VIC (C170 bitumen ⁽¹⁾)	8 parts mineral turpentine	Approximately 170	Sprayer jet	72	28
	8 parts lighting kerosene			76	24
	8 parts Pegasol R150			90	10
	4 parts diesel			94	6
Inverleigh VIC (C170 bitumen ⁽¹⁾)	8 parts lighting kerosene	Unknown	Road sample after spraying	96.5	3.5
	8 parts Pegasol R150			95	5
	8 parts Mexcut V			99.5	0.5
	8 parts diesel			98.5	1.5
South Australian trials (C170 bitumen ⁽¹⁾)	2.4 parts lighting kerosene	174	Road sample after spraying	74	26
	4.2 parts lighting kerosene	172		76	24
Gracefield NZ (180-200 bitumen ⁽¹⁾)	5 parts lighting kerosene	Unknown	Road sample 3 minutes after spraying	83	17
	10 parts lighting kerosene			85	15

¹ Type of bitumen added to the sprayer.

Source: Chester (1986a, 1986b); Glover (1989); Herrington and Ball (1994); Meydan (1998).

The trials conducted at Coldstream and Inverleigh compared the percentage loss of a range of different oils during spraying. Significantly greater amounts of oil loss were observed during the Coldstream trial than the Inverleigh trial. Even though this was the case, the percentage of flux oil (diesel) loss (i.e. 6% and 1.5%, respectively) was less than the percentage of lighting kerosene loss (i.e. 24% and 3.5%, respectively) in both trials which appears to reflect the differences in volatility of the two oils. The difference in oil loss observed during the two trials could possibly be due to the binders being heated to a lower temperature in the sprayer in the Inverleigh trial than the Coldstream trial, however, no information about binder temperature is included in Meydan (1998).

The trials conducted in South Australia and Gracefield determined the amount of lighting kerosene loss when different amounts of this cutter were added to a sprayer. Overall, similar percentage losses of lighting kerosene were observed during spraying in the Coldstream, South Australian and Gracefield trials (i.e. 15% to 24%). Much less lighting kerosene was lost during spraying in the Inverleigh trial (3.5%). The report on the Gracefield trial (Herrington & Ball 1994) also did not include any information about the binder temperature in the sprayer.

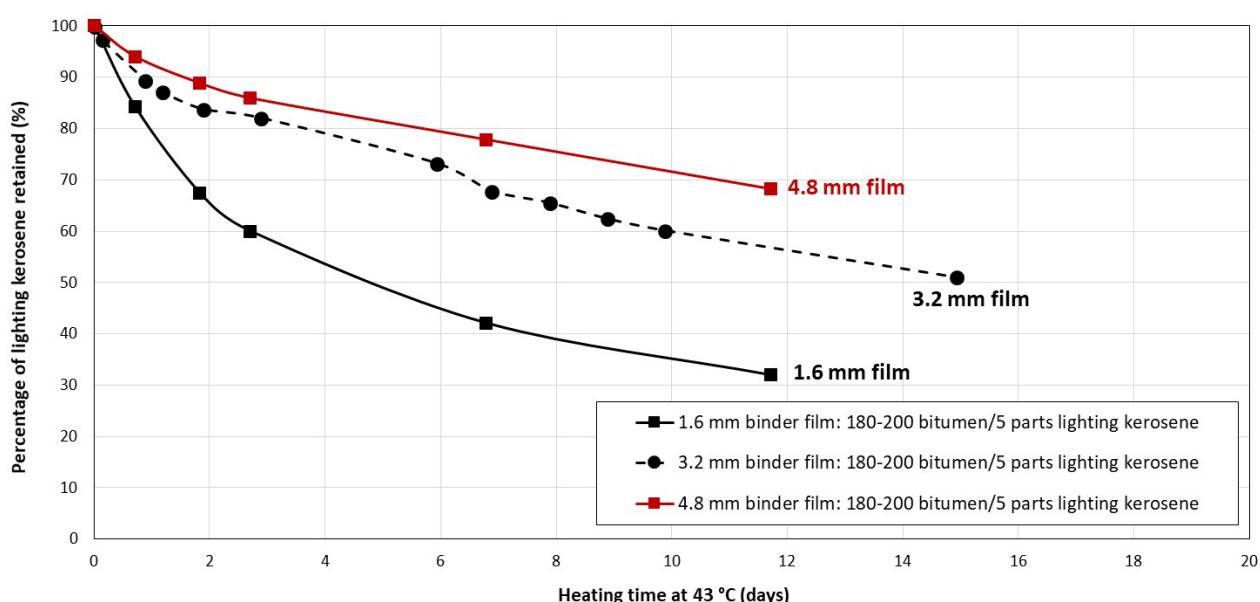
3.2.3 Laboratory Studies of Cutter Loss from Binder Films

A series of laboratory studies was conducted by Patrick (1987), Meydan (1998) and Dickinson (1986, 1987, 1988, 1989) during the 1980s and 1990s to investigate the relative rate of cutter or flux oil loss from thin binder films which were kept at constant temperature. These experiments were all performed by initially preparing thin binder films by pouring appropriate masses of binder into suitable rectangular or circular metal trays, placing the trays in a constant temperature environment and then monitoring the mass of the binder films over time. The reduction in mass of the binder films over time gave a direct indication of the amount of cutter or flux oil which had been lost by the binder films.

Patrick (1987) studied the effects of a variety of different experimental parameters on the rate of oil loss from blends of bitumen and oil at temperatures of 15 and 43 °C. Initial experiments monitored the rate of lighting kerosene loss from thin films containing either 5 or 10 parts lighting kerosene. These experiments investigated the effects of temperature, cutter concentration, bitumen type and binder film thickness on the rate of lighting kerosene loss from the films. The binder films contained either 180-200 or 80-100 penetration grade bitumen.

Figure 3.1 shows the results obtained by Patrick when binder films with thicknesses of 1.6, 3.2 and 4.8 mm were tested at 43 °C for periods up to 15 days. All films shown in the figure initially contained 180-200 penetration grade bitumen and 5 parts lighting kerosene. The y-axis in Figure 3.1 corresponds to the percentage of cutter remaining in the films compared to the original amount of cutter which was added to the blends (i.e. a result of 50% on the y-axis in the figure corresponds to a lighting kerosene concentration of 2.5 parts). The results obtained in these experiments indicated that there was a decrease in the rate of lighting kerosene loss as the binder film thickness was increased (when cutter concentrations were expressed in terms of the percentage cutter initially added to the films). The same trend was observed when binder films containing 180-200 penetration grade bitumen and 10 parts lighting kerosene were tested. These films also had thicknesses of 1.6, 3.2 and 4.8 mm, respectively.

Figure 3.1: Cutter loss experiments conducted by Patrick with different thickness binder films



Source: Adapted from Patrick (1987).

The results obtained by Patrick with binder films containing lighting kerosene indicated that the rate of cutter loss was significantly decreased if the temperature of the experiment was decreased to 15 °C. The rate of cutter loss (when expressed as a percentage of the initial concentration of cutter in the films) also increased when the cutter concentration in the films was increased (i.e. from 5 to 10 parts). The type of bitumen used in the cutter blends had less of a marked effect on the rate of cutter removal from the films as use of harder 80-100 penetration grade bitumen instead of 180-200 penetration bitumen only caused a slight reduction in the rate of lighting kerosene loss from the films.

After experiments were completed using bitumen/lighting kerosene blends, Patrick investigated the effects of the use of different oils in the blends. Experiments were conducted at 15 and 43 °C using blends containing 5 and 10 parts mineral turpentine, and 5 parts diesel. These experiments were conducted using 3.2 mm binder films which contained 180-200 penetration grade bitumen. The results of these experiments showed the same trends as observed for blends containing lighting kerosene in terms of changes in the rate of oil removal with both temperature and cutter concentration. The rate of oil removal from the films followed the order mineral turpentine > lighting kerosene > diesel which appeared to reflect the relative volatilities (i.e. boiling point ranges) of the three oils studied.

Patrick numerically compared the initial rates of oil removal in the different experiments after he found that plots of percentage oil lost versus the square root of heating time (rather than plots of percentage oil retained versus heating time as shown in Figure 3.1) gave linear plots for percentage oil lost results between 0% and 50%. These percentage oil loss results are equivalent to percentage oil retained results of between 100% and 50% in Figure 3.1 (as the % oil retained in the films = 100% – % oil lost from the films). Plots involving the square root of heating time deviated from linear behaviour when more than about half of the amount of added oils had evaporated from the films. Patrick compared the slopes obtained in the linear regions of his ‘percentage oil lost’ versus ‘square root of time’ plots to obtain numerical information about the differences in the initial rates of oil loss from each of the films. This analysis, however, did not yield numerical information about the relative rates of oil loss which occurred after longer heating times (i.e. when significantly more than 50% of the added oils had been lost from the films).

Based on the trends observed in the study, Patrick concluded that the rate of oil removal from a binder film was mainly controlled by the diffusion of the oil to the surface of the film (which would be controlled by the thickness and viscosity of the binder film). Once the oil had diffused to the surface of the film it could then evaporate into the air. More volatile oils would be more prone to evaporate once they had reached the film surface (which would increase their rate of removal from the binder films). Use of a lower temperature in the experiments would be expected to significantly reduce the rate of oil removal from the films as it would both increase the viscosity of the binder film (which would increase the time it would take for the oil to diffuse to the surface) and decrease the relative volatility of the oil (which would decrease the rate of evaporation from the surface).

Meydan (1998) conducted similar experiments to Patrick using 1 mm binder films which contained C170 bitumen blended with 8 different types of narrow boiling point range hydrocarbon solvents. Experiments were performed at temperatures of 25, 35, 36, 45 and 60 °C using films which contained either 3 or 6 parts of each solvent. The types of solvents included in the study included four aliphatic solvents with different boiling point ranges (which would be expected to show very low results in AS 3568 aromatic content tests) and four aromatic solvents with different boiling point ranges (which would be expected to show very high results in AS 3568 aromatic content tests). These types of solvents were selected to determine the effect of cutter aromatic content and boiling point on the rate of loss of cutter from binder films.

Meydan analysed the results obtained in the experiments using a similar method to Patrick but instead plotted % oil retained results (as shown in Figure 3.1) versus the square root of the heating time. He then compared the slopes obtained in the linear regions of the plots (i.e. for % oil retained results between 100% and about 50%) to obtain numerical comparisons between the initial rate of loss of each of the solvents under each set of experimental conditions. The results obtained by Meydan agreed with those obtained by Patrick as the initial rate of solvent loss increased as solvent concentration in the binder film increased. There was also a marked increase in the initial rate of solvent loss with increasing test temperature.

The results obtained by Meydan indicated that the boiling point properties of the solvent affected the initial rate of solvent loss from the binder films, but the aromatic content of the solvent had no effect on the initial rate of solvent removal. When experiments conducted using the same solvent concentration and temperature were compared, there appeared to be a correlation between the initial rate of solvent loss and the average boiling point of the solvent tested. The average boiling point of each solvent was defined as '(initial boiling point – final boiling point)/2'. Solvents with higher average boiling points showed lower initial rates of solvent loss in the experiments than solvents with lower average boiling points.

Several studies were conducted by Dickinson between 1986 and 1989 to investigate various factors which could influence the rate of cutter removal from binder films. These studies, however, predominantly focussed on developing a complex theoretical model which was initially based on only five duplicate experiments which monitored the mass loss of the narrow boiling point range 'theoretical-type oil' Pegasol R150 from blends of C170 bitumen and Pegasol R150. Initial experiments were conducted using 1 or 5 mm binder films which contained between 11 and 17 parts Pegasol R150 (Dickinson 1986). Four of the duplicate experiments were conducted at 36 °C and the other duplicate test was conducted at 30 °C. A relatively pure theoretical-type oil was used in these experiments to simplify the modelling of the data.

The theoretical model developed by Dickinson utilised a solution to Fick's diffusion equation (Crank 1975) which was applicable to a thin film of material on a solid surface where a volatile component could evaporate into the air over time. The model considered each binder film to be composed of several different horizontal layers where the concentration of cutter in each of the layers varied over time as cutter was lost from the film. The model included the vapour pressure of the cutter at the test temperature (which is related to cutter volatility) as well as the rate of diffusion of cutter in the different layers in the film (which was assumed to be related to the viscosity of the bitumen/cutter blend in each individual layer). Relationships between cutter boiling point and vapour pressure were assumed to be the same as that of pure aliphatic hydrocarbons with the same average boiling point as vapour pressure data for cutters was not available. A generic relationship between the rate of diffusion of the cutter in the film (i.e. the cutter's diffusion coefficient) and the viscosity of the bitumen/cutter blend in each layer was also assumed.

The experimental data obtained in the five duplicate tests was fitted to the model using a computer program as the numerical calculations involved in the model were extremely complex. The model fitted the experimental data which was obtained in each experiment using three adjustable fitting parameters. Use of the model and associated adjustable fitting parameters yielded good fits to the results obtained for the five sets of duplicate laboratory tests which were obtained for binder films which contained blends of C170 bitumen and Pegasol R150.

Dickinson (1987, 1988, 1989) later tried to extend the model he had developed to account for wide boiling point range cutters (which are typically used in sprayed sealing applications), variations in temperature which would occur at a sprayed sealing site, and the presence and orientation of the aggregate in a sprayed seal. The results of various versions of the extended model were compared to the measured changes in oil content in the lighting kerosene, Pegasol R150 and diesel sections of the Coldstream trial site (Section 3.2.1) to determine if the model could be validated. None of the versions of the extended model predicted changes in oil concentration that matched up well with the actual changes in oil content which occurred in the three Coldstream trial sections over time.

3.2.4 Laboratory Studies of Bitumen Viscosity Reduction Due to the Use of Different Cutters

The only study that appears to have investigated the changes in the viscosity of binders when different types of cutters are added to bitumen was conducted by Chester (1987). Investigations were conducted by Herrington and Patrick (1998) into the effects of adding different amounts of flux oil (diesel) and three types of heavy flux oil (waste oil vacuum bottoms, tall oil pitch and a rejuvenating oil) on the viscosity of 180-200 penetration grade bitumen but the types of materials included in the study did not include any cutter oils.

Studies conducted by Chester involved performing viscosity tests at 9.8, 20.0, 30.3, 40.5, 50.8 and 61.0 °C on blends of C170 bitumen with three different cutters (i.e. lighting kerosene, power kerosene and Mobil Pegasol R150) which had varying aromatic contents (i.e. 20%, 36% and 97%, respectively). Tests were conducted using a Haake rotational viscometer. The investigation utilised C170 bitumen from two different sources and cutter concentrations in the range between 3.9 and 16.7 parts. The viscosity of blends containing each of the three cutters was measured using one of the samples of C170 bitumen (sample 1). The other sample of C170 bitumen (sample 2) was blended with only lighting and power kerosene. A full set of viscosity results for all concentrations studied was only able to be obtained at a test temperature of 30.3 °C due to limitations in the viscosity range which could be effectively measured by the Haake rotational viscometer.

The results obtained by Chester suggested that power kerosene reduced the viscosity of bitumen samples 1 and 2 by a slightly greater amount than lighting kerosene (if the same concentration of cutter was added to the blends). Addition of Pegasol R150 to bitumen sample 1 caused a larger reduction in bitumen viscosity than lighting or power kerosene if the same cutter concentrations (in parts) were used. Based on the trends observed in the experiments, Chester concluded that cutters with higher aromatic contents appeared to cause a larger reduction in binder viscosity than cutters with lower aromatic contents if the same cutter concentration was added to a bitumen sample. She did, however, note in her report that this conclusion was based on a limited data set.

The changes in viscosity of blends of petroleum products (e.g. bitumen and cutter) are typically modelled by considering the viscosity and relative amounts of each of the different components in the blend rather than the chemical properties of the materials (Centeno et al. 2011; Zhmud 2014). Even though Chester concluded that more aromatic cutters reduced the viscosity of bitumen to a greater extent than cutters with lower aromatic contents, the effects of neat cutter viscosity on the viscosity of the blends was not considered during the analysis of the results.

3.2.5 Aggregate Wetting Tests

Three experimental studies were conducted during the late 1990s and early 2010s to investigate the effect of the addition of cutter on the ability of binders to effectively wet aggregates during sprayed sealing (Maccarrone et al. 1997; Austroads 2012a, 2012b). These studies primarily focussed on investigating the effects of the addition of cutter to PMBs on aggregate wetting behaviour as the main purpose of the studies was to update Austroads documents related to recommended cutter levels to be used when PMBs were used to construct sprayed seals. Austroads (2005) contains a list of recommended cutter levels to be used when C170 bitumen is used in sprayed sealing. Recommended cutter levels to be used when PMBs are used in sprayed seal construction are currently listed in Austroads (2018).

Studies by Maccarrone and co-workers were conducted in response to aggregate stripping problems which occurred at the time when PMBs were used to construct sprayed seals. During the 1990s, a number of sealing failures associated with aggregate stripping shortly after construction had occurred when PMBs were used in sprayed sealing. As a result of these failures, Maccarrone et al. developed an aggregate wetting test which could be used in the laboratory to assess the degree of aggregate wetting that occurred when different types of binders and aggregate were initially brought into contact. This test assessed the amount of binder coating that occurred on aggregates as a function of temperature. It was noted in Section 3.1 that if aggregates are sufficiently wetted by binder during sprayed seal construction, effective adhesion between binder and aggregate can then occur.

Maccarrone et al. conducted aggregate wetting tests using 1.7 mm thick films of C170 bitumen, S10E, S35E, S15E and S20E grade binders which contained between 0 and 6 parts lighting kerosene (Mobil Pegasol 3345). Aggregate wetting tests were performed by initially conditioning the binder films and aggregate at the desired test temperature, and then pushing a single type of clean, dry unprecoated aggregate into the binder films by hand and then immediately removing the aggregate. The degree of binder coating on the aggregate was then assessed visually in terms of the percentage of the aggregate surface which was covered by binder. Maccarrone et al. conducted aggregate wetting tests using a single type of 10 mm hornfels aggregate. Tests were performed using temperatures in the range between 10 and 60 °C. Most binder films contained 1% by mass of the adhesion agent Megamine BA HPR.

Maccarrone et al. found that the degree of binder coating on aggregates increased as the temperature was increased for all binder types studied. For each specific binder type (e.g. C170 bitumen or C170 bitumen with 2 parts cutter) there was little coating of the binder on the aggregate at low temperatures. As the test temperature was increased the percentage of binder coating on the aggregates increased. Above a certain temperature 100% binder coating occurred on the aggregate particles. The lowest temperature at which 100% coating occurred will be referred to as the 'initial 100% coating temperature' for each type of binder film described in this report (as per Austroads 2012a, 2012b). This temperature corresponds to the lowest temperature where aggregates are completely coated by binder when they are pushed into binder films and immediately removed by hand.

The results of aggregate wetting tests which used films containing C170 bitumen and different amounts of lighting kerosene indicated that the initial 100% coating temperature of each type of binder film decreased as the amount of cutter added to the binder was increased. Films which contained PMBs yielded initial 100% coating temperature results which were higher than those observed for films containing C170 bitumen. Adding cutter to the PMB films also reduced the initial 100% coating temperature results obtained.

Maccarrone et al. tried to relate the initial 100% coating temperature results to the viscosity of the binders at that temperature in a similar way to that performed by Dickinson during earlier studies of binder-aggregate adhesion (Section 3.1). The viscosity of each binder type at the initial 100% coating temperature was determined by measuring the complex viscosity of each material in a dynamic shear rheometer (DSR) in the temperature range between 20 to 50 °C using a test frequency of 1.5 Hz. The results obtained in these experiments were then used to determine the complex viscosity of each binder at the initial 100% coating temperature (i.e. the lowest temperature at which binders completely coated the aggregates).

The results of the viscosity analysis indicated that the complex viscosity of each set of samples which contained the same neat binder were overall similar at the initial 100% coating temperature. In the case of the four binders containing C170 bitumen, the complex viscosity of blends containing 0, 2, 4 and 6 parts lighting kerosene were all in the range between 4000 and 12 000 Pa s at the initial 100% coating temperature for each binder film. The average complex viscosity at the initial 100% coating temperature for all binders containing C170 bitumen was about 8000 Pa s.

This trend in viscosity results differed from those originally obtained by Dickinson (1961, 1984) who observed that the viscosity of neat 180-200 penetration grade bitumen could be higher than that of a cutback binder at the pavement temperature for effective binder-aggregate adhesion to occur in sprayed seals. Differences between the two studies could possibly be due to the differences in the types of experiments conducted as Dickinson's studies assessed actual adhesion between binder and aggregate after these materials had been in contact for various periods of time, whereas studies by Maccarrone et al. investigated the amount of initial aggregate wetting which occurred when binder and aggregate were brought into contact for a brief time.

The sensitivity of Dickinson's results to the addition of cutter could also possibly be influenced by the high level of cutter used in the original set of field trials and laboratory experiments (> 10 parts, Section 3.1). It was noted in Section 3.2.3 that laboratory studies of oil loss from binder films indicated that the initial rate of oil loss was higher for films which contained higher levels of oil when tests were conducted at the same test temperature. As relatively high levels of cutter were used in Dickinson's studies compared with studies by Maccarrone et al. (0 to 6 parts cutter), the results obtained by Dickinson could possibly be more affected by loss of cutter from the binder films.

Two additional studies were conducted by Austroads in the early 2010s (Austroads 2012a, 2012b) which used the test developed by Maccarrone et al. to further investigate the factors which affected aggregate wetting. These studies involved conducting aggregate wetting tests using thin binder films containing C170 bitumen, S10E and S20E grade binders and blends of each of these materials with up to 14 parts of a single type of high flash point cutter (Shell Mexcut H). Aggregate wetting tests were performed without adding an adhesion agent to the binder.

The Austroads studies investigated the effects of aggregate geological type and precoating of aggregates on initial 100% coating temperature results. Studies of the effects of aggregate type were performed using clean and dry 14 mm basalt, hornfels and greywacke aggregates and binder films containing C170 bitumen and between 0 and 4 parts high flash point cutter. Investigations into the effects of aggregate precoating were performed using C170 bitumen, S10E and S20E grade binder films which contained either 0 or 6 parts high flash point cutter. The basalt aggregates used in these tests were precoated with different amounts of a diesel/C170 bitumen blend. The results of these experiments indicated that initial 100% coating temperature results were unaffected by the type of aggregate used during testing. Precoating of basalt aggregates also did not appear to markedly affect initial 100% coating results.

The Austroads studies also investigated the effect of contact time between binder and aggregate on the degree of aggregate coating that was observed. These experiments were conducted using clean, dry 14 mm basalt aggregates and 14 mm basalt aggregates which were precoated using the diesel/C170 bitumen blend described above. The results of these experiments indicated that binder wetting on aggregates over time was governed by complex processes which appeared to be influenced by binder viscosity as well as other factors. Even though this was the case, the degree of binder wetting on aggregates appeared to increase when either the contact time or the temperature of the experiment was increased. The use of precoated aggregates increased the degree of aggregate wetting that was observed over time for binder films containing C170 bitumen and S10E grade binders. The results obtained for S20E grade binder films unexpectedly showed that precoated aggregates showed lower amounts of binder wetting over time than when unprecoated aggregates were used in the experiments.

3.3 Summary and Tests Included in the Current Study

Based on the results of previous research, cutters are added to hot binders when sprayed seals are constructed in cooler weather to ensure that the binder which is sprayed on the road surface is sufficiently fluid to effectively wet the aggregates when they are applied and also assist in initial aggregate reorientation. If the binder can effectively wet the aggregate, effective adhesion between binder and aggregate can then occur. Even though the binder is sprayed hot, it rapidly cools to the temperature of the pavement. After a sprayed seal has been constructed, the cutter is expected to evaporate from the seal over time so that the binder film is sufficiently strong for the seal to retain aggregate under traffic. If the rate of cutter loss is too low, then aggregate loss can occur under traffic or flushing of the binder can occur during periods of hot weather.

A number of road trials and laboratory studies were conducted in 1980s and 1990s to investigate the rate of evaporation of different oils from sprayed seals. The results of these investigations all indicated that cutter loss from sprayed seals was slower than expected, and flux oil loss from sprayed seals was faster than expected. The results of laboratory studies indicated that the rate of oil loss over time was dependent on the relative volatility (i.e. distillation properties) of the oil, the thickness of the binder film and the temperature of the experiment.

The results obtained in a number of studies also indicated that binder viscosity was an important factor which affected initial wetting of aggregates during sprayed seal construction and short-term binder/aggregate adhesion. Binder viscosity was also identified as an important factor in the longer term because if insufficient cutter was lost from a seal over time, the binder would not be sufficiently viscous to retain the aggregate under traffic. Flushing of the binder could also occur during hot weather if the viscosity of the binder in the seal was too low.

The current version of AS 3568 (Section 2.1) includes a range of specified tests for cutters, high flash point cutters and flux oils which include the chemical and distillation properties of the oils, as well as specified limits relating to the viscosity of the neat oils. Previous studies have indicated that the rate of cutter loss from sprayed seals, and so seal performance, is influenced by the distillation properties (volatility) of the oil which is added to the binder. The viscosity of a neat oil would also be expected to affect the viscosity of the binder/oil blend which is present on the road surface when aggregate is applied and so would also be expected to affect seal performance. The results obtained in one limited study suggested that the chemical composition of an oil (i.e. aniline point or aniline content) could possibly affect the viscosity of a bitumen/oil blend. The chemical composition of an oil could also affect the compatibility of oils and binders when they are mixed as materials with markedly different chemical compositions often do not readily mix together. AS 3568 currently includes a miscibility requirement which assesses whether different oils and bitumen will suitably mix.

AS 3568 also includes a number of handling, rather than seal performance tests, which include flash point, fluidity and water content tests. These tests assess whether oils used to reduce the viscosity of binders in sprayed sealing are either flammable materials (which need to be handled and stored appropriately), are contaminated with particulate matter or other materials, or contain water (which can result in foaming when hot binder and oil is mixed). As these tests are handling, rather than performance tests, flash point tests were not performed on all oil samples included in the study, and water content tests were not performed. All oil samples utilised in the study were liquids at room temperature and appeared clean and free of particulate matter.

Density at 15 °C tests were performed on the sample of C170 bitumen used in the study as well as each of the oils included in the investigation. Although density tests can give some indication of the differences in molecular weight of the chemical components in a material (Section 2.1.1), it was not thought that the results of density tests would correlate with seal performance as no previous studies had tried to correlate oil density with performance. Density tests are included in petroleum product specifications primarily as many fuels are sold in terms of the volume of fuel delivered rather than mass (Nadkarni 2007). Including density requirements in petroleum product specifications allows the purchaser to convert fuel volumes into mass of product delivered, if needed. It also allows suppliers to sell petroleum products in terms of the mass of product delivered, if required by the customer.

It was noted in Section 1 that the main aim of the study was to identify the key properties of cutters that affect sprayed seal performance so that this information could be used as a basis for producing an updated version of AS 3568. Seven different commercially available oils/solvents were selected for study based on advice from Queensland Department of Transport and Main Roads. The seven oils included representative samples of cutter oil (Jet A1), high flash point cutter (Viva Energy Mexcut HF75) and flux oil (diesel) as well as samples of mineral turpentine and three commercially available oils which are manufactured by IOR Pty. Ltd. in Queensland (Enersol kerosene, Enersol K and Enersol HFK). Mineral turpentine was included in the study as it represented a material which was more volatile and had a higher aromatic content than Jet A1. The three Enersol products were selected as they represented materials with quite low aromatic contents which showed different levels of volatility (i.e. boiling point ranges) compared with Jet A1.

After the oils were selected, each of the materials was subjected to a range of AS 3568-specified tests which previous studies had suggested give information about sprayed seal performance. Each of the neat oils was also analysed chemically to determine the chemical differences between each of the materials. Laboratory performance tests were conducted using blends containing C170 bitumen and various amounts of each of the oils. A single sample C170 bitumen was used throughout the study.

Laboratory sprayed seal performance tests initially involved assessing the miscibility of each of the oils with the sample of C170 bitumen used in the study to determine whether the aromatic content (or aniline point) of an oil gave information about its miscibility with bitumen. The relative rate of loss of each of the oils from sprayed seals over time was then investigated by monitoring the mass loss from thin binder films containing various amounts of each of the oils when films were kept at constant temperature for periods up to 30 days (in a similar way to the experiments described in Section 3.2.3). The effects of the use of different oils on C170 bitumen viscosity reduction and the recommended cutter levels listed for C170 bitumen in Austroads (2005) was investigated using the complex viscosity results obtained in DSR tests for various blends of C170 bitumen and oil. The results of DSR complex viscosity tests on various bitumen-oil blends were also compared to more traditional Brookfield viscosity test results. The difference in the initial aggregate wetting ability of different C170 bitumen-oil blends was also assessed in the study by determining initial 100% coating temperature results using the method developed in Austroads (2012a, 2012b).

The experimental method developed by Dickinson (1961, 1984) to assess initial binder aggregate-adhesion was not used in the study to assess sprayed seal performance as the type of equipment used in these experiments was purpose-built by Dickinson and so was not available for use in the project. Similarly, no assessment of relative oil loss during spraying (Section 3.2.2) was performed during the project as such an assessment would require a full-scale road trial to be performed. A full-scale road trial was not included in the scope of the project.

4. Neat Bitumen and Oil Properties

4.1 C170 Bitumen Properties

A single commercial sample of C170 bitumen was utilised in the project. This sample was initially subjected to a range of selected Australian bitumen specification tests to determine if the sample was representative of its bitumen grade. The sample of C170 bitumen was split into 1 litre subsamples prior to use and prepared for testing using the oven method described in AS/NZS 2341.21.

Table 4.1 shows the test results obtained for the sample of C170 bitumen. Tests on the bitumen sample were performed using the latest versions of the Australian Standard test methods listed in AS 2008. Viscosity at 135 °C and softening point tests were performed using the latest versions of AS/NZS 2341.4 and AS 2341.18, respectively. The sample met the specified requirements for C170 bitumen, where tested, and so was deemed to be suitable for use in the project.

Table 4.1: Binder test results obtained for the C170 bitumen sample

Property	Test result	AS 2008 specification limits for C170 bitumen ⁽¹⁾
Sampling date	5/7/2016	—
Viscosity at 60 °C (Pa s)	192	140–200
Viscosity at 135 °C (Pa s)	0.34	0.25–0.45
Penetration at 25 °C (0.1 mm)	66	62 min.
Viscosity at 60 °C after rolling thin film oven (RTFO) treatment (Pa s)	332	—
Percentage increase in viscosity at 60 °C after RTFO treatment (%)	173	300 max.
Density at 15 °C (kg/m ³)	1048.3	Report on request
Softening point (°C)	49.0	—

¹ AS 2008:2013.

4.2 Neat Oil Properties

Oil samples which were utilised in the study were obtained from three different Australian commercial suppliers and were used as received. Representative samples of cutter oil (Jet A1), high flash point cutter (Mexcut HF75) and flux oil (diesel) were obtained from Viva Energy. These materials will be referred to as ‘Jet A1’, ‘high flash point cutter’ and ‘diesel’, respectively in this report. The sample of mineral turpentine used in the study was obtained from Recochem Incorporated. Samples of Enersol kerosene, Enersol K and Enersol HFK were obtained from IOR Pty. Ltd.

4.2.1 AS 3568-related Test Results

Each of the samples of oil included in the study was subjected to a range of AS 3568 tests which previous studies have suggested give information about sprayed seal performance (Section 3.3). These tests were conducted by the Viva Energy Geelong Refinery Laboratory in Victoria. Oil samples were tested using the latest versions of the AS 3568-specified test methods except that density at 15 °C tests were conducted using ASTM D4052 rather than ASTM D1298.

ASTM D1298 determines the density of a liquid at a specific temperature by manually inserting a hydrometer into the liquid and reading off the hydrometer scale. ASTM D4052 is a more accurate method with better repeatability and reproducibility (Nadkarni 2007) where a small volume of liquid (1 to 2 mL) is placed in an oscillating sample tube and the change in tube oscillation frequency (which is directly related to the mass of the sample) is used to calculate density. The specification for Jet A1 in Australia and New Zealand (Joint Inspection Group 2016) allows either ASTM D1298 or ASTM D4052 to be used to determine the density at 15 °C of aviation fuel. This indicates that both test methods are considered to be equivalent when Jet A1 is used in this application.

Viscosity tests were conducted on the seven different oils at the AS 3568-specified temperature of 40 °C as well as 60 °C. Tests were performed at 60 °C as the viscosity of bitumen samples in AS 2008, and cutback bitumen samples in AS 2157, is determined at 60 °C rather than 40 °C. The viscosity at 60 °C results obtained for the oils allowed comparisons to be made between the viscosity of the neat oils and viscosity at 60 °C results obtained for various bitumen/oil blends. The results obtained in viscosity tests were reported by the Geelong Refinery Laboratory in terms of kinematic viscosity units (i.e. mm²/s). These results were converted into dynamic viscosity units (i.e. mPa s) using the method and equation included in AS 3568. Viscosity results have been shown in both kinematic and dynamic viscosity units in Table 4.2 and Table 4.3.

Table 4.2 shows the results obtained when samples of Jet A1, high flash point cutter and diesel were tested. Flash point tests on these three oils were conducted as part of standard quality control testing associated with release of these materials to the market and so flash point results have been included for informational purposes only. Flash point tests on the sample of Jet A1 were performed using the IP170 test method (Energy Institute 2014), rather than an AS 2106-related test method. Corresponding tests on samples of high flash point cutter and diesel were performed using ASTM D93. The *Australian Code for the Transport of Dangerous Goods by Road and Rail* (National Transport Commission 2018) allows the flash point of materials to be determined using an AS 2106-related test method, or various different ASTM test methods which include ASTM D93.

Table 4.2: AS 3568-related test results for samples of Jet A1, high flash point cutter and diesel

Property	Jet A1	High flash point cutter	Diesel
AS 3568 oil type used for specification compliance assessment	Cutter oil	High flash point cutter	Flux oil
Aniline point (°C)	59.2	62.8	71.0
Aromatic content (% volume)	15.4	16.9	24.3
Density at 15 °C (kg/m ³)	795.1	814.3	847.4
Distillation range			
Initial boiling point (IBP) (°C)	161.8	202.0	193.1
% of original volume recovered at:			
150 °C	0	0	0
200 °C	66	0	1
250 °C	100	100	15
300 °C	100	100	68
350 °C	100	100	96
Final boiling point (FBP) (°C)	232.3	236.3	357.9
Flash point (°C) ⁽¹⁾	48.0 ⁽²⁾	82.0 ⁽³⁾	79.5 ⁽³⁾
Viscosity at 40 °C (mm ² /s)	1.15	1.57	3.38
Viscosity at 40 °C (mPa s)	0.903	1.26	2.82
Viscosity at 60 °C (mm ² /s)	0.960	1.19	2.31
Viscosity at 60 °C (mPa s)	0.743	0.946	1.91

¹ Results included for informational purposes only.

² Tested using IP170 (Energy Institute 2014).

³ Tested using ASTM D93.

The results obtained for samples of Jet A1, high flash point cutter and diesel were compared to the specified requirements in AS 3568 for cutter oil, high flash point cutter and flux oil, respectively (as listed in Table 2.1). Each of these materials met specified requirements, where tested, for the AS 3568-specified oil types that the test results were compared to.

Table 4.3 shows the AS 3568-related test results that were obtained for samples of mineral turpentine, Enersol kerosene, Enersol K and Enersol HFK.

Table 4.3: AS 3568-related test results for samples of mineral turpentine and Enersol products

Property	Mineral turpentine	Enersol kerosene	Enersol K	Enersol HFK
AS 3568 oil type used for specification compliance assessment	Cutter oil	Cutter oil	High flash point cutter	High flash point cutter
Aniline point (°C)	23.4	74.4*	80.8	83.0
Aromatic content (% volume)	44.9	2.7*	7.0*	6.9*
Density at 15 °C (kg/m ³)	813.0	760.7*	794.3	796.5
Distillation range				
Initial boiling point (IBP) (°C)	149.2	148.2	194.0	184.3
% of original volume recovered at:				
150 °C	0	0	0	0
200 °C	100*	78	0	2
250 °C	100	100	54*	46*
300 °C	100	100	100	83
350 °C	100	100	100	100
Final boiling point (FBP) (°C)	184.0	233.5	285.7*	335.8*
Viscosity at 40 °C (mm ² /s)	0.830	1.11	2.12	2.35
Viscosity at 40 °C (mPa s)	0.661	0.833	1.66	1.85
Viscosity at 60 °C (mm ² /s)	0.690	0.890	1.56	1.71
Viscosity at 60 °C (mPa s)	0.548	0.658	1.20	1.32

* Test result that does not meet the requirements of AS 3568 for the oil type that was compared.

The test results obtained for the four oils listed in Table 4.3 were compared to specified requirements of cutter oil or high flash point cutter in AS 3568 based on their volatilities or typical/specified flash point test results which are published by the suppliers of these products. The test results which did not meet AS 3568 requirements for the oil type that was used in the comparison are marked with an asterisk in the table.

The test results for mineral turpentine were compared with the specified requirements for cutter oil as mineral turpentine is a more volatile solvent than Jet A1 and has a typical boiling point range of 148 to 200 °C and typical flash point of 31 °C (Recochem 2017). The analogous results for Enersol kerosene were compared to the specified requirements for cutter oil as the supplier's product specification for this material indicates the specified limit for flash point is 38 °C minimum (IOR Energy 2013). The test results for Enersol K and Enersol HFK were compared to the specified requirements for high flash point cutter as the product specifications for these materials indicate specified flash point test limits of 76 °C minimum and 67 °C minimum, respectively, for these two products (IOR Energy 2010, 2014).

The mineral turpentine and Enersol kerosene samples did not meet AS 3568 requirements for cutter oil, where tested. The sample of mineral turpentine failed one of the distillation range test requirements, while the sample of Enersol kerosene did not meet the requirements of aniline point, aromatic content or density at 15 °C tests. The samples of Enersol K and Enersol HFK both failed the aromatic content requirement for high flash point cutter in AS 3568. These samples also failed two of the distillation range requirements for high flash point cutter.

If the aniline point and aromatic content results shown in Table 4.2 and Table 4.3 are compared, the sample of mineral turpentine contains a larger proportion of aromatic hydrocarbons than any of the other oils studied. The three Enersol products seem to contain quite low proportions of aromatic hydrocarbons compared to the other oils studied. These products appear to mostly contain aliphatic hydrocarbons.

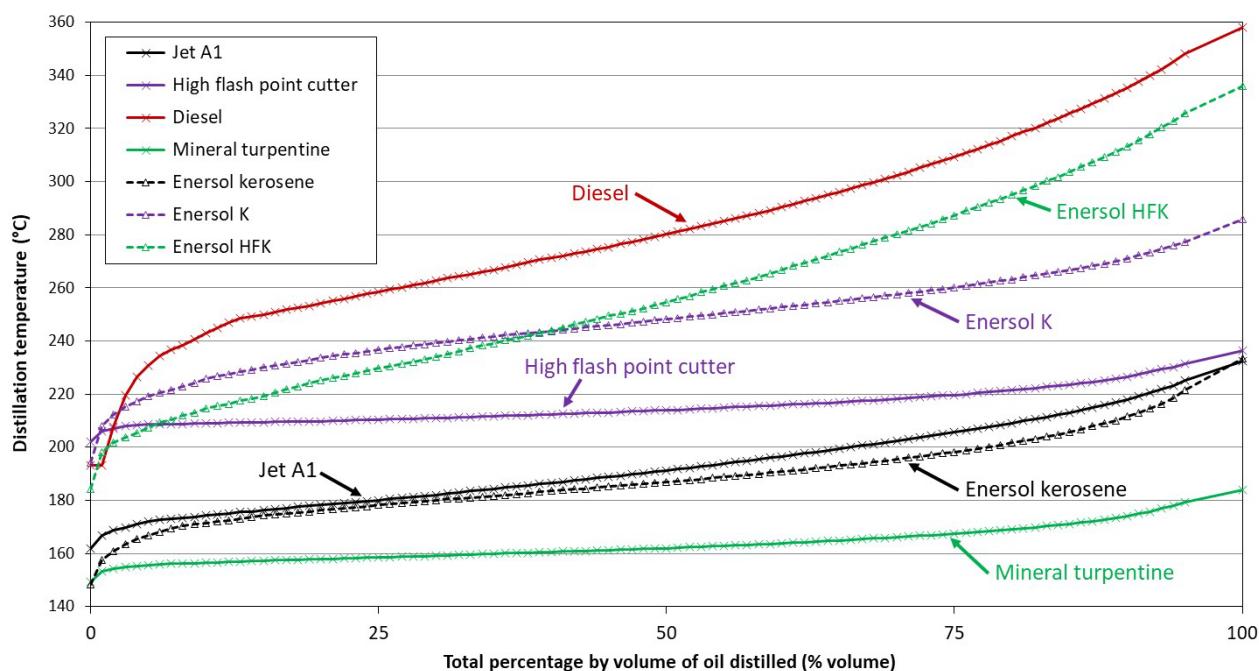
4.2.2 Comparisons of Boiling Point Behaviour

It was noted in Section 3.3 that a number of previous studies have indicated that the rate of loss of an oil from a sprayed seal over time was dependent on the volatility (i.e. distillation properties) of the oil. The distillation range properties included in AS 3568 are obtained by distilling samples of liquids using ASTM D86. During these tests, 100 mL of liquid is initially placed in a distillation flask which contains a thermometer. The distillation flask is then connected to a cooled condenser tube. During ASTM D86 tests, the liquid is heated at a specified rate while the temperature of the vapour phase above the liquid is monitored. The amount of liquid which is evaporated and then condensed in the condenser tube is collected in a measuring cylinder. The raw results of ASTM D86 tests yield information about the volume of liquid that has been collected in the measuring cylinder against the temperature of the vapour phase in the distillation flask.

Although the distillation property results shown in Table 4.2 and Table 4.3, which relate to the percentage by volume of oil distilled at various temperatures, give some information about relative volatilities of the oils, further information can be obtained using the raw experimental results obtained using ASTM D86. During ASTM D86 tests, the temperature at which various percentage amounts of oil are distilled is monitored throughout the test. These results can be used to plot distillation curves for each of the oils studied.

Figure 4.1 shows the distillation curves that were obtained for each of the oils during ASTM D86 tests. The graph shows plots of temperature against the total percentage by volume of each oil which was distilled. Individual datapoints which were obtained during ASTM D86 tests are shown as crosses or triangles in the figure. Initial boiling point (IBP) and final boiling point (FBP) results obtained for each of the oils correspond to the temperatures at which 0% and 100%, respectively, of the total percentage by volume of each oil was distilled. Liquids which have distillation curves associated with lower y-axis values on the graph are more volatile than those where the distillation curves are located at higher y-axis values on the graph.

Figure 4.1: Distillation curves obtained for each of the oils studied



The results shown in Figure 4.1 indicate that mineral turpentine was the most volatile of the oils studied as this material showed a boiling point range of between 149.2 and 184.0 °C. Jet A1 and Enersol kerosene were less volatile than mineral turpentine and overall showed similar boiling point behaviour. The order of decreasing volatility of the other oils generally followed the order: high flash point cutter > Enersol K > Enersol HFK > diesel.

The boiling point range of a substance gives an indication of the number of chemical components that are present in a material as pure materials which contain only one chemical component have a very narrow boiling point range (typically 1 to 2 °C for typical pure hydrocarbons) (Rand 2003). Substances which contain various chemical components will show wider boiling point ranges as each of the different chemicals will have a different boiling point. Substances which are less pure (i.e. those which contain a wider variety of different chemicals) will therefore show a wider boiling point range than those which are purer.

Based on the results of ASTM D86 tests, the samples of high flash point cutter and mineral turpentine contained the fewest number of different chemical components (i.e. they were the purest oils studied). The difference between the IBP and FBP results obtained for these two materials were 34.3 °C and 34.8 °C, respectively. Samples of diesel and Enersol HFK showed the widest difference between IBP and FBP results (i.e. 164.8 °C and 151.5 °C, respectively). These results indicated that these oils contained a wider range of different chemical species than the other oils included in the study.

4.2.3 Chemical Characterisation Tests

In order to further investigate the differences in chemical composition of the oils, samples of each oil were subjected to Gas Chromatography-Mass Spectrometry (GC-MS) tests at the School of Chemistry, Monash University. GC-MS is an analytical method where a sample is initially separated into its individual chemical components using a gas chromatograph (Sparkman, Penton & Kitson 2011). Once the chemical components have been separated, they are then automatically fed into a mass spectrometer. The results obtained from the mass spectrometer analysis can then be used to directly identify the different chemical components present in a sample.

During the GC component of the test, samples are initially injected into a capillary column and the temperature of the column is raised over time with an inert (carrier) gas flowing at a constant rate through the column. Individual chemical components are released from the column at various times (retention times) dependent on their boiling point properties and chemical interactions with the column. Materials with higher boiling points generally show longer retention times in the GC component of the test.

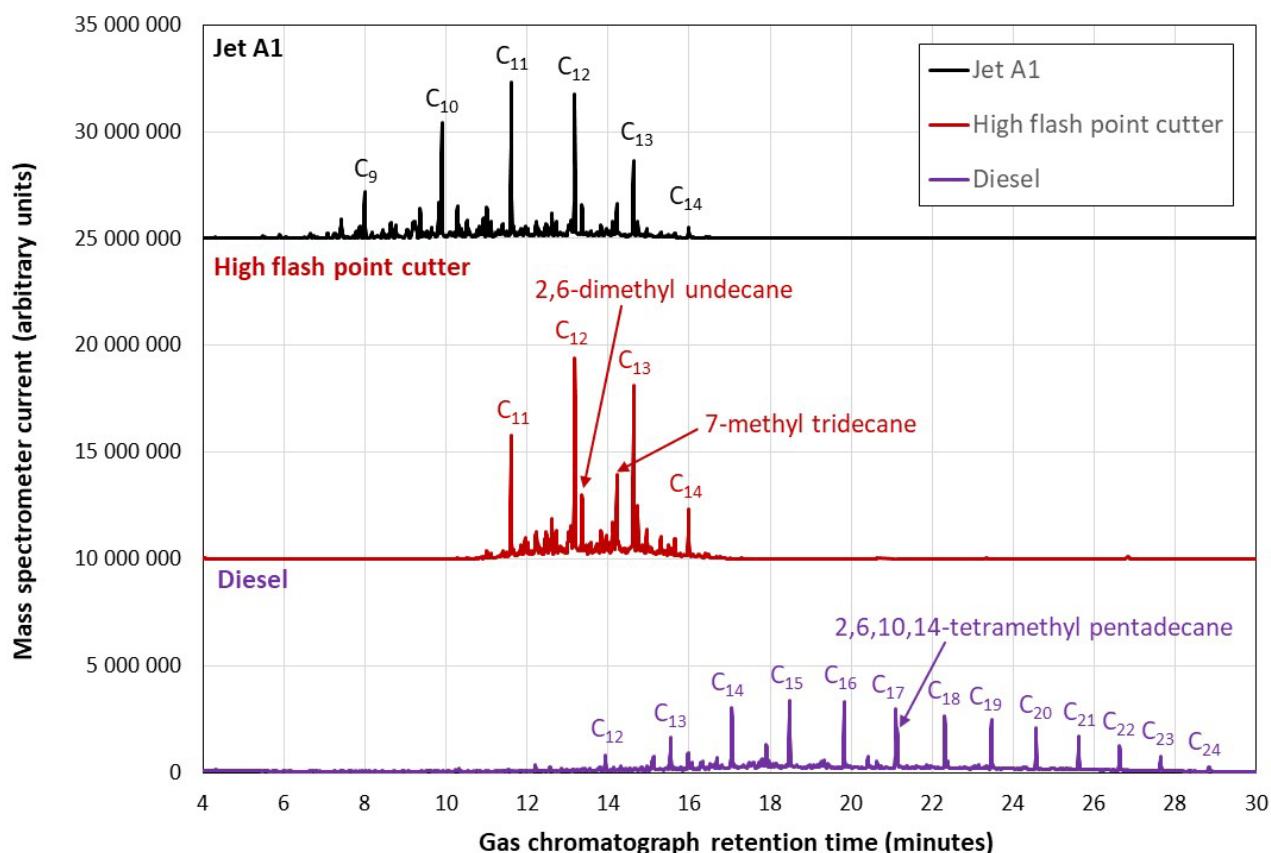
After the individual chemical components have been separated by GC, they are each fed into a mass spectrometer which is an instrument which is held under very high vacuum (Silverstein, Bassler & Morrill 1981). Individual chemical components are first ionised by a high-energy electron beam to produce a beam of positively charged species. This process causes the molecules in each GC fraction to break into a variety of different positively charged fragments. The mass spectrometer determines the total current due to positively charged species as a function of GC retention time. This current is influenced by both the relative concentration of each chemical component in a sample and how each material breaks into fragments.

The mass spectrometer also determines the mass of the different positively charged fragments in each GC fraction by passing each of the ionised fractions through a magnetic field (as positively charged species with different masses interact differently with a magnetic field). This provides information about the mass of the different fragments for each different chemical component in a sample. The mass results obtained for each chemical component in a sample can then be compared to a database of MS fragmentation results which have been obtained for a very large number of different chemicals. This comparison enables the chemical species present in each of the GC fractions to be directly identified based on their MS mass fragmentation patterns.

GC-MS tests were conducted on samples of each of the seven oils using an Agilent HP 6980 GC-MS which was interfaced with a HP5973 mass selective detector. Tests were performed by injecting 1 μL of each of the oils into the instrument. The GC component of the test was performed using a HP-5 ms ultra-inert GC capillary column (5% phenyl methyl siloxane) with dimensions of 30 m x 0.25 mm x 0.25 μm and an inert helium carrier gas. The flow rate of helium during the experiments was 1 mL/min. The GC oven which contained the column was initially held at 35 °C for 3 minutes. The oven temperature was then increased to 250 °C using a heating rate of 9 °C/minute. The MS component of the test was conducted using an electron ionisation potential of 70 eV in full scan mode. Chemical species in each of the oils were identified by comparing the MS fragmentation results obtained for each of the GC-separated fractions with the results included in the *Wiley Registry of Mass Spectral Data* database (McLafferty 2005). This database contains mass spectroscopy results for over 300 000 different chemical compounds.

Figure 4.2 shows plots of the current recorded by the mass spectrometer versus GC retention time which were obtained for samples of Jet A1, high flash point cutter and diesel. The results obtained for Jet A1 and high flash point cutter have been shifted to higher y-values on the graph so that the results obtained for the three oils can be included in the same graph. Figure 4.2 also includes labels for the chemical species associated with the major peaks shown in the figure which were obtained by comparing the MS fragmentation results for each of these GC fractions with those contained in McLafferty (2005). The MS fragmentation results overall indicated that each of the seven oils studied contained various proportions of aliphatic and aromatic hydrocarbons. Aliphatic hydrocarbons in the oils predominantly included saturated, straight chain linear hydrocarbons and saturated, branched hydrocarbons. These types of chemicals are generally referred to as alkanes.

Figure 4.2: GC-MS results obtained for samples of Jet A1, high flash point cutter and diesel



Note: The labels C₉, C₁₀ etc. correspond to straight chain hydrocarbons (i.e. alkanes) with the general chemical formula C_nH_{2n+2}.

Most of the peaks obtained for the seven oils corresponded to the presence of saturated, linear alkanes. These have been labelled as C₉, C₁₀, etc. in Figure 4.2 and Figure 4.3 where the number in the label corresponds to the number of carbon atoms in the molecule. These types of materials have the general chemical formula C_nH_{2n+2} (where n is the number of carbon atoms in each molecule). For example, a material labelled as C₁₂ in either Figure 4.2 or Figure 4.3 is a linear alkane with chemical formula C₁₂H₂₆. Linear alkanes with larger numbers of carbon atoms have higher boiling points than those with fewer numbers of carbon atoms (Rumble 2018).

The results obtained for the sample of Jet A1 indicated that it predominantly consisted of linear alkanes with carbon numbers of between 9 and 14. The sample of high flash point cutter contained linear alkanes with carbon numbers between 11 and 14 and some branched alkanes (as indicated in the figure). These results suggested that the sample of high flash point cutter was a more refined material (i.e. it contained fewer different chemical components) than Jet A1. The chemical species present in the high flash point cutter sample appeared to indicate that it contained chemicals which were very similar to the higher boiling point fractions of the Jet A1 sample.

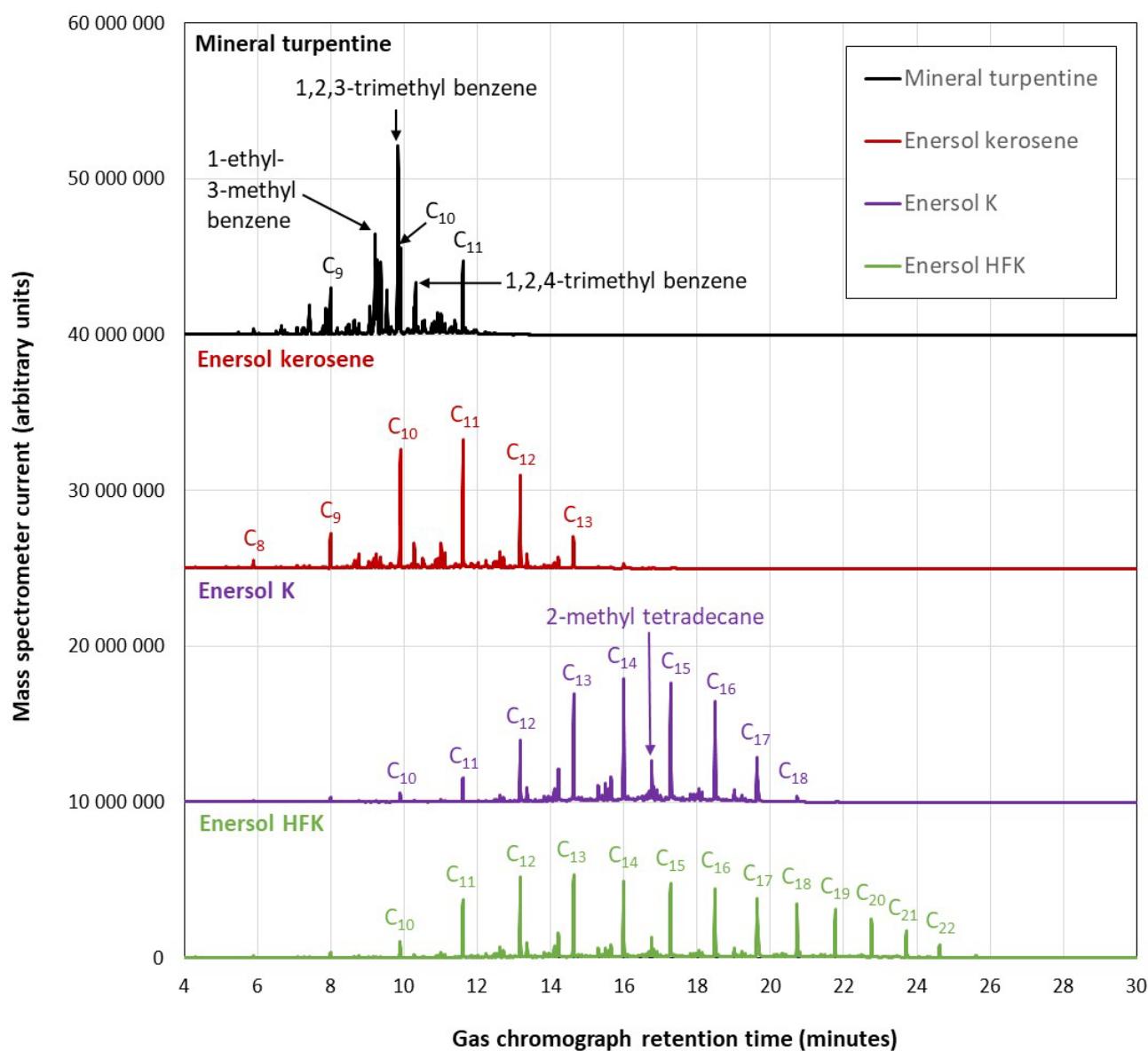
The diesel sample appeared to contain a wider range of linear alkanes than the other two oils indicating it was a less pure/refined material. The carbon numbers of the linear alkanes varied between 12 and 24. The results of GC-MS tests on the high flash point cutter and diesel samples overall appeared to agree with those obtained in ASTM D86 tests (Section 4.2.2) as both sets of tests indicated that the high flash point cutter sample was a relatively pure material, while the diesel sample contained a wider range of different chemical components.

All oil samples, except the sample of diesel, showed the presence of the same chemical species as peaks at the same GC retention time. In the case of the diesel sample, the peaks associated with the various chemical species were recorded at different retention times than the other oil samples. The most likely explanation for this is that the diesel sample interacted chemically with the column in the GC component of the test in a different way to the other oil samples studied.

Figure 4.3 shows the analogous results to Figure 4.2 which were obtained for the mineral turpentine, Enersol kerosene, Enersol K and Enersol HFK samples. In agreement with the results of ASTM D86 tests (Section 4.2.2), the results of GC-MS tests also indicated that the sample of mineral turpentine was a relatively pure material which contained linear alkanes with carbon numbers between 9 and 11. The GC-MS results additionally indicated that the mineral turpentine sample contained a relatively large proportion of aromatic hydrocarbons rather than aliphatic hydrocarbons (e.g. linear or branched alkanes). This result appeared to agree with the high aromatic content (44.9% volume) and low aniline point (23.4 °C) results obtained for this oil in conventional AS 3568-specified tests (Table 4.3). The aromatic hydrocarbons associated with the mineral turpentine sample included 1,2,3-trimethyl benzene, 1-ethyl-3-methyl benzene and 1,2,4-trimethyl benzene.

The samples of the three Enersol products predominantly contained linear alkanes which had varying ranges of carbon numbers. The Enersol kerosene sample contained the smallest number of different linear alkanes which had carbon numbers between 8 and 13. The Enersol K sample contained a wider number of different linear alkanes with carbon numbers between 10 and 18. The Enersol HFK sample contained linear alkanes with carbon numbers between 10 and 22. This range of different carbon numbers (22 – 10 = 12) was the same as the range of carbon numbers (24 – 12 = 12) observed for the sample of diesel. This result indicates that the samples of Enersol HFK and diesel contained a wider range of different chemical species than the other oils included in the study. This observation also appears to agree with the results obtained in ASTM D86 tests (Section 4.2.2).

Figure 4.3: GC-MS results obtained for samples of mineral turpentine, Enersol kerosene, Enersol K and Enersol HFK



Note: The labels C_9 , C_{10} etc. correspond to straight chain hydrocarbons (i.e. alkanes) with the general chemical formula C_nH_{2n+2} .

4.3 Summary

Samples of the C170 bitumen and oils which were used in the study were subjected to a range of AS 2008 or AS 3568 tests. The sample of C170 bitumen met AS 2008-specified requirements for C170 bitumen, where tested, and so was deemed to be suitable for use in the project. Samples of Jet A1, high flash point cutter and diesel, which were selected for use in the project to represent various AS 3568 oil grades, met the requirements for cutter oil, high flash point cutter and flux oil, respectively, where tested. The results of selected AS 3568 tests on samples of mineral turpentine and Enersol kerosene indicated that these materials did not meet specified requirements for cutter oil. Similarly, Enersol K and Enersol HFK samples did not meet AS 3568-specified requirements for high flash point cutter.

An analysis of the boiling point behaviour of each of the oils indicated that the volatility of the oils followed the general order mineral turpentine > Jet A1/Enersol kerosene > high flash point cutter > Enersol K > Enersol HFK > diesel. The results of ASTM D86 and GC-MS tests indicated that the mineral turpentine and high flash point cutter samples were the purest oils included in the study (i.e. they contained the fewest number of different chemical components). The Enersol HFK and diesel samples appeared to contain a wider range of different chemical components than the other oils included in the study. All oils included in the study contained various amounts of aliphatic and aromatic hydrocarbons. The aliphatic hydrocarbons in the oils were predominantly linear alkanes.

5. Stability of Oil Blends with C170 Bitumen

In order for a binder-oil blend to perform satisfactorily during sprayed sealing it is first necessary that the oil and bitumen are suitably miscible. Due to this, AS 3568 includes a qualitative miscibility requirement in Clause 4.3 which is based on a visual assessment of a blend of bitumen and oil. This miscibility assessment involves initially mixing one part by volume of an oil at ambient temperature with one part by volume of bitumen at a temperature of 80 °C. The mixture is then allowed to cool to ambient temperature. AS 3568 indicates that an oil is suitable for use in terms of its miscibility with bitumen if the bitumen-oil blend visually does not separate, or there is no obvious precipitation of bitumen, after the blend has been allowed to stand at ambient temperature for one hour.

It was noted in Section 3.3 it was initially thought that the chemical properties of an oil (i.e. aromatic content or aniline point) may affect the miscibility of an oil with bitumen as materials with markedly different chemical compositions often do not readily mix together. Seven blends containing 60% w/w C170 bitumen and 40% w/w of each of the oils studied were initially prepared using the method described in Section 5.1 (Section 5.1 also includes information about the other types of bitumen-oil blends which were prepared during the study). Each of these blends was then subjected to quantitative, rather than qualitative, long-term storage tests where the degree of separation of the binders was investigated after the samples had been allowed to stand unstirred for three days.

A longer separation time was used in the study than indicated by Clause 4.3 in AS 3568 to give more time to allow the samples to separate. Quantitative, rather than qualitative/visual tests, were used in the study as it was thought that this would give more information about bitumen-oil miscibility. Blends were prepared using 60% w/w C170 bitumen and 40% w/w oil as these blends on average contained 53% by volume C170 and 47% by volume oil at 15 °C (i.e. 1.1 parts by bitumen and 1 part by volume oil at 15 °C). These parts by volume were of similar order to those specified in Clause 4.3 in AS 3568. Blend component concentrations in terms of mass percentages were converted into percentages by volume at 15 °C using the mass of components added to each blend and the density at 15 °C results obtained for each material (as shown in Table 4.1, Table 4.2 and Table 4.3).

All bitumen-oil blends were prepared in the study by weighing each of the components, as the volume of components can vary with temperature (this is particularly the case for heated bitumen samples). It is also difficult to accurately measure the volume of bitumen samples due to the dark colour of the material. Due to this all bitumen-oil blends were prepared during the study with varying weight percentages (rather than volume percentages or parts) of bitumen and oil.

5.1 Bitumen-oil Blend Preparation

Bitumen-oil blends were prepared for use in the study using 1 litre subsamples of the C170 bitumen sample which was used in the investigation. Cold bitumen subsamples were heated immediately prior to blend manufacture by heating them in an oven set to 120 °C for one hour. After heating, the bitumen subsamples typically had a temperature of between 95 and 100 °C. AS/NZS 2341.21 allows C170 bitumen samples to be heated in an oven with a set temperature up to 150 °C if the oven method is used to heat bitumen samples. A lower temperature than 150 °C was used to both produce and reheat bitumen-oil blends to minimise any oil loss that would occur during either blend preparation or sample reheating prior to testing.

Preliminary tests using an 850 g blend containing 94% w/w C170 bitumen and 6% w/w mineral turpentine indicated that use of a set oven temperature of 120 °C, and the blend preparation procedure described below, resulted in less than 0.04% w/w loss (i.e. 6.00 – 5.96 = 0.04% w/w) of mineral turpentine during blend preparation. Preliminary bitumen heating experiments were conducted using a blend containing mineral turpentine as this was the most volatile oil included in the study (Section 4.2.2).

Bitumen-oil blends were produced in the study by initially adding an appropriate mass of oil to a metal tin followed by an appropriate mass of heated bitumen subsample. Both components were weighed to the nearest 0.01 g using a two-figure (Shinko Denshi: Model AJH-4200CE) balance. After the components were added, they were then mixed thoroughly with a spatula. Blends containing ≤ 12% w/w oil were returned to the 120 °C oven for an additional 5 minutes after initial mixing with the lid placed on the top of the tin as they appeared to be quite viscous when initially mixed. After a further 5 minutes of heating, these samples were then mixed again with a spatula to ensure that the oil was evenly dispersed in the binder. Samples which contained 40% w/w oil which were used in stability tests were quite fluid when initially mixed. Due to this, stability test blends were not heated in the oven for an additional 5 minutes as it appeared that the oils could be effectively blended with C170 bitumen without the additional heating step.

Table 5.1 provides the formulations used to produce the various bitumen-oil blends which were tested during the study as well as total mass of each binder blend which was produced. Blends of the types listed in the table were produced using each of the seven oils. In the case of blends containing 2, 4 and 6% w/w of each oil, larger 1700 g blends were initially produced. These 1700 g samples were split into four equal sized subsamples immediately after the blends were prepared. Three of these subsamples were later used in mass loss, viscosity (DSR and Brookfield) and aggregate wetting experiments, respectively. Different subsamples of each of these blends were initially produced to reduce the amount of sample reheating required during the study as these samples were subjected to a wide variety of tests. It was thought that if sample reheating was minimised then there would be less oil loss from the binders when the different tests were performed.

The other bitumen-oil blends that were prepared in the study were subjected to fewer tests and so were not split into different subsamples prior to testing. The tests conducted on blends which contained 9% w/w, 12% w/w and 40% w/w oil are listed in Table 5.1.

Table 5.1: Summary of bitumen-oil blends produced in the study

Blend formulation		Total mass of binder blend (g)	Tests in which sample was utilised
% w/w C170 bitumen	% w/w oil		
98	2	1700	1700 g samples were split into 4 subsamples immediately after manufacture. Separate subsamples were used for mass loss, viscosity (DSR and Brookfield) and aggregate wetting tests.
96	4		
94	6		
91	9	400	Viscosity (DSR and Brookfield)
88	12		
60	40	750	Stability

After the bitumen-oil blends were prepared, the lids on the metal tins were secured and the samples were stored under ambient conditions until required for use. Blends containing ≤ 12% w/w of each oil were reheated immediately prior to testing by heating them in an oven set to 120 °C for a minimum amount of time so that they were fluid enough to stir and pour. They were then mixed thoroughly with a spatula prior to use. Blends containing 40% w/w of each oil were quite fluid at room temperature and therefore did not require heating prior to testing. These blends were thoroughly mixed with a spatula at room temperature prior to use.

Oil concentrations which have been expressed in terms of the percentage of oil by mass in a blend (as in Table 5.1) have been converted into concentrations in terms of parts of oil (when required during the study) using the masses of C170 bitumen and oil added to a particular blend and the density at 15 °C of the two components (from Table 4.1, Table 4.2 or Table 4.3). Blend concentrations in terms of parts of oil were calculated from mass and density results obtained for each blend component, when required, using Equation 1.

$$\text{parts oil} = \frac{m_{oil} \times \rho_{bit} \times 100}{\rho_{oil} \times m_{bit}}$$

where

m_{oil} = mass of oil added to the blend (g)

ρ_{bit} = density at 15 °C of C170 bitumen sample added to the blend (kg/m³)

ρ_{oil} = density at 15 °C of oil sample added to the blend (kg/m³)

m_{bit} = mass of C170 bitumen sample added to the blend (g)

5.2 Stability Tests

Stability tests were conducted on blends containing 60% w/w C170 bitumen and 40% w/w oil using a modified version of AS/NZS 2341.27. This method has been traditionally used to monitor the degree of separation which occurs when bituminous emulsions are allowed to stand unstirred at ambient temperature (23 ± 3 °C) for 3 days. Tests were performed by initially transferring 500 mL of each bitumen-oil blend to 500 mL measuring cylinders which contained stopcocks at graduations of 50 mL and 450 mL (as per AS/NZS 2341.27). Figure 5.1 shows a photograph of a binder sample after it had been transferred to the type of measuring cylinder used for testing. Each bitumen-oil blend was then allowed to stand for 3 days at 23 ± 3 °C and the top and bottom 50 mL portions of each sample were collected by opening the stopcocks.

Figure 5.1: Photograph of a bitumen-oil blend undergoing a stability test



The degree of separation that had occurred in the bitumen-oil blends was quantitatively assessed by determining the dynamic viscosity of 60 °C of the upper and lower 50 mL fractions after samples had been stored for 3 days. These results were then compared with the analogous viscosity at 60 °C results which were obtained for the original bitumen-oil blends. Dynamic viscosity at 60 °C tests were conducted according to AS/NZS 2341.4 using a Brookfield viscometer (Model LVDV-II+P). All tests were conducted using a Brookfield SC4-18 spindle to ensure that the torque level obtained during viscosity tests was within the range recommended in AS/NZS 2341.4. Viscosity at 60 °C tests were performed as the Australian cutback bitumen specification (AS 2157) specifies the properties of different cutback bitumen grades in terms of their viscosity at 60 °C results. The upper and lower 50 mL fractions were also inspected after storage to determine if there were any obvious lumps of bitumen in the samples.

The stability of the blends was quantitatively compared by calculating % stability results for each of the blends. Percentage stability results were calculated using Equation 2.

$$\% \text{ stability} = \frac{[\text{top}_{visc} - \text{bot}_{visc}] \times 100}{\text{blend}_{visc}} \quad 2$$

where

% stability = percentage stability result

top_{visc} = viscosity at 60 °C of top 50 mL of sample after storage (Pa s)

bot_{visc} = viscosity at 60 °C of bottom 50 mL of sample after storage (Pa s)

blend_{visc} = viscosity at 60 °C of original bitumen-oil blend (Pa s)

Table 5.2 summarises the results obtained for each of the seven different C170 bitumen-oil blends which were subjected to stability tests. The table also includes the percentage by volume at 15 °C of each of the components in the blends, as well as the viscosity at 60 °C results obtained for the original blends and lower and upper 50 mL fractions. Table 5.2 also includes the relevant aniline point and aromatic content results obtained for each of the neat oils (from Table 4.2 and Table 4.3). After 3 days of storage, there were no lumps of bitumen in any of the 50 mL fractions.

The % stability results obtained from each of the bitumen-oil blends were all within the range of –2 to +1% which indicated that none of the blends had separated during storage. This was also confirmed by comparing the viscosity at 60 °C results obtained for the upper and lower 50 mL fractions of each blend with the repeatability requirements of AS/NZS 2341.4. The standard indicates that duplicate tests by the same operator using the same viscometer should not be considered suspect unless they differ by more than 7% of their mean. In the case of each of the seven bitumen-oil blends, the difference between the viscosity results for the upper and lower fractions was in all cases less than 1% of the mean value obtained for each sample. This percentage difference is markedly lower than the repeatability requirement for duplicate tests in AS/NZS 2341.4.

Although the seven types of oil showed a wide range of aniline point (23.4 to 83.0 °C) and aromatic content (2.7 to 44.9 °C) results, none of the bitumen-oil blends separated to any extent after they were stored at 23 ± 3 °C for 3 days. Based on this result, it appears that the results of AS 3568-specified aniline point and aromatic content tests do not provide information about the suitability of an oil in terms of its miscibility with bitumen.

Table 5.2: Stability test results obtained for 60% w/w C170 bitumen 40% w/w oil blends after 3 days of storage

Oil type	Jet A1	High flash point cutter	Diesel	Mineral turpentine	Enersol kerosene	Enersol K	Enersol HFK
% stability (%)	0.8	0.0	0.8	-1.9	-0.4	-0.8	-0.1
Oil aniline point (°C)	59.2	62.8	71.0	23.4	74.4	80.8	83.0
Oil aromatic content (% volume)	15.4	16.9	24.3	44.9	2.7	7.0	6.9
% volume C170 bitumen in blend at 15 °C (%)	53.2	53.8	54.8	53.8	52.3	53.1	53.3
% volume oil in blend at 15 °C (%)	46.8	46.2	45.2	46.2	47.7	46.9	46.7
Viscosity at 60 °C of original bitumen-oil blend (Pa s)	0.0251	0.0367	0.0794	0.0190	0.0238	0.0434	0.0484
Viscosity at 60 °C of upper 50 mL fraction after 3 days storage (Pa s)	0.0264	0.0375	0.0809	0.0188	0.0238	0.0451	0.0498
Viscosity at 60 °C of lower 50 mL fraction after 3 days storage (Pa s)	0.0262	0.0375	0.0802	0.0192	0.0239	0.0455	0.0499

6. Mass Loss Tests

It was noted in Section 3 that previous research has indicated that sprayed seal performance is significantly affected by the rate of cutter loss from a sprayed seal if cutter is used during the construction of the seal. If the rate of cutter loss is too low, then the viscosity of the binder will be too low for the binder film to effectively retain aggregate under traffic. The sprayed seal can also flush in periods of hot weather. The results of previous research have also indicated that the rate of cutter loss from sprayed seals is influenced by the volatility (i.e. boiling point properties) of the oil.

The relative rates of loss of each of the oils studied were investigated in the laboratory by measuring the mass loss from thin (2 mm) binder films which contained oil concentrations of between 0 and 6% w/w using a similar experimental protocol as used in previous studies (Section 3.2.3). A binder film thickness of 2 mm was used in the experiments as the average thickness of the binder film in a single-single seal is typically in the range between 1 and 3 mm (i.e. binder application rates are typically of the order of between 1 and 3 L/m²) (Austroads 2017b).

Oil concentrations of 0, 2, 4 and 6% w/w were studied as these corresponded to oil concentrations of 0, 2.7, 5.5 and 8.4 parts for blends which contained the sample of representative cutter oil which was used in the study (i.e. Jet A1). Oil concentrations in terms of weight percentages were converted into oil concentrations in parts using Equation 1 (Section 5.1). This range of oil levels was chosen as it was considered representative of those recommended in Austroads (2005) when C170 bitumen is used to construct single-single seals using 10 mm or larger aggregates (i.e. between 0 and 8 parts for seals constructed at various pavement temperatures). Mass loss tests were conducted at three different temperatures (i.e. 40, 50 and 60 °C) to investigate the rate of oil loss that occurred at various representative pavement temperatures after sprayed seal construction. Binder films were subjected to long-term heating for periods up to 30 days at each test temperature.

The results obtained in each set of mass loss tests were compared to AS 3568-specified initial boiling point (IBP) and final boiling point (FBP) results which were obtained for each of the neat oils to determine if correlations could be found between mass loss results and the boiling point properties of the oils. Comparisons were also made with the results obtained for the neat oils in aniline point and aromatic content tests to determine if the AS 3568-specified chemical properties of the oils affected their rate of loss from the binder films. Dynamic shear rheometer (DSR) tests were also conducted on binder film samples after they were heated for 30 days at each test temperature to investigate how differences in the amount of oil lost from the films affected binder film viscosity.

6.1 Mass Loss Test Experimental Design

6.1.1 Adding Appropriate Amounts of Binder to Metal Dishes

Thin (2 mm) binder films were produced for mass loss tests using bitumen-oil subsamples which were prepared and reheated prior to testing using the method described in Section 5.1. Samples for mass loss tests were initially prepared by pouring an appropriate mass (12.7 ± 0.1 g) of each reheated binder subsample into 100 mL metal dishes which had an internal diameter of 78.6 mm. The aluminium dishes and associated aluminium screw-top lids used in the study were obtained from Plasdene Glass-Pak Pty. Ltd. (Catalogue number: IM-100-1761-SR). After an appropriate mass of binder was added to each dish, the dishes were tightly sealed using their lids and the samples were stored at ambient temperature until required in mass loss tests. Binder films of 2 mm thickness were produced immediately prior to mass loss tests using the method described in Section 6.1.2.

An appropriate amount of binder sample was added to each of metal dishes by initially weighing each empty dish on a four-figure analytical balance (Ohaus: Model PA214C) to the nearest 0.0001 g. Dishes were then transferred to a two-figure balance (Shinko Denshi: Model AJH-4200CE) and 12.7 ± 0.1 g of binder was added. This process was followed as it was difficult to add binder to a dish when the four-figure balance was used as it was surrounded by a cover which reduced the influence of air draughts on mass measurements. After an appropriate mass of binder was added to each dish, the dishes were then re-weighed on the four-figure analytical balance to the nearest 0.0001 g so that the mass of binder added could be accurately determined. The lids were then immediately secured on the dishes to prevent the loss of any oil.

The mass of bitumen and oil which was individually added to each dish (which was used to generate the results shown in Section 6.2) was determined using the measured mass of binder added to each dish (as determined using the four-figure analytical balance) and the individual masses of bitumen and oil which were added to produce each of the original bitumen-oil blends which were used in the experiments.

A binder mass of 12.7 ± 0.1 g was added to the dishes based on an initial series of experiments where different amounts of C170 bitumen (i.e. between 8.0 and 16.0 g) were added to various dishes, and flat binder films were produced using the method described in Section 6.1.2. The thickness of the binder films was then determined using a hand-held digital caliper as a function of the mass of C170 bitumen added to the dishes. Binder films of 2 mm thickness were produced when 12.7 g of C170 bitumen was added to the dishes.

6.1.2 Binder Film Formation

Flat 2 mm binder films were prepared immediately prior to mass loss tests by heating prepared dishes containing binder in an oven set to 120 °C for 5 minutes with the lids still secured on the dishes. After 5 minutes of heating, the dishes were then allowed to cool on a flat laboratory bench. The lids were then removed from the dishes and the samples were inspected to ensure that the binder had formed a flat, even film. Samples were heated in the oven and then allowed to cool with the lids fastened on the dishes to minimise any oil loss that occurred during binder film formation. After the dishes were inspected, the lids were secured on the dishes until the commencement of mass loss tests. In the rare cases where flat binder films were not produced on initial heating, samples were subjected to a further 5 minutes of heating using the same process as described above. Figure 6.1 shows a representative photograph of a metal dish containing a 2 mm binder film.

Figure 6.1: Representative photograph of metal dish containing a 2 mm binder film



6.1.3 Mass Loss Tests

Mass loss tests were performed in a controlled-temperature room which had width, length and height dimensions of 1.87 m, 2.05 m and 2.42 m, respectively, and a temperature control of ± 0.2 °C. Experiments were conducted using a bench in the room whose uppermost surface was 0.91 m above the floor of the controlled-temperature room. The set-point temperature of the room that was used in experiments conducted at 40, 50 and 60 °C was initially determined by monitoring the temperature on the top of the bench using a calibrated digital thermocouple. A controlled-temperature room, rather than a fan-forced oven, was used during mass loss tests as it was thought that this would better simulate the loss of oils from sprayed seals in the field as oils could evaporate into a larger air volume than an oven. The air flow in the controlled-temperature room was also significantly lower than the typical air flow in a fan-forced oven.

Mass loss tests were conducted by initially allowing the controlled-temperature room to come to the desired test temperature. The required number of closed metal dishes needed for experiments conducted at each temperature were then placed on the bench in the room and the lids were then removed. Zero heating time in the experiments was taken to be the time when all lids were removed from the dishes. All mass loss tests which were conducted in the study were performed in duplicate (i.e. experiments conducted at each test temperature included two samples of each type of binder film). Binder film samples were placed randomly on the bench in all experiments. Figure 6.2 shows a photograph illustrating the placement of dishes during a mass loss test.

Figure 6.2: Photograph of the placement of dishes during a mass loss test



Mass loss test results were obtained at each test temperature by monitoring the mass of each binder film as a function of total heating time in the room. The mass of the binder films was monitored two times during the first day of heating for experiments conducted at 40 °C, while it was monitored three times during the first day of heating for experiments conducted at 50 and 60 °C. The mass of the binder films was then monitored daily (except for days which occurred on weekends or public holidays) for experiments conducted at each of the three temperatures up to a total heating time of 30 days.

The mass of the binder films was determined after specific heating times by initially securing the lids on the dishes in the controlled-temperature room. Heating was deemed to have stopped when the lids were secured on all dishes. The sealed dishes were then immediately transferred to a laboratory bench which was outside the controlled-temperature room. They were then allowed to cool to room temperature prior to weighing. The lid on each dish was removed immediately prior to weighing and the mass of each dish was determined to the nearest 0.0001 g using the four-figure analytical balance. After each dish was weighed, the lid on the dish was re-secured.

After all samples associated with a specific temperature/heating time had been weighed, they were all transferred to the controlled-temperature room at the same time. The lids on each dish were then removed so that the binder films could be subjected to further heating. Additional heating was taken to have commenced when all lids were removed from the dishes.

6.2 Mass Loss Test Results

6.2.1 C170 Bitumen Film Results

Figure 6.3 shows the results that were obtained in mass loss tests for 2 mm C170 bitumen films when testing was conducted at 40 °C, 50 °C and 60 °C over a 30-day period. The mass of the C170 bitumen films showed a very small increase as the heating time was increased at each test temperature. Due to this, the y-axis in Figure 6.3 is expressed in terms of the percentage change in film mass compared to the original mass of bitumen which was added to each of the dishes. Percentage mass results were obtained from the results of duplicate tests by initially calculating the percentage mass change result for each of the duplicate samples. The results obtained for each set of duplicate samples were then averaged. Individual results for duplicate samples were all within ±0.01% of the average value.

Figure 6.3: Mass loss test results obtained for C170 bitumen films

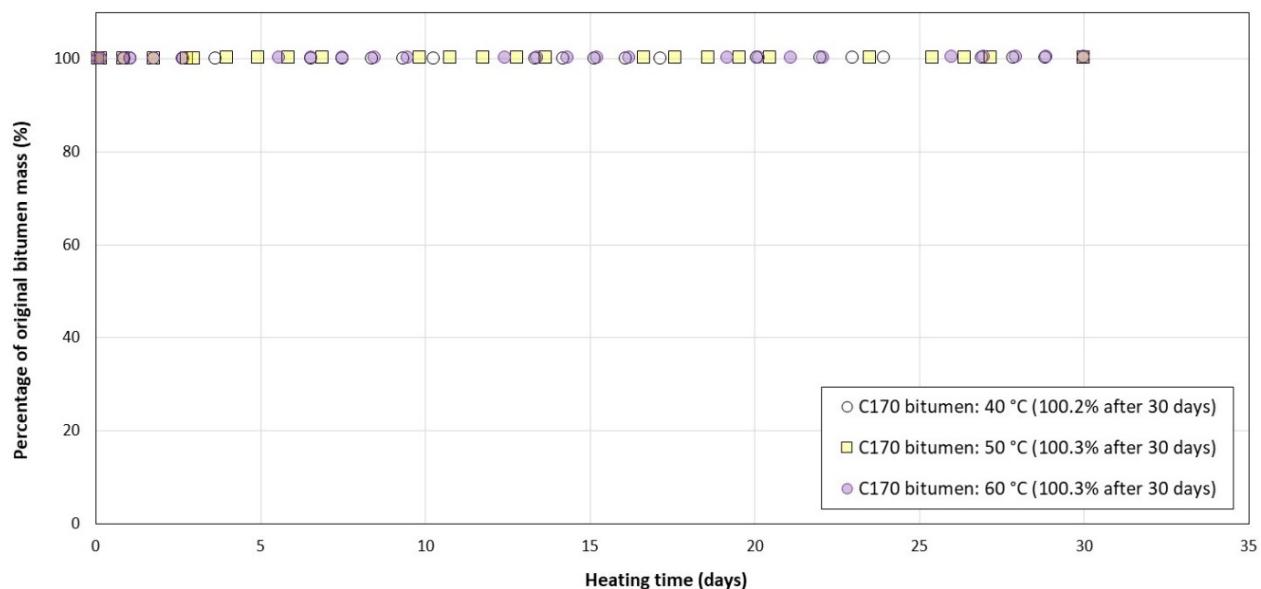


Figure 6.3 also shows the percentage mass change results which were obtained for C170 bitumen films after 30 days of heating (i.e. 100.2% for tests conducted at 40 °C, and 100.3% for tests conducted at 50 and 60 °C). These very small mass increases are likely to be due to bitumen oxidation occurring during heating. As these changes are all significantly less than 1%, the changes in mass observed for the C170 bitumen-oil blends included in Section 6.2.2 can be essentially attributed to loss of oils from the different binder films.

6.2.2 Results Obtained from Films Containing C170 Bitumen and Oil

Figure 6.4 to Figure 6.9 show representative mass loss results which were obtained for 2 mm binder films containing C170 bitumen and oil which illustrate the overall trends observed during the study as a function of heating time. The analogous results obtained for other C170 bitumen-oil blends during mass loss tests are included in Appendix A.

Figure 6.4 and Figure 6.5 show the results obtained when binder films containing 2% w/w of each of the seven oils were heated at 40 °C for periods up to 30 days. Figure 6.4 shows the mass loss results obtained for films containing 2% w/w Jet A1, high flash point cutter and diesel. Neat samples of these oils met AS 3568 requirements for cutter oil, high flash point cutter, and flux oil, respectively, where tested (Section 4.2.1). The results obtained for films containing 2% w/w mineral turpentine are also included in the figure. Figure 6.5 shows the analogous results for binder films containing 2% w/w of each of the Enersol oils (i.e. Enersol kerosene, Enersol K and Enersol HFK) when these binder films were subjected to long-term heating at 40 °C.

Figure 6.4: Mass loss results obtained at 40 °C for films containing 2% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

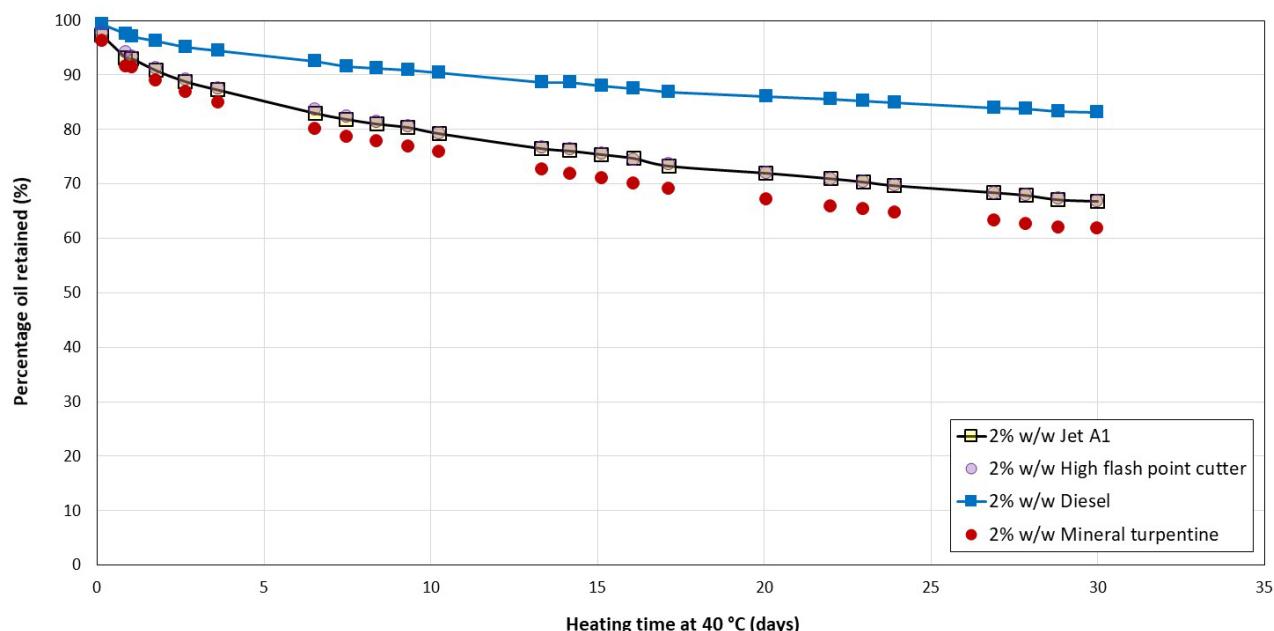
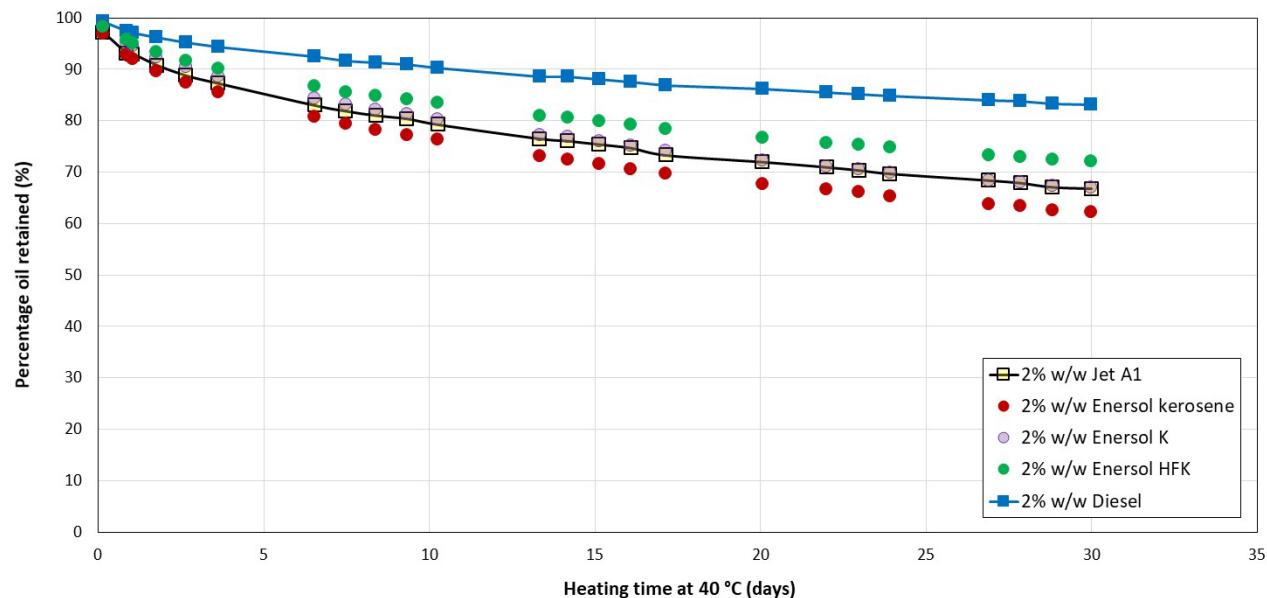


Figure 6.5: Mass loss results obtained at 40 °C for films containing 2% w/w of each of the Enersol oils



The results obtained for binder films containing Jet A1 and diesel are plotted as line plots in the figures shown in Section 6.2.2 and Appendix A so that the results obtained for films containing other oil types can be easily compared with the representative samples of cutter oil (Jet A1) and flux oil (diesel) that were used in the study. There was a reduction in mass of all binder films which contained oil as the heating time was increased (due to loss of oil from the films). Mass loss results for films which contained oil (as shown in Section 6.2.2 and Appendix A) have been plotted as the percentage mass of oil retained in the films after different periods of heating. A percentage oil retained result of 50% indicates that half the original added mass of oil was retained in a binder film after heating.

Percentage oil retained results were determined from the results of duplicate tests by initially calculating the percentage oil retained result obtained for each of the duplicate samples and then averaging the result. Individual results obtained in all duplicate tests were all within $\pm 1\%$ of the average value.

The results shown in Figure 6.4 and Figure 6.5 (as well as other mass loss tests) agreed with the results obtained during road trials which were conducted in the 1980s and 1990s (Section 3.2.1) in that an appreciable amount of flux oil (i.e. diesel) was found to evaporate from the binder films over time (e.g. after 30 days of heating at 40 °C only 83% of the diesel remained in a binder film which initially contained 2% w/w diesel). The results obtained in mass loss tests therefore appear to confirm previous observations that flux oils are not retained in sprayed seals for years and are better to be considered as slowly evaporating cutters.

The rate of oil loss from a film initially containing 2% w/w Jet A1 at 40 °C was greater than that of the corresponding film containing diesel as the datapoints for Jet A1 are all lower than those for diesel in Figure 6.4 (i.e. Jet A1 was lost from a binder film faster than diesel). The datapoints obtained for films initially containing 2% w/w high flash point cutter (Figure 6.4) and 2% w/w Enersol K (Figure 6.5) were very similar to those obtained for Jet A1 indicating that the rate of loss of all three oils was quite similar. Films initially containing 2% w/w mineral turpentine and Enersol kerosene showed slightly higher rates of oil loss than the film containing Jet A1. As the datapoints for the film initially containing 2% w/w Enersol HFK (Figure 6.5) were all higher than those obtained for the film containing Jet A1, the rate of oil loss of Enersol HFK was lower than that of Jet A1.

Figure 6.6 and Figure 6.7 show the mass loss test results which were obtained for binder films containing 4% w/w of each of the oils when tests were performed at 50 °C. Overall, the rate of oil loss from the binder films was found to increase (when results were expressed in terms of the percentage oil retained) if either the test temperature or the initial amount of oil in the films was increased. The results shown in Figure 6.6 and Figure 6.7 illustrate that the rate of oil loss from the binder films became more similar for some of the oils when the test temperature was increased. The results shown in Figure 6.6 indicate that the rate of oil loss from films initially containing 4% w/w Jet A1, high flash point cutter and mineral turpentine were overall quite similar when tests were conducted at 50 °C. The film which initially contained 4% w/w diesel showed the slowest rate of oil loss of all the binder films studied.

The results shown in Figure 6.7 illustrate that the rates of oil loss from films initially containing 4% w/w Enersol kerosene and Enersol K were only slightly greater than the rate of oil loss observed for the binder film initially containing 4% w/w Jet A1 when tests were conducted at 50 °C. The film initially containing 4% w/w Enersol HFK, by contrast, showed a rate of oil loss which was between that observed for films containing Jet A1 and diesel.

Figure 6.6: Mass loss results obtained at 50 °C for films containing 4% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

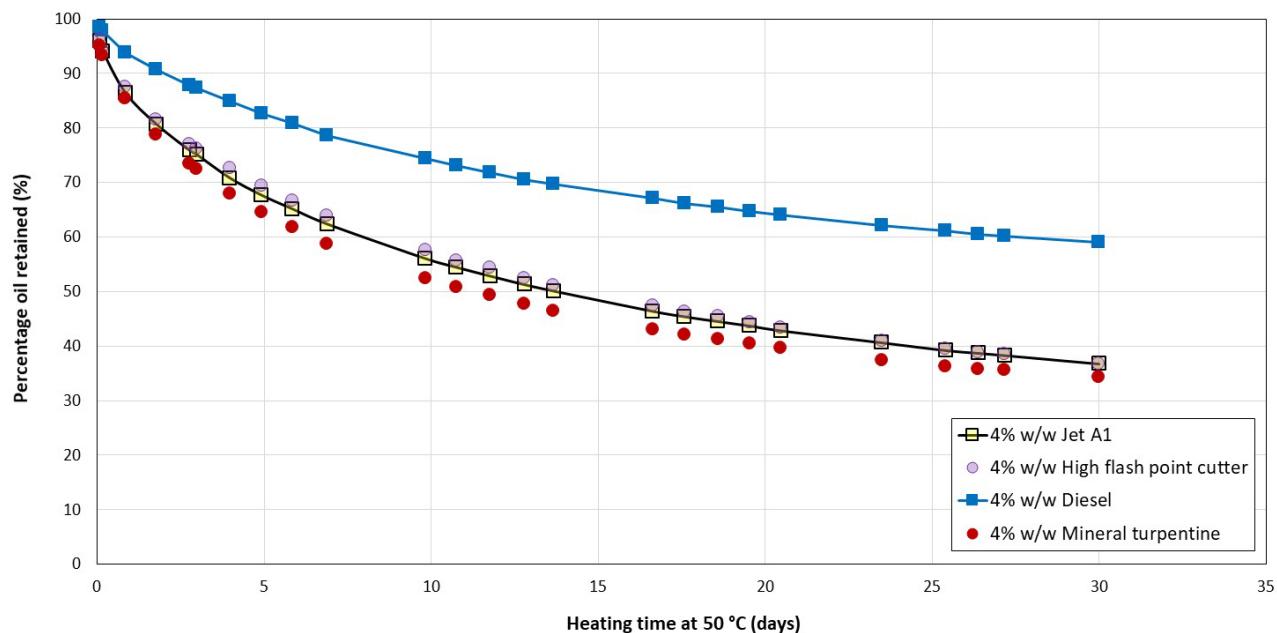


Figure 6.7: Mass loss results obtained at 50 °C for films containing 4% w/w of each of the Enersol oils

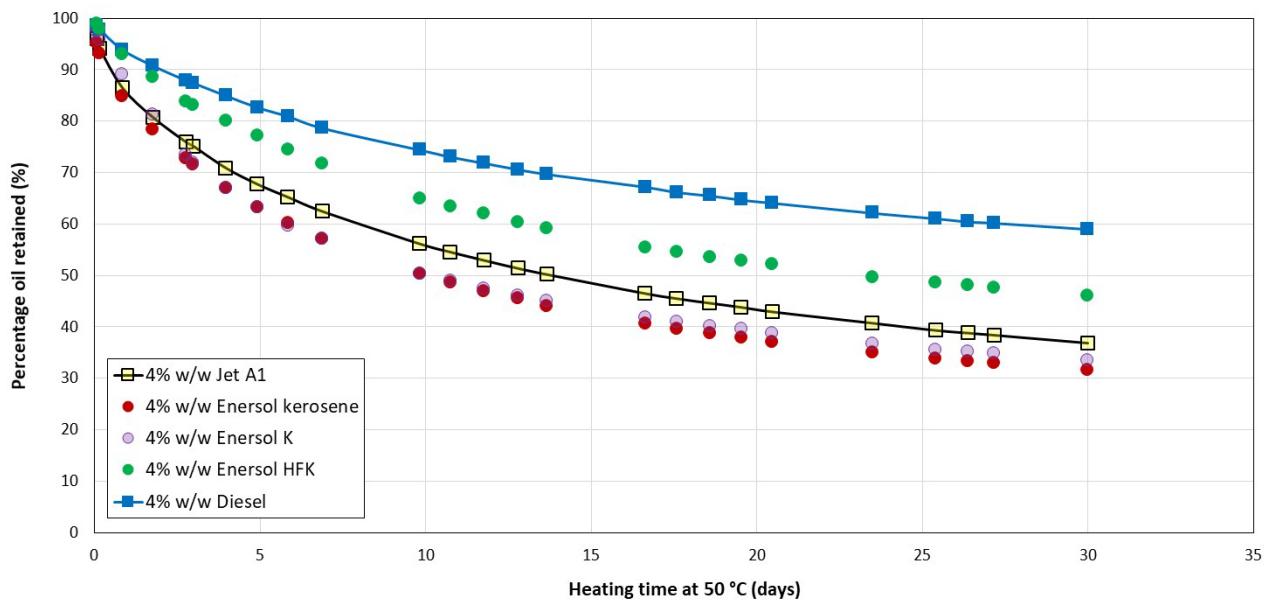


Figure 6.8 and Figure 6.9 show the mass loss test results which were obtained for binder films containing 6% w/w of each of the oils when tests were conducted at 60 °C. The results shown in Figure 6.8 indicate that the rate of oil loss from films initially containing 6% w/w high flash point cutter and mineral turpentine were overall quite similar to the comparable film containing Jet A1 when tests were conducted at 60 °C. The film initially containing 6% w/w diesel again showed the slowest rate of oil loss of all the binder films studied. After 30 days of heating at 60 °C only 36% of the diesel which was originally added remained in the binder film (i.e. 64% of the diesel had been lost during the experiment).

Figure 6.8: Mass loss results obtained at 60 °C for films containing 6% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

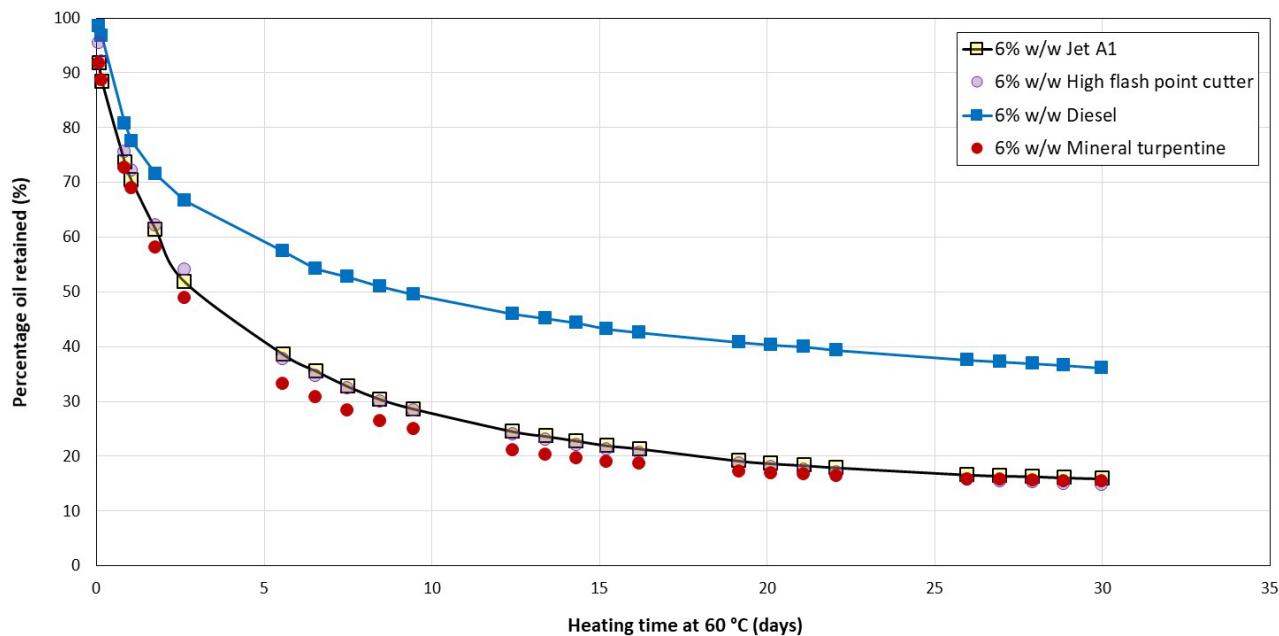
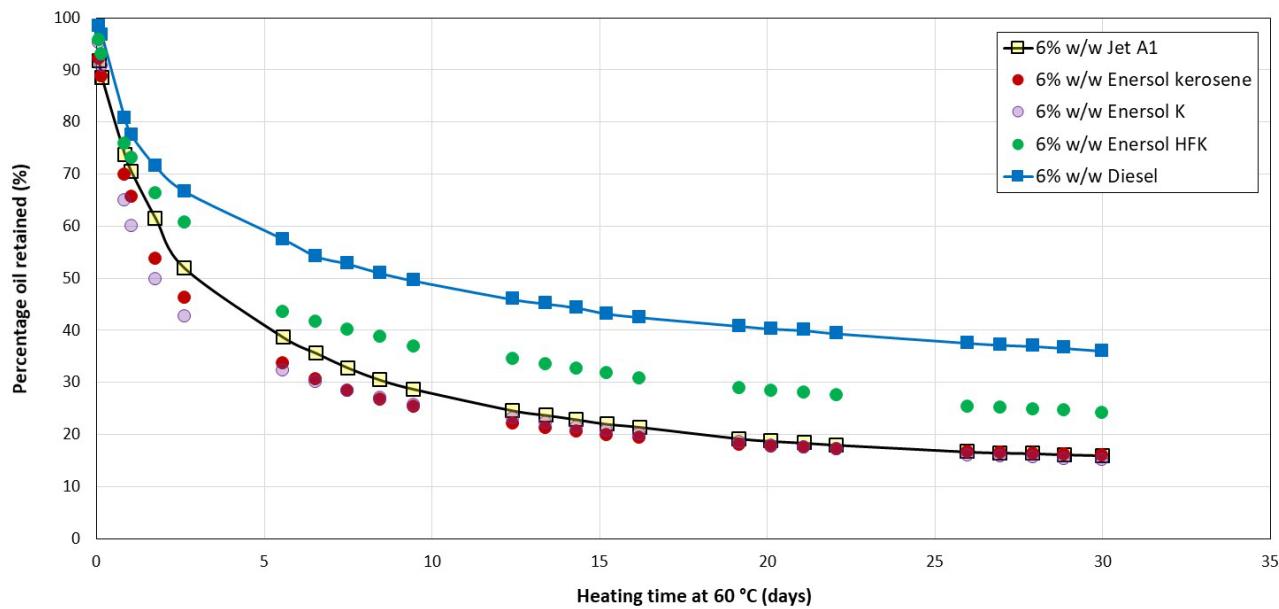


Figure 6.9: Mass loss results obtained at 60 °C for films containing 6% w/w of each of the Enersol oils



The results shown in Figure 6.9 indicate that the rates of oil loss of films initially containing 6% w/w Enersol kerosene and Enersol K were slightly higher than that of the analogous film containing Jet A1 for heating times less than about 10 days. For heating times greater than 10 days, the mass of Enersol kerosene and Enersol K remaining in the films was very similar to the analogous film containing Jet A1. As in the case of the 50 °C experiments (Figure 6.7), the film initially containing 6% w/w Enersol HFK showed a rate of oil loss which was between that observed for analogous films containing Jet A1 and diesel.

Overall, the results of mass loss tests indicated that the rate of oil loss from the binder films increased (when results were expressed in terms of the percentage of oil retained) if either the test temperature or the initial amount of oil in the films was increased. The rate of oil loss from films containing all oils, except Enersol HFK and diesel, became more similar to analogous films containing Jet A1 as the test temperature was increased. Binder films containing Enersol HFK and diesel consistently showed lower rates of oil loss than analogous films containing Jet A1.

6.3 Mass Loss Test Data Analysis

6.3.1 Comparisons of Amounts of Oil Loss with Films Containing Jet A1

The results of mass loss tests were quantitatively assessed by comparing the percentage oil retained results obtained for each type of binder film after 30 days of heating at each test temperature (Table 6.1). The results obtained after 30 days of heating were used in the analysis as it was thought they would better reflect the long-term loss of cutter from a sprayed seal. If insufficient cutter is lost from a sprayed seal in the long-term, then it is more likely aggregate would be lost from a seal under traffic as the binder would be too soft to effectively retain the aggregate. Flushing of the binder in the seal would also be more likely to occur during periods of hot weather.

The results shown in Table 6.1 include the percentage oil retained results which were obtained for each binder film studied after they were heated for 30 days at the three different test temperatures, as well as a comparison of the results obtained for each binder film with those obtained for films containing the same initial concentration of Jet A1 which were conducted at the same test temperature. Binder film mass loss results were compared to analogous results for films containing Jet A1 as Jet A1 was considered to be representative of a standard cutter oil in the study.

Table 6.1: Comparison of percentage oil retained results after 30 days of heating with films containing Jet A1

Binder film type	Percentage oil retained result after 30 days of heating (%)			Variation in percentage oil retained result from a comparable film containing Jet A1 after 30 days of heating (%)			Range of percentage oil retained results compared to Jet A1 for each oil type (%)
Test temperature (°C)	40	50	60	40	50	60	
2% w/w Jet A1	67	54	40	–	–	–	–
4% w/w Jet A1	53	37	22	–	–	–	
6% w/w Jet A1	45	29	16	–	–	–	
2% w/w high flash point cutter	67	51	33	0	–3	–7	–7 to +4
4% w/w high flash point cutter	56	37	21	+3	0	–1	
6% w/w high flash point cutter	49	31	15	+4	+2	–1	
2% w/w diesel	83	72	55	+16	+18	+15	+15 to +26
4% w/w diesel	76	59	42	+23	+22	+20	
6% w/w diesel	71	51	36	+26	+22	+20	
2% w/w mineral turpentine	62	48	38	–5	–6	–2	–6 to 0
4% w/w mineral turpentine	48	34	22	–5	–3	0	
6% w/w mineral turpentine	39	26	15	–6	–3	–1	
2% w/w Enersol kerosene	62	50	37	–5	–4	–3	–5 to 0
4% w/w Enersol kerosene	47	32	20	–5	–5	–2	
6% w/w Enersol kerosene	40	25	16	–5	–4	0	
2% w/w Enersol K	67	50	33	0	–4	–7	–7 to +3
4% w/w Enersol K	56	33	20	+3	–4	–2	
6% w/w Enersol K	47	27	15	+2	–2	–1	
2% w/w Enersol HFK	72	58	44	+5	+4	+4	+4 to +9
4% w/w Enersol HFK	62	46	30	+9	+9	+8	
6% w/w Enersol HFK	54	38	24	+9	+9	+8	

The 'variation in percentage oil retained' results shown in Table 6.1 were calculated by subtracting the result obtained for each type of binder film (e.g. 56% for a film initially containing 4% w/w high flash point cutter after 30 days heating at 40 °C) from the analogous result obtained for a film containing the same initial concentration of Jet A1 which was heated at the same test temperature (e.g. 53% for a film initially containing 4% w/w Jet A1 after 30 days heating at 40 °C). In the case of experiments conducted using 4% w/w high flash point cutter at 40 °C, this yielded a variation in percentage oil retained result of +3% (i.e. 56% – 53% = 3%, Table 6.1) which indicated that 3% more high flash point cutter was retained in a binder film after 30 days of heating than the comparable binder film containing Jet A1. Negative results in the three variation in percentage oil retained columns in Table 6.1 indicate that less oil was retained in a binder film after 30 days of heating than a comparable film contained Jet A1 which was heated at the same test temperature. Positive results in these three columns indicate that a greater amount of oil was retained in the films after 30 days of heating than a comparable film which contained Jet A1.

The last column of Table 6.1 compares the range of differences in mass loss results obtained after 30 days of heating for each type of oil with the results obtained for analogous films containing Jet A1. In the case of binder films containing diesel and Enersol HFK, percentage oil retained results obtained after 30 days of heating were always higher than comparable films containing Jet A1. This indicates that less diesel and Enersol HFK were lost from the binder films compared with Jet A1 in all experiments. The percentage oil retained results obtained for films containing diesel were between 15 and 26% higher than those obtained for analogous films containing Jet A1 after 30 days of heating if the results from all binder films containing these two oils were considered. Films containing Enersol HFK showed percentage oil retained results after 30 days of heating which were between 4 and 9% higher than analogous films containing Jet A1.

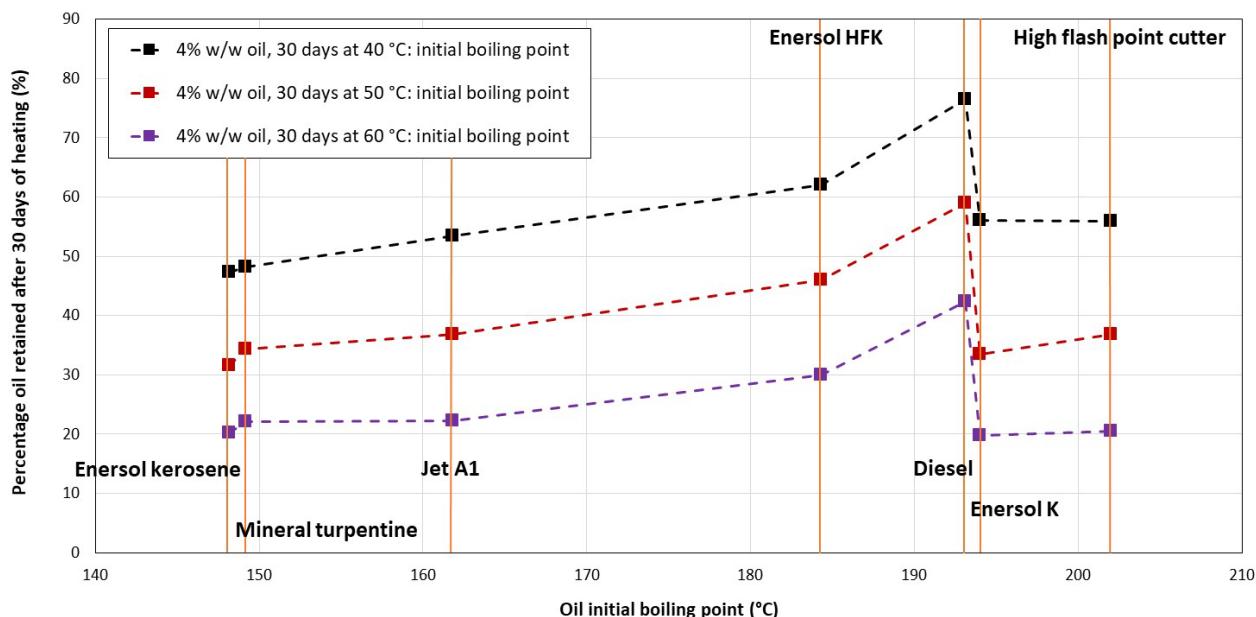
The results shown in the last column of Table 6.1 varied between –7 and +4% for films containing high flash point cutter, mineral turpentine, Enersol kerosene and Enersol K indicating that percentage oil retained results after 30 days of heating were between 7% lower and 4% higher than analogous films containing Jet A1. These results appear to indicate that the amount of oil loss observed from binder films containing these four types of oil after extended heating was either slightly higher or essentially comparable to analogous films containing Jet A1. If sprayed seals were constructed using oils which evaporated from a seal at the same rate as Jet A1, then suitable sprayed seal performance would be expected in the longer term. If the oils evaporated at a slightly higher rate than Jet A1, aggregate loss under traffic or flushing of the seal in hot weather would be less likely to occur over time than when a standard cutter oil (e.g. Jet A1) was used in sprayed seal construction.

6.3.2 Comparisons with Neat Oil Boiling Point Behaviour

The results obtained in mass loss tests after 30 days of heating were compared with the AS 3568-specified IBP and FBP results obtained for each of the neat oils to ascertain whether these currently specified properties could be related to mass loss test results. This assessment was performed by comparing the percentage oil retained results obtained after 30 days of heating for each for the nine sets of mass loss results which were performed using the same initial oil concentration and test temperature (i.e. 2% w/w oil-40 °C, 4% w/w oil-40 °C, 6% w/w oil-40 °C, 2% w/w oil-50 °C, 4% w/w oil-50 °C, 6% w/w oil-50 °C, 2% w/w oil-60 °C, 4% w/w oil-60 °C, 6% w/w oil-60 °C) with IBP and FBP results.

No correlation was found between percentage oil retained results obtained after 30 days of heating and IBP results for any of the nine sets of data which were compared. Figure 6.10 shows a representative example where the mass loss results obtained from films initially containing 4% w/w of each of the oils were compared with IBP results when mass loss tests were performed at 40, 50 and 60 °C, respectively. The points associated with each test temperature have been joined by dashed lines in the figure so it is easier to compare the results obtained at each test temperature with IBP results. Vertical orange lines have also been included so that the oil type associated with each datapoint can be easily identified.

Figure 6.10: Comparison of percentage oil retained results obtained in mass loss tests and neat oil initial boiling point results for films initially containing 4% w/w oil



The results shown in Figure 6.10 illustrate that there was not a general trend between percentage oil retained results obtained after 30 days of heating and neat oil IBP results for experiments conducted at either of the three test temperatures. This is particularly the case for binder films which contained Enersol K and high flash point cutter as films containing these two oils showed percentage oil retained results after 30 days of heating which were lower than those of films containing diesel even though these two neat oils had higher IBP results than diesel. A similar lack of correlation between percentage oil retained results and IBP results was observed when the other six sets of mass loss data were compared with the IBP results obtained for each of the neat oils.

Figure 6.11 to Figure 6.13 show comparisons between percentage oil retained results obtained after 30 days of heating and neat oil FBP results for each of the nine sets of data that were obtained during mass loss tests. Vertical orange lines have again been included in each of the figures so that oil type associated with each datapoint can be easily identified. Percentage oil retained results were found to vary in a regular way with oil FBP results for all nine sets of data that were compared. This result implied that there was a correlation between AS 3568-specified FBP results and percentage oil retained results obtained after 30 days of heating in mass loss tests.

Initial analysis of the results shown Figure 6.11 to Figure 6.13 involved attempting to fit each of the nine sets of data to a simple mathematical function which would allow correlation coefficient (R^2) values to be obtained for each set of experimental results which were compared. The values of R^2 obtained could then be used to numerically assess the ability of the selected equation to fit the experimental data. The results of simple curve fitting analysis, however, indicated that the mathematical relationship between percentage oil retained results and FBP results was considerably more complex than that which could be described by a simple linear, polynomial, exponential or logarithmic function. The lines in Figure 6.11 to Figure 6.13 which are associated with each of the nine sets of mass loss data therefore represent general trend lines which describe the experimental data. The difference between experimental percentage oil retained results and the general trend lines shown in the figures was in no cases greater than 4%.

Figure 6.11: Comparison of percentage oil retained results obtained in mass loss tests and neat oil final boiling point results for films initially containing 2% w/w oil

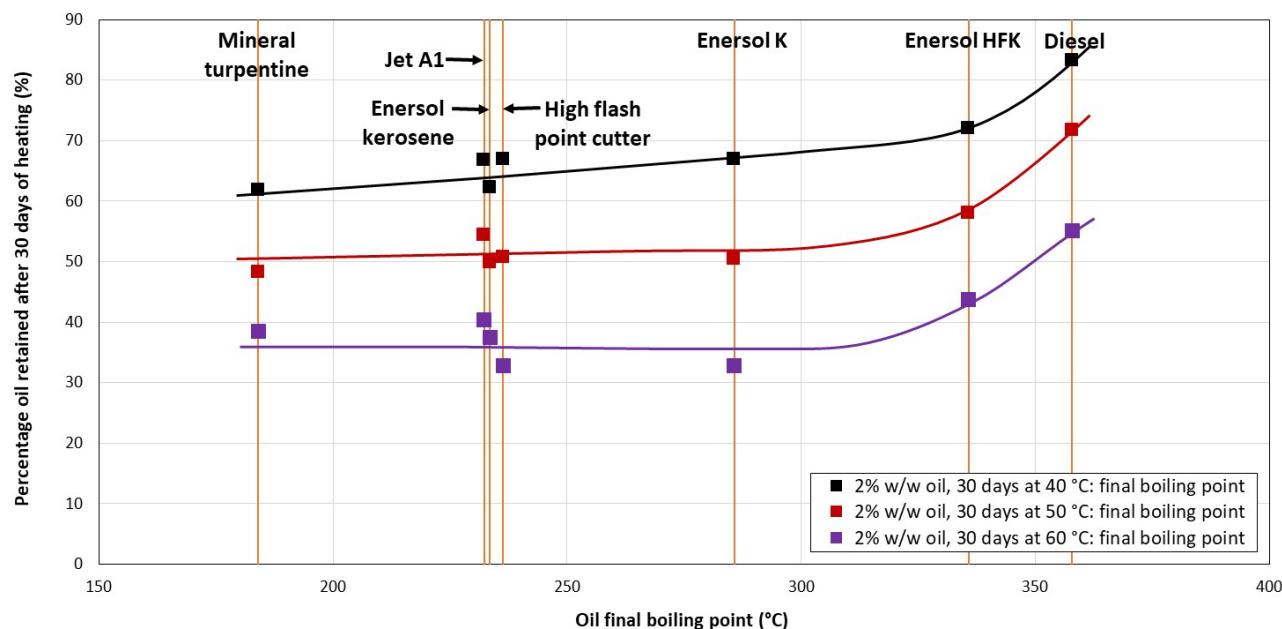


Figure 6.12: Comparison of percentage oil retained results obtained in mass loss tests and neat oil final boiling point results for films initially containing 4% w/w oil

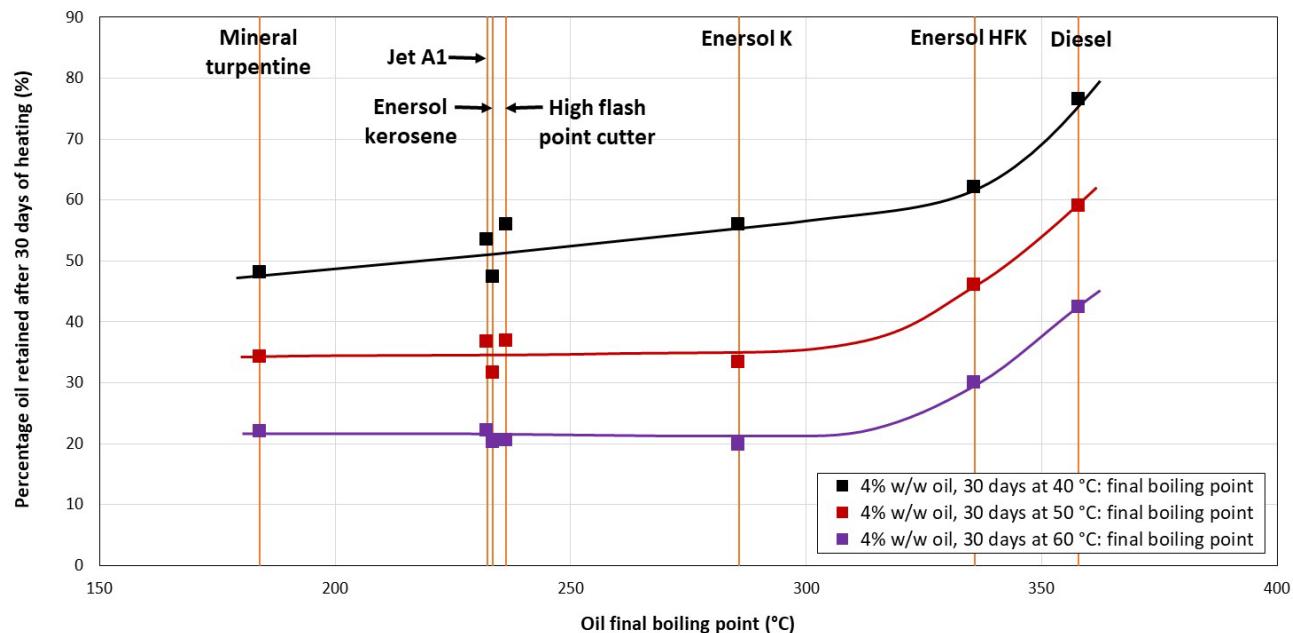
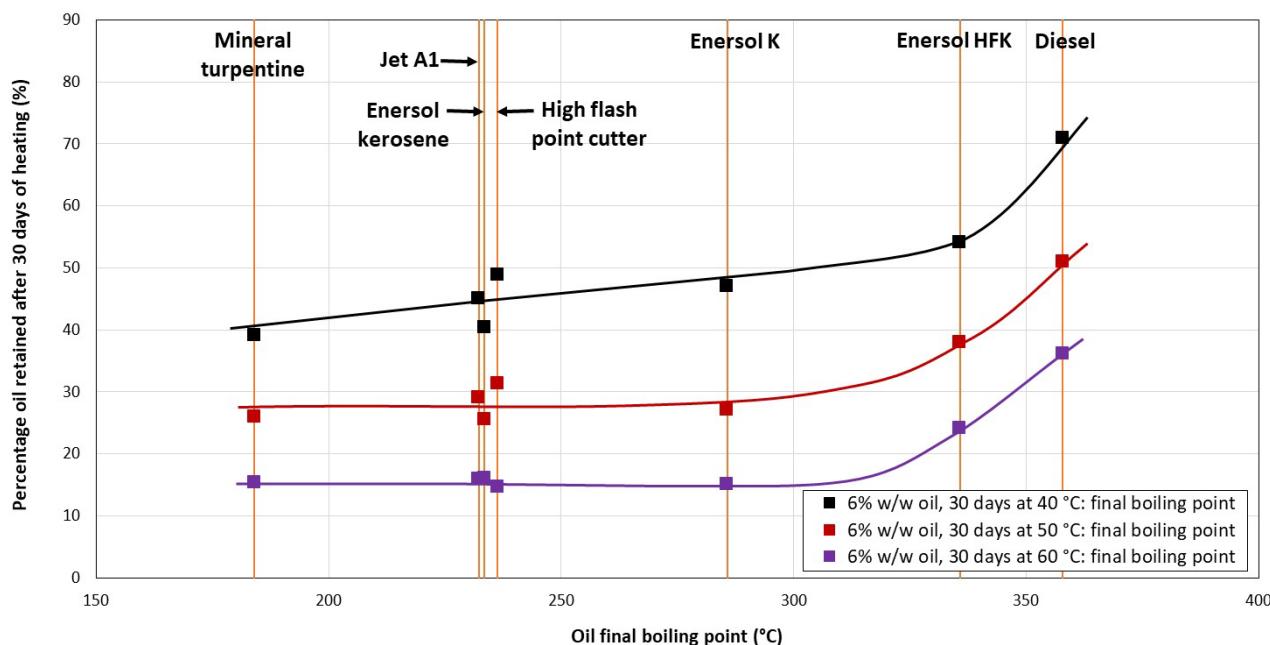


Figure 6.13: Comparison of percentage oil retained results obtained in mass loss tests and neat oil final boiling point results for films initially containing 6% w/w oil



The trend lines shown in Figure 6.11 to Figure 6.13 appear to indicate that there was overall a general increase in percentage oil retained results with oil FBP results when binder films initially containing 2% w/w, 4% w/w and 6% w/w oil were heated at 40 °C for 30 days. In the case of mass loss tests conducted at 50 °C and 60 °C, however, the percentage oil retained results obtained for films containing mineral turpentine, Enersol kerosene, high flash point cutter and Enersol K after 30 days of heating were overall very similar to those obtained from films containing Jet A1 at each initial oil concentration. Binder films containing Enersol HFK and diesel, by contrast, showed higher percentage oil retained results than analogous films containing Jet A1 in each set of experiments.

It was noted in Section 6.3.1 that binder films containing mineral turpentine, Enersol kerosene, high flash point cutter and Enersol K showed amounts of oil loss after 30 days of heating which were overall slightly higher or essentially the same as analogous films containing Jet A1 if the results of all mass loss tests were considered. The results of mass loss tests additionally indicated that binder films containing each of these four oils showed very similar percentage oil retained results after 30 days of heating to analogous films containing Jet A1 when tests were conducted at 50 °C and 60 °C. The FBP results obtained for these five oils were all lower than 286 °C (Table 4.2 and Table 4.3).

Mass loss test results obtained for binder films containing Enersol HFK and diesel indicated that less oil was lost over time than comparable films containing Jet A1 in all experiments. These two oils had FBP results which were both above 335 °C (Table 4.2 and Table 4.3).

Based on the results obtained in mass loss tests, and the observed correlation between mass loss test results and oil FBP results, it appears that oils which have FBP results of < 286 °C will be expected to show similar to slightly greater rates of oil loss in sprayed seals over time than seals constructed using a conventional cutter oil (i.e. Jet A1). Oils which have FBP results of > 335 °C would be expected to show lower rates of oil loss in sprayed seals than those constructed with a conventional cutter oil and their use could result in an increased risk of aggregate stripping/plucking under traffic or flushing of the binder in hot weather. Based on the results of the study, the oil FBP result at which an oil would switch from showing a similar to slightly greater rate of oil loss compared to a conventional cutter oil, to a lower rate of loss, would lie somewhere in the range between 286 °C and 335 °C.

The current Australian and New Zealand FBP specification limit for Jet A1 (which was considered to represent a conventional cutter oil in this study) is 300 °C maximum when it is used as an aviation fuel (Joint Inspection Group 2016). This maximum FBP requirement is towards the lower end of the identified range between 286 °C and 335 °C. Based on the results obtained in mass loss tests, and the currently specified FBP requirement for Jet A1, it appears that the FBP requirements for cutter oil and high flash point cutter could be increased to 300 °C maximum in an updated version of AS 3568.

6.3.3 Comparisons with AS 3568-specified Chemical Properties of the Neat Oils

Comparisons were also made between aniline point and aromatic content results obtained for each of the neat oils and percentage oil retained results obtained after 30 days of heating to ascertain whether there was any correlation between the AS 3568-specified chemical properties of the neat oils and the results obtained in mass loss tests. These were conducted by individually comparing each of the nine sets of mass loss results which were performed using the same initial oil concentration and test temperature with oil aniline point and aromatic content results, respectively (18 data sets in total). No correlations were found between percentage oil retained results obtained after 30 days of heating and the specified chemical properties of the oils for any of the 18 data sets that were compared.

Representative comparisons between mass loss test results obtained after 30 days of heating and oil aniline point/aromatic content results are shown in Figure 6.14 and Figure 6.15, respectively. The results shown in the two figures correspond to the mass loss results which were obtained from films which initially contained 4% w/w of each oil when binder films were heated at either 40, 50 or 60 °C. The points associated with each test temperature have been joined by dashed lines so it is easier to compare the results obtained at each test temperature with the specified chemical properties of the oils. Vertical orange lines have also been included so that the oil type associated with each datapoint can be easily identified. No trends between percentage oil retained results and aniline point results (Figure 6.14) or percentage oil retained results and aromatic content results (Figure 6.15) are obvious for the three test temperatures shown in each of the figures.

Figure 6.14: Comparison of percentage oil retained results obtained in mass loss tests and neat oil aniline point results for films initially containing 4% w/w oil

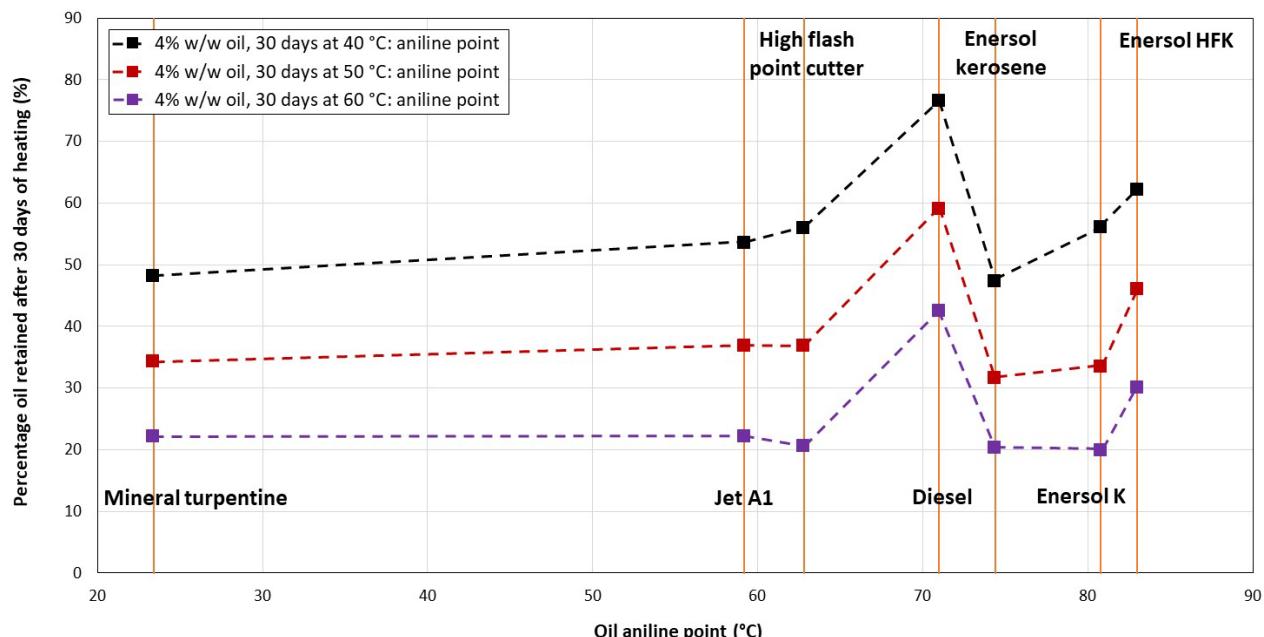
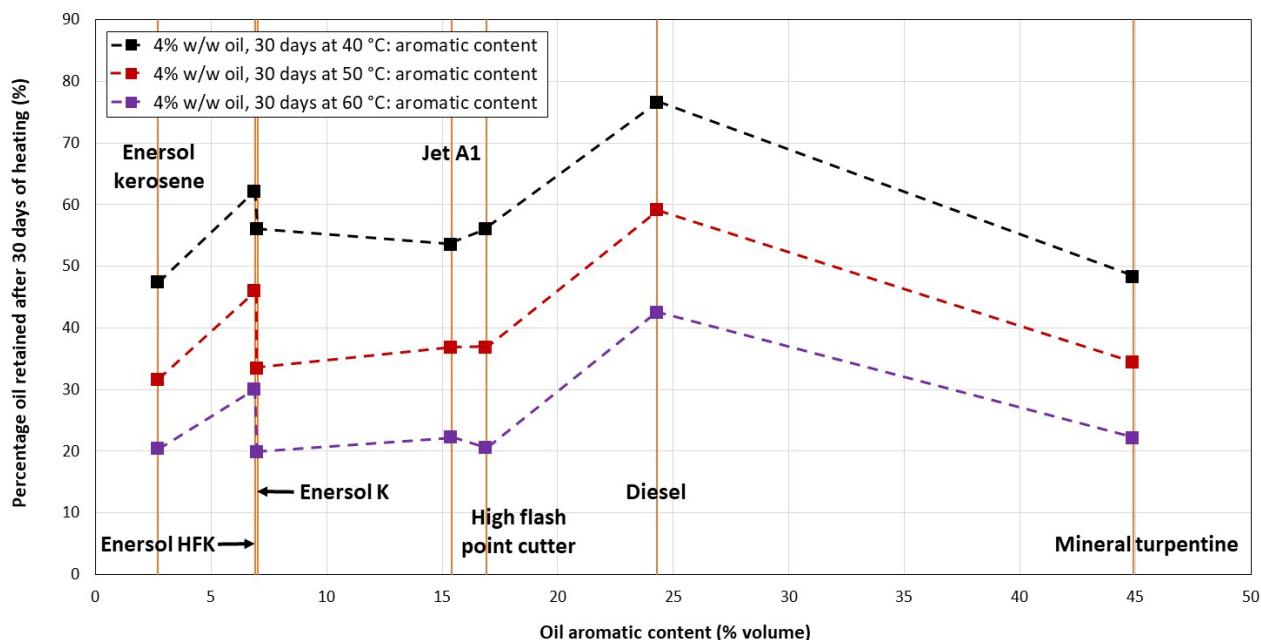


Figure 6.15: Comparison of percentage oil retained results obtained in mass loss tests and neat oil aromatic content results for films initially containing 4% w/w oil



6.4 Changes in Binder Viscosity During Mass Loss Tests

It was noted in Section 6 that if the rate of cutter loss from a sprayed seal is too low, then the viscosity of the binder would be expected to be too low for the seal to effectively retain aggregate under traffic. Flushing of the binder in a seal could also occur during periods of hot weather due to the low viscosity of the binder. In order to investigate how oil loss from the binder films actually affected binder film viscosity, the complex viscosity at 60 °C of one of each of the duplicate samples subjected to mass loss tests was determined using a DSR after mass loss tests had been completed (i.e. after 30 days of heating at each test temperature).

Complex viscosity at 60 °C tests were conducted on binder films which had been subjected to mass loss tests by initially removing the lids from the dishes and heating the films under a 240 V, 275 W lamp until the binder films were sufficiently fluid to be easily stirred with a spatula. The binder films were then thoroughly mixed with the spatula and subjected to DSR tests using test temperatures in the range between 15 and 65 °C and oscillation frequencies in the range between 0.63 and 63.09 rad/s using the DSR test equipment and testing protocol described in Section 7.1. Complex viscosity at 60 °C results were obtained for the binder films using the measured DSR results which were obtained at a test temperature of 60 °C and oscillation frequency of 1 rad/s. Master-curve fitting of the experimental data (as described in Section 7.2) was not performed, as it was possible to compare the complex viscosity of the different binder films under a single set of experimental conditions (i.e. 60 °C and 1 rad/s) which were used during DSR tests.

As the results of mass loss tests on C170 bitumen binder films had indicated that some degree of oxidation had occurred on extended heating (Section 6.2.1), a sample of the C170 bitumen used in the study was also subjected to DSR tests so that the complex viscosity at 60 °C result for a non-heat-treated C170 bitumen binder could be compared to those obtained for the binder films. The complex viscosity at 60 °C of an untreated C170 bitumen sample was determined to be 202 Pa s when a frequency of 1 rad/s was used in DSR tests. This result was overall similar to the viscosity at 60 °C result obtained for this binder when it was tested using a conventional capillary viscometer in accordance with AS 2008 (192 Pa s, Table 4.1).

Table 6.2 compares the complex viscosity at 60 °C results which were obtained for an untreated C170 bitumen sample and C170 bitumen films which were subjected to 30 days heating at the three temperatures used during mass loss tests. Although the results shown in Section 6.2.1 did not show significant changes in the mass of the C170 bitumen films after 30 days of heating at each test temperature, there was an appreciable increase in the viscosity of the binder films on extended heating. The change in the viscosity of the binder films increased as the test temperature increased.

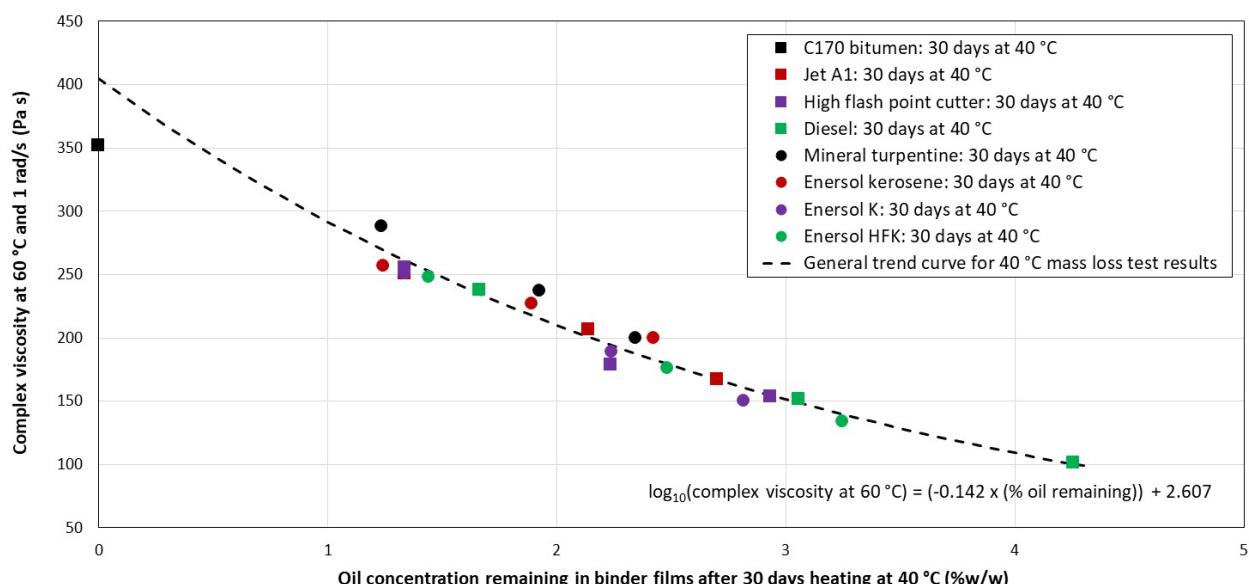
Table 6.2: Complex viscosity at 60 °C results obtained for a sample of untreated C170 bitumen and C170 bitumen films after 30 days of heating

Binder type	Binder complex viscosity at 60 °C and 1 rad/s (Pa s)
Untreated C170 bitumen	202
C170 bitumen film after 30 days heating at 40 °C	352
C170 bitumen film after 30 days heating at 50 °C	456
C170 bitumen film after 30 days heating at 60 °C	568

The complex viscosity at 60 °C of a C170 bitumen film after 30 days heating at 40 °C was 352 Pa s which was within the range of 260 to 380 Pa s specified in AS 2008 for Class 320 (C320) bitumen. The complex viscosity of a C170 bitumen film after 30 days of heating at 60 °C was within the range specified for Class 600 (C600) bitumen in AS 2008 (i.e. 500 to 700 Pa s).

Figure 6.16 shows a plot of the complex viscosity at 60 °C results which were obtained for the 22 different types of binder films which were subjected to 30 days of heating at 40 °C versus the concentration of oil remaining in each of the films. The x-axis in the plot has been expressed in terms of the remaining oil concentration in the films after 30 days of heating (in %w/w) rather than percentage oil retained results so that the data obtained from experiments conducted using different initial oil concentrations could be plotted on the same graph. The concentration of oil remaining in the films was calculated by multiplying the initial oil concentration in each film (e.g. 4% w/w) by the percentage oil retained result obtained for each film (e.g. 48%) after 30 days of heating (e.g. 4% x 0.48 = 1.92% w/w). The results associated with the C170 bitumen film, and binder films containing each of the seven different oils, have been shown as different types of datapoints in the figure.

Figure 6.16: Complex viscosity at 60 °C results obtained for binder films heated for 30 days at 40 °C



There appeared to be a general trend between the complex viscosity at 60 °C of the binder films after 30 days of heating and the concentration of oil remaining in the films for all binder films studied which contained oil. The complex viscosity of binder films containing oil overall decreased as the concentration of oil remaining in the films increased. Although the complex viscosity at 60 °C results obtained for films which contained oil are almost certainly affected by the initial viscosity of each oil present in each binder film (see Section 7.3 for details), as well as the exact chemical components which evaporated from the films over time, a general trend curve is included in Figure 6.16. This curve was determined by initially plotting $\log_{10}(\text{complex viscosity at } 60 \text{ °C})$ results against remaining oil concentration results for all binder films which contained oil and then fitting the data to a linear function. The curve generated from the logarithmic fit to the data is shown as a dashed line in Figure 6.16. The figure also includes the equation obtained from the logarithmic fit.

Extrapolation of the general logarithmic fit to the data obtained for binder films which contained oil yielded a y-intercept value of 405 Pa s, which was of the order of 50 Pa s higher than the complex viscosity result obtained for a C170 bitumen film after 30 days of heating at 40 °C (352 Pa s). Although the complex viscosity at 60 °C results obtained from binder films containing oil would be expected to be affected by other factors, this result suggests that binder films which contain oil may oxidise (i.e. harden) at a faster rate than those which contain only C170 bitumen.

Figure 6.17 and Figure 6.18 show analogous plots to Figure 6.16 where complex viscosity at 60 °C results have been plotted against remaining oil concentration results for the 22 different types of binder films which were heated for 30 days at 50 °C and 60 °C, respectively. These two plots appear to show the same general trend as shown in Figure 6.16 in that the complex viscosity results obtained from films which contained oil also showed a general decrease as the concentration of oil remaining in the films increased. Figure 6.17 and Figure 6.18 also include general trend curves which were calculated using the same method as used to determine the curve shown in Figure 6.16. The y-intercept values associated with the general trend curves which were obtained from films heated at 50 °C and 60 °C (i.e. 517 Pa s and 756 Pa s, respectively) were again higher than the complex viscosity at 60 °C results obtained for C170 bitumen films which were heated at the same temperature (i.e. 456 Pa s and 568 Pa s, respectively). These results also suggested that films which contained oil oxidised at a faster rate than films which contained only C170 bitumen.

Figure 6.17: Complex viscosity at 60 °C results obtained for binder films heated for 30 days at 50 °C

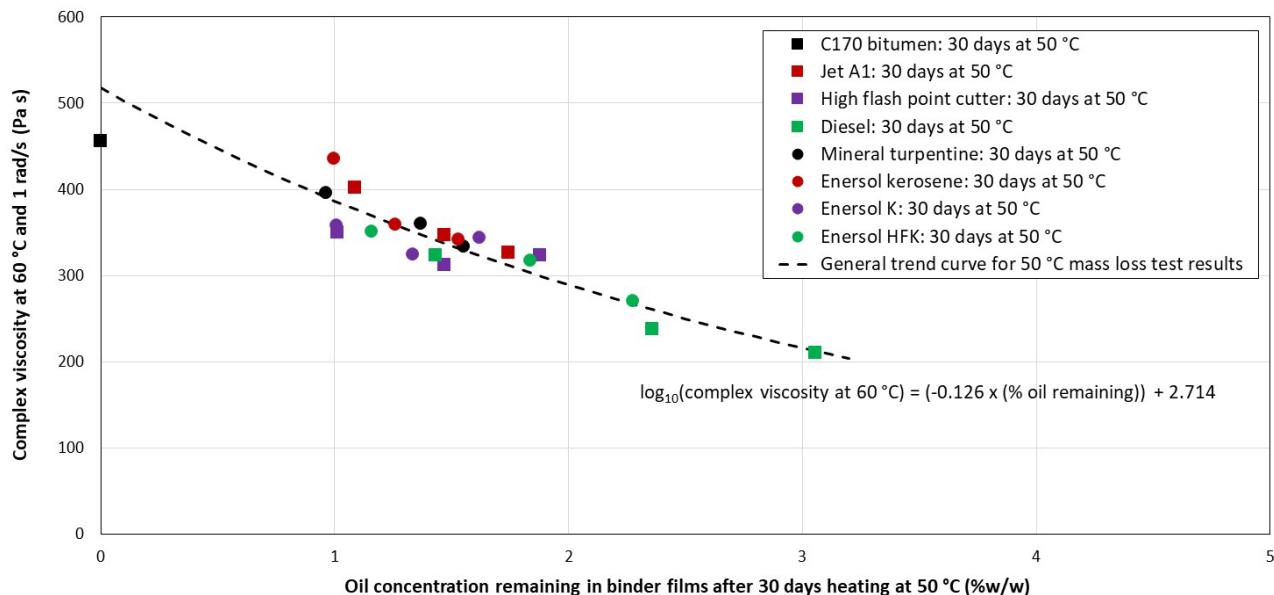
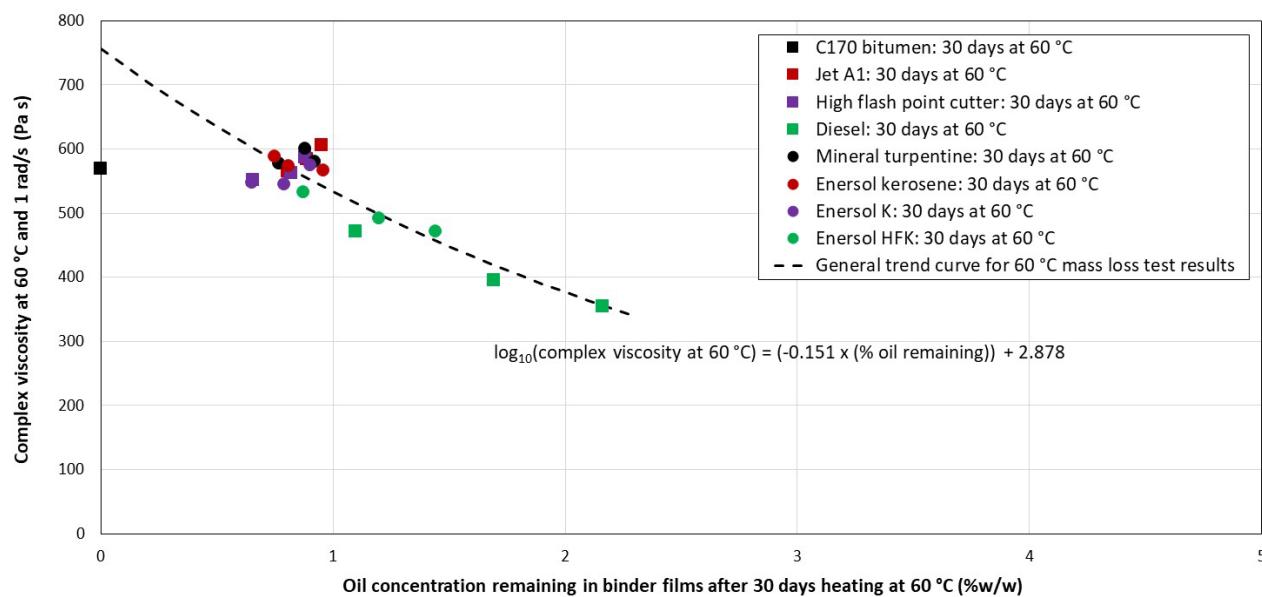


Figure 6.18: Complex viscosity at 60 °C results obtained for binder films heated for 30 days at 60 °C

Studies by Dickinson (2000) and Herrington (2012) into factors which affect the rate of oxidation (i.e. the viscosity increase) of bitumen films have indicated that the rate of diffusion of oxygen into films is affected by bitumen film viscosity. The rate of oxygen diffusion into bitumen films, and hence the rate of bitumen oxidation, is higher in films which have lower viscosities. The relatively higher rate of binder oxidation observed in mass loss tests for films which contained oil is therefore most likely due to the initial lower viscosity of the bitumen-oil blends compared to the viscosity of binder films which contained only C170 bitumen.

6.5 Summary

Mass loss tests were conducted at three test temperatures (i.e. 40, 50 and 60 °C) using 2 mm binder films which initially contained either 0, 2, 4 or 6% w/w of each of the seven oils which were included in the study. The results of these tests showed that films containing high flash point cutter, mineral turpentine, Enersol kerosene and Enersol K showed slightly higher to similar amounts of oil loss after 30 days of heating as comparable films containing the same initial concentration of Jet A1 which were heated at the same temperature. Films containing Enersol HFK and diesel consistently showed lower amounts of oil loss after 30 days of heating than comparable films which contained the same initial concentration of Jet A1 which were heated at the same temperature.

Percentage oil retained results which were obtained after 30 days of heating were compared with the results obtained for each of the neat oils in AS 3568-specified IBP, FBP, aniline point and aromatic content tests to ascertain whether the results obtained in mass loss tests could be correlated with test properties currently included in AS 3568. Correlations between mass loss test results and neat oil test results were assessed by individually comparing the nine sets of percentage oil retained results which were obtained in mass loss tests when the same initial oil concentration and test temperature was used during the experiments with each of the four AS 3568-specified test properties. No effective correlations were found between the nine sets of percentage oil retained results and either IBP, aniline point or aromatic content test results. Percentage oil retained results, however, varied in a regular way with neat oil FBP results for all nine data sets that were compared. This indicated that there was a relationship between neat oil FBP results and the relative amounts of oil loss observed from binder films over time at the three test temperatures investigated.

Tested oils which had FBP results of 286 °C or less, showed slightly higher to similar amounts of oil loss after 30 days of heating as comparable films containing the same initial concentration of Jet A1 which were heated at the same test temperature. Tested oils which had FBP results above 335 °C, consistently showed higher percentage oil retained results after 30 days of heating than comparable films containing Jet A1. If these results, and the current FBP specification requirements for Jet A1 aviation fuel are considered, then it appears that the FBP requirements for cutter oil and high flash point cutter could be increased to 300 °C maximum in an updated version of AS 3568.

DSR viscosity measurements which were performed on binder films after mass loss tests were completed indicated that the complex viscosity at 60 °C of the C170 bitumen films had increased significantly after 30 days of heating at each test temperature (i.e. the bitumen films had oxidised during heating). Greater changes in binder viscosity were observed for C170 bitumen films which were heated at higher temperatures. There appeared to be general trend between complex viscosity at 60 °C results obtained for films which contained bitumen and oil, and the concentration of oil remaining in the binder films after 30 days of heating, at each test temperature. The results of complex viscosity tests on binder films which contained oil appeared to indicate that binder films which contained oil oxidised (i.e. hardened) at a faster rate than films which only contained bitumen.

7. Viscosity Tests

The information obtained during the literature review (Section 3) indicated that early studies by Dickinson (1961, 1984) found that the viscosity of the binder at the pavement temperature was the most important factor that influenced initial adhesion between binder and aggregate when sprayed seals were constructed. The studies by Dickinson included conducting road trials at various pavement temperatures and determining minimum binder viscosities required for aggregate to be effectively retained in a sprayed seal, as well as conducting laboratory studies where aggregate was applied to binder films under various conditions and the initial adhesion of the aggregate to the binder was directly assessed. These studies investigated the combined effects of initial binder wetting of aggregates as well as the ability of the binder to effectively retain aggregate once binder and aggregate were brought into contact.

Later studies by Maccarrone et al. (1997) and Austroads (2012a, 2012b) focussed on relating binder viscosity to the degree of aggregate wetting which occurred at various pavement temperatures. These studies only focussed on aggregate wetting so did not consider the effects of adhesion between the binder and the aggregate. The studies, in a similar way to Dickinson, also found that the degree of aggregate wetting by binder was influenced by the viscosity of the binder. The relationship between binder viscosity and the degree of aggregate wetting obtained by Maccarrone et al., however, was different to that observed by Dickinson when both aggregate wetting and adhesion was considered.

The effects of the use of different oils on C170 bitumen viscosity reduction and the recommended cutter levels listed in AP-T39-05 (Austroads 2005) were investigated in the current study by initially measuring the rheological properties of blends which contained oil concentrations of between 0 and 12% w/w using a DSR. DSR tests were conducted using test temperatures in the range between 15 °C and 65 °C and test frequencies in the range between 0.63 and 63.1 rad/s. Oil concentrations of 0, 2, 4, 6, 9 and 12% w/w were studied as these corresponded to oil concentrations of 0, 2.7, 5.5, 8.4, 13 and 18 parts for blends which contained the sample of representative cutter oil which was used in this study (i.e. Jet A1). This range of oil levels was chosen as it was considerably larger than the range of cutter levels (i.e. 0 to 10 parts) which is recommended in AP-T39-05 when C170 bitumen is used to construct sprayed seals.

DSR tests were conducted in the range between 15 °C and 65 °C so that rheological results could be obtained for the range of pavement temperatures listed in Austroads (2005) (i.e. 20 °C to 45 °C) and complex viscosity results could also be obtained for the bitumen-oil blends at 40 °C and 60 °C. Complex viscosity at 40 °C results were obtained for the bitumen-oil blends as AS 3568 includes specified limits for the viscosity at 40 °C of cutter oil, high flash point cutter and flux oil. Complex viscosity at 60 °C results were obtained for the bitumen-oil blends as both the Australian bitumen specification (AS 2008) and the Australian cutback bitumen specification (AS 2157) specify different binder grades in terms of viscosity at 60 °C results.

The effects of the use of different oils on C170 bitumen viscosity reduction were studied by comparing the complex viscosity results obtained at 40 °C and 60 °C for the bitumen-oil blends with neat oil viscosity, aniline point and aromatic content results. These comparisons were made to determine if correlations could be found between currently specified AS 3568 test properties and the rheological results obtained for the different bitumen-oil blends.

The effects of the use of different oils on the recommended cutter levels listed in Austroads (2005) were initially conducted by determining the complex viscosity of C170 bitumen/Jet A1 blends which were representative of each of the different recommended cutter levels listed in AP-T39-05. The results obtained for the C170 bitumen/Jet A1 blends were then compared with those obtained for blends which contained other oils to ascertain how much of each oil would be required to match the viscosity of a blend of C170 bitumen and a conventional cutter oil (i.e. Jet A1) at each of the recommended levels.

As the rheological tests conducted in the study focussed on using the DSR, and the Australian cutback bitumen specification (AS 2157) requires that dynamic viscosity at 60 °C tests be conducted on cutback binders using either a capillary viscometer (using AS/NZS 2341.2) or a rotational viscometer (using AS/NZS 2341.4), selected bitumen-oil blends which were subjected to DSR tests were also tested using a Brookfield viscometer and AS/NZS 2341.4. A comparison between the complex viscosity results obtained using the DSR and conventional rotational viscosity tests is included in Section 7.5.

7.1 DSR and Brookfield Viscosity Test Experimental Protocols

DSR tests were performed during the study using a TA Instruments Ltd. dynamic shear rheometer (Model AR1500ex) which was fitted with an upper heated plate (UHP) asphalt environment system (Model AS2000ex). The temperature during testing was controlled through the use of a combined UHP and Peltier plate manifold and a water-cooling system which included a Julabo refrigerated/heating circulator (Model FP35-HE). DSR tests were conducted on samples of each binder using 25 mm diameter upper and lower DSR test plates.

The bitumen-oil blends included in Section 7.3, Section 7.4 and Section 7.5 were prepared and reheated immediately prior to DSR or conventional dynamic (Brookfield) viscosity tests using the methods described in Section 5.1. Samples of C170 bitumen were reheated immediately prior to DSR and Brookfield viscosity tests using the oven method described in AS/NZS 2341.21. DSR tests were conducted on the C170 bitumen sample in duplicate, while a single sample of C170 bitumen was subjected to Brookfield viscosity tests. DSR and Brookfield viscosity tests were conducted using single samples of the other bitumen-oil blends.

DSR tests were performed by initially installing the upper and lower test plates in the DSR and heating them to 40 °C. A sufficient amount of heated binder was then applied to the lower test plate with a spatula and the gap between the upper and lower test plates was then reduced to 1.05 mm. Excess binder (which extended beyond the circumference of the plates) was then removed. The gap between the upper and lower DSR test plates was then reduced to 1.00 mm for testing. DSR tests were conducted on binder samples using test temperatures of 15, 20, 30, 40, 50, 60 and 65 °C. Binder samples were subjected to oscillation frequencies of 0.63, 1.00, 1.59, 2.51, 3.98, 6.31, 10.00, 15.85, 25.12, 39.81 and 63.09 rad/s at each test temperature.

The complex viscosity results included in Section 6.4, Section 7.3 and Section 7.5 correspond to the measured values of complex viscosity obtained at either 40 °C or 60 °C in DSR tests when an oscillation frequency of 1 rad/s was used during testing. Measured values of complex viscosity were used in these cases (rather than obtaining complex viscosity results through the use of a master-curve function (Section 7.2)) as each DSR test included measurements on samples at these two temperatures (i.e. 40 °C and 60 °C) and an oscillation frequency of 1 rad/s.

In the case of the complex viscosity results included in Section 7.4 it was necessary to obtain complex viscosity results for the bitumen-oil blends at various temperatures in the range between 22.5 and 45 °C which were not included in DSR tests. Complex viscosity results at these test temperatures were therefore interpolated from the results obtained in DSR tests by initially fitting the full set of test results obtained for each binder sample in DSR tests (i.e. results obtained at different test temperatures and frequencies) to a master-curve function. The values of the model-fitting parameters obtained from the master-curve analysis were then used to calculate complex viscosity results for the bitumen-oil blends at a variety of different test temperatures and an oscillation frequency of 1 rad/s.

Dynamic viscosity tests on bitumen-oil blends were conducted at either 40 °C or 60 °C using AS/NZS 2341.4 and a Brookfield model LVDV-II+P viscometer. These tests were conducted using either a Brookfield SC4-29 or a Brookfield SC4-31 spindle. Different spindles were used during dynamic viscosity tests to ensure that the torque level obtained during each Brookfield viscosity test was within the range recommended in AS/NZS 2341.4.

7.2 Master-curve Fitting of DSR Test Results

Master-curve fitting of the experimental data was conducted by fitting all complex modulus (G^* , in Pa) results that were obtained for a particular sample in a DSR test (i.e. those obtained at different test temperatures and oscillation frequencies) to Equation 3. This fitting allowed values of the five model fitting parameters (i.e. α , β , γ , δ , a and b) to be determined for a binder sample.

$$\log_{10}(G^*) = \delta + \frac{\alpha}{1 + e^{[\beta + \gamma[a(T-T_{ref})^2 + b(T-T_{ref}) + (\log_{10} f)]]}} \quad 3$$

where

G^* = calculated complex modulus result obtained by fitting all temperature and frequency results obtained for a particular binder sample (Pa)

$\alpha, \beta, \gamma, \delta, a, b$ = model fitting parameters

T = test temperature (°C)

T_{ref} = reference temperature for master-curve generation (°C), taken to be 40 °C

f = test oscillation frequency (rad/s)

Equation 3 was chosen to fit the DSR test data as it has the same mathematical form as the 'sigmoidal-model function' which is described in Austroads Test Method AGPT/T274 (Austroads 2016). This function is used in Austroads (2016) to produce flexural stiffness master-curves for asphalt beams which are derived from flexural stiffness results obtained for beams at various different temperatures and test frequencies.

The values of the model fitting parameters (i.e. α , β , γ , δ , a and b) were determined for each binder sample by fitting all DSR results to Equation 3 using the solver function in Microsoft Excel. The data was fitted so that the correlation coefficient (R^2) obtained for each fit was greater than 0.999. A reference temperature of 40 °C was used in all fits to the experimental data. Table B 1 lists the values of the model fitting parameters obtained for each of the bitumen-oil blends which were fitted to the master-curve model.

Complex viscosity results were determined at selected temperatures during the study by initially calculating the DSR complex modulus result obtained for the binder at the desired test temperature and frequency (i.e. 1 rad/s). Complex modulus results were calculated by substituting the fitted values of α , β , γ , δ , a and b and the desired test temperature and frequency into Equation 3. Complex modulus results (in Pa) were then converted into complex viscosity results (Pa s) by dividing the complex modulus result calculated for the binder by the relevant oscillation frequency (i.e. 1 rad/s).

7.3 Comparisons Between Bitumen-oil Blend Viscosity Results and Neat Oil Properties

Table 7.1 and Table 7.2 show the complex viscosity results obtained at 40 °C and 60 °C, respectively, for bitumen-oil blends which contained between 2% w/w and 12% w/w of each of the oils studied. These results correspond to those directly measured by the DSR at the two test temperatures using an oscillation frequency of 1 rad/s. The complex viscosity of the C170 bitumen sample used in the study was 5647 Pa s at 40 °C, and 202 Pa s at 60 °C, when DSR tests were performed using the same test conditions.

Table 7.1: Complex viscosity at 40 °C results obtained for bitumen-oil blends

Oil type	Blend complex viscosity at 40 °C and 1 rad/s (Pa s)				
	2% w/w oil	4% w/w oil	6% w/w oil	9% w/w oil	12% w/w oil
Jet A1	1565	512	202	60.2	20.9
High flash point cutter	1583	578	228	69.4	27.7
Diesel	1959	864	366	135	52.0
Mineral turpentine	1490	481	170	53.8	23.6
Enersol kerosene	1481	461	180	54.8	19.7
Enersol K	1586	581	236	72.3	28.0
Enersol HFK	1669	608	260	85.9	31.0

Table 7.2: Complex viscosity at 60 °C results obtained for bitumen-oil blends

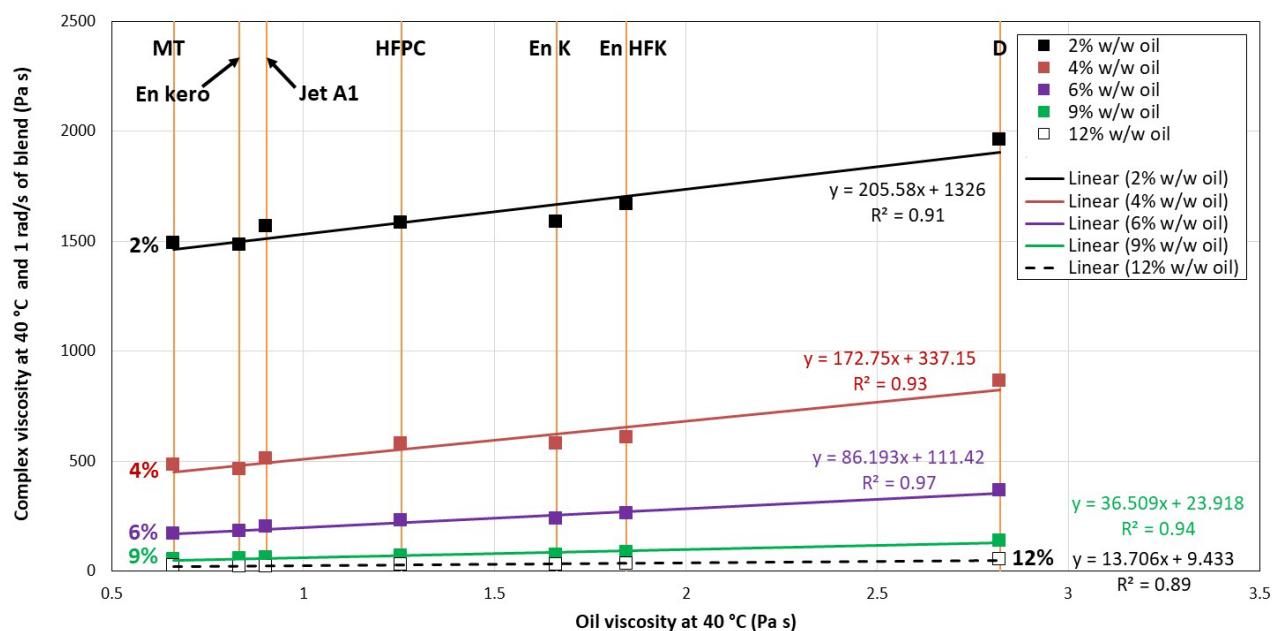
Oil type	Blend complex viscosity at 60 °C and 1 rad/s (Pa s)				
	2% w/w oil	4% w/w oil	6% w/w oil	9% w/w oil	12% w/w oil
Jet A1	85.8	37.7	18.5	7.77	3.69
High flash point cutter	86.5	39.8	21.3	8.65	4.61
Diesel	100	56.6	28.4	13.2	6.24
Mineral turpentine	83.5	35.8	16.8	7.45	3.39
Enersol kerosene	83.3	35.7	17.9	7.41	3.64
Enersol K	86.8	39.8	20.5	8.41	4.09
Enersol HFK	92.4	42.2	22.4	9.19	4.38

The results shown in Table 7.1 and Table 7.2 indicate that the complex viscosity of the blends decreased at both test temperatures as the concentration of each oil was increased. The change in complex viscosity results with oil concentration depended on the type of oil which was incorporated into the binder. Blends containing diesel showed higher viscosity results at 40 °C and 60 °C than other bitumen-oil blends when the results obtained at the same oil concentration and test temperature were compared.

The complex viscosity results obtained for the different bitumen-oil blends at both test temperatures were compared with the viscosity results obtained for each of the neat oils to ascertain if there was a correlation between the viscosity of the blends and neat oil viscosity when viscosity results for blends containing the same oil concentration were considered. Figure 7.1 shows plots of blend complex viscosity at 40 °C versus neat oil viscosity at 40 °C (from Table 4.2 and Table 4.3) for each of the five oil concentrations studied. The results associated with experiments conducted using blends containing different concentrations of oil have been shown as different types of datapoints in the figure. Vertical orange lines have also been included so that the oil type associated with each datapoint can be easily identified.

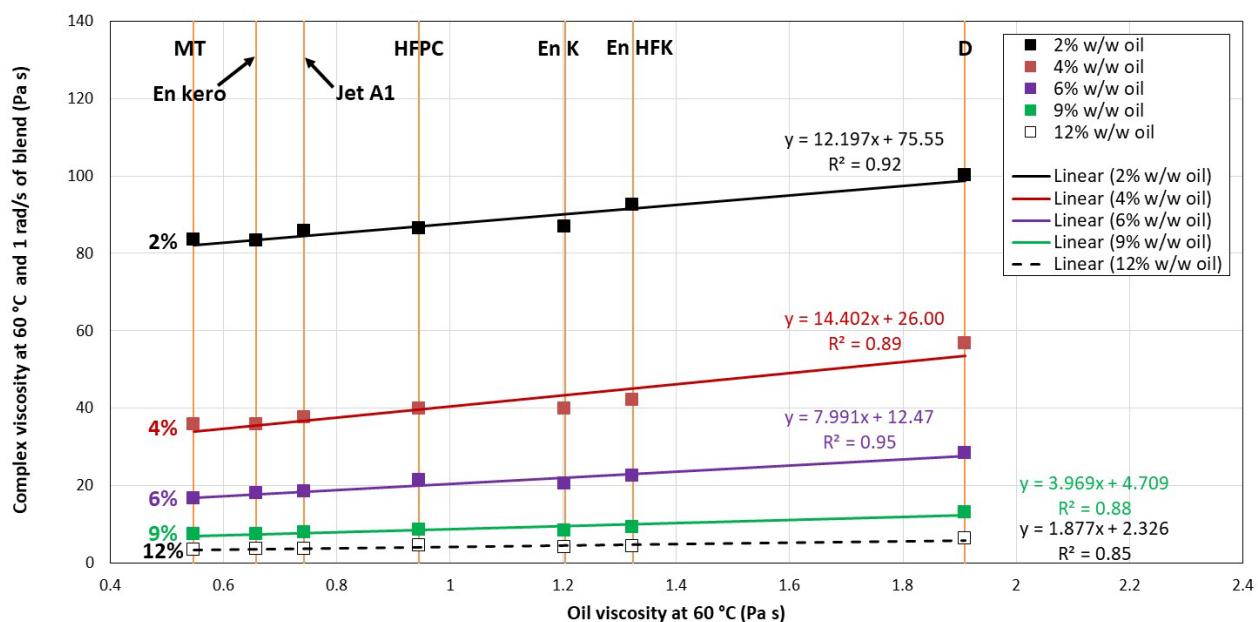
There appeared to be quite a good correlation between blend complex viscosity at 40 °C results and neat oil viscosity at 40 °C results when the results obtained at each different oil concentration were compared. Figure 7.1 includes linear fits to the experimental data obtained at each oil concentration as well as the equations and correlation coefficient (R^2) values obtained for each fit. The relatively high correlation coefficients obtained for the fits to the experimental data (≥ 0.89) indicated that there was a quite good correlation between complex viscosity results obtained for blends which contained the same concentration of oil, and the results of AS 3568-specified viscosity at 40 °C tests on each of the neat oils.

Figure 7.1: Blend complex viscosity at 40 °C results versus neat oil viscosity at 40 °C results for different bitumen-oil blends



Label key: MT = mineral turpentine, En kero = Enersol kerosene, HFFC = high flash point cutter, En K = Enersol K, En HFK = Enersol HFK, D = diesel.

Figure 7.2: Blend complex viscosity at 60 °C results versus neat oil viscosity at 60 °C results for different bitumen-oil blends



Label key: MT = mineral turpentine, En kero = Enersol kerosene, HFFC = high flash point cutter, En K = Enersol K, En HFK = Enersol HFK, D = diesel.

Figure 7.2 shows analogous comparisons between blend complex viscosity at 60 °C results and neat oil viscosity at 60 °C results (from Table 4.2 and Table 4.3) for each of the different oil concentrations studied. Quite good correlations were again seen between blend complex viscosity at 60 °C results and neat oil viscosity at 60 °C results at each oil concentration that was compared. The R² values obtained from linear fits to the experimental data obtained at each oil level were all ≥ 0.85.

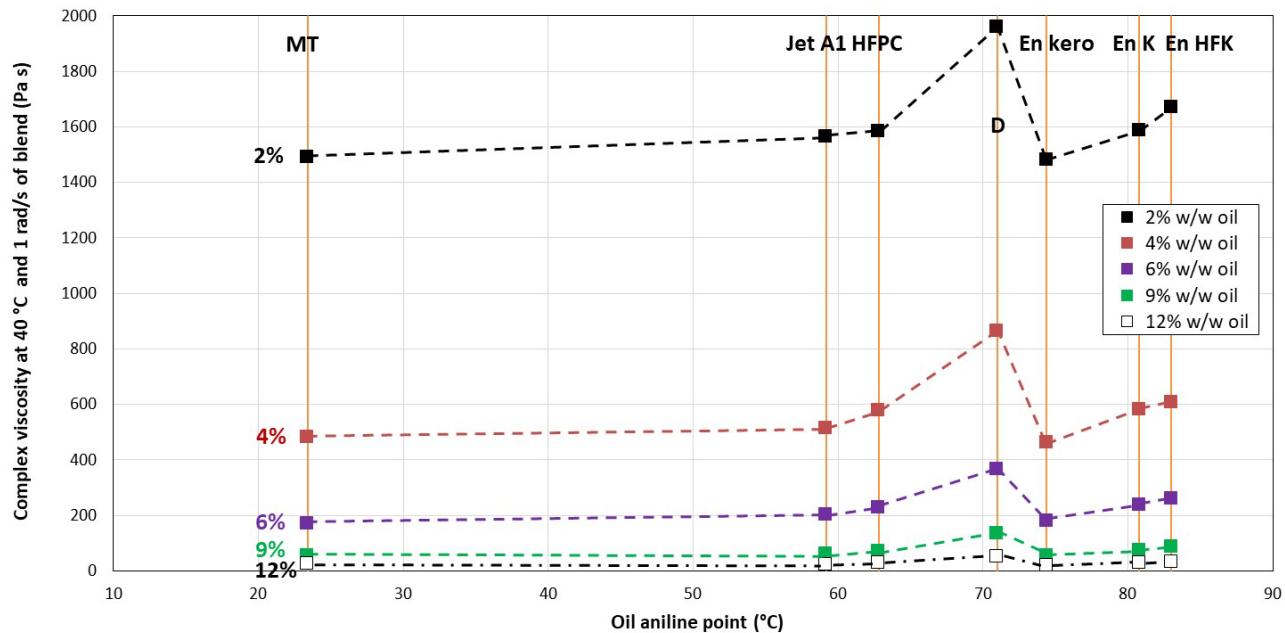
The results shown in Figure 7.1 and Figure 7.2 indicate that the complex viscosity of the bitumen-oil blends at each test temperature were affected by the concentration of oil in the blends and the viscosity of the neat oil at the same test temperature. These observations are consistent with typical viscosity blending models for general hydrocarbon mixtures (Centeno et al. 2011; Zhmud 2014) which estimate blend viscosity results based on the viscosities and relative amounts of the different components in a hydrocarbon blend.

The observed correlations between neat oil viscosity at 40 °C results and the complex viscosity at 40 °C results obtained for the different bitumen-oil blends (as shown in Figure 7.1) indicate that the results of AS 3568-specified viscosity at 40 °C tests give information about the ability of a particular oil to reduce the viscosity of C170 bitumen. Based on the results obtained in the study, the use of oils with lower viscosity at 40 °C results would be expected to produce bitumen-oil blends with lower viscosities than those obtained from oils with higher viscosity at 40 °C results if the same concentration by weight of each of the different oils was added to a sample of C170 bitumen.

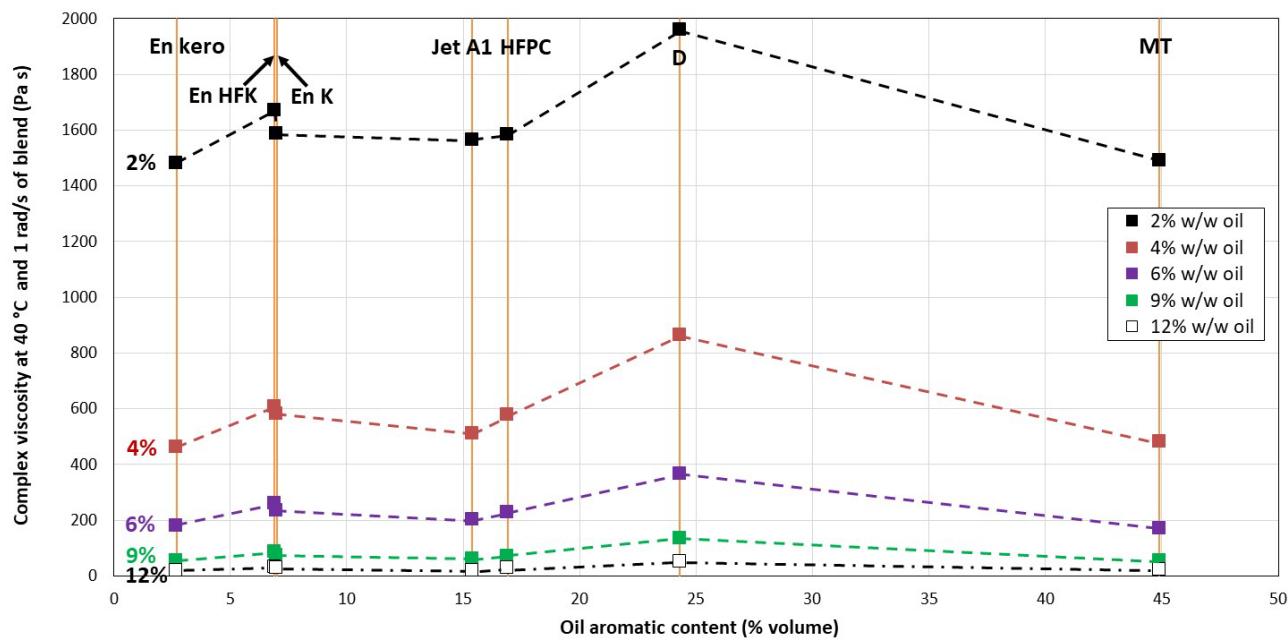
The complex viscosity results obtained for the bitumen-oil blends at each test temperature and oil concentration were also compared with AS 3568-specified aniline point and aromatic content results to determine whether the chemical properties of the neat oils affected their ability to reduce the viscosity of bitumen. No correlations were found between the viscosity results obtained at any particular oil concentration and test temperature and the results of AS 3568-specified chemical tests. This implies that the results in AS 3568-specified aniline point and aromatic content tests do not appear to provide information about the effectiveness of a tested oil to reduce the viscosity of C170 bitumen.

Figure 7.3 and Figure 7.4 show illustrative results where blend complex viscosity at 40 °C results were compared with neat oil aniline point and aromatic content results, respectively, at each of the five different oil concentrations studied. As in the case of Figure 7.1 and Figure 7.2, the results associated with experiments conducted using blends containing different concentrations of oil have been shown as different types of datapoints in these figures. These datapoints also have been joined by dashed lines so it is easier to compare the viscosity results obtained at each oil concentration with neat oil chemical properties. Vertical lines have also been included in Figure 7.3 and Figure 7.4 so that the oil type associated with each datapoint can be easily identified.

The results shown in Figure 7.3 and Figure 7.4 show that there was not a general trend between complex viscosity at 40 °C results and the chemical properties of the neat oils when blends containing the same concentration of oil were compared. This is particularly the case for blends which contained diesel which showed the highest viscosity at 40 °C results of all the bitumen-oil blends studied but diesel had the fourth-highest aniline content result and the sixth-highest aromatic content in terms of neat oil chemical properties. Although samples of mineral turpentine and Enersol kerosene showed very different results in aniline point and aromatic content tests, the complex viscosity at 40 °C results obtained for blends containing these two oils were overall quite similar.

Figure 7.3: Blend complex viscosity at 40 °C results versus neat oil aniline point for different bitumen-oil blends

Label key: MT = mineral turpentine, En kero = Enersol kerosene, HFPC = high flash point cutter, En K = Enersol K, En HFK = Enersol HFK, D = diesel.

Figure 7.4: Blend complex viscosity at 40 °C results versus neat oil aromatic content for different bitumen-oil blends

Label key: MT = mineral turpentine, En kero = Enersol kerosene, HFPC = high flash point cutter, En K = Enersol K, En HFK = Enersol HFK, D = diesel.

7.4 Effects of the Use of Different Oils on AP-T39-05 Recommended Cutter Levels

Austroads document AP-T39-05 (Austroads 2005) lists recommended cutter levels to be used during sprayed seal construction in terms of parts of cutter in the binder instead of %w/w. Recommended cutter levels depend on the pavement temperature during construction, the expected traffic volume on the seal, and the size of the aggregate used to construct the seal. Table 7.3 lists the recommended cutter levels for seals constructed using C170 bitumen. The mean temperature associated with each pavement temperature range included in AP-T39-05 has also been included in the table as these temperatures were used in the viscosity calculations which are described below.

The effects of the use of different oils on the recommended cutter levels in AP-T39-05 were determined by initially using the results obtained in DSR tests utilising the sample of C170 bitumen, and all bitumen-oil blends which contained Jet A1, to determine complex viscosity results at 1 rad/s for bitumen-Jet A1 blends at each of the mean pavement temperatures and recommended cutter levels listed in Table 7.3 (e.g. for a pavement temperature range of 20–25 °C, complex viscosity results were obtained for bitumen-Jet A1 blends at 22.5 °C for blends which contained 4, 6, 8 and 10 parts Jet A1). This analysis yielded a set of complex viscosity results which were relevant to the recommended levels listed in AP-T39-05 when the representative sample of cutter oil used in this study was blended with C170 bitumen.

Table 7.3: AP-T39-05 recommended cutter levels for C170 bitumen

Pavement temperature range (°C)	Mean pavement temperature used in equivalent oil level calculations (°C)	Traffic volume (v/l/d)	Recommended cutter level for 10 mm or larger aggregate (parts)	Recommended cutter level for 7 mm or smaller aggregate (parts)
20–25	22.5	< 100	8	10
		100–1500	6	8
		> 1500	4	6
26–32	29.0	< 100	6	8
		100–1500	4	6
		> 1500	2	4
33–38	35.5	< 100	4	6
		100–1500	2	4
		> 1500	0	2
39–45	42.0	< 100	2	4
		100–1500	0	2
		> 1500	0	0
> 45	45.0	< 100	0	2
		100–1500	0	0
		> 1500	0	0

Note: v/l/d = vehicles per lane per day.

Source: Austroads (2005).

The DSR results obtained for other bitumen-oil blends were then used to determine the concentration of other oils (in parts) which would be required to be added to C170 bitumen to match the viscosity of the bitumen-Jet A1 blends at each mean pavement temperature and recommended cutter level listed in Table 7.3. This provided information about the concentration of oil (in parts) which would be needed to reduce the viscosity of bitumen by the same amount as when a conventional cutter was used when different types of oils were used during sprayed seal construction.

7.4.1 Complex Viscosity Results Obtained for C170 Bitumen-Jet A1 Blends at AP-T39-05 Recommended Levels

Complex viscosity results relevant to the recommended cutter levels listed in AP-T39-05 were determined by initially calculating the complex viscosity at 1 rad/s results obtained for the sample of C170 bitumen and all samples which contained Jet A1 at each of the five mean pavement temperatures listed in Table 7.3. Complex viscosity results included in Section 7.4 were determined using the master-curve model fitting parameters obtained for each sample and Equation 3 as DSR tests were not actually performed at these mean pavement temperatures. Figure 7.5 shows plots of $\log_{10}(\text{complex viscosity})$ results versus the concentration (in parts) of Jet A1 in each of the blends for the five mean pavement temperatures listed in Table 7.3. Jet A1 concentrations in terms of parts of oil were determined for each of the samples subjected to DSR tests using Equation 1. The oil concentration and complex viscosity results which were used to generate the plots shown in Figure 7.5 are included in Table B 2.

Figure 7.5: Complex viscosity results obtained for C170-Jet A1 blends at different mean pavement temperatures

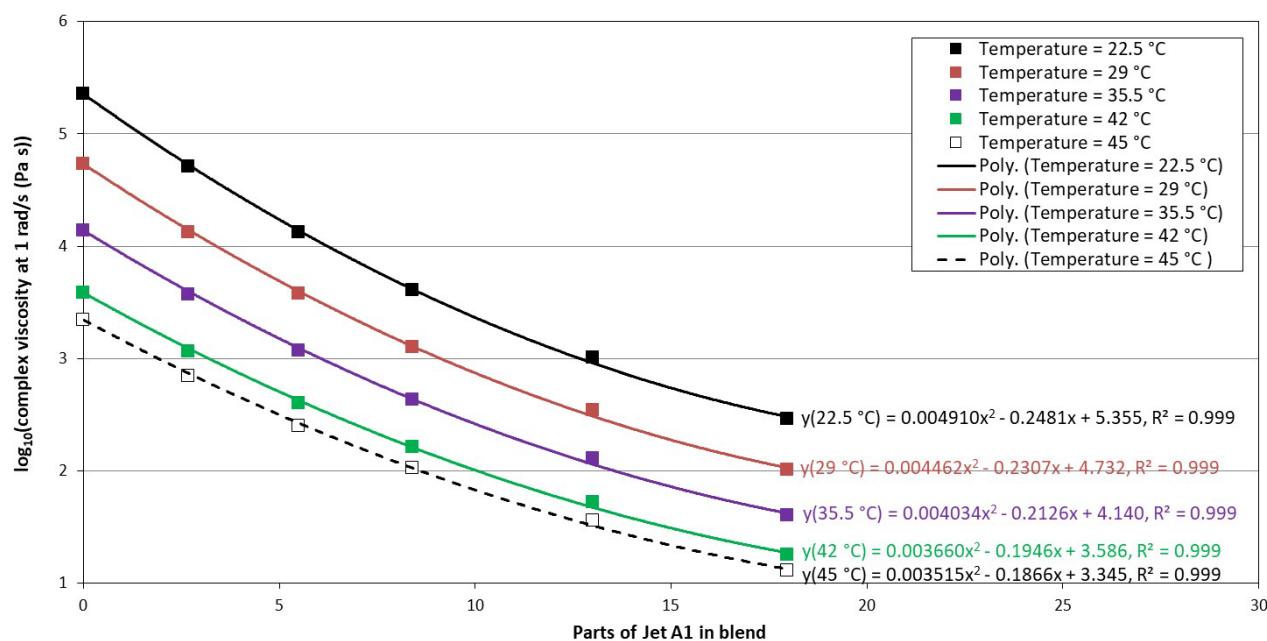


Figure 7.5 also includes fits to the sets of data obtained at each mean pavement temperature which were used to obtain complex viscosity results at each of the recommended cutter levels/mean pavement temperatures listed in Table 7.3 and the values of R^2 obtained from the fits. These fits were obtained by fitting the $\log_{10}(\text{complex viscosity})$ versus oil concentration results obtained at each mean pavement temperature to a second-order polynomial function (i.e. $\log_{10}(\text{complex viscosity}) = ax^2 + bx + c$). The value of c in the fits to the experimental data were set to the $\log_{10}(\text{complex viscosity})$ result obtained for the C170 bitumen sample at each mean pavement temperature as this yielded significantly better fits to each set of experimental data.

Complex viscosity results that were associated with the different cutter levels recommended at each mean pavement temperature were determined by substituting the appropriate Jet A1 concentrations in the relevant equation which was determined at each pavement temperature. For example, complex viscosity results at a mean pavement temperature of 22.5 °C and recommended cutter levels of 4, 6, 8 and 10 parts were determined by substituting values of 4, 6, 8 and 10 parts into the uppermost equation shown in Figure 7.5.

Table 7.4 shows the complex viscosity results which were obtained for bitumen-Jet A1 blends at each of the different mean pavement temperatures/recommended cutter levels listed in Table 7.3. The complex viscosity results obtained for these blends appeared to show a fair degree of variation (i.e. they varied between 734 and 27 616 Pa s) when the results obtained at different mean pavement temperatures and recommended cutter levels were compared. These results appear to indicate that the recommended cutter levels included in AP-T39-05 are not based on the premise that a binder needs to have a viscosity lower than a certain specific level (as proposed by Maccarrone et al. (1997)) for it to effectively wet and then adhere to aggregates in a sprayed seal.

The complex viscosity results included in Table 7.4, however, appear to be broadly consistent with early studies by Dickinson (1961, 1984) who observed that binders which contained cutter needed to have lower viscosities at the pavement temperature, than binders which did not contain cutter, in order for effective aggregate wetting and aggregate adhesion to occur when sprayed seals were constructed. The complex viscosity results obtained at higher recommended cutter levels in this study were all lower than those obtained at lower recommended cutter levels for each pavement temperature range included in AP-T39-05.

Table 7.4: Complex viscosity results obtained for C170 bitumen-Jet A1 blends corresponding to each of the recommended cutter levels listed in AP-T39-05

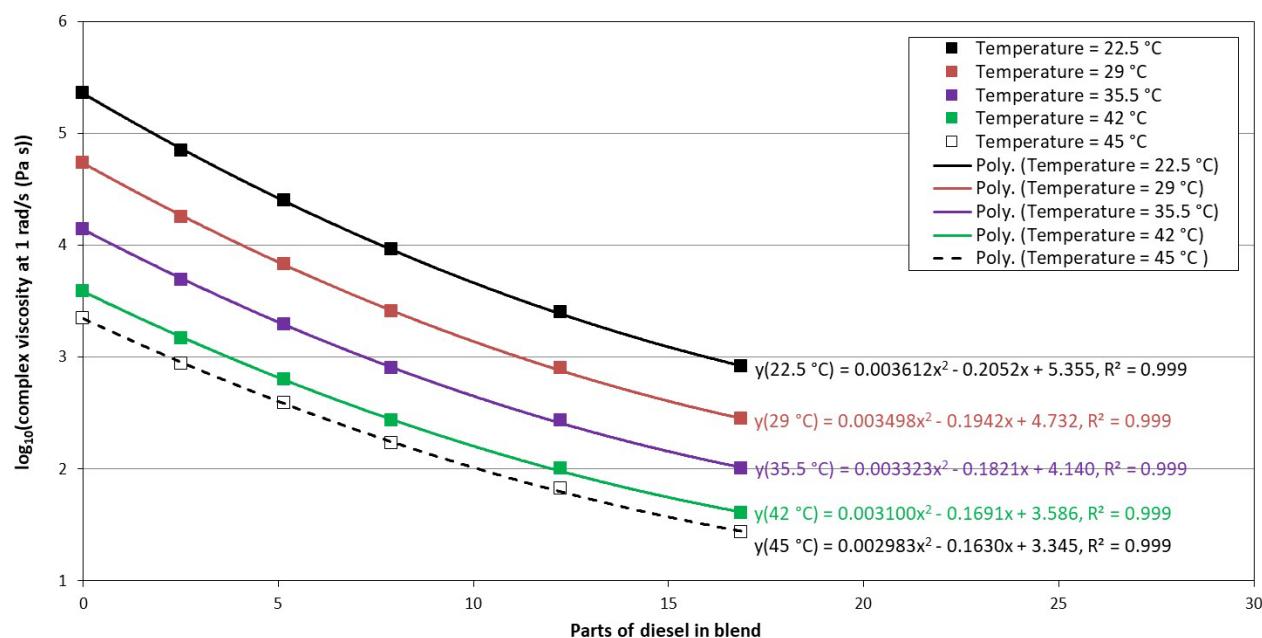
AP-T39-05 pavement temperature range (°C)	Mean pavement temperature used in equivalent oil level calculations (°C)	AP-T39-05 recommended cutter level (parts)	Complex viscosity at 1 rad/s result obtained for C170 bitumen-Jet A1 blend at recommended cutter level (Pa s)
20–25	22.5	10	2 316
		8	4 833
		6	11 043
		4	27 616
26–32	29.0	8	1 486
		6	3 225
		4	7 598
		2	19 439
33–38	35.5	6	1 022
		4	2 260
		2	5 381
		0	13 803
39–45	42.0	4	734
		2	1 626
		0	3 853
> 45	45.0	2	967
		0	2 212

7.4.2 Matched Complex Viscosity Results for Other C170 Bitumen-oil Blends

After complex viscosity results were obtained for the bitumen-Jet A1 blends at each of the recommended cutter levels and mean pavement temperatures listed in Table 7.3, DSR results obtained for the other bitumen-oil blends were analysed in the same way as described above to produce $\log_{10}(\text{complex viscosity})$ versus parts of oil plots for the other six oil types studied at each of five mean pavement temperatures. These results were then fitted to a second-order polynomial function so that the concentration of other oils required to match the complex viscosity results obtained for bitumen-Jet A1 blends could be determined at each AP-T39-05 recommended cutter level. The value of c in the second-order polynomial fits to the $\log_{10}(\text{complex viscosity})$ versus oil concentration data was again taken to be the $\log_{10}(\text{complex viscosity})$ result obtained for the C170 bitumen sample at each mean pavement temperature as this yielded significantly better fits to the experimental data.

Figure 7.6 shows an illustrative example of the plots obtained when the DSR results obtained for different types of bitumen-diesel blends were subjected to the same method of data analysis as had been performed for the bitumen-Jet A1 blends. The oil concentration and complex viscosity results which were used to generate $\log_{10}(\text{complex viscosity})$ versus 'parts of oil' plots for all bitumen-oil blends that were subjected to DSR tests are included in Table B 2. Figure 7.6 additionally shows the fits to the results obtained for the different bitumen-diesel blends when the data obtained at each mean pavement temperature was fitted to a second-order polynomial function. The equations and R^2 values obtained from each fit are also included in Figure 7.6. The values of the fitted parameters which were obtained when the DSR results for other bitumen-oil blends were analysed in the same way are included in Table B 3.

Figure 7.6: Complex viscosity results obtained for C170-diesel blends at different mean pavement temperatures



Equivalent oil levels which were needed to match the viscosity of bitumen-Jet A1 blends were determined by substituting the complex viscosity result obtained for a bitumen-Jet A1 blend (e.g. 2316 Pa s for a mean pavement temperature of 22.5 °C and recommended cutter level of 10 parts) into the fitted equation obtained for the selected bitumen-oil blend which was determined at the same mean pavement temperature. This equation was then solved analytically to determine the amounts of other oils which would be needed to produce the same complex viscosity result as a bitumen-Jet A1 blend for each of the recommended cutter levels and mean pavement temperatures included in Table 7.4. For example, for a mean pavement temperature of 22.5 °C and recommended cutter level of 10 parts, substitution of $\log_{10}(2316 \text{ Pa s}) = 3.347$ as the y-value in the uppermost equation included in Figure 7.6 indicated that 12.41 parts of diesel would need to be added to C170 bitumen to achieve the same complex viscosity result at 22.5 °C as a comparable blend which contained 10 parts Jet A1 (i.e. the diesel concentration would need to be 124% of that of the Jet A1 blend in order to have a comparable complex viscosity).

Table 7.5 lists the concentrations of each of the six oils which would need to be added to C170 bitumen in order to match the complex viscosity results obtained for the bitumen-Jet A1 blends at each mean pavement temperature and recommended cutter level included in Table 7.4. The values in brackets in the table correspond to the percentage amounts of each oil required to give the same complex viscosity results. The percentage results obtained for each type of oil were overall quite similar if the results obtained at different mean pavement temperatures and recommended cutter levels were considered. Due to this similarity, Table 7.5 lists the mean percentage results which were obtained for each oil. These were obtained by averaging the numbers in brackets in Table 7.5 for each oil type.

The results shown in Table 7.5 appear to indicate that if mineral turpentine was used to reduce the viscosity of C170 bitumen during sprayed seal construction then on average 91% of the amount listed in AP-T39-05 would be needed to be added to give the same amount of viscosity reduction as a conventional cutter oil. High flash point cutter or Enersol kerosene would on average be expected to produce a viscosity reduction comparable to that of conventional cutter oil if AP-T39-05 recommended cutter levels were used during the construction of sprayed seals. The use of Enersol K, Enersol HFK or diesel would require the use of cutter oil levels which were on average 5%, 11% or 20%, respectively, higher than AP-T39-05 levels in order to match the viscosity reduction observed with a conventional cutter oil.

Information from the field indicates that cutter oil can be added to a sprayer to an accuracy which is generally within the order of about ±10% of the desired level. If this level of accuracy is considered, then all oils except diesel would be expected to produce a satisfactory level of C170 bitumen viscosity reduction if AP-T39-05 recommended levels were used during sprayed seal construction. In the case of diesel, of the order of 20% more diesel would need to be added to the sprayer than AP-T39-05 levels in order for the oil to produce the same viscosity reduction as a conventional cutter oil.

Table 7.5: Oil concentrations required to match the complex viscosity of C170 bitumen-Jet A1 blends for different AP-T39-05 recommended cutter levels

Mean pavement temperature used in equivalent oil level calculations (°C)	AP-T39-05 recommended cutter level (parts)	Equivalent oil concentration needed to match the complex viscosity of C170 bitumen-Jet A1 blend (parts)					
		High flash point cutter	Diesel	Mineral turpentine	Enersol kerosene	Enersol K	Enersol HFK
22.5	10	10.49 (105%)	12.41 (124%)	9.32 (93%)	10.34 (103%)	10.82 (108%)	11.32 (113%)
	8	8.40 (105%)	9.85 (123%)	7.33 (92%)	8.22 (103%)	8.69 (109%)	9.09 (114%)
	6	6.30 (105%)	7.34 (122%)	5.42 (90%)	6.14 (102%)	6.53 (109%)	6.84 (114%)
	4	4.20 (105%)	4.87 (122%)	3.58 (90%)	4.08 (102%)	4.37 (109%)	4.57 (114%)
29.0	8	8.27 (103%)	9.74 (122%)	7.36 (92%)	8.10 (101%)	8.54 (107%)	8.95 (112%)
	6	6.20 (103%)	7.25 (121%)	5.45 (91%)	6.05 (101%)	6.41 (107%)	6.72 (112%)
	4	4.13 (103%)	4.80 (120%)	3.60 (90%)	4.02 (101%)	4.27 (107%)	4.48 (112%)
	2	2.06 (103%)	2.39 (120%)	1.79 (90%)	2.01 (101%)	2.13 (107%)	2.24 (112%)
35.5	6	6.09 (102%)	7.14 (119%)	5.48 (91%)	5.96 (99%)	6.26 (104%)	6.57 (110%)
	4	4.05 (101%)	4.72 (118%)	3.62 (91%)	3.96 (99%)	4.17 (104%)	4.37 (109%)
	2	2.02 (101%)	2.35 (118%)	1.80 (90%)	1.98 (99%)	2.08 (104%)	2.18 (109%)
	0	0	0	0	0	0	0
42.0	4	3.98 (100%)	4.65 (116%)	3.65 (91%)	3.91 (98%)	4.07 (102%)	4.26 (107%)
	2	1.98 (99%)	2.31 (116%)	1.82 (91%)	1.95 (98%)	2.03 (102%)	2.13 (107%)
	0	0	0	0	0	0	0
45.0	2	1.97 (99%)	2.30 (115%)	1.83 (92%)	1.94 (97%)	2.01 (101%)	2.10 (105%)
	0	0	0	0	0	0	0
Mean percentage result obtained for oil		102%	120%	91%	100%	105%	111%

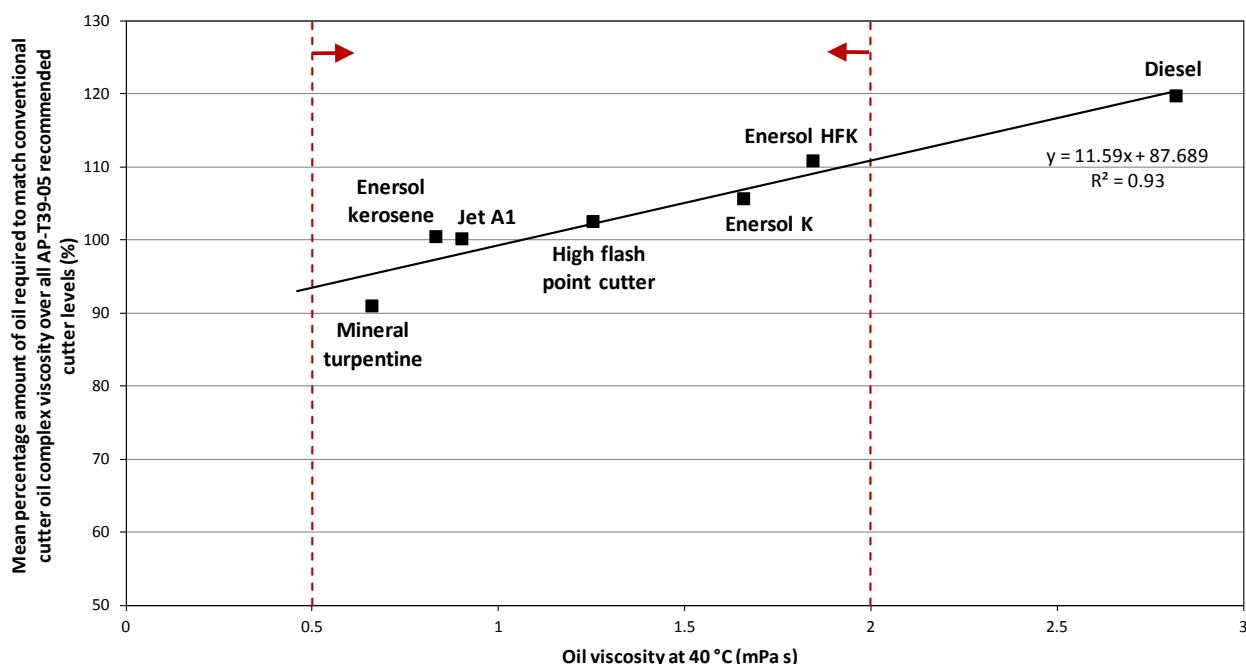
Note: Values in brackets correspond to the percentage amount of oil required to be added to C170 bitumen to match the complex viscosity result obtained for a C170 bitumen-Jet A1 blend.

7.4.3 AS 3568 Specification Implications

The current version of AS 3568 (Table 2.1) includes a viscosity at 40 °C specification limit of 2.0 mPa s maximum, for cutter oil and high flash point cutter which is intended to ensure that the viscosity of a blend of oil and binder is in the appropriate viscosity range for effective sprayed sealing (Section 2.1.1). The mean percentage results obtained for each oil (as shown in Table 7.5) were compared to the viscosity at 40 °C results obtained for each neat oil (from Table 4.2 and Table 4.3) to ascertain if AS 3568-specified viscosity results could be used to provide information about whether AP-T39-05 recommended cutter levels would be suitable for use during sprayed seal construction.

Figure 7.7 shows a plot of the mean percentage of oil that was required to match the complex viscosity results obtained for bitumen-Jet A1 blends over all AP-T39-05 recommended cutter levels against the viscosity at 40 °C (in mPa s) of each oil. The different types of oils corresponding to each datapoint have been labelled in the figure for easy reference. As blends containing Jet A1 were considered to represent blends of C170 bitumen and a conventional cutter oil, the mean percentage result obtained for Jet A1 blends is 100% in Figure 7.7.

Figure 7.7: Mean percentage of oil required to match the complex viscosity of a conventional cutter oil over all AP-T39-05 recommended cutter levels versus the viscosity at 40 °C of the neat oil (in mPa s)

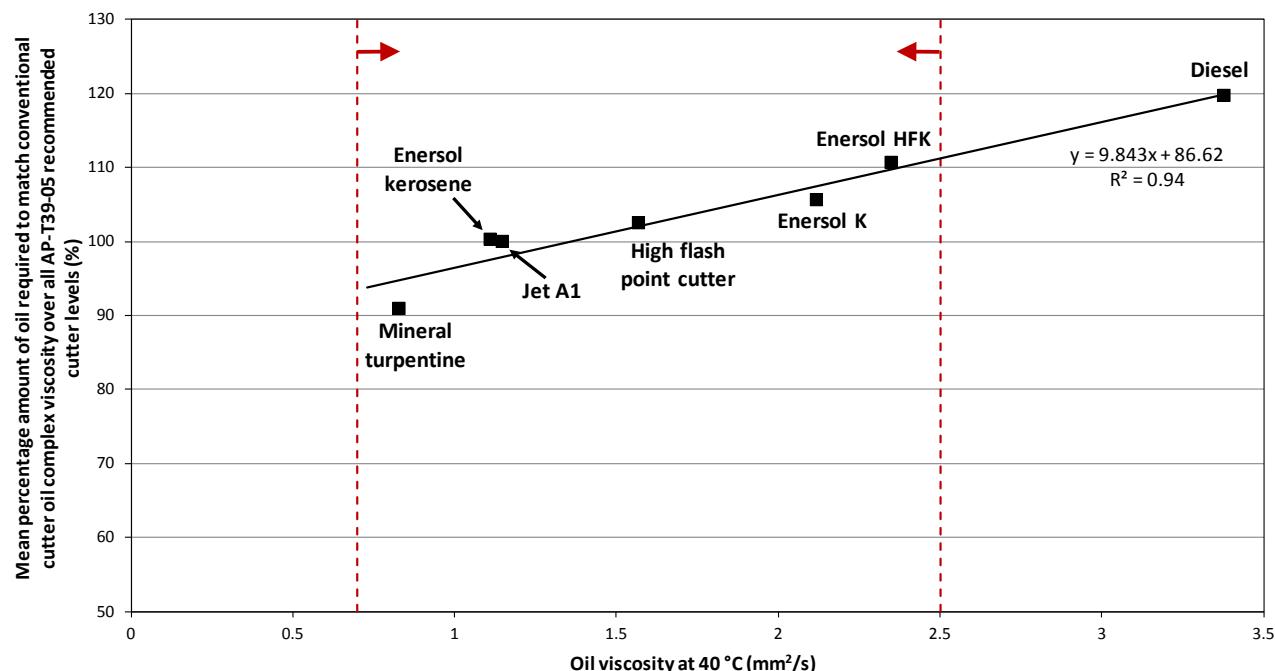


The results shown in Figure 7.7 indicate that there was a very good linear relationship ($R^2 = 0.93$) between oil viscosity at 40 °C results and the mean percentage amounts needed for each of the oils to yield the same complex viscosity results as blends that contained Jet A1 over all AP-T39-05 recommended cutter levels. This result appears to indicate that neat oil viscosity at 40 °C test results provide information about the average amount of a tested oil which is required to be added to C170 bitumen to give the same amount of complex viscosity reduction as a conventional cutter oil (i.e. Jet A1).

Based on this result, and considering that cutters can be added to a sprayer to within the order of about $\pm 10\%$ of the desired level (Section 7.4.2), it appears that neat oils with viscosities of between 0.5 and 2.0 mPa s would produce a satisfactory level of C170 bitumen viscosity reduction if AP-T39-05 recommended levels were used during sprayed seal construction. The results of this study therefore suggest that the viscosity at 40 °C requirements in AS 3568 for cutter oil and high flash point could be changed from a maximum limit of 2.0 mPa s to a range of 0.5 to 2.0 mPa s. These proposed lower and upper limits are shown as red dashed lines and red arrows in Figure 7.7. Including a lower viscosity at 40 °C requirement in AS 3568 would limit the use of very low viscosity oils during sprayed seal construction.

It was noted in Section 2.1.2 that the South Australian specification for high flash point cutter, and the Western Australian specifications for cutter and flux oils, include viscosity at 40 °C limits in terms of kinematic viscosity units (i.e. mm²/s) rather than dynamic viscosity units (i.e. mPa s). Figure 7.8 shows an analogous plot to Figure 7.7 where neat oil viscosity results (from Table 4.2 and Table 4.3) have been plotted on the x-axis in kinematic viscosity units (i.e. mm²/s).

Figure 7.8: Mean percentage of oil required to match the complex viscosity of a conventional cutter oil over all AP-T39-05 recommended cutter levels versus the viscosity at 40 °C of the neat oil (in mm²/s)



A very good linear correlation ($R^2 = 0.94$) was also found between oil kinematic viscosity results and the mean percentage amounts needed for each of the oils to yield the same complex viscosity results as blends that contained Jet A1 over all AP-T39-05 recommended cutter levels. If cutters can be added to a sprayer to an accuracy of about $\pm 10\%$, then oils with kinematic viscosity at 40 °C results between 0.7 and 2.5 mm²/s appear to be able to produce a satisfactory level of C170 bitumen viscosity reduction if AP-T39-05 recommended levels are used during sprayed seal construction. These kinematic viscosity limits are shown as red dashed lines and red arrows in Figure 7.8.

Including viscosity at 40 °C limits of either 0.5 to 2.0 mPa s or 0.7 to 2.5 mm²/s in an updated version of AS 3568 would allow the results of ASTM D445 tests on samples of neat oils to be expressed in either dynamic or kinematic viscosity units. This would allow for the difference in viscosity at 40 °C reporting requirements currently specified by different Australian jurisdictions.

7.5 Comparisons Between DSR Complex Viscosity and Brookfield Viscosity Results

The complex viscosity results obtained for the bitumen-oil blends in DSR tests were compared with those obtained in conventional rotational viscosity tests by conducting Brookfield viscosity tests at either 40 °C or 60 °C on blends which were expected to yield conventional viscosity results in the range that could be measured using either a Brookfield SC4-29 or a Brookfield SC4-31 spindle. As the lowest rotational speed available on the Brookfield viscometer used in the study was 0.3 rpm, the maximum viscosity that could be measured with the SC4-31 spindle was 100 Pa s, while the maximum viscosity that could be measured with the SC4-29 spindle was 312 Pa s.

Due to the viscosity constraints associated with the Brookfield spindles, Brookfield viscosity tests were conducted at 40 °C on blends which contained 6, 9 and 12% w/w of each of the oils, except diesel. Brookfield viscosity tests were only conducted on bitumen-diesel blends which contained 9 and 12% w/w diesel as the viscosity of blend containing 6% w/w diesel was expected to have a viscosity higher than could be measured by a SC4-29 spindle based on the complex viscosity result obtained for this sample in DSR tests (366 Pa s, Table 7.1). Brookfield viscosity tests were performed at 60 °C on all blends which were subjected to DSR tests as the most viscous binder (i.e. C170 bitumen) yielded a complex viscosity result at 60 °C of 202 Pa s (Section 7.3).

Table 7.6 shows the Brookfield viscosity results which were obtained at 40 °C for blends that could be effectively measured using Brookfield spindles SC4-29 or SC4-31. The Brookfield viscosity at 60 °C results that were obtained for all blends subjected to DSR tests are included in Table 7.7. Information about the type of spindle used in each test is also included in the tables.

Table 7.6: Brookfield viscosity at 40 °C results obtained for selected bitumen-oil blends

Oil type	Blend dynamic viscosity at 40 °C (Pa s)		
	6% w/w oil	9% w/w oil	12% w/w oil
Jet A1	197 ⁽¹⁾	52.7	18.2
High flash point cutter	221 ⁽¹⁾	67.0	24.2
Diesel	—	128 ⁽¹⁾	49.5
Mineral turpentine	157 ⁽¹⁾	42.6	13.8
Enersol kerosene	162 ⁽¹⁾	46.2	15.8
Enersol K	233 ⁽¹⁾	72.9	26.8
Enersol HFK	248 ⁽¹⁾	77.5	29.4

¹ Binder samples tested using a Brookfield SC4-29 spindle. Other binders were tested using a Brookfield SC4-31 spindle.

Table 7.7: Brookfield viscosity at 60 °C results obtained for bitumen-oil blends

Oil type	Blend dynamic viscosity at 60 °C (Pa s)					
	0% w/w oil	2% w/w oil	4% w/w oil	6% w/w oil	9% w/w oil	12% w/w oil
C170 bitumen	204 ⁽¹⁾	—	—	—	—	—
Jet A1	—	80.4	35.8	16.9	6.41	2.87
High flash point cutter	—	86.9	39.1	19.2	7.92	3.57
Diesel	—	96.8	50.8	27.4	12.7	6.31
Mineral turpentine	—	80.6	31.5	13.8	5.43	2.28
Enersol kerosene	—	81.6	31.8	15.4	6.07	2.51
Enersol K	—	87.9	39.5	20.3	8.59	3.96
Enersol HFK	—	88.3	40.8	21.0	9.13	4.36

¹ The C170 bitumen sample was tested using a Brookfield SC4-29 spindle. Other binders were tested using a Brookfield SC4-31 spindle.

The complex viscosity results which were directly measured in DSR tests at either 40 °C and 60 °C, and an oscillation frequency of 1 rad/s, were compared to those obtained for the same samples at the same test temperature in Brookfield viscosity tests in order to determine if a correlation existed between DSR results and conventional rotational viscosity test results. Figure 7.9 shows a plot of DSR complex viscosity results versus Brookfield viscosity results for both test temperatures which were investigated. The results associated with experiments conducted at each test temperature have been shown as different types of datapoints.

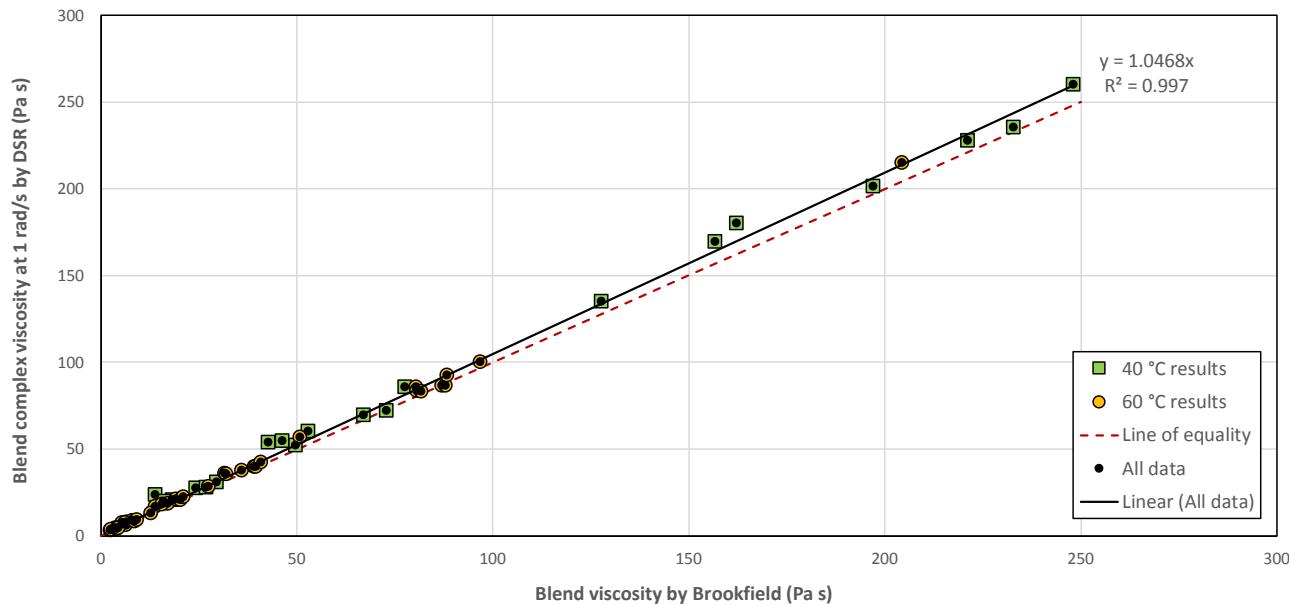
Figure 7.9: Complex viscosity by DSR versus viscosity by Brookfield viscometer for various bitumen-oil blends

Figure 7.9 includes a dashed red line which corresponds to the case where the results obtained in both tests are the same as well as a linear fit to the experimental data which was obtained at both test temperatures and the value of R^2 obtained from the fit. The complex viscosity results obtained in DSR tests were on average slightly higher than those obtained in Brookfield viscosity tests. The linear fit to the experimental data (with the y-intercept of the fit set to zero) indicated that DSR complex viscosity results were on average about 5% higher than those obtained in Brookfield viscosity tests.

Even though the actual viscosity results obtained by the two methods differed slightly, the R^2 value obtained from the fit (0.997) indicated that there was an excellent correlation between DSR complex viscosity and conventional Brookfield viscosity results for blends which had Brookfield viscosity results between 2 and 248 Pa s.

The viscosity at 60 °C of the sample of C170 bitumen was determined by three different methods during the study (i.e. AS/NZS 2341.2 (Table 4.1), AS/NZS 2341.4 (Table 7.7) and DSR complex viscosity tests (Section 7.3)). The results of these tests yielded viscosity at 60 °C results of 192 Pa s, 204 Pa s and 202 Pa s, respectively. All three results were within the repeatability requirements of AS/NZS 2341.2 and AS/NZS 2341.4 as the difference between the lowest and highest values was less than 7% of the mean value obtained in all three tests.

7.6 Summary

The effects of the use of different oils during sprayed seal construction on C170 bitumen viscosity reduction and the recommended cutter levels listed in AP-T39-05 were investigated by measuring the complex viscosity of blends containing between 0 and 12% w/w of each oil using a DSR at various test temperatures. Good correlations were found between viscosity at 40 °C and 60 °C results obtained for each of the neat oils and complex viscosity results obtained for blends which contained the same concentration of oil at the two test temperatures. These results indicated that AS 3568-specified viscosity at 40 °C tests can be used to provide information about the ability of a sample of tested oil to reduce the viscosity of C170 bitumen.

No correlation was found between the results of AS 3568-specified aniline point or aromatic content tests and the degree of viscosity reduction observed for the bitumen-oil blends at any of the test temperatures or oil concentrations where results were compared. These results indicated that AS 3568-specified chemical tests do not provide information about the ability of a tested oil to reduce the viscosity of C170 bitumen.

An investigation into the effects of the use of different oils on the recommended cutter levels listed in AP-T39-05 indicated that the results of AS 3568-specified viscosity at 40 °C tests could be used to provide information about the average amount of oil which would need to be added to bitumen to give a comparable viscosity reduction to a blend containing C170 bitumen and a conventional cutter oil (i.e. Jet A1). Oils which had higher viscosity at 40 °C results overall needed to be added to C170 bitumen at higher concentrations than those with lower viscosity at 40 °C results in order to achieve the same amount of viscosity reduction as C170 bitumen-Jet A1 blends when all recommended cutter levels in AP-T39-05 were considered. As cutters can be added to a sprayer within the order of about $\pm 10\%$ of the intended level, oils with viscosity at 40 °C results in the range between either 0.5 to 2.0 mPa s, or 0.7 to 2.5 mm²/s, appear to be able to produce a satisfactory level of C170 bitumen viscosity reduction if AP-T39-05 recommended levels are used during sprayed seal construction. The current viscosity at 40 °C specification limit in AS 3568 is 2.0 mPa s maximum.

An excellent correlation was found between conventional Brookfield viscosity results and DSR complex viscosity results measured using an oscillation frequency of 1 rad/s for blends which had Brookfield viscosity results between 2 and 248 Pa s. The results obtained in DSR tests were on average about 5% higher than those obtained in Brookfield viscosity tests.

8. Aggregate Wetting Tests

The effects of the use of different oils during sprayed seal construction on the initial wetting of aggregates by binder was investigated by determining initial 100% coating temperatures for bitumen-oil blends containing between 0% w/w and 6% w/w of each oil using the method developed in Austroads (2012a, 2012b). Initial 100% coating temperature results were defined in previous studies to correspond to the lowest temperature at which all tested aggregates were completely coated by binder when aggregate particles were pushed into thin binder films and immediately removed by hand. This type of experiment was conducted during the current study as the results obtained in Austroads (2012a, 2012b) indicated that initial 100% coating temperature results obtained for different binders were independent of the type of aggregate used in the experiments (for the basalt, hornfels and greywacke aggregates investigated). Initial 100% coating results also did not appear to be markedly affected when basalt aggregates were precoated with different amounts of a diesel/C170 bitumen blend. It was therefore thought that initial 100% coating temperature results would give information about the initial wetting of aggregate by binder which was not significantly affected by either the type of aggregate, or whether the aggregate had been precoated, when it was used during sprayed seal construction.

8.1 Aggregate Wetting Test Experimental Design

Aggregate wetting tests were conducted using 2 mm binder films which were produced prior to testing using the same 100 mL metal dishes and experimental protocols which were used to produce binder films for mass loss tests (see Section 6.1.1 and Section 6.1.2 for details). The only variation to this process was that 12.7 ± 0.1 g of binder was added to each metal dish by determining the mass of each empty dish to the nearest 0.01 g using a two-figure (Shinko Denshi: Model AJH-4200CE) balance. The mass of binder added to each dish was also determined using the same two-figure balance. Samples were not reweighed using a four-figure analytical balance as aggregate wetting tests did not involve accurately monitoring the mass of the binder films over time.

Aggregate wetting tests were performed in the same controlled-temperature room which was utilised during mass loss tests (see Section 6.1.3 for details). Tests were conducted by initially equilibrating the room to each desired test temperature. Aggregate wetting tests were performed on binder films at temperatures in the range between 17 and 50 °C. Fresh binder film samples were used to conduct tests at each temperature. The temperature of each test was monitored using a calibrated digital thermocouple which was attached to the bench on which samples were placed.

After the room had equilibrated to each desired test temperature, the required number of closed metal dishes containing flat binder films were placed on the controlled-temperature room bench. Samples were then allowed to thermally equilibrate on the bench for 30 minutes prior to aggregate wetting tests being performed.

The aggregate used during testing was a 14 mm basalt aggregate which was obtained from the Boral Dunnstown quarry in Victoria. Prior to use, the aggregate was sieved to obtain the proportion of aggregate that passed a 13.5 mm sieve and was retained on a 9.5 mm sieve. It was then washed with water and dried in an oven at 110 °C. The basalt aggregate sample used in this study was the same sample that was used in Austroads (2012a, 2012b). The aggregate particles obtained after sieving and drying had a range of different shapes. Only aggregates that could be easily manipulated by hand, and had a flat side that could be placed in a binder film, were used in aggregate wetting experiments.

Aggregate wetting tests were conducted on each binder film after it had equilibrated to the desired test temperature by initially opening the lid of each dish immediately prior to testing. Tests were then conducted by visually assessing the percentage of binder coating which occurred when five different aggregate particles were pushed into each binder film by hand and then immediately removed using a pair of pliers. The process of pushing an aggregate particle into a binder film, and then removing it, typically took about 2 seconds to perform.

Figure 8.1 shows photographs of the different stages involved in conducting an aggregate wetting test when a single aggregate particle was pushed into a binder film and immediately removed by hand. The percentage aggregate coating results shown in Section 8.2 and Appendix C are the average of the results obtained for each set of five aggregate particles.

Figure 8.1: Photographs of the process involved in conducting an aggregate wetting test

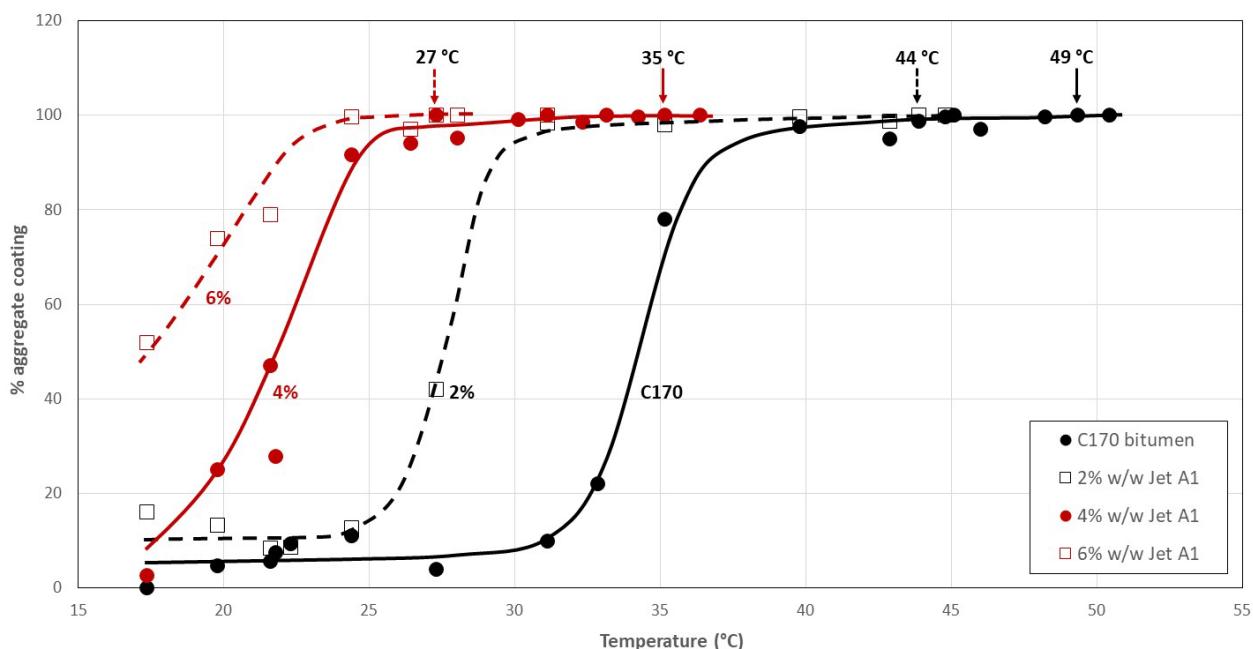


Initial 100% coating temperature results for each type of binder film were taken to be the lowest temperature at which all five tested aggregates showed 100% binder coating at that particular temperature and all higher temperatures. Determinations of initial 100% coating temperature results were typically performed by firstly conducting aggregate wetting tests with each type of binder at approximately 5 °C intervals. Once an approximate temperature for 100% coating was obtained, further experiments were conducted using each type of binder film at approximately 1 °C intervals at temperatures close to where 100% coating was expected to occur.

8.2 Aggregate Wetting Test Results

Figure 8.2 shows the aggregate wetting test results which were obtained for binder films containing C170 bitumen and either 0, 2, 4 or 6% w/w Jet A1. In all cases, the degree of binder coating on the aggregates was lower at lower test temperatures. C170 bitumen films and films containing 2% w/w Jet A1 showed quite low amounts of binder coating on the aggregates at low temperatures ($< 25^{\circ}\text{C}$). As the test temperature was increased all binder films showed an abrupt increase in the amount of binder coating on the aggregates over a relatively small temperature range (typically of the order of 10°C). The lines in Figure 8.2 give an overall indication of the trends observed in aggregate wetting tests for each type of binder film as the test temperature was varied. The temperature labels in the figure correspond to the initial 100% coating temperature results which were obtained for each of the four different binder films.

Figure 8.2: Aggregate wetting test results obtained for films containing C170 bitumen and different levels of Jet A1



Note: The arrows indicate the initial 100% coating temperature results obtained for each type of binder film.

The results obtained in aggregate wetting tests indicated that the overall trend between percentage aggregate coating results and temperature shifted to lower test temperatures as the Jet A1 concentration in the binder films was increased. The initial 100% coating temperature results obtained for each type of binder film also shifted to lower temperatures as the Jet A1 concentration in the films was increased. These observations agreed with the trends observed previously when aggregate wetting tests were conducted using films containing C170 bitumen and different amounts of a high flash point cutter (Shell Mexcut H) in Austroads (2012b).

Binder films containing C170 bitumen and either 0, 2, 4 or 6% w/w of each of the other six oils included in the study showed the same overall trends in aggregate wetting tests as films which contained different amounts of Jet A1 in terms of the changes in percentage coating results with test temperature and oil concentration. The results obtained for the other C170 bitumen/oil blends in aggregate wetting tests are included in Appendix C. The results included in Appendix C have been plotted in the same way for each oil type as those shown for films containing C170 bitumen and different concentrations of Jet A1 in Figure 8.2. These plots include the initial 100% coating temperature results obtained for each oil concentration studied.

Table 8.1 summarises the initial 100% coating temperature results which were obtained for each of the seven oils at the different oil concentrations studied. The initial 100% coating temperature result shown for all oils at an oil concentration of 0% w/w is the result obtained for a C170 bitumen film.

Overall, initial 100% coating temperature results showed a decrease as the concentration of oil in the binder films increased. This result agreed with the results observed in previous studies (Maccarrone et al. 1997; Austroads 2012b). Although initial 100% coating temperature results appeared to be affected by the concentration of oil in the binder films, there was not a marked difference in initial 100% coating temperature results if binder films containing the same concentration of each oil were compared.

Binder films containing 2% w/w and 4% w/w oil showed a 5 °C variation in initial 100% coating temperature results (as these films showed results in the ranges between 42–47 °C and 31–36 °C, respectively). A 3 °C variation in initial 100% coating temperature results was observed for binder films which contained 6% w/w oil (as the initial 100% coating temperature results varied between 27–30 °C).

Table 8.1: Initial 100% coating temperature results obtained for binder films containing C170 bitumen and different levels of oil

Oil type	Initial 100% coating temperature (°C)			
	0% w/w oil	2% w/w oil	4% w/w oil	6% w/w oil
Jet A1	49	44	35	27 (L)
High flash point cutter	49	42 (L)	36 (H)	28
Diesel	49	43	35	30 (H)
Mineral turpentine	49	43	31 (L)	28
Enersol kerosene	49	43	33	27 (L)
Enersol K	49	46	35	27 (L)
Enersol HFK	49	47 (H)	35	29
Range of initial 100% coating results (°C)	–	42–47	31–36	27–30

Note: The labels (L) and (H) correspond to the lowest and highest initial 100% coating temperature results obtained for the tested oils at each oil concentration.

Although there was not a marked difference in initial 100% coating temperature results obtained when binder films containing the same concentration of oil were compared, the results obtained at each oil concentration were compared to ascertain whether there was any general trend between the type of oil present in the binder films and initial 100% coating temperature results. Table 8.1 includes labels (L) and (H) which designate the lowest and highest initial 100% coating temperature results which were obtained at each oil concentration. If the type of oil which was blended with C170 bitumen affected the initial wetting of aggregate by binder, then it would be expected that binder films containing specific oils would show consistently higher or lower initial 100% coating temperature results.

The results shown in Table 8.1 indicate that there was no consistent trend in the initial 100% coating results obtained for a particular bitumen/oil blend over the three oil concentrations studied. If the results obtained for films containing 2% w/w oil are compared, films containing high flash point cutter showed the lowest initial 100% coating temperature result. At an oil concentration of 4% w/w, films containing mineral turpentine showed the lowest initial coating result, while at an oil concentration of 6% w/w films containing Jet A1, Enersol kerosene and Enersol K showed the lowest initial 100% coating temperature results. At oil concentrations of 2% w/w, 4% w/w and 6% w/w, films containing Enersol HFK, high flash point cutter and diesel, respectively, showed the highest initial 100% coating results.

As there did not appear to be any consistent trend between the type of oil included in a binder film and initial 100% coating temperature results at all three oil concentrations, the range of initial 100% coating results shown in Table 8.1 at each oil concentration likely reflects the error in aggregate wetting tests. The results of aggregate wetting tests therefore appear to indicate that for the seven oils included in the study, the use of different oils did not significantly affect the initial wetting of aggregate by binder. Increasing the concentration of oil in a blend, however, allowed aggregates to be wetted by binder at lower temperatures.

8.3 Summary

A series of aggregate wetting tests was performed using 2 mm binder films to investigate the effects of using different oils in sprayed seal construction on the initial wetting of aggregate by binder. The results of these tests indicated that the concentration of oil present in a C170 bitumen/oil blend affected the ability of a binder to wet aggregate. Binder films containing higher concentrations of oil were more able to wet aggregate at lower temperatures than films which contained lower concentrations of oil. There was not a significant difference in initial aggregate wetting performance, in the case of the seven oils included in the study, if the results obtained for binder films containing the same concentration of each oil were compared.

9. Proposed Changes to AS 3568

This section summarises the correlations observed between the AS 3568-specified test results obtained for each of the seven different oils included in the study with the results observed in laboratory sprayed seal performance tests which were conducted on blends containing C170 bitumen and each of the oils. It also contains a review of the test methods and tests currently listed in AS 3568 in terms of whether the methods are current and/or typically used by testing laboratories. Section 9.4 includes a summary of proposed textural changes to a revised version of AS 3568. It also includes a revised specification table for cutter oil and high flash point cutter which could be included in an updated version of the standard.

During the project, the conclusions of the research and likely implications with respect to an updated version of AS 3568 were discussed with members of the Austroads Bituminous Surfacings Working Group (BSWG) during meetings which were held three times per year. This group includes Austroads jurisdiction representatives from Australia and New Zealand, representatives of sprayed seal construction companies, as well as bituminous product and oil suppliers which supply materials for road construction.

A review of Austroads member specification documents (see Section 2.1.2 and Section 2.2.1 for details) indicated that heavy flux oil is included in VicRoads sprayed sealing specification documents (VicRoads 2017) but is not used by other Austroads jurisdictions. Feedback from BSWG members, however, indicated that heavy flux oil is no longer used to construct sprayed seals in either Victoria or Tasmania. As heavy flux oil is not currently used to construct sprayed seals in either Australia or New Zealand, BSWG members agreed that the current references to heavy flux oil in AS 3568, as well as specification requirements for this material, could be removed from an updated version of the standard.

During BSWG meetings held during the project, it was also agreed that the specified properties of cutter oil could either meet the tabulated values listed in a future version of AS 3568 or meet the specified requirements of certified Jet A1 aviation fuel. This change to AS 3568 would be similar to current Western Australian specification requirements for cutter oil which allow cutter oils to be certified against either local specification requirements (as shown in Table 2.6), or the specified requirements of Jet A1 aviation fuel (Joint Inspection Group 2016), prior to their use in sprayed seal construction.

Although the properties of flux oils were not extensively studied in this project, BSWG members agreed that current AS 3568-specified properties for flux oil should be replaced by a statement in the standard indicating that flux oils shall be certified to meet relevant national legislated requirements for automotive diesel fuel. Diesel fuel sold in Australia is currently required to meet the requirements of the Australian automotive diesel fuel specification (*Fuel Standard (Automotive Diesel) Amendment Determination 2009 (No. 1)*) while diesel fuel sold in New Zealand currently needs to meet the requirements specified in the *NZ Petroleum Products Specifications Regulations* (Petroleum Products Specifications Regulations 2002 (SR2002/210)).

The Australian automotive diesel fuel specification currently allows diesel fuel to be sold which contains up to 5% by volume of biodiesel. The biodiesel that is added to conventional diesel initially needs to meet the requirements of *Fuel Standard (Biodiesel) Amendment Determination 2009 (No. 1)*. Blends of conventional diesel and biodiesel need to be certified against the standard requirements for automotive diesel fuel as well as two additional specified requirements which include cetane number and water content. If the AS 3568-specified requirements for flux oil are changed so that flux oil needs to meet the requirements for automotive diesel fuel, then it should be feasible to include up to 5% biodiesel in flux oils used to construct sprayed seals in Australia.

It was noted in Section 2.2.1 that cutter oil and flux oil which are used in sprayed seal construction in New Zealand typically need to meet the requirements of Jet A1 aviation fuel or automotive diesel fuel, respectively. Including the option of using certified Jet A1 aviation fuel as cutter oil, and specifying flux oil to meet national specification requirements for automotive diesel fuel in a future version of AS 3568 will allow AS 3568 to be more easily adopted in New Zealand.

As it was agreed during BSWG meetings that flux oil would be specified in a future version of AS 3568 as meeting relevant national legislated requirements for automotive diesel fuel, and the specified requirements and references to heavy flux oil would be removed, the discussion included in Section 9.1 and Section 9.2 predominantly focusses on determining appropriate specification limits and test methods relevant to cutter oil and high flash point cutter.

9.1 Observed Correlations between AS 3568-specified Test Properties and Sprayed Seal Performance

During the study, seven different oils were initially subjected to a series of AS 3568-specified tests which previous studies had suggested gave information about sprayed seal performance. The results obtained in these tests were compared to a series of laboratory performance tests which investigated the stability/miscibility of each oil with C170 bitumen, the relative rates of oil loss over time from C170 bitumen films containing different amounts of each oil, as well as the effects of the use of different oils on C170 bitumen viscosity reduction and aggregate wetting behaviour.

The results of stability/miscibility tests (Section 5) indicated that all oils studied were miscible with bitumen. The oils also did not separate from bitumen when samples were stored for three days at ambient temperature. Investigations into the effects of the use of different oils on the initial aggregate wetting performance of binders (Section 8) also did not find significant differences in aggregate wetting performance if the oils included in the study were added to C170 bitumen at the same oil concentration. Enhanced aggregate wetting performance at lower temperatures was observed if binder films contained higher concentrations of each oil.

No correlations were found during the study between the results obtained in any of the performance tests and AS 3568-specified aniline point and aromatic content tests even though the results obtained for the different neat oils varied significantly (i.e. aniline content results obtained for the different oils varied between 23.4 and 83.0 °C and aromatic content results varied between 2.7 and 44.9% volume (Table 4.2 and Table 4.3)). As no correlations were found between aniline point and aromatic content test results and the results of laboratory performance tests it appears that these currently specified neat oil properties do not provide information about the relative performance of different oils during sprayed seal construction. Due to this, it appears that current aniline point and aromatic content specification requirements could be removed from a future version of AS 3568.

The results of mass loss tests (Section 6) indicated that there was a correlation between percentage oil retained results obtained from 2 mm binder films after 30 days of heating and neat oil final boiling point (FBP) results for each of the nine oil concentration/heating temperature conditions used in the study. There was no effective correlation between the results obtained in mass loss tests and neat oil initial boiling point (IBP) results. Binder films which contained oils which had FBP results of 286 °C or less showed similar to slightly higher rates of oil loss over time as films which contained the representative sample of a conventional cutter oil which was used in this study (i.e. Jet A1). Binder films which contained oils with FBP results of 335 °C or greater showed significantly lower rates of oil loss than comparable films containing Jet A1.

If the results of mass loss tests, and the current FBP specified requirements for Jet A1 aviation fuel (i.e. 300 °C maximum) (Joint Inspection Group 2016) were both considered, then it appeared that the FBP requirements for cutter oil and high flash point cutter could be increased from 270 °C maximum to 300 °C maximum in a future version of AS 3568.

Although no direct correlations were found between the results of mass loss tests and neat oil IBP results in the current study, it appears sensible to include the current AS 3568-specified IBP requirements for cutter oil and high flash point cutter (i.e. 140 °C minimum) in an updated version of AS 3568 to limit the use of very volatile oils (e.g. petrol) during sprayed seal construction. Very volatile oils would be expected to have very low flash points which may increase the safety risks associated with their use.

Investigations into the effects of the use of different oils on C170 bitumen viscosity reduction indicated that the viscosity of a C170 bitumen/oil blend was affected by the concentration of oil in the blend and the viscosity of the neat oil at the test temperature. These observations indicated that current AS 3568-specified viscosity at 40 °C results could be used to provide information about the ability of a sample of tested oil to reduce the viscosity of C170 bitumen. The results of DSR complex viscosity tests also indicated that use of oils with viscosity at 40 °C results in the range between 0.5 and 2.0 mPa s (or 0.7 and 2.5 mm²/s) would be able to produce a satisfactory level of C170 bitumen viscosity reduction if Austroads (AP-T39-05) recommended cutter levels were used during sprayed seal construction and the error associated with adding cutter to a sprayer (typically ±10% of the intended level) was considered.

It was noted in Section 2.1.2 that while most Australian jurisdictions specify viscosity at 40 °C test results for oils to be used to reduce the viscosity of binders in terms of dynamic viscosity units (i.e. mPa s), the specified viscosity at 40 °C requirements for some of the oils used in South Australia, and all of the oils used in Western Australia are expressed in terms of kinematic viscosity units (i.e. mm²/s). Including viscosity at 40 °C limits of either 0.5 to 2.0 mPa s or 0.7 to 2.5 mm²/s in an updated version of AS 3568 would allow the results of ASTM D445 tests on samples of neat oils to be expressed in terms of either dynamic or kinematic viscosity units depending on the jurisdiction to which oils were supplied. Differences in jurisdiction practice could be incorporated as a note to the specification table in an updated version of AS 3568 which stated: '*Viscosity at 40 °C results shall be reported in either dynamic viscosity units (i.e. mPa s) or kinematic viscosity units (i.e. mm²/s) as required by the purchaser*'.

For jurisdictions which specify viscosity at 40 °C test results on neat oils in terms of dynamic viscosity units, the specified method for these tests (ASTM D445) initially provides viscosity results in terms of kinematic viscosity units (i.e. mm²/s). Although ASTM D445 provides a means of converting viscosity results from kinematic viscosity units to dynamic viscosity units, it requires laboratories to conduct an additional density measurement on samples at 40 °C in order to convert kinematic viscosity results into dynamic viscosity results. The current version of AS 3568 currently includes a note under the specification table for cutter oil, high flash point cutter and flux oil which includes an equation that can be used for the conversion. Retention of this note in an updated version of AS 3568 would allow testing laboratories to express viscosity at 40 °C results in terms of dynamic viscosity units without requiring them to conduct an additional test.

9.2 Review of Other AS 3568-specified Test Properties

9.2.1 Density at 15 °C

The current version of AS 3568 specifies that density at 15 °C tests shall be conducted using ASTM D1298 or AS 2341.6 (Table 2.1), however, the samples of oil which were utilised in this study were tested for density at a commercial refinery laboratory (Viva Energy Geelong) using ASTM D4052. The manufacturer of Enersol kerosene, Enersol K and Enersol HFK (IOR Pty. Ltd.) also uses ASTM D4052 to determine density at 15 °C results for these products (Gerard Carmody, personal communication, November 2017). It was noted in Section 4.2.1 that ASTM D4052 is a more accurate method than ASTM D1298 as it has better repeatability and reproducibility limits (Nadkarni 2007).

The specification for Jet A1 aviation fuel in Australia and New Zealand (Joint Inspection Group 2016) allows either ASTM D1298 or ASTM D4052 to be used to determine density at 15 °C results when this fuel is used in aviation applications. This equivalence, combined with the use of ASTM D4052 by fuel testing laboratories, suggests that density at 15 °C tests on samples of cutter oil and high flash point cutter could be conducted using either ASTM D1298 or ASTM D4052 in an updated version of AS 3568.

A review of the Australian National Association of Testing Laboratories (NATA) list of laboratory accreditations for testing (which was conducted in December 2018) indicated that no laboratories traditionally associated with road construction were accredited for AS 2341.6. The only Australian laboratory which was NATA accredited for this test was located in New South Wales and was associated with a company that produced chemicals from coal tar coke. This company was also NATA accredited for ASTM D1298. As AS 2341.6 no longer appears to be used as a NATA-accredited test by oil suppliers which supply materials for road construction, AS 2341.6 could be removed as a specified test in an updated version of AS 3568.

At the November 2018 BSWG meeting, possible changes to the density at 15 °C specification limits for cutter oil and high flash point cutter in AS 3568 were discussed. It was considered that the density at 15 °C results obtained from testing oils against the requirements of AS 3568 were only used in practice to convert delivered volumes of oil into mass amounts if needed. As a result of this, it was agreed that the current numerical range of specified density at 15 °C results for cutter oil and high flash point cutter would be replaced by a ‘report’ requirement in an updated version of AS 3568. This would be similar to the current requirement listed for the seven different bitumen grades in the Australian bitumen specification (AS 2008) where density at 15 °C results on bitumen samples are required to be reported if requested by the customer. No specified numerical limits for density at 15 °C are included for the different bitumen grades included in AS 2008.

9.2.2 Flash Point

The current version of AS 3568 indicates that flash point tests shall be conducted using AS 2106, however this standard, which includes an overview of different types of closed cup flash point tests as well as six different methods by which the flash point of flammable liquids can be determined, was last updated in 1980. In 1999, AS 2106 was republished as seven different standards which included a standard which described the applicability of different types of closed cup flash point tests (AS 2106.0), as well as six separate standards corresponding to each of the different flash point test methods. This indicates that the method for determining flash point in AS 3568 needs to be updated in order to reflect changes that have occurred over time.

AS 3568 currently indicates that flash point tests shall be conducted on samples of cutter oil and high flash point cutter using an Abel closed cup apparatus while flash point tests on flux oil need to be conducted using a Pensky-Martens closed cup apparatus (Table 2.1). The current standard relating the use of an Abel closed cup apparatus is AS/NZS 2106.1 while that relevant to the use of a Pensky-Martens closed cup apparatus is AS 2106.2. AS/NZS 2106.1 is applicable for flash point determinations on flammable liquids which have flash point results between –5 and 66.5 °C based on precision estimates included in the standard, while AS 2106.2 is applicable for testing samples which have flash point results above 40 °C.

As AS 3568 specified flash point requirements for cutter oil and high flash point cutter are 38 °C minimum and 61.5 °C minimum, respectively, AS/NZS 2106.1 can only effectively be used to measure the flash point of high flash point cutters over a very limited range (i.e. high flash point cutters with flash points only up to 66.5 °C). Similarly, AS 2106.2 does not appear to be suitable for determining the flash point of cutter oils which have flash point results below 40 °C. These observations suggest that both AS/NZS 2106.1 and AS 2106.2 should be included as options to measure the flash point of cutter oils and high flash point cutters in an updated version of AS 3568. Guidance on the relevant test method to use in these tests could be provided by including a note to the relevant specification table which stated: *‘Flash point tests shall be conducted using the method of test which is applicable for the flash point test result obtained for the sample being tested.’*

During 2016, the Australian Asphalt Pavement Association (AAPA) published an industry specification for oils used to reduce the viscosity of binders in sprayed sealing which was intended to reflect the properties of commercially available oils which were in use at the time and laboratory quality control testing practices. This specification was published in AAPA Advisory Note 21 (Australian Asphalt Pavement Association 2016). The Advisory Note was developed by obtaining input from different commercial oil suppliers and indicated that flash point tests on neat oils could be conducted using ASTM D93 or ASTM D3828, rather than AS 2106.

ASTM D93 is very similar to AS 2106.2 in that it describes the means by which a Pensky-Martens closed cup apparatus can be used to determine the flash point of petroleum products with flash points in the range between 40 and 370 °C. ASTM D3828 can be used to determine the flash point of petroleum products with flash points in the range between –30 and 300 °C using a small-scale closed cup tester.

The *Australian Code for the Transport of Dangerous Goods by Road and Rail* (National Transport Commission 2018) indicates that a variety of different methods can be used to determine the flash point of flammable liquids which are transported in Australia. Suitable methods include six different International Organisation for Standardization (ISO) methods, any of the AS 2106-related methods (including AS/NZS 2106.1 and AS 2106.2) and four different ASTM standards (which include ASTM D93 and ASTM D3828). As the Australian Dangerous Goods Code allows the use of either AS/NZS 2106.1, AS 2106.2, ASTM D93 or ASTM D3823 to be used to assess the flammability of oils during transport, all four methods could be used to measure the flash point of cutter oils and high flash point cutters in an updated version of AS 3568. As the type of test to be used is dependent on the flash point result obtained for a specific sample, further guidance (as described above) could be provided as a note to the specification table in an updated version of AS 3568.

The current version of AS 3568 includes a note to the specification table for cutter oil, high flash point cutter and flux oil which indicates that oils with flash points lower than the specified limits can be used if sprayed sealing practices meet relevant safety legislation requirements. As road construction companies no longer use very low flash point cutters during sprayed seal construction due to safety concerns, this note could be removed from an updated version of AS 3568.

9.2.3 Miscibility

The miscibility requirements currently included in the AS 3568 specification table for cutter oil, high flash point cutter and flux oil specify that the oils shall be completely miscible with bitumen and that no precipitation of bitumen shall occur when bitumen and oil are mixed. Clause 4.3 of AS 3568 indicates that the miscibility of the different types of oil is assessed by mixing one part by volume of oil at ambient temperature with one part by volume of bitumen at a temperature of 80 °C. The mixture is then allowed to cool to room temperature. If no precipitation of bitumen is observed after the mixture is allowed to stand at room temperature for one hour then the oil is deemed miscible with bitumen.

As miscibility requirements are included in the AS 3568 specification table this implies that these tests should be conducted as part of routine quality control testing of the oils prior to their use in sprayed seal construction. Discussions with oil suppliers, however, indicated that none of the suppliers conducted miscibility tests on a routine basis. AAPA Advisory Note 21 (Australian Asphalt Pavement Association 2016) also does not include any reference to miscibility tests which provides further evidence that these types of tests have not been widely performed in the past. Although the outline of a procedure to assess bitumen/oil miscibility is included in AS 3568, this procedure is not a conventional detailed test method. Testing laboratories therefore cannot be NATA accredited for the miscibility tests currently included in AS 3568 even if they were conducted.

During the BSWG meeting held in November 2018, the miscibility requirements for oils in an updated version of AS 3568 were discussed. It was noted that oils used in sprayed seal construction needed to be miscible with binders at the point of use but Clause 4.3 of AS 3568 did not provide enough detail to be considered a test method and so it should be removed from an updated version of AS 3568. BSWG members agreed to include the statement '*Cutter oil, high flash point cutter and flux oil shall be completely miscible with bitumen and no precipitation shall occur*' in the text of a revised version of AS 3568 to reflect the requirement that oils need to be miscible with binders. Including this information in the text of AS 3568 (rather than in the specification table for cutter oil and high flash point cutter) and removing Clause 4.3 from a revised version of AS 3568, would allow oil/binder miscibility to be specified without requiring testing laboratories to conduct a specific miscibility test.

9.2.4 Fluidity and Water Content

AS 3568 currently also includes fluidity and water content requirements in the specification table for cutter oil, high flash point cutter and flux oil. Fluidity requirements state that oils must be clean and free of particulate matter and they must be liquid at the point of use. The requirement that the oils need to be liquid at the point of use does not appear to be required in an updated version of AS 3568 as the specified property ranges for boiling point and/or viscosity at 40 °C test results in the proposed revised version of AS 3568 already effectively specify that the oils must be liquids (i.e. not solids or gases).

The proposed IBP requirement for cutter oil and high flash point cutter of 140 °C minimum effectively specifies that these oils cannot be gases at ambient temperature as gases would have IBP and FBP results which were much lower than ambient temperature. As the proposed viscosity at 40 °C specification range for these two materials of 0.5 to 2.0 mPa s (or 0.7 to 2.5 mm²/s) is well within the viscosity range of typical liquids at ambient temperature (i.e. between 0.2 and 10 000 mPa s or between 0.3 to 70 000 mm²/s (Mezger 2014)), the proposed viscosity limits effectively specify that the oils cannot be gases or solids. Gases have very low viscosities at ambient temperatures (typically in the range between 0.01 and 0.02 mPa s) and solids have very high viscosities that cannot be effectively measured as solids do not readily flow (Mezger 2014). The range of viscosity at 40 °C values included in the Australian and New Zealand automotive diesel fuel specifications (i.e. 2.0–4.5 mm²/s) will also limit the viscosity of flux oil in the proposed revised version of AS 3568 to a range which is well within the viscosity range observed for typical liquids.

The current version of AS 3568 indicates that oils used to reduce the viscosity of binders need to have a water content of ≤ 0.1% by volume when oils are tested using AS 2341.9. This method is also used to determine the water content of bituminous emulsions in the Australian bituminous emulsion specification (AS 1160) and requires the use of a Dean and Stark distillation apparatus. Percentage water content results obtained using AS 2341.9 are equivalent to the number of millilitres of water present in 100 g of a tested sample. Water content tests are included in AS 3568 primarily to ensure that hot binder does not foam when binder and oil are mixed. AAPA Advisory Note 21 (Australian Asphalt Pavement Association 2016) does not include water content tests in the industry specification which suggests that water content tests are not currently routinely performed by oil testing laboratories.

Although AS 3568 includes a maximum water content requirement for oils used in sprayed sealing applications, the specification for Jet A1 in Australian and New Zealand (Joint Inspection Group 2016) does not include water content tests when this fuel is used in aviation applications. It would be thought that the amount of water in aviation fuel would need to be kept as low as possible because if it was present in large amounts it could freeze during flight and block the fuel lines to aircraft engines.

The properties of kerosene-water blends have been extensively studied due to the concerns mentioned above about water freezing in aircraft fuel lines during flight (Baena-Zambrana et al. 2013; Coordinating Research Council 2014). Mixtures of kerosene-type materials and water visibly exist in three different forms depending on the amount of water present (Baena-Zambrana et al. 2013). If a very low concentration of water is present, the water can dissolve in the kerosene and the liquid still appears to be clear. If the amount of water in the fuel is greater than the amount that can dissolve, a water in kerosene emulsion will form which produces a cloudy, dull or hazy liquid. If the water concentration is higher than this, a separate water layer will form below the cloudy, dull or hazy kerosene liquid. The Australian and New Zealand specification for Jet A1 includes a visual assessment test on fuel samples which requires these materials to be ‘clear and bright’ at ambient fuel temperature. This visual test essentially specifies that only dissolved water can be present in a Jet A1 sample prior to its use in aviation applications.

West et al. (2018) recently conducted extensive studies to quantitatively determine the maximum amount of water that could be dissolved in a wide range of kerosene-type solvents in order to determine the maximum water concentrations present when these liquids still appeared ‘clear and bright’. Solvents studied included traditional aviation turbine fuels of varying aromaticity (including Jet A1), US military jet fuels, synthetic-based aviation fuels and blendstocks with various chemical compositions, highly aromatic mixtures, synthetic jet fuels and a sample of aviation gasoline. The results of these experiments indicated that the maximum amount of water that could be dissolved in these solvents was in the range between 0.004 and 0.02% by volume at 20 °C (when water concentrations were expressed in the same units as used in AS 2341.9). It therefore appears that kerosene-type solvents will only appear ‘clear and bright’ if the concentration of water in the oils is well below the current AS 3568-specified requirement of ≤ 0.1% by volume.

Based on the discussion above, it appears that the current water content test requirement for cutter oil and high flash point cutter in AS 3568 could be replaced by an appearance requirement that the oil needs to appear ‘clear and bright’ in a revised version of the standard. This requirement could then be combined with the current visual fluidity requirement that ‘oils shall be clean and free of particulate matter’ in an updated version of the specification table for cutter oil and high flash point cutter. At the BSWG meeting held in November 2018, the wording of the proposed new appearance requirement for cutter oil and high flash point cutter was discussed. It was agreed that a revised version of the specification table for cutter oil and high flash point cutter would include an appearance requirement which stated that oils shall be ‘*Clear, bright and visually free from solid matter and undissolved water at ambient temperature*’.

Although it was noted above that it has been proposed to replace the current AS 3568-specified properties for flux oil with relevant national legislated requirements for automotive diesel fuel, the national diesel specifications in Australia and New Zealand were not developed considering that diesel would be added to hot bitumen. The Australian diesel fuel specification includes a free water and sediment requirement of 0.05% by volume maximum when samples are tested using ASTM D2709. This test involves centrifuging a 100 mL diesel sample, determining the volume of free water and sediment that is present in a sample after centrifuging at ambient temperature, and then expressing the result as a percentage. This test, however, does not determine the concentration of dissolved water in a diesel sample. The Australian diesel specification limit for free water and sediment corresponds to a limit of 0.06% by volume maximum when the concentration of free water is expressed in the same units as used in AS 2341.9.

Studies by Shah et al. (2010) and Bogalhos et al. (2012) have indicated that the solubility of water in diesel is typically no more than 0.01% by volume (when the concentration of dissolved water is expressed in the same units as used in AS 2341.9). If both free water and dissolved water are considered, then the Australian diesel specification essentially specifies that the total water content of diesel should be ≤ 0.07% by volume (i.e. 0.06% + 0.01% = 0.07% by volume). As AS 3568 currently specifies that the water content of flux oil can be higher than this (i.e. ≤ 0.1% by volume), it would be expected that use of the Australian diesel specification to specify the properties of flux oil would be unlikely to result in binder foaming when hot binder and flux oil are mixed.

The New Zealand automotive diesel fuel specification requires the water content of diesel be ≤ 200 mg/kg when samples are tested by ASTM D6304. This test determines the total amount of water in a diesel sample (i.e. both dissolved and free water) using a Karl Fischer titration apparatus. The New Zealand diesel fuel specification limits the concentration of water in a diesel sample to ≤ 0.02% by volume when expressed in the same units as used in AS 2341.9. As this maximum limit for water content is less than the current AS 3568 requirement of ≤ 0.1% by volume for flux oil, use of the New Zealand automotive diesel fuel specification is also unlikely to result in foaming if blends of hot bitumen and flux oil are mixed during sprayed seal construction.

9.3 AS 3568 Clause 3 Definitions

AS 3568 currently includes definitions for cutter oil, flux oil and sprayed sealing work in Clause 3 but does not include a definition for high flash point cutter. The definition for flux oil indicates that flux oil produces a long-term viscosity reduction of a binder which appears to conflict with results obtained in road trials which were conducted in the 1980s and 1990s (Section 3.2.1) which showed that flux oils were not retained in sprayed seals for years. The definition for sprayed sealing work in Clause 3 also refers to ‘primer-seals’ which has been changed to ‘initial seals’ in the most recent version of Austroads (2018). Proposed changes to the definitions in Clause 3 of AS 3568 have been included in Section 9.4.

9.4 Proposed Modifications to an Updated Version of AS 3568

Based on the results of the study and the discussion above, the following textural revisions to AS 3568 are proposed:

- removal of the references to heavy flux oil in the standard and removal of the specification table for heavy flux oil

- updates to the definitions for cutter oil, high flash point cutter, flux oil and sprayed sealing work to include the following:
 - *Cutter oil: a light petroleum distillate added to a bituminous binder to temporarily reduce its viscosity. Cutter oils are typically lost from sprayed seals over a period of months*
 - *High flash point cutter: a light petroleum distillate similar to cutter oil which has a higher flash point than cutter oil*
 - *Flux oil: a petroleum distillate used to reduce the viscosity of a bituminous binder over a longer period than cutter oil or high flash point cutter*
 - *Sprayed sealing work: includes primes, initial seals and seals constructed using bituminous binders*
- a statement in the standard indicating that flux oil should meet the relevant Australian or New Zealand national specification requirements for automotive diesel fuel
- a sentence in the standard stating that '*Cutter oil, high flash point cutter and flux oil shall be completely miscible with bitumen and no precipitation shall occur*'.

A proposed revised specification table for cutter oil and high flash point cutter is included in Table 9.1.

Table 9.1: Proposed revised specification table for cutter oil and high flash point cutter

Property	Requirement				Method of test	
	Cutter oil ⁽¹⁾		High flash point cutter			
	Min.	Max.	Min.	Max.		
Appearance	Clean, bright and visually free from solid matter and undissolved water at ambient temperature				–	
Flash point (°C)	38	–	61.5	–	AS/NZS 2106.1 or AS 2106.2 or ASTM D93 or ASTM D3828 ⁽²⁾	
Distillation range					ASTM D86	
Initial boiling point (IBP) (°C)	140	–	140	–		
Final boiling point (FBP) (°C)	–	300	–	300		
Viscosity at 40 °C (mPa s) or Viscosity at 40 °C (mm ² /s) ⁽³⁾	0.5 ⁽⁴⁾ 0.7 ⁽⁵⁾	2.0 ⁽⁴⁾ 2.5 ⁽⁵⁾	0.5 ⁽⁴⁾ 0.7 ⁽⁵⁾	2.0 ⁽⁴⁾ 2.5 ⁽⁵⁾	ASTM D445 ⁽⁶⁾	
Density at 15 °C (kg/m ³)	Report				ASTM D1298 or ASTM D4052	

1 Oils which have been certified to meet the requirements of Jet A1 aviation fuel may also be used as cutter oil.

2 Flash point tests shall be conducted using the method of test which is applicable for the flash point test result obtained for the sample being tested.

3 Viscosity at 40 °C test results shall be reported in either dynamic viscosity units (i.e. mPa s) or kinematic viscosity units (i.e. mm²/s) as required by the purchaser.

4 Specified limits when viscosity at 40 °C results are reported in dynamic viscosity units (i.e. mPa s).

5 Specified limits when viscosity at 40 °C results are reported in kinematic viscosity units (i.e. mm²/s).

6 ASTM D445 initially yields viscosity at 40 °C results in kinematic viscosity units (i.e. mm²/s). Viscosity results shall be converted into dynamic viscosity units (if required by the purchaser) using the equation:

$$\eta = \frac{\nu \times \rho \times 10^{-3}}{1 + f(T - 15)}$$

where

η = viscosity in dynamic viscosity units (mPa s)

ν = viscosity in kinematic viscosity units (mm²/s)

ρ = measured oil density at 15 °C (kg/m³)

f = oil coefficient of expansion (°C⁻¹) = 0.00061 °C⁻¹ for bitumen and related products

T = viscosity test temperature (°C)

9.5 AS 3568 Update Status

The Standards Australia committee, CH-025: Bitumen and Related Materials (for Roadmaking) will be responsible for drafting a revised version of AS 3568. This committee currently includes an independent committee chairman, as well as industry, technical and Austroads jurisdiction representatives from Australia and New Zealand. A project proposal for updating AS 3568 was submitted to Standards Australia by the CH-025 committee chairman on 6 September 2018. This proposal was endorsed by Standards Australia on 14 November 2018 indicating that revision work could commence.

The Standards Australia process for updating standards initially involves the relevant committee drafting a revised version of the standard. The standard is then reviewed by the Standards Australia technical editor and then released for public comment. Comments received during the public comment period are then addressed by the relevant committee prior to a revised version of the standard being published. Australian Standards can become joint Australian/New Zealand standards if they are also endorsed by Standards New Zealand.

10. Summary and Conclusions

Australian Standard AS 3568 is currently used by Australian jurisdictions either directly, or as a basis, for local specifications relating to the types of cutter oils used to reduce the viscosity of binders in sprayed seal construction. This standard, however, was last updated in 1999 and specifies some materials which are no longer available in the marketplace. Some oils which do not meet the requirements of AS 3568 have also been found to perform satisfactorily during sprayed seal construction.

New Zealand, South Africa, USA and the European Union do not directly specify the properties of oils used to reduce the viscosity of binders during sprayed seal construction, however, the distillation (i.e. boiling point) properties of the oils are indirectly included in South African, USA and European Union cutback binder specifications. The main aim of this study was to identify the key properties of cutter oils which affected sprayed seal performance so that this information could be used to provide input into an updated version of AS 3568 which would include specified test properties which better reflected field performance and currently available products.

During the study, the results obtained for seven different oils in a range of AS 3568-specified tests were compared with the results obtained in four different laboratory sprayed seal performance tests which were conducted after each of the oils was blended with a single sample of C170 bitumen. Oils studied included representative samples of cutter oil, high flash point cutter and flux oil (which met current AS 3568-specified requirements where tested) as well as four commercially available solvents (i.e. mineral turpentine, Enersol kerosene, Enersol K and Enersol HFK). The AS 3568-specified tests and performance tests included in the study were predominantly selected based on review of previous research into the properties of cutter oils which was conducted between the 1960s and early 2010s. Sprayed seal performance tests investigated the stability/miscibility of each oil with C170 bitumen, the relative rates of oil loss over time from binder films containing different amounts of each oil, as well as the effects of the use of different oils on C170 bitumen viscosity reduction and initial aggregate wetting behaviour.

The results of stability/miscibility tests and initial aggregate wetting tests indicated that there was not a marked difference in the performance of the oils studied. Although the neat oils showed a variety of different results in AS 3568-specified chemical tests (i.e. aniline point and aromatic content tests) all oils appeared to be suitably miscible with C170 bitumen. The initial aggregate wetting performance of each of the seven oils was also found to be similar if the results obtained for bitumen/oil blends containing the same concentration of oil were compared.

Mass loss tests were conducted during the study by monitoring the rate of oil loss which occurred when 2 mm binder films containing either 2, 4 or 6% w/w of each oil were heated for up to 30 days at three different test temperatures (i.e. 40, 50 or 60 °C). A correlation was found between the percentage of oil retained in each type of binder film after 30 days of heating and neat oil final boiling point (FBP) results for each of the nine sets of oil concentrations/heating temperatures studied. Based on the results of this study, it appears that AS 3568-specified FBP results can be used to provide information about the rate at which different oils are lost from sprayed seals.

The results of mass loss tests also indicated that tested oils which had FBP results of 286 °C or less showed similar to slightly greater rates of oil loss as films containing the representative sample of cutter oil which was used in the study (i.e. Jet A1). Tested oils which had FBP results of 335 °C or greater consistently showed lower rates of oil loss than comparable films which contained Jet A1. Based on these results, and considering the current FBP requirement of 300 °C maximum when Jet A1 is used as an aviation fuel, the specified FBP requirement for cutter oil and high flash point cutter has been proposed to be increased from 270 °C maximum to 300 °C maximum in an updated version of AS 3568.

Investigations into the effects of the use of different oils on C170 bitumen viscosity reduction showed that the viscosity of a C170 bitumen/oil blend was influenced by the viscosity of the neat oil used to produce the blend as well as the concentration of oil in the blend. This observation implied that AS 3568-specified viscosity at 40 °C results could be used to provide information about the ability of a tested oil to reduce the viscosity of C170 bitumen. A study of the effects of the use of different oils on the recommended cutter levels listed in Austroads document AP-T39-05 indicated that AP-T39-05 recommended cutter levels could be used when sprayed seals were constructed with C170 bitumen if the viscosity at 40 °C of the neat oil was between either 0.5 and 2.0 mPa s, or 0.7 and 2.5 mm²/s. These revised viscosity at 40 °C limits have been proposed to be included in an updated version of AS 3568.

Based on the results obtained in this study and input from the Austroads Bituminous Surfacings Working Group (BSWG) a number of changes to AS 3568 have been proposed. Proposed changes include removal of references and the specification table for heavy flux oil (as this material is no longer used by Australian or New Zealand jurisdictions) as well as specifying that flux oil used in sprayed sealing operations should comply with national specified requirements for automotive diesel fuel (as agreed by BSWG). A revised specification table for cutter oil and high flash point cutter has also been proposed.

The main changes proposed to the specification table for cutter oil and high flash point cutter include removal of current AS 3568 requirements for aniline point and aromatic content (as the results of this study did not indicate that these test properties were related to sprayed seal performance) and replacement of the current water content specified requirement with a visual ‘clean and bright’ assessment. The current specification requirement for water content has been proposed to be removed as a literature review of the solubility of water in kerosene-type solvents indicated that samples of cutter oil and high flash point cutter would only be visually ‘clean and bright’ if they met current AS 3568 water content requirements. Variations to some of the test methods included in AS 3568 have also been proposed as some of the test methods currently included in the standard have either been superseded or are not commonly used by oil testing laboratories.

Standards Australia approved a project proposal to update AS 3568 on 14 November 2018. The results of this study can therefore be used as input into an updated version of the standard. A revised version of AS 3568 will be drafted by the Standards Australia committee CH-025: Bitumen and Related Materials (for Roadmaking). This committee currently includes an independent committee chairman, as well as industry, technical and Austroads jurisdiction representatives from both Australia and New Zealand.

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Appendix A Mass Loss Results Not Included in the Main Body of the Report

Figure A 1: Mass loss results obtained at 40 °C for films containing 4% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

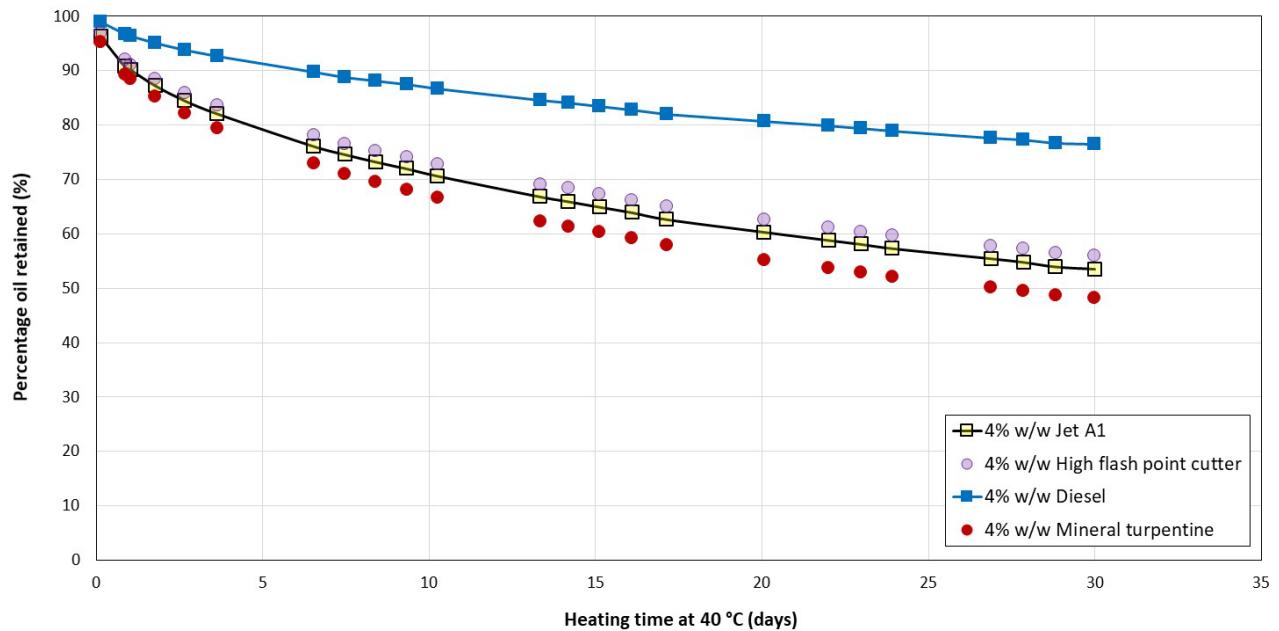


Figure A 2: Mass loss results obtained at 40 °C for films containing 4% w/w of each of the Enersol oils

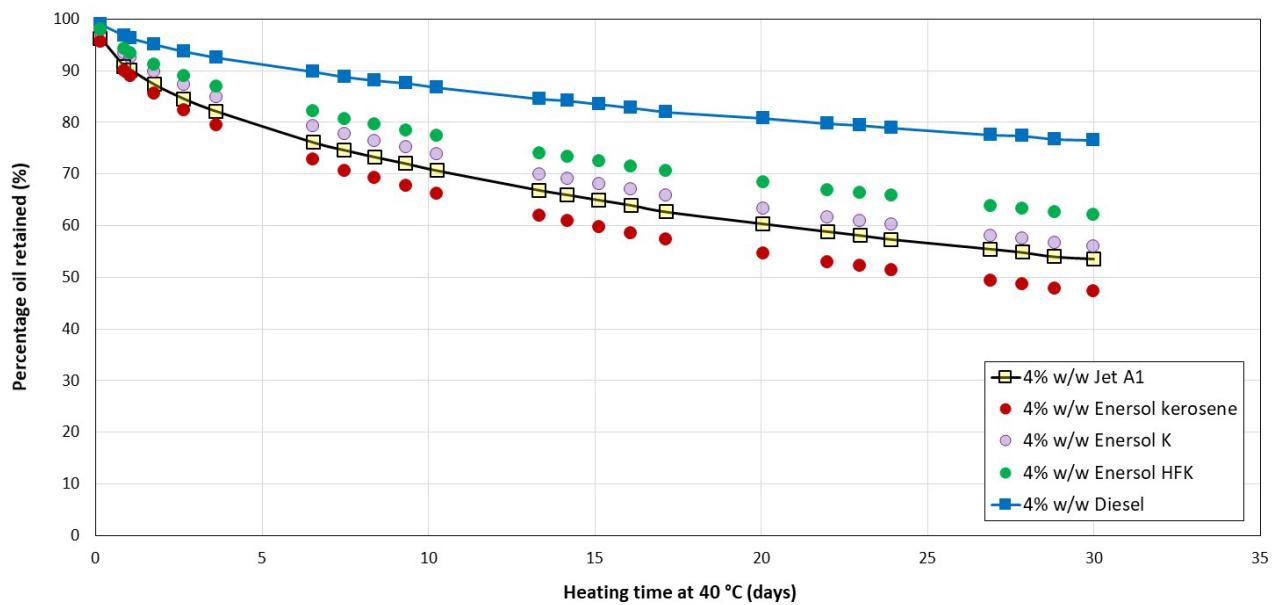


Figure A 3: Mass loss results obtained at 40 °C for films containing 6% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

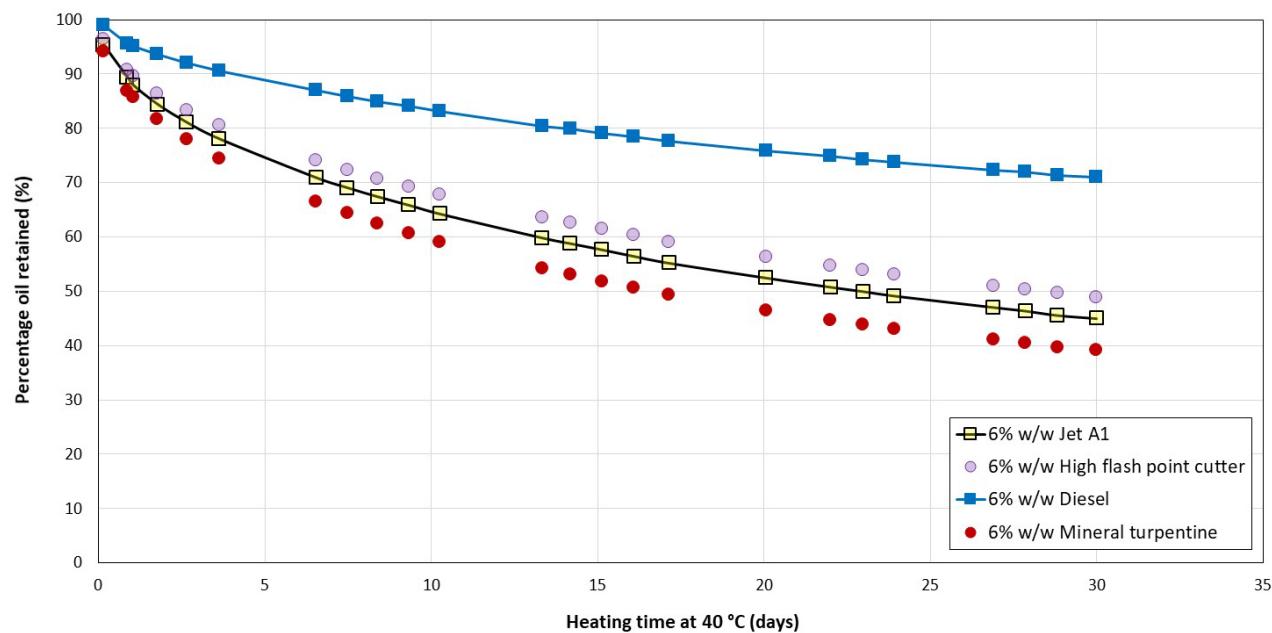


Figure A 4: Mass loss results obtained at 40 °C for films containing 6% w/w of each of the Enersol oils

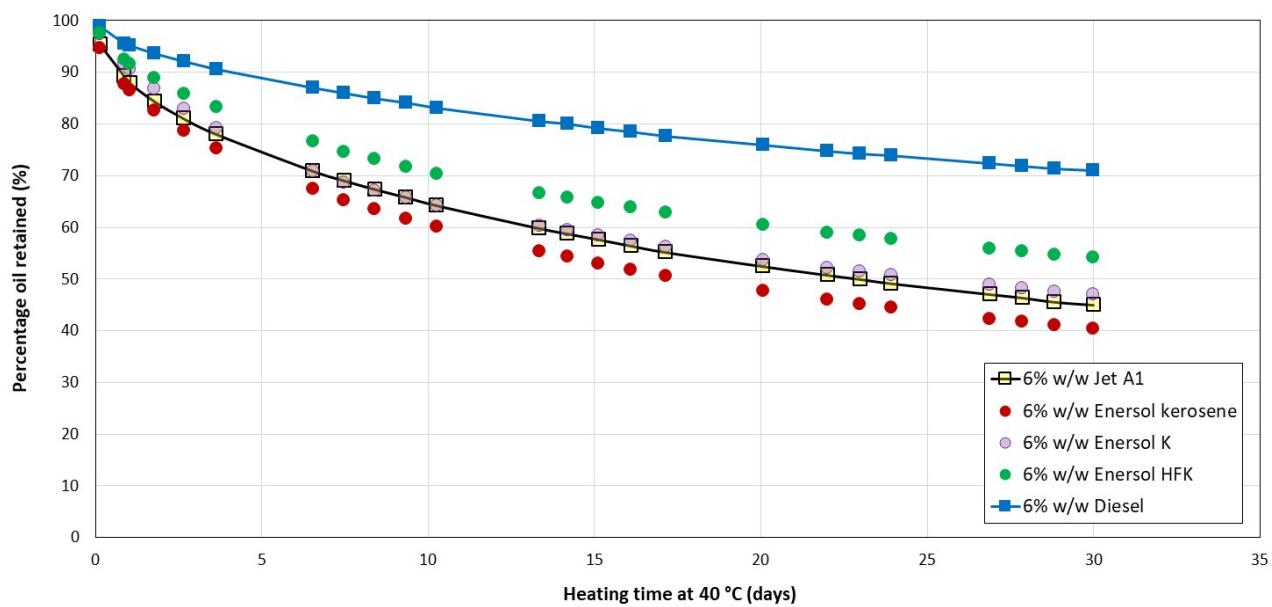


Figure A 5: Mass loss results obtained at 50 °C for films containing 2% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

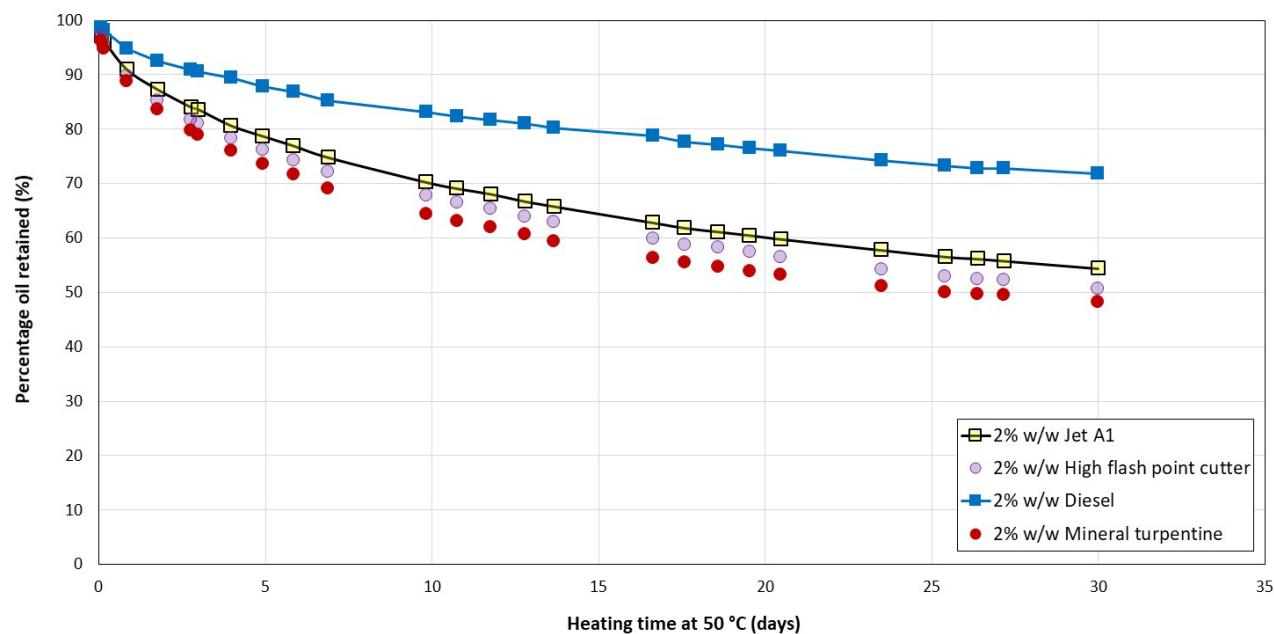


Figure A 6: Mass loss results obtained at 50 °C for films containing 2% w/w of each of the Enersol oils

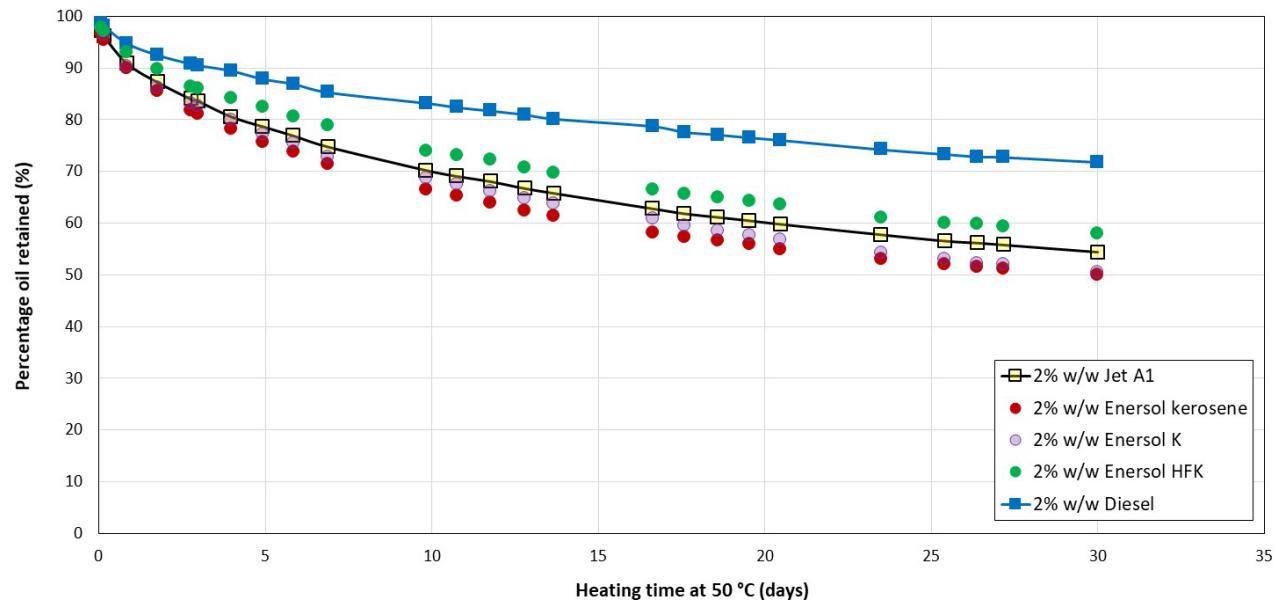


Figure A 7: Mass loss results obtained at 50 °C for films containing 6% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

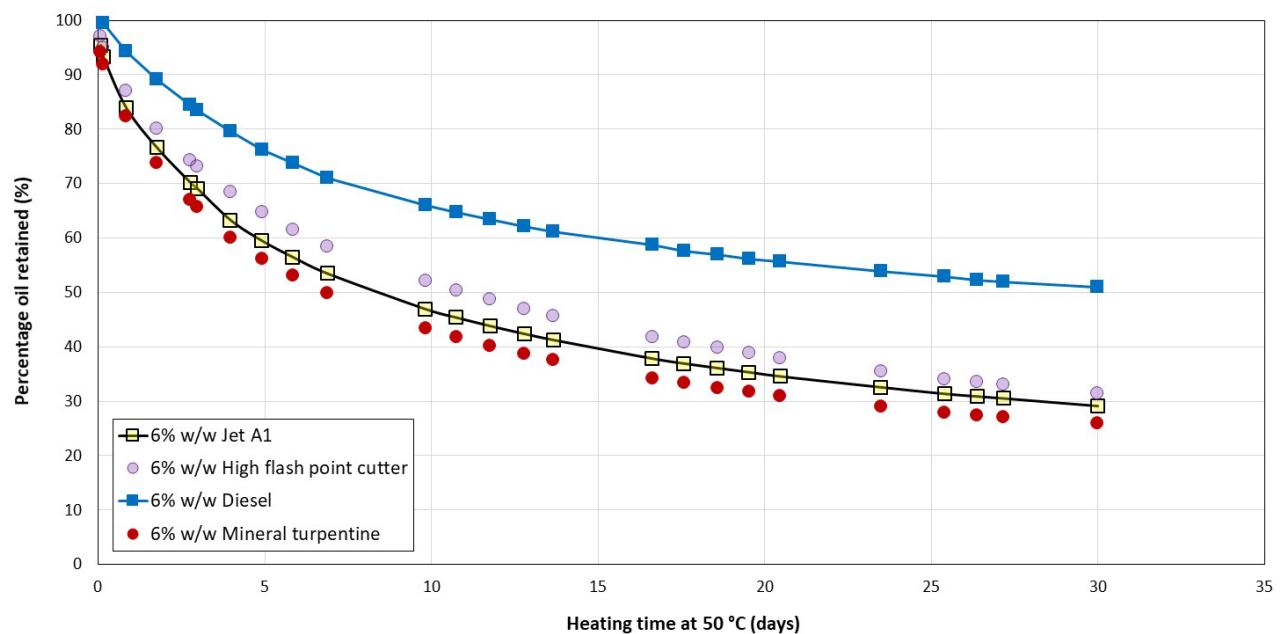


Figure A 8: Mass loss results obtained at 50 °C for films containing 6% w/w of each of the Enersol oils

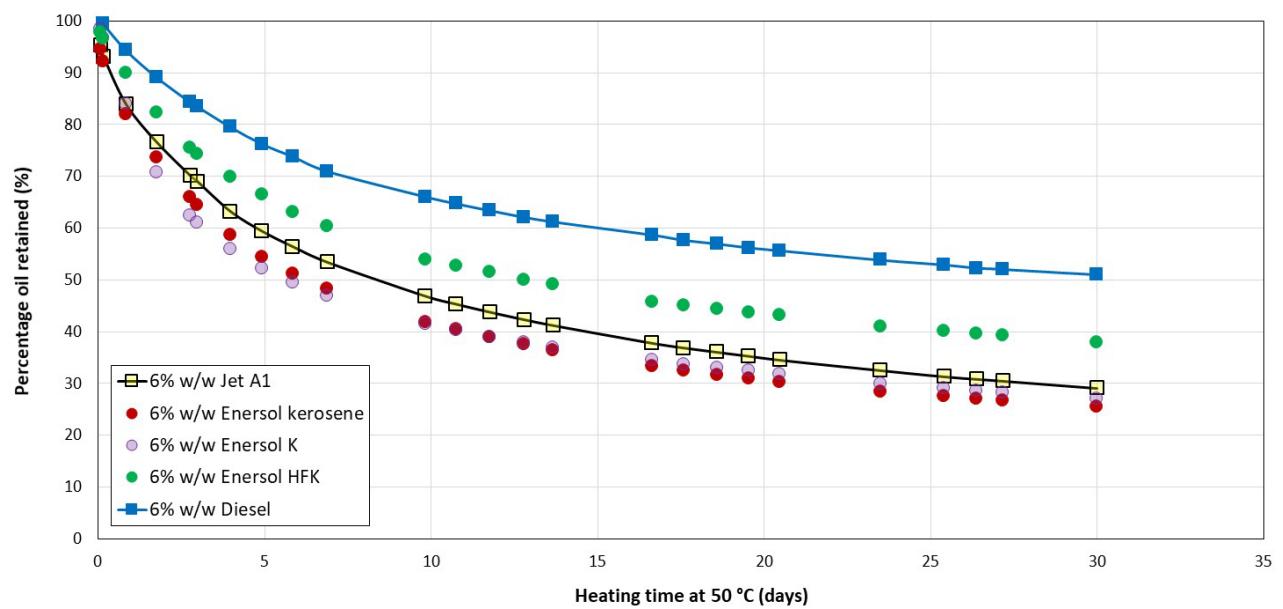


Figure A 9: Mass loss results obtained at 60 °C for films containing 2% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

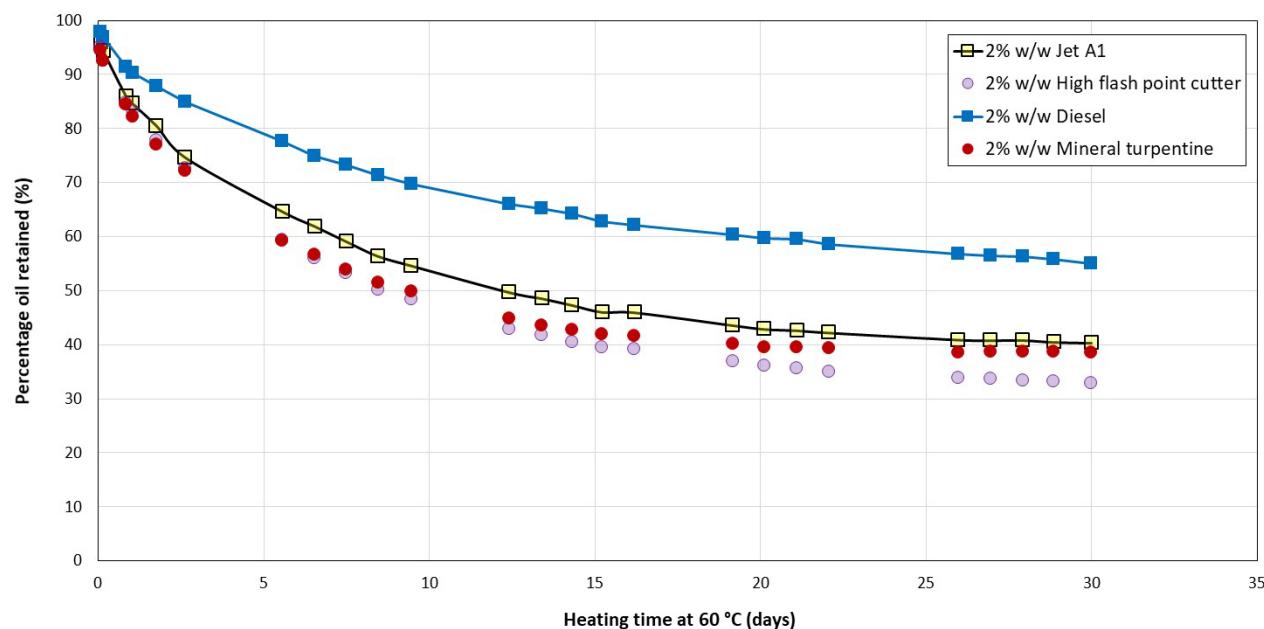


Figure A 10: Mass loss results obtained at 60 °C for films containing 2% w/w of each of the Enersol oils

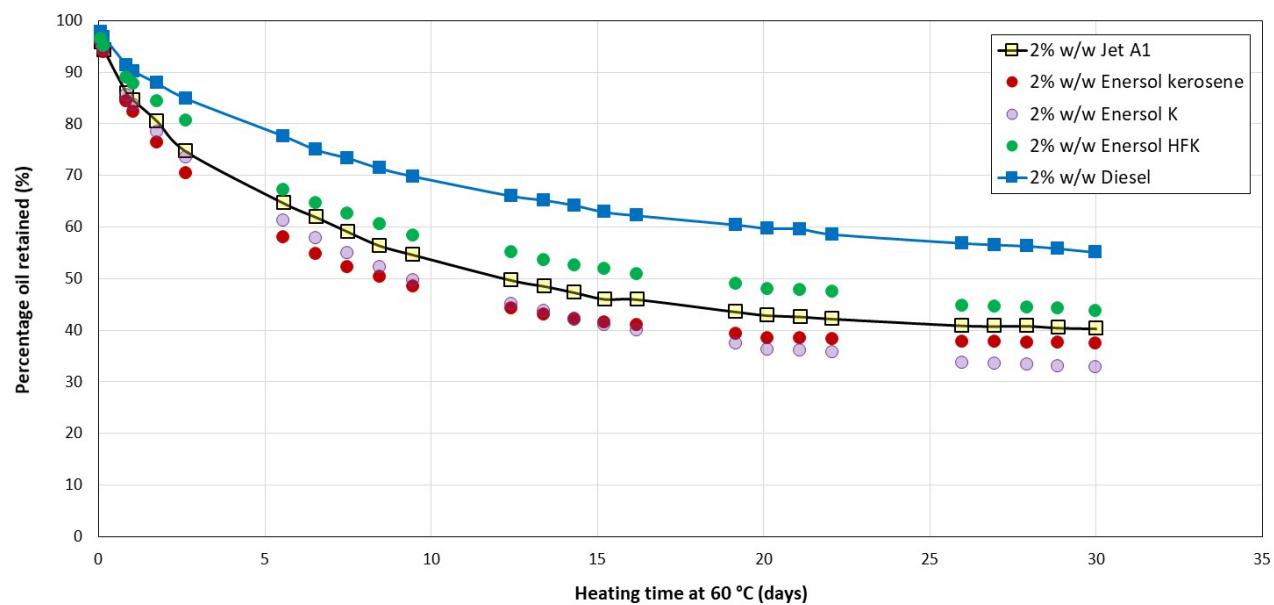


Figure A 11: Mass loss results obtained at 60 °C for films containing 4% w/w Jet A1, high flash point cutter, diesel and mineral turpentine

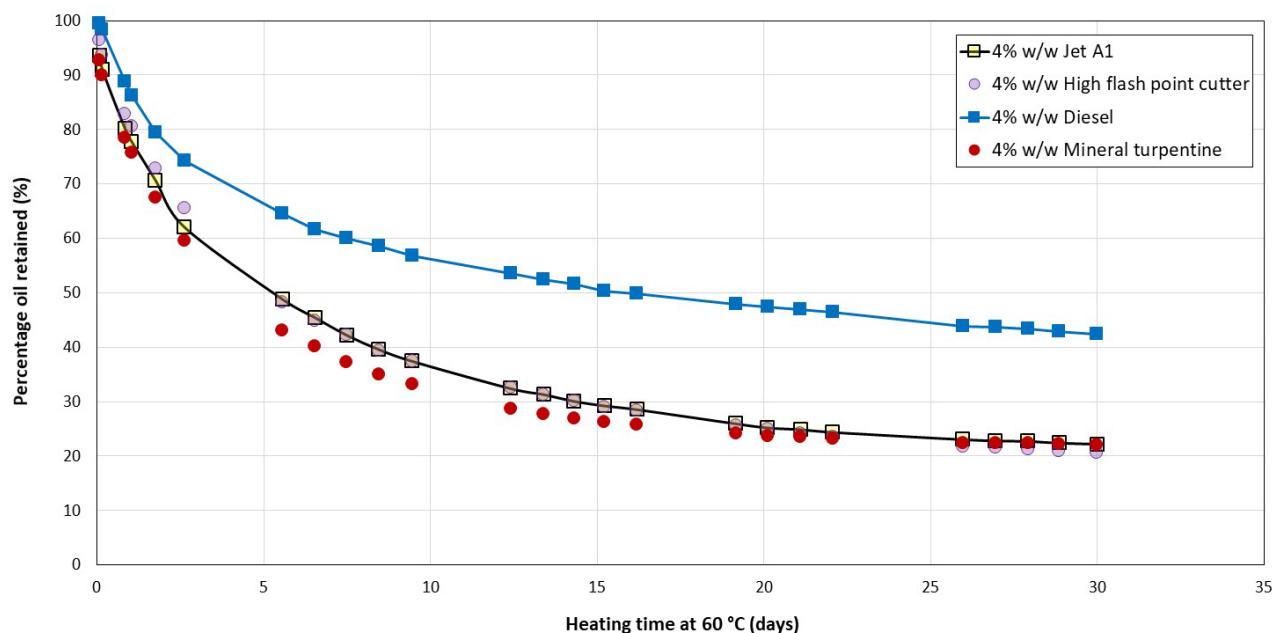
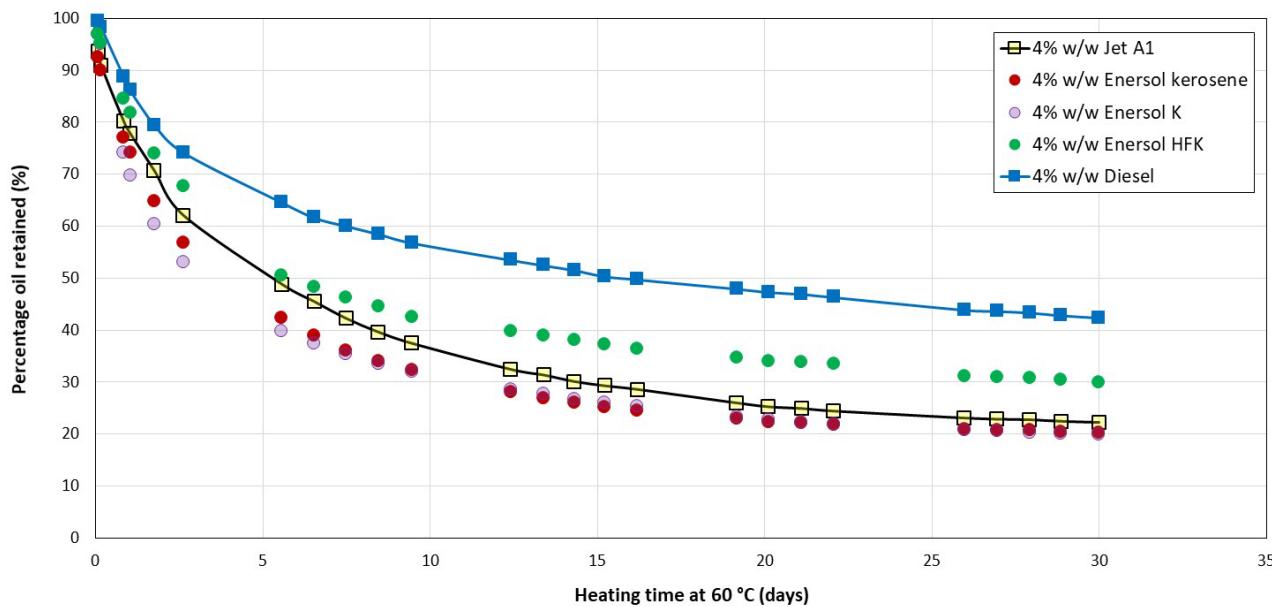


Figure A 12: Mass loss results obtained at 60 °C for films containing 4% w/w of each of the Enersol oils



Appendix B DSR Results not Included in the Main Body of the Report

Table B 1: Fitted master-curve model parameters obtained for the bitumen-oil blends

Binder description	α	β	γ	δ	a	b
C170 bitumen – test 1	52.26	-1.303	-0.1090	-37.34	0.0007803	-0.08788
C170 bitumen – test 2	52.16	-1.329	-0.1111	-37.49	0.0007724	-0.08759
2% w/w Jet A1	56.58	-1.099	-0.09255	-39.22	0.0006806	-0.07804
4% w/w Jet A1	56.12	-1.098	-0.09410	-39.35	0.0006419	-0.07126
6% w/w Jet A1	81.391	-0.9630	-0.06009	-56.57	0.0005680	-0.06572
9% w/w Jet A1	81.09	-0.9804	-0.05960	-57.14	0.0005557	-0.06122
12% w/w Jet A1	82.62	-0.9877	-0.05942	-58.85	0.0007253	-0.05372
2% w/w high flash point cutter	228.3	-2.773	-0.07786	-211.6	0.0007423	-0.07992
4% w/w high flash point cutter	229.4	-2.748	-0.07721	-212.8	0.0007437	-0.07283
6% w/w high flash point cutter	235.1	-2.782	-0.07864	-219.0	0.0007132	-0.06670
9% w/w high flash point cutter	240.2	-2.783	-0.07786	-224.3	0.0006910	-0.05938
12% w/w high flash point cutter	242.6	-2.756	-0.07564	-226.7	0.0006878	-0.05231
2% w/w diesel	196.8	-2.567	-0.07567	-179.4	0.0007256	-0.08056
4% w/w diesel	199.4	-2.584	-0.07663	-182.5	0.0007099	-0.07481
6% w/w diesel	200.3	-2.567	-0.07650	-183.5	0.0007124	-0.06965
9% w/w diesel	209.8	-2.624	-0.07785	-193.5	0.0006065	-0.06260
12% w/w diesel	214.7	-2.660	-0.07702	-198.9	0.0005987	-0.05986
2% w/w mineral turpentine	96.34	-1.646	-0.07496	-77.57	0.0006773	-0.07784
4% w/w mineral turpentine	97.93	-1.674	-0.07647	-79.77	0.0006270	-0.07030
6% w/w mineral turpentine	156.4	-1.764	-0.05004	-131.2	0.0005734	-0.06450
9% w/w mineral turpentine	157.3	-1.792	-0.05027	-133.1	0.0005838	-0.06041
12% w/w mineral turpentine	195.1	-2.530	-0.07274	-179.3	0.0007502	-0.06160
2% w/w Enersol kerosene	257.3	-2.895	-0.07626	-240.6	0.0007370	-0.07989
4% w/w Enersol kerosene	260.5	-2.864	-0.07572	-243.8	0.0007327	-0.07106
6% w/w Enersol kerosene	262.8	-2.874	-0.07618	-246.5	0.0007272	-0.06526
9% w/w Enersol kerosene	266.0	-2.853	-0.07496	-249.7	0.0007212	-0.05843
12% w/w Enersol kerosene	283.6	-3.004	-0.07994	-268.9	0.0008144	-0.05423
2% w/w Enersol K	286.0	-3.041	-0.08073	-269.8	0.0007632	-0.07906
4% w/w Enersol K	287.1	-3.033	-0.08022	-271.1	0.0007630	-0.07316
6% w/w Enersol K	300.2	-3.117	-0.08436	-285.1	0.0006814	-0.06691
9% w/w Enersol K	306.7	-3.116	-0.08327	-291.8	0.0006625	-0.05950
12% w/w Enersol K	328.7	-3.210	-0.08601	-314.5	0.0005614	-0.05250
2% w/w Enersol HFK	360.2	-3.338	-0.08352	-344.6	0.0008015	-0.08033
4% w/w Enersol HFK	368.4	-3.382	-0.08616	-353.5	0.0007719	-0.07376
6% w/w Enersol HFK	379.6	-3.429	-0.08887	-365.3	0.0007307	-0.06784
9% w/w Enersol HFK	402.4	-3.515	-0.09236	-388.8	0.0006359	-0.06083
12% w/w Enersol HFK	406.0	-3.489	-0.09011	-392.5	0.0006343	-0.05365

Table B 2: Complex viscosity results obtained from master-curve fitting of the DSR data for different bitumen-oil blends

Binder description	Parts oil in binder	Complex viscosity at 1 rad/s (Pa s)				
		22.5 °C	29 °C	35.5 °C	42 °C	45 °C
C170 bitumen	0	226 560	53 989	13 803	3 852	2 212
2% w/w Jet A1	2.69	50 419	13 110	3 712	1 157	700
4% w/w Jet A1	5.49	13 136	3 745	1 162	396	250
6% w/w Jet A1	8.42	4 032	1 259	430	161	106
9% w/w Jet A1	13.02	1 009	344	128	52.3	35.7
12% w/w Jet A1	17.97	289	100	39.7	17.8	12.8
2% w/w high flash point cutter	2.63	55 792	14 306	3 955	1 197	713
4% w/w high flash point cutter	5.37	15 848	4 322	1 285	422	262
6% w/w high flash point cutter	8.23	5 199	1 528	491	175	113
9% w/w high flash point cutter	12.73	1 228	395	140	55.0	37.2
12% w/w high flash point cutter	17.55	361	127	49.5	21.6	15.3
2% w/w diesel	2.52	70 047	17 775	4 864	1 456	863
4% w/w diesel	5.15	24 815	6 707	1 964	631	387
6% w/w diesel	7.90	9 076	2 558	787	268	169
9% w/w diesel	12.25	2 487	788	270	101	66.4
12% w/w diesel	16.87	825	278	101	40.2	27.2
2% w/w mineral turpentine	2.63	47 448	12 508	3 579	1 124	681
4% w/w mineral turpentine	5.37	11 694	3 394	1 068	368	233
6% w/w mineral turpentine	8.23	3 198	1 023	357	136	90.4
9% w/w mineral turpentine	12.75	919	313	116	47.6	32.6
12% w/w mineral turpentine	17.58	456	148	52.8	21.1	14.4
2% w/w Enersol kerosene	2.81	51 537	13 408	3 758	1 151	689
4% w/w Enersol kerosene	5.74	12 240	3 401	1 032	346	217
6% w/w Enersol kerosene	8.81	3 926	1 171	383	139	91.0
9% w/w Enersol kerosene	13.65	954	306	109	43.2	29.4
12% w/w Enersol kerosene	18.81	333	110	41.2	17.5	12.4
2% w/w Enersol K	2.69	56 274	14 177	3 858	1 153	684
4% w/w Enersol K	5.50	16 360	4 400	1 289	418	258
6% w/w Enersol K	8.42	5 389	1 590	508	178	114
9% w/w Enersol K	13.04	1 240	401	141	55.0	36.9
12% w/w Enersol K	17.99	346	126	49.8	21.4	15.0
2% w/w Enersol HFK	2.69	62 385	15 571	4 195	1 242	735
4% w/w Enersol HFK	5.48	17 809	4 798	1 401	451	277
6% w/w Enersol HFK	8.40	6 153	1 781	559	193	123
9% w/w Enersol HFK	13.02	1 512	489	170	64.7	42.8
12% w/w Enersol HFK	17.94	404	142	54.3	22.9	15.9

Table B 3: Model fitting parameters obtained when $\log_{10}(\text{complex viscosity})$ results obtained for different bitumen-oil blends were fitted to a second-order polynomial function

Binder description	Mean pavement temperature used viscosity calculations (°C)	Fitted parameters obtained by fitting the experimental data to an equation of the form $\log_{10}(\text{complex viscosity}) = ax^2 + bx + c$		
		a	b	c
Jet A1	22.5	0.004910	-0.2481	5.355
	29	0.004462	-0.2307	4.732
	35.5	0.004034	-0.2126	4.140
	42	0.003660	-0.1946	3.586
	45	0.003515	-0.1866	3.345
High flash point cutter	22.5	0.004397	-0.2359	5.355
	29	0.004258	-0.2238	4.732
	35.5	0.004098	-0.2106	4.140
	42	0.003924	-0.1966	3.586
	45	0.003684	-0.1899	3.345
Diesel	22.5	0.003612	-0.2052	5.355
	29	0.003498	-0.1942	4.732
	35.5	0.003323	-0.1821	4.140
	42	0.003100	-0.1691	3.586
	45	0.002983	-0.1630	3.345
Mineral turpentine	22.5	0.007299	-0.2816	5.355
	29	0.006517	-0.2600	4.732
	35.5	0.005720	-0.2376	4.140
	42	0.004959	-0.2152	3.586
	45	0.004633	-0.2051	3.345
Enersol kerosene	22.5	0.005021	-0.2445	5.355
	29	0.004686	-0.2305	4.732
	35.5	0.004350	-0.2155	4.140
	42	0.004030	-0.1997	3.586
	45	0.003891	-0.1923	3.345
Enersol K	22.5	0.003924	-0.2265	5.355
	29	0.003926	-0.2162	4.732
	35.5	0.003869	-0.2047	4.140
	42	0.003752	-0.1922	3.586
	45	0.003677	-0.1861	3.345
Enersol HFK	22.5	0.003551	-0.2160	5.355
	29	0.003508	-0.2057	4.732
	35.5	0.003447	-0.1948	4.140
	42	0.003359	-0.1833	3.586
	45	0.003307	-0.1777	3.345

Note: All fits yielded an R^2 value of 0.999 or greater.

Appendix C Aggregate Wetting Results Not Included in the Main Body of the Report

Figure C 1: Aggregate wetting test results obtained for films containing C170 bitumen and different levels of high flash point cutter

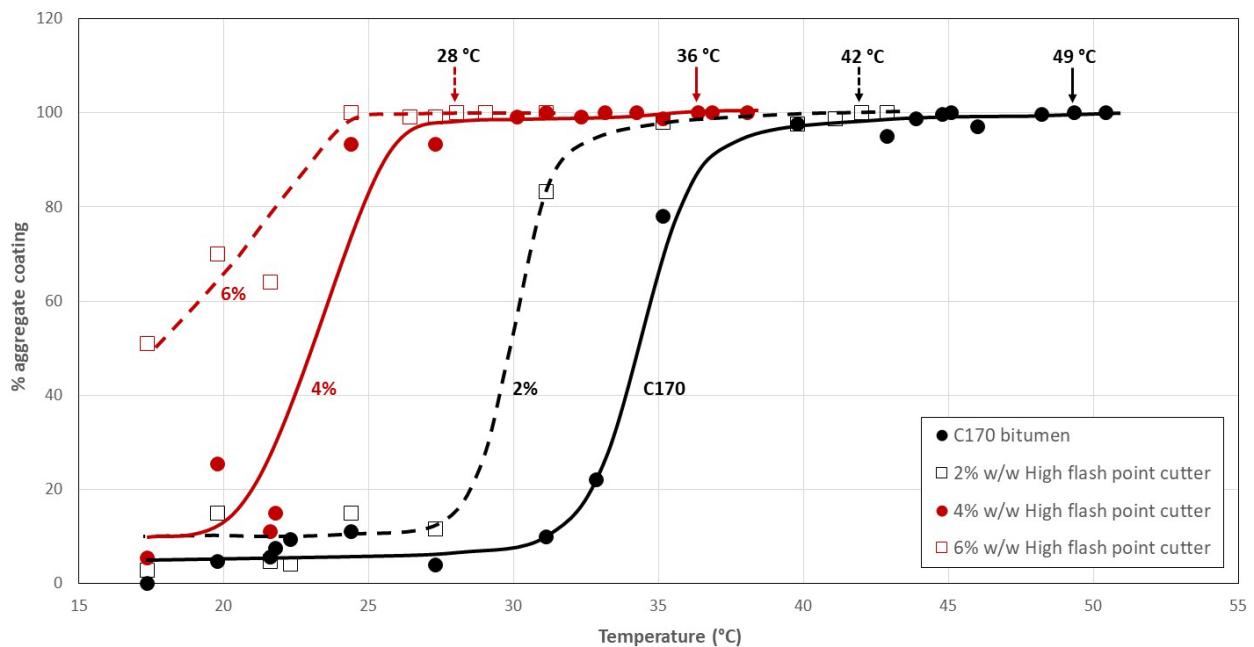


Figure C 2: Aggregate wetting test results obtained for films containing C170 bitumen and different levels of diesel

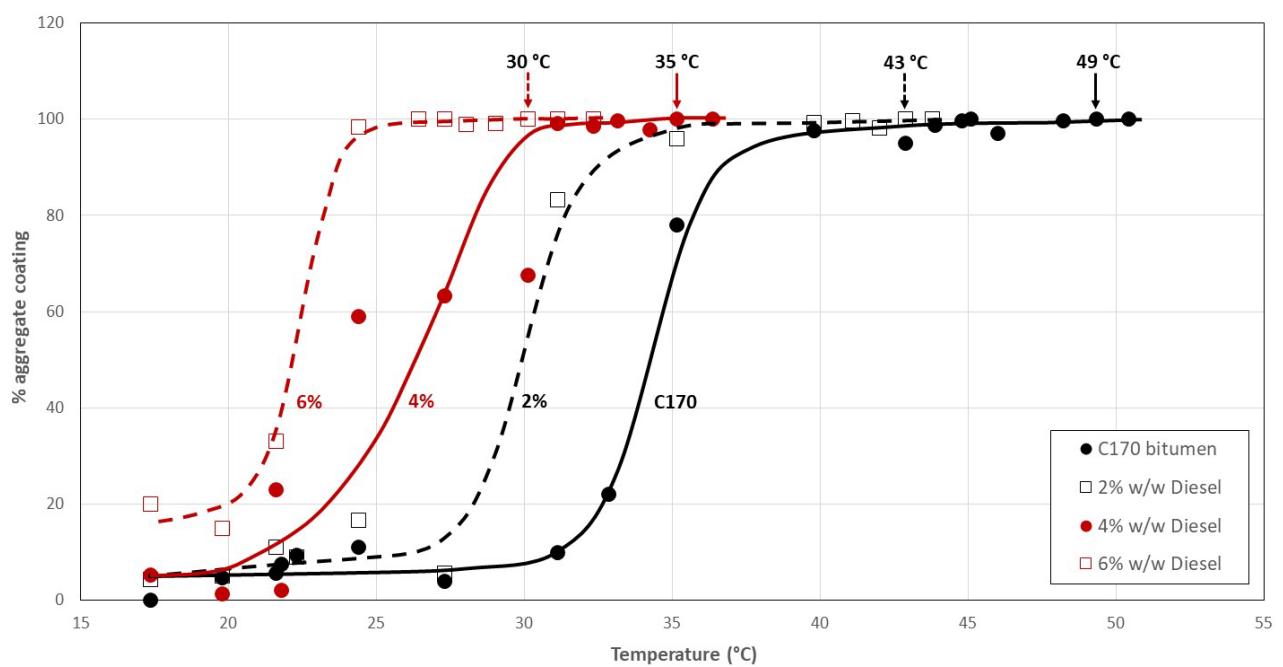


Figure C 3: Aggregate wetting test results obtained for films containing C170 bitumen and different levels of mineral turpentine

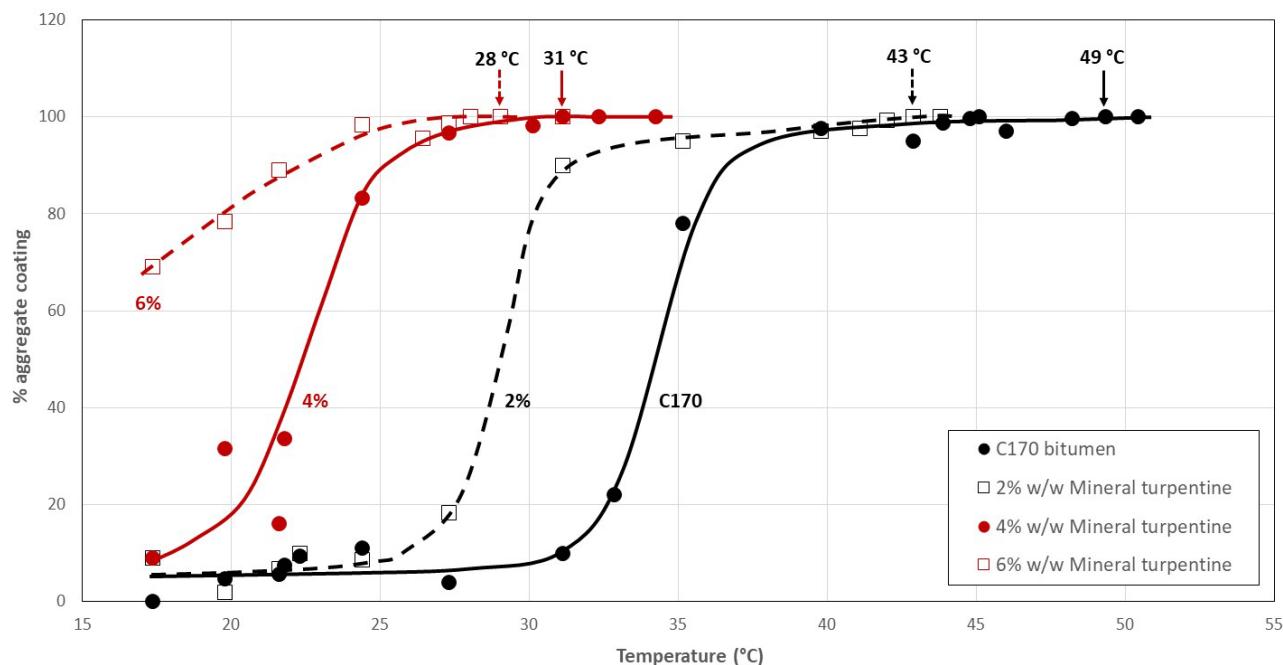


Figure C 4: Aggregate wetting test results obtained for films containing C170 bitumen and different levels of Enersol kerosene

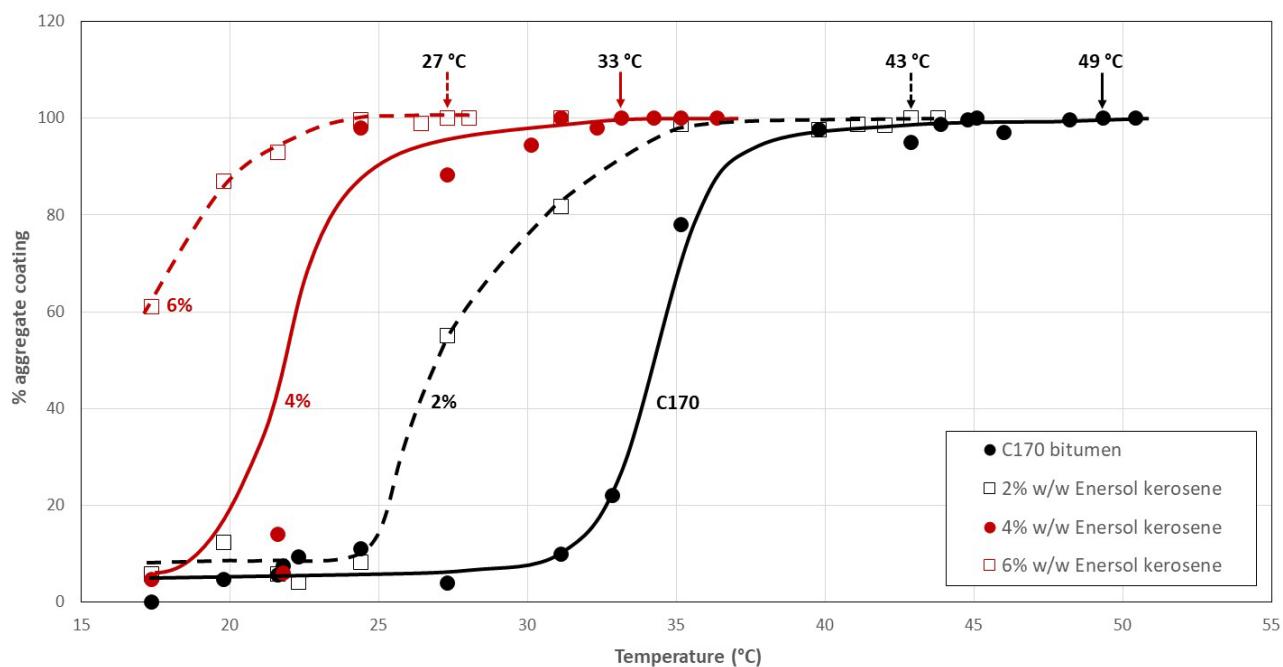


Figure C 5: Aggregate wetting test results obtained for films containing C170 bitumen and different levels of Enersol K

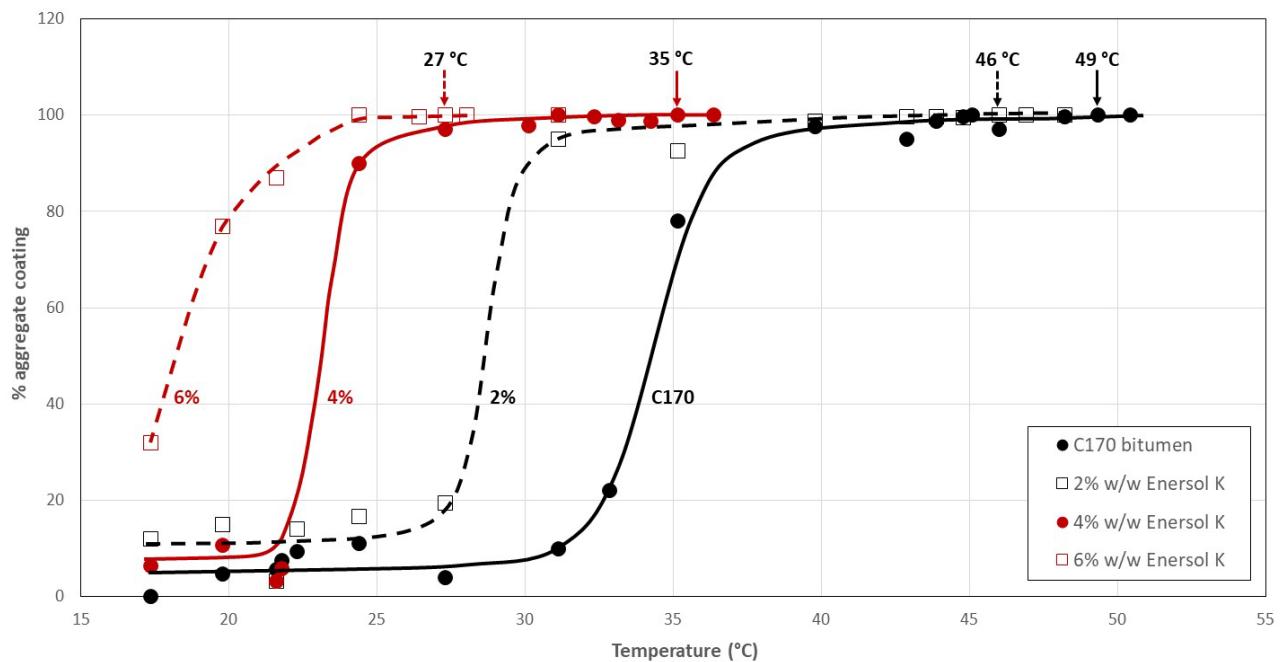
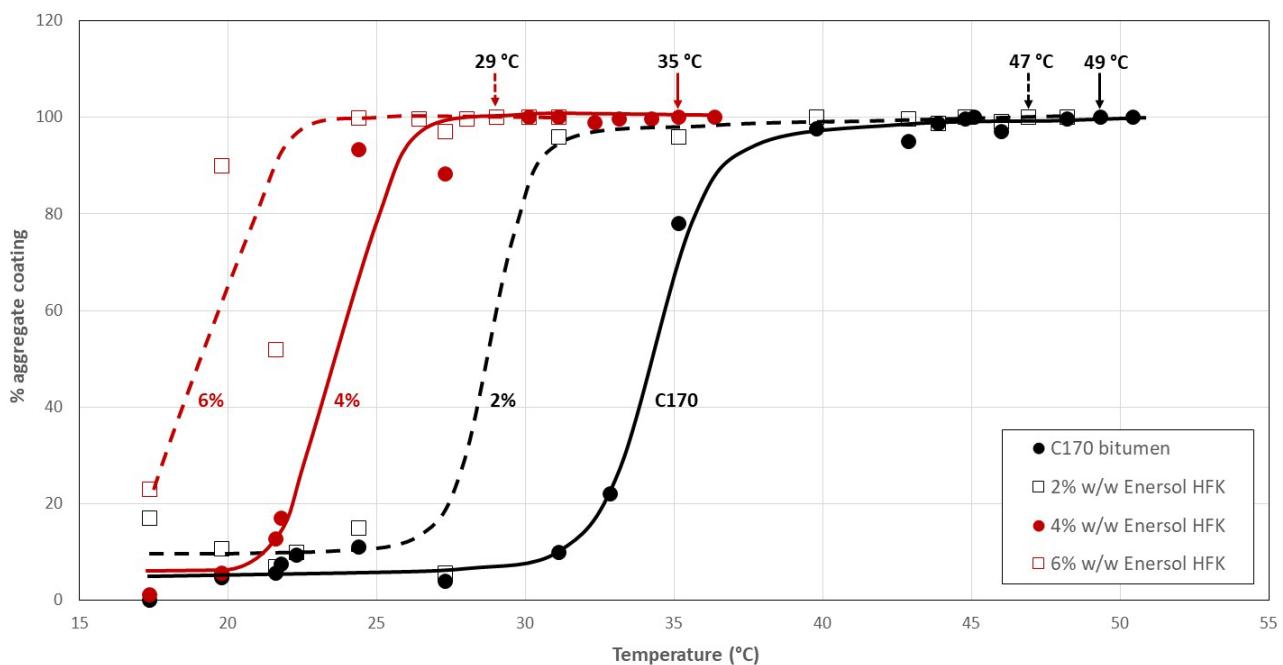


Figure C 6: Aggregate wetting test results obtained for films containing C170 bitumen and different levels of Enersol HFK





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