Performance benefits of polymer modified bitumen binders for thin surfacings

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Executive summary

Polymer modified binders (PMBs) are often used in thin asphalt and chipseal surfacings with the aim of reducing temperature susceptibility and providing improved performance compared with conventional bitumens. Improved performance benefits claimed for the use of PMB modified thin surfacings include reduced rutting and fatigue cracking in dense asphalt, reduced chip loss in chipseals and open graded porous asphalts (OGPA), reduction in reflective cracking in both dense mix and seals and hence improved waterproofing, and reduced flushing in seals.

Modified bitumen binders are considerably more expensive than conventional binders, and it is important that the predicted benefits of their use in New Zealand can be demonstrated to justify the extra costs associated.

The aim of this research was to try to identify field data from New Zealand and overseas that supported the expected performance enhancements gained from using PMBs in thin surfacings.

A wide variety of polymer types are used worldwide for bitumen modification. The use and specification of PMBs internationally was reviewed and compared with practice in New Zealand. In New Zealand and internationally elastomeric polymers (typically SBS, SBR type), at 3–5% concentration are the most widely used. Internationally the use of crumb rubber from recycled tyres is also very common. Crumb rubber has been employed in New Zealand on occasion over the past few decades but is not currently in use. New Zealand also differs from many international jurisdictions where roading authorities provide specifications or guidance on selection and appropriate use of PMBs in surfacings. In New Zealand, the physical requirements for PMBs are usually based on softening point and torsional recovery and limits are set based on past experience but the NZ Transport Agency does not have a specification for PMBs.

There is a large body of laboratory work demonstrating the beneficial effects of polymer modification on the physical behaviour of asphalt mixes and to a lesser extent chipseal surfacings, for example the use of wheel tracking experiments to confirm that PMB mixes are less susceptible to rutting. The findings from such studies are often used to support claims of improved performance in the field, although the loading conditions and other experimental variables employed in laboratory testing are known to differ substantially from those occurring in practice. A review of laboratory work on PMBs was beyond the scope of the current project. Instead the literature was searched for evidence from field trials and field data in general that supported the supposed benefits of PMBs in thin asphalt and chipseal surfacings.

Given that PMBs have been widely used in surfacings for over 40 years the number of controlled trials reported were relatively few, especially in the case of chipseal surfacings. Comparison of different studies is also very difficult in that important details such as underlying pavement condition, climate and traffic levels, which can have an important effect on performance, are often not reported. Further detailed information of the type, composition and sometimes even the concentration of the polymers used is usually not provided.

Evidence from studies of the behaviour of thin asphalt surfacings is often contradictory with many reporting no clear difference between the performance of PMB and unmodified binders. Most studies relied on a mixture of quantitative measurements (eg for rutting) and visual assessments to arrive at an overall performance rating, and the majority focused on early life (< five years) behaviour. A major study, conducted in the USA, combined data from other earlier studies including field trial data and long term pavement performance (LTPP) sites. It concluded that PMBs did provide significant improvements in surface life of up to potentially 10 years depending on the underlying pavement condition and climate factors. On balance there appears to be a good body of evidence supporting anecdotal observations that

PMBs provide significant benefits to thin asphalt surfacings compared with unmodified binders (site and construction variables being equal)).

The potential benefits of PMBs in chipseals include better chip retention and reduced flushing and bitumen tracking, but there have been only a few reported investigations where the field performance of PMB seals has been compared with control sections using unmodified binders. These studies show only a relatively small benefit from the use of PMB binders based on early life performance. In New Zealand (and internationally), PMB seals tend to be employed in higher traffic volume/stress sites or on sites where the pavement condition is poorer so that over the network as a whole there is insufficient data for meaningful direct lifetime comparison with unmodified binders with equivalent site variables.

Abstract

Research was undertaken at WSP Opus Research in 2018 to investigate evidence from field studies supporting the performance benefits of polymer modified binders (PMBs) in thin asphalt and chipseal road surfacings. Improved performance benefits claimed for the use of PMB modified thin surfacings include reduced rutting and fatigue cracking in dense asphalt, reduced chip loss in chipseals and open graded porous asphalts and reduced flushing in seals.

The use and specification of PMBs internationally was reviewed and compared with practice in New Zealand. New Zealand follows international practice in that elastomeric polymers (typically SBS, SBR type), at 3–5% concentration are most widely used. In New Zealand, the physical requirements for PMBs are usually based on softening point and torsional recovery and limits are set based on past experience but contrary to many overseas jurisdictions the NZ Transport Agency does not have a specification or provide any formal guidance for the use of PMBs.

Although site and construction variables can have a significant influence on performance, there exists a good body of evidence supporting anecdotal observations that PMBs provide significant benefits to thin asphalt surfacings compared with unmodified binders. In contrast there is very little data available from field studies showing significant improvements in chipseal performance from use of PMBs.

1 Introduction

Polymer modified binders (PMBs) are often used in thin asphalt and chipseal surfacings with the aim of reducing temperature susceptibility and providing improved performance compared with conventional bitumens. The presumed benefits gained by polymer modification in New Zealand are usually based on qualitative assessment, past experience or overseas practice.

Modified bitumen binders are considerably more expensive than conventional binders, and it is important that the predicted benefits of their use in New Zealand can be demonstrated to justify the extra costs.

The principal aim of this research was to try to identify quantitative data from New Zealand and overseas that supported the expected performance enhancements gained from using PMBs in thin surfacings. In the present context performance relates to resistance to physical damage such as rutting, cracking and chip loss, not other functionality such as skid resistance or permeability (in the case of porous surfacings).

The key objectives of the research were:

1. To determine international practice in the use and specification of PMBs and how this compares with New Zealand practice.
2. To identify quantitative evidence supporting the performance benefits of PMBs in chipseals and thin asphalt surfacings, including open graded porous asphalt (OGPA) and stone mastic asphalt (SMA), in comparison with non-PMB surfacings, and drawing on international and local experience and research.

2 Polymer modified bitumen

Polymer modified binders (PMBs) are made up of a bituminous binder and a small amount of added polymer (typically up to 5 wt% but more usually 3–4 wt%). Depending on the type and concentration, the polymer additive changes the properties of the binder resulting in (among other changes): greater elastic recovery, higher softening point, greater viscosity, greater cohesive strength and greater ductility (Yildirim 2007).

Modification of tars and pitches involving natural and synthetic polymers was patented as early as 1843; however, it was not until the 1950s that PMBs were used on a commercially large scale when Neoprene latex began to be used in North America. By the 1980s, new polymers were being developed for bitumen modification and were being used in both Europe and in the US (Yildirim 2007).

There are two main families of polymers currently used in roading applications: plastomers and elastomers (examples are listed in table 2.1). In general plastomers act to increase the viscosity and stiffness of the bitumen at service temperatures but have a lesser effect on binder elasticity. Elastomers impart both viscous and elastic properties to the bitumen binder (Awwad and Shbeeb 2007). Elastomer modified bitumens exhibit greater recovery upon unloading than the original bitumen.

In both the USA and Europe, a wide range of other polymers also find application as shown below. Some polymers are also used in combination. For example, polyethylene (PE) is often used in conjunction with elastomers such as polybutadiene (PBD) in order to prevent or retard segregation of the dispersed PE particles (Morrison et al 1994). Other specialist polymer types such as epoxy resin modified binders find niche application in bridge deck surfacings for example, but are used in relatively small quantities due to the high costs.

Table 2.1 Types and classification of polymer modifiers (adapted from King and Johnston 2012)

Polymer type	Examples	Classification
Natural rubber (Homopolymers)	Natural rubber Polyisoprene Isoprene Natural rubber latex	Thermoset elastomers
Synthetic latex/rubber (random copolymers)	Styrene-butadiene rubber (SBR) Polychloroprene latex (neoprene) Polybutadiene (PBD) Styrene	Thermoset elastomers
Block copolymers	Styrene-butadiene-styrene (SBS) Styrene-isoprene-styrene Styrene-butadiene (SB) diblock Acrylonitrile-butadiene-styrene Reactive-ethylene-terpolymers	Thermoplastic elastomers
Reclaimed rubber	Crumb rubber modifiers (CR)	Thermoset elastomer
Plastics	Low/high density polyethylene (LDPE, HDPE) Ethylene acrylate copolymer Ethyl-vinyl-acetate (EVA)	Thermoplastic plastomers

Polymer type	Examples	Classification
	Polyvinyl chloride Ethylene-propylene-diene-monomer (EPDM) Ethyl-methacrylate (EMA) Ethyl-butyl-acrylate	

Thermoplastic elastomers are the most commonly used polymers as bitumen modifiers in the road construction industry, with the most common of those being the SBS copolymer (Hunter et al 2015; Saba et al 2012; Vonk and Gooswilligen 1989).

PMBs are used in hot binder applications as in asphalt manufacture and cut-back bitumen sealing but are also used in emulsified form. There are two distinct approaches using polymer modified emulsions (PME) for roading applications:

1. PME are mixtures (co-emulsions) of a bitumen emulsion with an emulsified polymer (for instance, latex)
2. Polymer modified bitumen emulsion is an emulsion of a PMB.

3 International practices and specifications

Generally construction of both asphalts and chipseals using PMBs needs to be undertaken with more care than construction using un-modified bitumen. Under certain conditions, asphalt mixtures containing PMBs can be difficult to compact, as they are in general more viscous than conventional binders particularly at rolling and compaction temperatures. This difficulty in compaction can lead to excessive in-situ air voids, resulting in reduced durability due to the acceleration of oxidation (ageing) and water ingress (moisture damage) (Artamendi et al 2016).

Chipseals constructed using PMBs can suffer from poor adhesion of the binder to the chip. This risk is reduced through the use of PMB emulsions.

A summary of international practice in the use and specification of PMBs is presented below.

3.1 Australia

In Australia, the principal polymer types employed are SBS, PBD, EVA and crumb rubber. Australia has been using PMBs in pavement construction since the early 1980s, when PMBs were marketed for use in Australian pavements (Austroads 1992; Oliver 1983). These were initially based on ‘scrap rubber’, and later synthetic elastomers and plastomers (Oliver 1983). The result of this development was that the use of PMBs was largely dictated by supply (ie what was offered and available) rather than demand (ie what was needed) and individual states devised their own specifications that largely reflected what was available in the marketplace (Booth et al 1995; Oliver 1990). At that stage, the specifications did not distinguish between the use of PMB for sprayed seal or for asphalt.

The first Austroads PMB specification was published in 1992 and distinguished between asphalt and sprayed seal use (Austroads 1992). This was followed later by specification of properties (Austroads 1996; Austroads 1997), rationalisation of the number of grades available in 2000 (Austroads 2000a) and reduced yet again in 2006 (Austroads 2006). Upper and lower bands were placed on some test properties in 2010 (Austroads 2010a), and the introduction of consistency 6% to replace viscosity at 60ºC in 2014 (Austroads 2014).

Table 3.1 Development of the Austroads PMB specification

Pre 1990 Recipe	1992 Typical (APRG 7)	1997 Specified (APRG 19)	2000 Rationalised (AP-T04-00)	2006 Rationalised (AP-T41-06)	2010 Banded (AG:PT/T190)	2014 Consistency 6% (AG:PT/T190)
Sealing grades						
3% SB[a]	SB3	S10E	S10E	S10E	S10E	S10E
4% SBS	SB4	S15E	S15E	-	S15E[b]	S15E[b]
5% SBS	SB5	S20E	S20E	S20E	S20E	S20E
6% SBS	SB6	S25E	S25E	S25E	S25E	S25E
7% SBS	SB7	S30E	S30E	-	-	-
3% PBD[c]	(SB3A in SA only)	S35E	S35E	S35E	S35E	S35E
5 parts (4.8%) CR[d]	SR5	S40R	S40R			
18 parts (15%) CR[d]	SR15	S45R[e]	S45R	S45R S15RF[f]	S45R S15RF	S45R S15RF
20 parts (17%) CR[d]	SR17	S50R	S50R	S18RF[f]	S18RF	
25 parts (20%) CR[d]	SR20	S55R	S55R	S55R	(S20RF in NSW only)	

Pre 1990 Recipe	**1992 Typical (APRG 7)**	**1997 Specified (APRG 19)**	**2000 Rationalised (AP-T04-00)**	**2006 Rationalised (AP-T41-06)**	**2010 Banded (AG:PT/T190)**	**2014 Consistency 6% (AG:PT/T190)**
30 parts (25%) CR[(d)]	SR25	S60R				
			Asphalt grades			
	AB1	A25E	A25E	A25E	A25E	A25E
EVA	AB2	A35P	A35P	A35P	A35P	A35P
EVA/EMA	AB3	A30P	A30P	-	-	-
4% SBS	AB4	A20E	A20E	A20E	A20E	A20E
5% SBS	AB5	A15E	A15E	A15E	A15E	A15E
6% SBS	AB6	A10E	A10E	A10E	A10E	A10E
5 parts CR	AB25	A40R	A40R			
35 parts (25–30%) CR			A27RF	A27RF	A27RF	A27RF[(g)]

Notes: [(a)] Styrene butadiene; [(b)] Properties for S15E post 2010 are experimental, and are to be regarded as trial values for such period until manufacturing capabilities are proven; [(c)] Polybutadiene; [(d)] Parts of crumb rubber (CR) to 100 parts of bitumen (by mass at 15°C), and % of crumb rubber as total binder (by mass at 15°C); [(e)] R = crumb rubber modified, factory blend; [(f)] RF = crumb rubber modified, field produced; [(g)] Specification for two grades of crumb rubber (Size 16 and size 30) are available

Table 3.2 Properties specified in Australian PMB specification (Austroads 2014)

Test	Units	Method	Parameters
Compression limit	mm	AGPT/T132	70°C, 2 kg, 3-monthly, crumb rubber only
Consistency	Pa.s	AGPT/T121	60°C, 3-monthly
Consistency 6%	Pa.s	AGPT/T121	60°C, 3-monthly, TBR
Elastic recovery	%	AGPT/T121	60°C, 100 s, 3-monthly
Flash point	°C	AGPT/T112	annually
Loss on heating	% mass	AGPT/T103	annually
Rubber content	%	AGPT/T142	Weekly, crumb rubber only
Segregation	%	AGPT/T108	3-monthly
Softening point	°C	AGPT/T131	C, each batch
Stiffness	kPa	AGPT/T121	15°C, 3-monthly, sprayed seal binders
Stiffness	kPa	AGPT/T121	25°C, 3-monthly, asphalt binders
Torsional recovery	%	AGPT/T122	25°C, 30 s, each batch
Viscosity	Pa.s	AGPT/T111	165°C, each batch

The current specification framework for PMBs, AGPT/T190 (Austroads 2014), is very detailed. It is based on a number of test procedures and limit values that have been in use for a number of years. Its purpose is to achieve a consistent performance for both chipseal and asphalt surfacings. This document outlines both specifications for PMBs and crumb rubber. It contains four tables outlining the specifications for each type of seal and type of PMB:

- PMBs for sprayed sealing
- PMBs for asphalt sealing
- field produced crumb rubber binders
- requirements for crumb rubber.

Tables detailing the testing framework can be found in appendix A.

A second document: AP-T235-13 (Austroads 2013) outlines a selection of PMBs for different treatments and surface conditions to assist in the use of the above specification document AGPT/T190 (Austroads 2014).

3.2 South Africa

In South Africa approximately 150,000 km of roads have bituminous surfacings. Of this total 80% are chipseals and at least 70% of reseals make use of PMBs (Louw 2008). PMBs are not commonly used for first coat seals. In an earlier paper Rossmann (2000) provides a different estimate, based on an industry questionnaire, that estimates around 58% of seals involve the use of PMBs. The principal polymer types used in spray seals are SBS (20%), SBR (8%) and crumb rubber (16%) (Distin 2008). PMBs for sealing are usually applied as hot binders with 3–5% polymer content in the case of SBS and SBR types and 20–24% in the case of crumb rubber modifiers (Distin 2008). However, Rossmann estimates that in both chip/spray seals and asphalts the distribution of polymer use is 16% SBS, 26% SBR and 35% crumb rubber. The proportion of PMB seals laid in South Africa is far higher than used in New Zealand where PMB seals which make up around 10% of the network (Towler et al 2010).

In South Africa the specifications and requirements for the use of PMBs are set out in the document ‘TG1’. The specification framework can be found in appendix A, tables A.5 to A.11. This document ensures that the consistency and rheological properties of the binder are appropriate for a variety of service conditions of traffic and climate and that the performance characteristics are met and not compromised during application (SANRAL 2013).

Table 3.3 Properties of hot applied polymer modified binders for surfacing seals from TG1 (Asphalt Academy 2007)

Test	Units	Method	Parameters
Elastic recovery	%	MB-4	15°C
Elastic recovery	%	MB-4	15°C after rolling thin film oven test (RTFOT)
Force ductility	Newtons	EN 13703	5°C
Flash point	°C	ASTM D93	
Loss on heating	% mass	MB-3	After RFTO
Softening point	°C	MB-17	
Softening point Diff	°C	MB-17	After RFTO
Storage stability	°C	MB-6	160°C
Dynamic viscosity	Pa.s	MB-18	165 C

A technical guidance document provides advice on the construction of PMB seals in South Africa (Asphalt Academy 2007). Consideration of the following issues is recommended: Weather conditions:

- Do not spray if there is a threat of rain, or windy conditions (wind chill causes a skin to form on the PMB).
- The substrate needs to be completely dry. If there is the risk of showers, consider postponing sealing operations.
- Pavement and air temperatures should be at least 25°C and rising prior to spraying.
    - Spray run lengths: reduce the length of spray runs compared with conventional binders, as aggregate spreading and rolling must be carried out as soon as possible after spraying of the binder.
    - Shady areas: commence the spray run in these areas, thereby minimising the time delay for aggregate spreading and rolling.
    - Cutter: where cutter has been added to the PMB, the road should be closed to traffic overnight, and rolling continue next morning.

3.3 UK/Europe

In Europe, as at 2009, polymer modified bitumen consumption was 1.5 million tonnes (Mt) out of 16.6 Mt total bitumen consumption. The remainder was made up of 13.8 Mt unmodified paving grade bitumen and 1.2 Mt was used for industrial purposes (Planche 2011). Hence on average about 10% of bitumen for paving applications involved the use of PMB. Also, Zhu et al (2014) quote a figure of <20% of total bitumen being polymer modified based on data released by the European Asphalt Association. The main polymer types used were thermoplastic elastomers, principally SBS and SBR typically at 3.5% loading by weight. Plastomers such as EVA are still used but the majority of the market is dominated by elastomers. King and Johnston (2012) state that worldwide, elastomeric polymers account for 75% of polymers used for bitumen modification (not including crumb rubber).

The current UK and European specification framework is *BS EN 14023:2010: Framework standard for polymer modified binders* (British Standards 2010) This standard outlines the characteristics and specifications required for polymer modified bitumens for use in the construction of roads (European Committee for Standardization 2010). The specification frame work is detailed in appendix A and outlines the following characteristics:

- consistency at service temperature
- consistency at elevated service temperature
- cohesion
- durability
- brittleness at low service temperature
- strain recovery.

Table 3.4 Selected parameters from the European/UK polymer modified bitumen framework specifications (European Committee for Standardisation 2010)

	Test	Units	Method	Parameters
	Penetration	0.1 mm	EN 12607-1	25℃
	Penetration	0.1 mm	EN 1426	After RTFOT
	Softening point diff	°C	EN 12607-1	
	Softening point	°C	EN 1426	After RTFOT
	Flash point	°C	EN ISO 2592	
Cohesion testing	Force ductility	J/cm^3	EN 13589 then EN 13703	Either 0, 5, 10, 15, 20 or 25 °C 50 mm/min traction
Resistance to hardening	Loss on heating	% mass	EN 12607-1	
Regional requirement	Elastic recovery	%	EN 13398	10 or 25°C
Additional properties	Storage stability – difference in softening point	°C	EN 13399 EN 1427	After RFTOT
	Storage stability – difference in penetration	0.1 mm	EN 13399 EN 1426	

3.4 USA

In the USA elastomers (principally SBS) are the most commonly used polymer modifier at concentrations of 1–5%. In both the USA and Europe a wide range of other polymers, however, also find application and some polymers are also used in combination. For example polyethylene is often used in conjunction with elastomers such as PBD in order to prevent or retard segregation of the dispersed PE particles (Morrison et al 1994). Other specialist polymer types such as epoxy resin modified binders find niche application in bridge deck surfacings, for example, but are used in relatively small quantities.

Multiple specifications for bitumen are used in the USA by different states, including performance and older viscosity-based specifications. These do not specifically include polymer grades or types and often additional tests are employed to confirm the presence of polymers as required. Crumb rubber modified bitumens are an exception and have had a dedicated specification (ASTM D6114), until it was withdrawn in 2018.

The older American performance-based specification is AASHTO M320. A revised performance-based specification (AASHTO M332) based on the multiple stress creep recovery (MSCR) test, has also been released and adopted by some states (and New Zealand). Both standards cover the specification of asphalt binders graded by performance but do not distinguish polymer modified bitumens from standard bitumens (or bitumens modified by other means such as phosphoric acid). The term asphalt binder applies to the petroleum residue either with or without the addition of modifiers (AASHTO 2016).

3.5 Summary table

Table 3.5 Summary of bitumen specifications related to or including PMBs (excluding crumb rubber)

Binder test and method	**Australia (Austroads) AGPT/T190:2014**	**South Africa (Asphalt Academy) TG1:2007**	**European Union (CEN) EN 14023:2010**	**USA (AASHTO) M320:2016**
Hot binders before ageing				
Penetration	-	-	EN 1426	-
Dynamic viscosity (165°C)	AGPT/T111	MB-18	-	T 316
Dynamic shear	-	-	-	T315
Softening point	AGPT/T131	MB-17	EN1427	-
Elastic recovery	AGPT/T121	MB-4		-
Torsional recovery	AGPT/T122		EN 13398	-
Storage stability	AGPT/T108	MB-6	Not applied	-
Force ductility	-	EN13703	EN 13589 then EN 13703	-
Flash point	AGPT/T112	ASTM D93	-	T48
Consistency	AGPT/T121	-	-	-
Consistency 6%	AGPT/T121	-	-	-
Stiffness	AGPT/T121	-	-	-
Compression limit	AGPT/T132	-	-	-
Fraass breaking point (a)	-	-	EN 12593	-
After ageing (RTFOT)				
Mass change	AGPT/T103	MB-3	EN 12607-1	T240
Softening point change	-	MB-17	EN 12607-1	-
Penetration change	-	-	EN 12607-1	-
Elastic recovery	-	MB-4	EN 13398	-
MSCR				T350
After pressure ageing vessel	-	-	-	R28
Dynamic shear	-	-	-	T315
Creep stiffness	-	-	-	T313
Direct tension	-	-	-	T314
Low temperature performance	-	-	-	R49

Note: '–' means that this test is not specified.

(a) Fraass breaking point: it involves a test apparatus which determines the brittle behaviour of bitumen at low temperatures. The Fraass breaking point is the temperature at which the first crack appears in the coating of a thin, flat steel plaque, flexed under descending temperatures.

4 Performance properties of PMBs

Polymer modification of asphalt binders has increasingly become the norm in designing high performance pavements, particularly in the United States, Canada, Europe and Australia (Yildirim 2007). PMBs are, however, more expensive than conventional binders and the higher material and construction costs need to be offset against cost savings, either immediately by faster installation, or over the whole life of the pavement (Sharpe et al 2012; Asphalt Academy 2007).

There is a very large body of literature describing laboratory studies of the effects of polymer modification on the properties of bitumen, asphalt mixes, and to a lesser extent, chipseals. A full review of this work is beyond the scope of the current project. Some recent reviews include Zhu et al (2014), Hunter et al (2015), Yildrim (2007) and Lo Presti (2013), the latter on crumb rubber modification. Polacco et al (2015) have reviewed in detail the literature on the interaction and morphology of various polymer types blended or reacted in bitumen.

In thin asphalt surfacing mixes polymer modification is typically found to improve asphalt mix resistance to deformation during wheel tracking or other creep type tests simulating rutting in the field (eg Radziszewski 2007; Tayfur et al 2007). Fatigue and thermal cracking laboratory tests also show improved performance relative to unmodified materials (eg Palit et al 2004; Souliman et al 2016).

In chipseals, polymer modification can result in improved chip retention (higher cohesive and tensile strength), and reduced bleeding in laboratory wheel tracking experiments (eg Serfass et al 1992; Louw 2008; Estakhri et al 2017; Kim and Lee 2009; Kim et al 2017).

Researchers have also studied the effects of binder ageing (oxidation) on PMB properties. In the field oxidation results an increase in binder stiffness which contributes to fatigue and thermal cracking and chip loss. Generally the elastic properties of PMBs are lost to some extent as ageing proceeds (Ruan et al. 2003). Overall however, the relative increase in stiffness is less than that of unmodified bitumens under the same conditions and scission of the polymer chain may result in the shorter polymer fragments acting as a plasticiser (Urquhart et al 2014; Tarefder and Yousefi 2015; Ahmed et al 2016). Long-term ageing studies have shown that in the laboratory OGPA modified with 4% SBS performs better in terms of ravelling and fatigue cracking resistance compared with unmodified mixes (Wu et al 2017). In laboratory studies epoxy resin modification has been shown to improve resistance to oxidation of the binder material. It reduces the embrittlement usually seen in ageing of the porous asphalt binder which results in chip loss when exposed to shear stresses from traffic (Wu et al 2017).

5 Evidence of performance benefits in service

5.1 Asphalt mix

While there is a large number of laboratory studies suggesting the beneficial effects of PMBs when used in thin surfacings, there are fewer documented studies actually quantifying the performance benefits in the field.

A systematic comparison of studies evaluating field performance of PMB surfacings compared with unmodified materials is difficult given that the projects involved span many decades over which time practice and materials have changed. There are numerous proprietary formulations of polymer modifiers used worldwide and detailed properties of these materials are often not available or the properties measured. Also, they are not directly comparable between studies (eg torsional recovery, softening point, phase angle). The condition of the underlying pavement, traffic levels, layer thickness and climate among other factors, can have a very significant effect on thin surfacing performance and lifetimes. These factors also vary enormously and often not well documented in study reports. Most studies have been undertaken *ex post facto* on surfaces constructed as part of normal maintenance operations rather than specifically designed as trials. Many studies emphasise the fact that ‘poor’ performance of asphalt mixes is often related to design or construction problems rather than being specifically related to the binder used.

Table 5.1 summarises a number of studies on thin asphalt surfacings, work relating to chipseals is dealt with in the section below. Performance criteria typically include rutting and cracking resistance and ravelling in the case of porous asphalts.

Table 5.1 Field performance investigations and summaries for PMB thin asphalt surfacings

Year of investigation	Location	Number of PMB sections	Polymer	Field age at time of investigation	Conclusions	Reference
1989	USA	1	SBS	2 years	A significant improvement in rutting was found compared with the control section	Fleckenstein et al 1992
1990	USA	3	SB, SBR, EVA	1–2 years	Mixed performance. Some improvement relative to controls for ravelling. EVA section showed a tendency for brittle failure.	Rogge et al 1992
1990	USA, Canada, Austria	31	Various including PE,EVA,SBR,SBS	<5 years	No significant difference observed compared with control sections. Assessments mainly qualitative.	Button 1992
1992	Australia	8	EVA, SBS, GTR	5.5 years	Significant cracking and rutting performance observed compared with control sections.	Williamson and Gaughan 1992

Year of investigation	Location	Number of PMB sections	Polymer	Field age at time of investigation	Conclusions	Reference
1992	Saudi Arabia	3	SBS, PE	1 year	No significant difference between control and PMB sections.	Al Dhalaan et al 1992
1993	USA	6	Various including EVA,SBR,SBS	Various up to 6 years	No significant difference observed compared with control sections.	Elmore et al 1993
1995	USA and Canada	20	Various including LDPE, EVA,SBR,SBS	Various up to 9 years	Mixed performance. No clear improvement relative to controls for rutting. EVA sections showed a tendency for brittle failure.	Stroup-Gardiner and Newcomb 1995
1996	USA	7	Various including PE, SBS, neoprene, ground tyre rubber (GTR)	5–7 years	Improved performance with respect to rutting but not cracking.	Ponniah and Kennepohl 1996
1997	USA (Alaska)	16	Various including SBS, GTR	2–12 years	Significant improvement in low temperature cracking resistance compared with control sites (rutting was not investigated).	Raad et al 1997
1997	USA	7	SB,EVA	5–6 years	Improved cracking resistance but no improvement in rutting compared with the control sites.	Harmelink 1997
1997	UK	37 (all porous asphalt)	SBS, EVA, GTR	8–12 years	Mixed performance. No clear improvement relative to unmodified sections.	Nicholls 1997
1998	USA	8	GTR,SB (plus fibre modified)	6 years	Improved cracking resistance (except for GTR) compared with the control.	Mallick et al 2000
2002	USA	1	Various including LDPE, SBR,SBS	11 years	Improved cracking performance noted for most PMB sections relative to controls (except for LDPE)	McDaniel and Shah 2003
2004	USA	8	Various including LDPE, SBR,SBS,GTR	8 years	Significant improvement observed in rutting	Battey 2004

Year of investigation	Location	Number of PMB sections	Polymer	Field age at time of investigation	Conclusions	Reference
					particularly for the SBS and SB types at 4–6%.	
2004	Netherlands	24 (all porous asphalt)	Various including EVA, GTR and SBS	End of life-about 9–12 years	No significant improvement in life compared with control sections observed.	Voskuilen et al 2004
2002	Switzerland	16	Various including PE,EVA,EPDM,SBS	14–19 years	PMBs showed some improved performance in cracking resistance.	Dumont and Ould-Henia 2004 Lapalu et al. 2015
2007	USA	97	Various	Various	See text below	Von Quintus et al 2007
2011	Canada	7	Various including SB,SBS	8 years	Mixed performance. No clear improvement relative to the controls.	Hesp et al. 2009 Erskine et al 2012

Saba et al (2012) reported on a field test conducted in Norway from 2001 to 2009, to study the effect of a PMB used in asphalt surfacing mixes on the development of rutting. Based on field measurements they concluded that the asphalt concrete (AC) 16 asphalt surfacing containing PMB 60 (a Norwegian specification for a PMB containing thermoplastic elastomers and a softening point higher than 60°C (Finset 2010)) had about 40% less rutting than the same asphalt surfacing mix containing an unmodified 70/100 pen binder. The use of the PMB also improved the performance of a surfacing material containing relatively low-quality aggregates.

The PMB grades in Norway have changed since this trial, with new products now available, and with Norway adopting the CEN standard EN 14023 for PMBs from 2008. Using a combination of laboratory testing and 14 field test studies, Jörgensen et al (2016) reconfirmed that most of the selected PMB asphalt sections showed reduced rutting. They concluded that ‘according to the policy of using the asphalt wearing course that gives the best value for money, PMB is justified as a better choice than bitumen for most of the test sections’.

A comprehensive analysis of field trials, accelerated pavement trials and comparative field data from the USA and Canada was conducted by Von Quintus et al (Asphalt Institute 2005). Data from 32 different locations or trials with 97 PMB modified asphalt sections and appropriate controls were compared. The authors note that in some cases site features for the control sections selected sometimes differed from the PMB sections as they were not necessarily built immediately adjacent to the PMB sections. Performance was assessed in terms of rutting, fatigue, transverse and longitudinal cracking. Various polymer types and concentrations and asphalt types were present in the sections evaluated. Polymers used included SBS, EVA, GTR, SBS and various thermoplastic polyolefin types. Overall the results showed clear reductions in rutting and cracking, both fatigue and transverse (thermal), for PMB mixes, but there was considerable scatter in the data and in some cases the PMB sites showed more distress than the control sites. Similar observations have been made in many other studies (see table 5.1). In addition to direct comparison of distress levels the authors used mechanistic-empirical distress models to predict the increase in life expected from PMB mixes. Data from the control sections was used to calibrate the models used for rutting and cracking progression and normalise for differences in mix design, traffic etc between sites. The estimated increase in life for asphalt overlays (compared with an unmodified mix design life of 20 years), ranged from 0–10 years depending on traffic, climate and underlying pavement type and condition.

A similar study was conducted on asphalt overlays in Colorado (Von Quintus and Mallela 2005), based on 16 sites with PMB modified asphalt. In that study PMB overlays were found to have an increase in service life of about three years (compared with a 10-year design life for unmodified mixes).

Over the last 10 years interest has grown in the use of epoxy modified bitumen. The epoxy modified bitumen concept was originally developed by Shell Oil in the 1960s. Epoxy modified bitumen has since found a niche application in fatigue resistant dense asphalt surfacings on bridge decks (Balala 1969; Rebbechi 1980; Gaul 1996). Epoxy modified bitumen is also being used in open graded porous asphalt surfacings in New Zealand (Herrington 2010; Wu et al 2017). Field trials of two different epoxy mixes (20% and 30% air voids) were constructed in 2007 in Christchurch and these are performing well, though so is the unmodified control section.

A trial of epoxy modified SMA was constructed in the UK in 2012 but the performance of the material has not been reported to date (Elliott et al 2013). Evidence for the improved performance obtainable from epoxy modified binders is provided by the very long lives (> 40 years) reported for very heavily trafficked bridges such as the Bay Bridge in San Francisco (Gaul 1996).

5.2 Chipseals

In contrast to hot mix asphalt surfacings there have been few reported studies comparing the ‘side-by-side’ performance of unmodified and PMB chipseals.

A trial was constructed in Indiana in the USA, in 1990 (McDaniel 1995). Adjacent, straight sections were constructed on the same highway so traffic and other factors affecting performance were the same for each seal. The sections were constructed using various aggregates as the main purpose of the trial was to assess aggregate friction performance. After three years both unmodified and PMB seals showed reflective cracking but no significant difference in severity was observed.

A trial was conducted in 1989 consisting of 44 test sections constructed on a length of highway in Nevada (Davis et al 1991). The PMB binders studied included SBS, EVA and crumb rubber modified materials, with two different grades of unmodified bitumen being used as a control. Seal condition was measured in terms of aggregate loss, embedment, bleeding and reflective cracking. After three months all sections were performing well. After winter (11 months) one of the PMB and one of the control binders showed significant deterioration but the other sections were still performing well. There was no clear trend indicating improved performance due to polymer modification, although the survey period was quite short.

A trial of SBS polymer modified emulsion seals was conducted in New Zealand in 1995 (Patrick 2000). The trial was intended to evaluate the benefits of constructing PMB seals using emulsion instead of hot binders, and so was only monitored for one year. Eight sections at four sites ranging from Auckland to Christchurch were constructed but with control sections at only two of the sites. The sites were selected as being high stress. Apart from some early chip loss at one site the PME seals performed well but no better than the control sites.

Trials were conducted by the Minnesota Department of Transportation in 1999 using PMB and unmodified bitumen emulsions (Wood 1999). The author states that PMB emulsion seals ‘appeared to enhance early chip retention’, but no data is presented.

In the early 1990s a chipseal trial was conducted in Australia which investigated a wide variety of PMBs. (Austroads 2000b). A variety of sites were selected across Western Australia and Queensland. The PMBs were investigated for use over cracked pavements. Binders were either applied manually as crack sealant or were applied as a stress absorbing membrane. The oldest (Carnarvon), trials were initially established in 1992 with other treatments applied in 1993 and 1995. All sites have been resealed since 2004 (Halligan 2007).

The original road at the Carnarvon site was a narrow two-lane road constructed with poor local gravel that over time block cracked. The road was widened using a sand clay material which cracks quite readily.

The best performing binder was S10E grade (see Austroads 2010b), which started cracking at eight years and the control, unmodified C170 bitumen, which started cracking at seven years. Heavily modified binders such as S25E, S20E and 18% crumb rubber cracked early in their life as did S35E. From this and other trials, the Western Australian road authorities commented that the more heavily modified binders were too cohesive and ended up bonding to one side of a crack while the other side debonded as the crack expanded. Binders with a more viscous response (as opposed to elastic response) performed better through two mechanisms: 1) with a lower viscosity more binder flows into the crack at time of sealing and 2) the lower elasticity and viscosity allows the binder to move with seasonal changes in crack width.

Sprayed seal PMB trials were established by Austroads at Coober Pedy in South Australia in November 2011 and Cooma in New South Wales in February 2012 (Patrick et al 2013). The purpose of the trials was to measure and rank the relative performance of the current grades of Australian PMBs being used as strain alleviating membranes, and their ability to limit pavement cracking reflecting through to the surface (Austroads 2010a). A subsequent site inspection of these trials occurred in February 2014, where an expert assessment team noted that at this stage of life the un-modified control bitumen, a C170 (Standards Australia 1997), was performing just as well as the PMBs in the Coober Pedy trial, while at Cooma the condition of the control was generally poor but the S10E (≈ 3% SBS) and the S20E (≈ 5% SBS) were in poorer condition than the control (Patrick 2014). From a more recent inspection in October 2017, the following recommendations were made (Robert Urquhart, 8 November 2018, pers comm). At the Cooper Pedy site, there is no evidence to date of any significant cracking in any of the trial sections, so further monitoring is required in 2019/2020 to see any significant difference between the binders. At the Cooma site, the conditions have worsened since 2014 and all sections of the trial site showed significant cracking. The assessment team believes that the presence of a heavily cement stabilised basecourse below the seal have caused all sections to crack at the same time and stopped any performance differences between the binders being observed.

Kim and Lee (2009) in a North Carolina DOT report compared the performance of PMB emulsion seals to those constructed with unmodified emulsion. Seven PMB emulsion seal sections and seven unmodified emulsion seals were constructed at a single site. The polymer type was SBS probably at 2–3% concentration but this is not stated. A visual assessment after two years concluded that the PMB seals had performed better in terms of chip loss, rut depth (presumably due to chip embedment or reorientation) and flushing. Based on laboratory test performance and extrapolation of visual assessments of field sites after two years, the authors suggest PMB seals are likely to have a two year increase in life compared with unmodified seals. A life cycle cost analysis showed that a two year increase in life would make PMB seals cost effective compared with unmodified bitumen emulsion seals (assuming a five year life for the unmodified seals).

Im and Kim (2016) compared three different PMB emulsions including two SBS modified binders and an SBR latex co-emulsion at a low (5,000 AADT) traffic volume site using single and two coat seals. After 11 months the unmodified binder at the single seal site had a performance rating of less than half that of the PMB emulsions. The two coat seal performance, however, showed much smaller differences between the binder types with the latex co-emulsion binder performing only as well as the unmodified bitumen.

Estakhri et al (2017) conducted a study using field data from seals constructed in Texas. Forty seal sections each one lane wide and 150m long were constructed using SBS and crumb rubber modified binders and three unmodified binders. A mixture of emulsified and hot binders was used. The sections were spread over a number of locations and each binder was used in multiple sections to help minimise effects of localised features and effects. The seals were evaluated primarily in terms of chip loss and bleeding (flushing). The extent and severity of these parameters were assessed qualitatively and combined to determine an overall percentage surface condition index (SCI), where 0% is bad and 100% is good. The sites were divided into three traffic levels: <1,000 AADT, 1,000–5,000 AADT and >5,000 AADT. The sites were evaluated after one to three years. The SCI scores for chip loss and bleeding were combined to give an overall median SCI score of 78.5% for the PMB sections compared with 72.5% for the unmodified sections, indicating better performance for the PMB seals. To put this in context, the SCI values for chip loss ranged from 45% to 100% and those for bleeding from about 37% to 100%, so the magnitude of the difference in the overall median score is quite small.

6 New Zealand case studies and practice

6.1 Background

The use of PMBs in New Zealand largely mirrors international practice. However, the range of polymer types employed in New Zealand is limited compared with that of Europe and the USA (table 2.1). Crumb rubber modified bitumen is used extensively in South Africa and in some parts of Australia, but is not currently used commercially in New Zealand. The majority of PMB in New Zealand is used in hot mix asphalt thin surfacings, stress absorbing interlayers and as waterproofing layers. The practice of using PMB in base course stabilisation is very uncommon in New Zealand in contrast with South Africa where approximately 7% of all PMB is used for this purpose (Rossmann 2000).

The main polymer types used in New Zealand are SBS and SBR type elastomers typically at a concentration of 3–5%, although up to 5.5% is sometimes specified. PMBs are employed for the same purposes as overseas, namely for improved resistance to rutting (at higher road temperatures) and fatigue cracking.

PMB chipseals are believed to help control early life chip loss in higher trafficked areas and have also been employed in attempts to reduce flushing. Regarding chipseal surfacings, the principal difference between the usage of PMBs in New Zealand and overseas (particularly the USA), lies in the more extensive use internationally, of PMB emulsions for chipsealing. PMB emulsions provide safety benefits as the material is sprayed below 90°C and generally contains no, or a reduced concentration of, kerosene and so the explosion risk is removed. Various environmental benefits are also often claimed for bitumen emulsions but these may not be clear cut, depending on the distance the material (including typically 30% water) must be transported. This can affect CO_2 emissions, due to the presence of kerosene and the risk of waterway contamination through runoff (Ball 2010). In the UK for example (in 2005), 98% of chipseals were constructed with emulsions (Nicholls 2008). In New Zealand hot cut-back bitumens are still used in parallel with emulsions as is also the case in South Africa (Louw 2008). A significant difference is that kerosene cutters are used frequently in chipseals in New Zealand in both conventional and PMB seals (both emulsions and hot applied); however, in South Africa only 2% of sealing binders are cutback (Distin 2008).

Use of crumb rubber from waste tyres is commonplace in some states in the USA, Australia and South Africa but the use of crumb rubber in New Zealand is hampered by the lack of a consistent and reliable local material supply and the high capital cost of plant required for incorporation of crumb rubber into asphalt and chipseal bitumens (Wu et al 2015). Plant operated by the major New Zealand contractors and used for SBS and SBR polymer modification of bitumen cannot be simply adapted for use with mechanically ground crumb rubber. However, a recent study using devulcanised crumb rubber has been undertaken in New Zealand. The project demonstrated that production of a modified binder with this material in New Zealand using the same plant as used to manufacture SBS modified bitumen is technically and logistically possible (Wu 2017).

Since 2012, a thermosetting epoxy resin-modified bitumen has been used in OGPA surfacings in numerous major projects in New Zealand. The technology has been adapted from that used in specialised bridge deck surfacings and is currently unique to New Zealand (OECD 2008; Wu et al 2017). Epoxy modified mixes are laid using conventional equipment but require minor modifications to be made to the asphalt plant.

6.2 Analysis of the asphalt surfacings on the Auckland motorway system

An analysis of databases from the NZ Transport Agency (the Transport Agency), Auckland Transport and Hamilton, Wellington, Christchurch and Dunedin City Councils was undertaken by Chappell (2017). Thin asphalt surfacings including OGPA, SMA and dense mixes were included in the study, which compared surfacing life in terms of traffic loading (equivalent standard axles) to pavement deflection measured by falling weight deflectometer. Only the Transport Agency and Auckland Transport databases were found to hold sufficient data for the analysis. The PMB binders used in the mixes studied are not stated but are likely to be SBS type at about 4% concentration.

Overall, it appears that for pavement deflections of less than 0.2 mm, PMB mixes were performing better than unmodified mixes. With respect to OGPA surfacings in particular, it was noted that in early 2000s after PMB was made mandatory for the Transport Agency's Auckland South network, the OGPA surfacing life on average increased by about two years (Chappell 2017).

6.3 Analysis of the RAMM database

The New Zealand Road Assessment and Maintenance Management (RAMM) database was used to compare the lifetimes and failures of PMB modified surfacings with equivalent conventional thin surfacings (OGPA, SMA and chipseals).

The objective for the comparative performance analyses was to understand the added benefit from using a PMB over conventional bitumen surfaces. The main challenge for this analysis was to undertake a fair comparison when the application of these surfaces was significantly different. In practice there would have been a particular reason why engineers had chosen PMB binders over conventional binders in the first place. There is a strong likelihood that this was done because surfaces incorporating PMB would have been subjected to higher stress conditions.

The analyses were undertaken according to the following principles:

- Attempt to remove or fully account for external factors that impact on the surfacing performance, for example traffic loadings. However, specific comparative analysis was limited due to the sample numbers being insufficient for such an analysis.
- Attempt to isolate the performance of the surfacing from the performance of the underlying pavements. Again, PMB binders are often used in cases where the pavement has defects that the engineer wants to address through early intervention. For example, cracked surfaces are often resurfaced using PMB.
- Sufficient data is required for the analyses, not only for the bitumen type used but also for the contextual data used in the variable analyses.
- The assumption was made that the PMBs used were essentially the same. SBS at 3–4% concentration is the most common PMB type used in New Zealand but various proprietary formulations have been used by different contractors and these have changed over time.

Given the above, it was decided to undertake the assessment on thin asphalt surfaces as the dataset contained a smaller disparity in the number of sites using different binder types. Asphalt surfaces were also considered to be more likely to have failure mechanisms related to the surface layer itself compared with chipseals where failure was more often a direct reflection of the underlying pavement condition.

It was further observed there was a more pronounced performance issue with thin asphalt surfaces than with chipseals. The SCI for AC surfaces is an order of magnitude higher compared with chipseals (NZ Transport Agency 2016b).

The dataset for the analysis included all asphalt historical records for surfaces that had been replaced and asphalt surfaces still in service on state highways. The entire dataset comprised 3,702 sections, which reduced to 2,976 following the data cleansing of sections with insufficient contextual data. Table 6.1 shows the number of sections for the different asphalt surfaces and different pavement types. Note that the section numbers represent the number of data points. The total length of the road sections in the dataset was approximately 1,850 km (carriageway length).

Table 6.1 Distribution of asphalt types used on respective pavements

	RAMM pavement use type							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**Total**
Traffic range (ADT)	**< 100**	**100–500**	**501–2,000**	**2,001–4,000**	**4,001–10,000**	**10,001–20,000**	**> 20,000**	
Asphalt types	**Number of data points**							
Dense graded asphalt (AC)	0	4	82	70	253	248	44	**701**
Open graded porous asphalt (OGPA)	2	0	35	53	238	580	519	**1,427**
Stone mastic asphalt (SMA)	0	4	107	159	224	270	84	**848**
Total	**2**	**8**	**224**	**282**	**715**	**1.098**	**647**	**2,976**

There is a fair distribution of asphalt types with an obvious bias towards using OGPA on the more heavily trafficked roads (urban motorways). The pavement strength for asphalt surfaced roads is within expected ranges (SNP > 3) (refer to figure 6.1). However, there seem to be some surfaces used on weaker pavements (SNP <3).

The age distribution for the asphalt surfaces in figure 6.1is illustrated in figure 6.2 and shows a relatively young cohort of surfaces. More than half the surfaces are less than seven years, suggesting the replacement rate for asphalt surfaces is around 14% annually.

Figure 6.1 Distribution of AC surfaces for traffic and adjusted structural number (SNP)

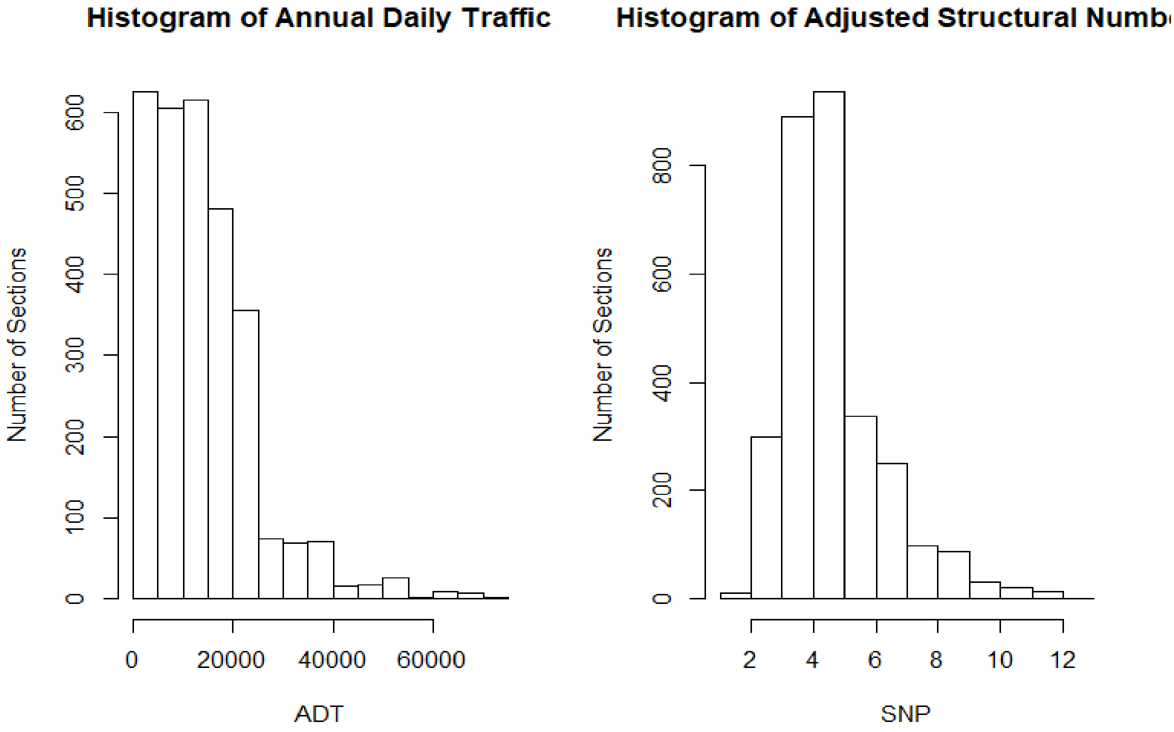


Figure 6.2 Age distribution for asphalt surfaces

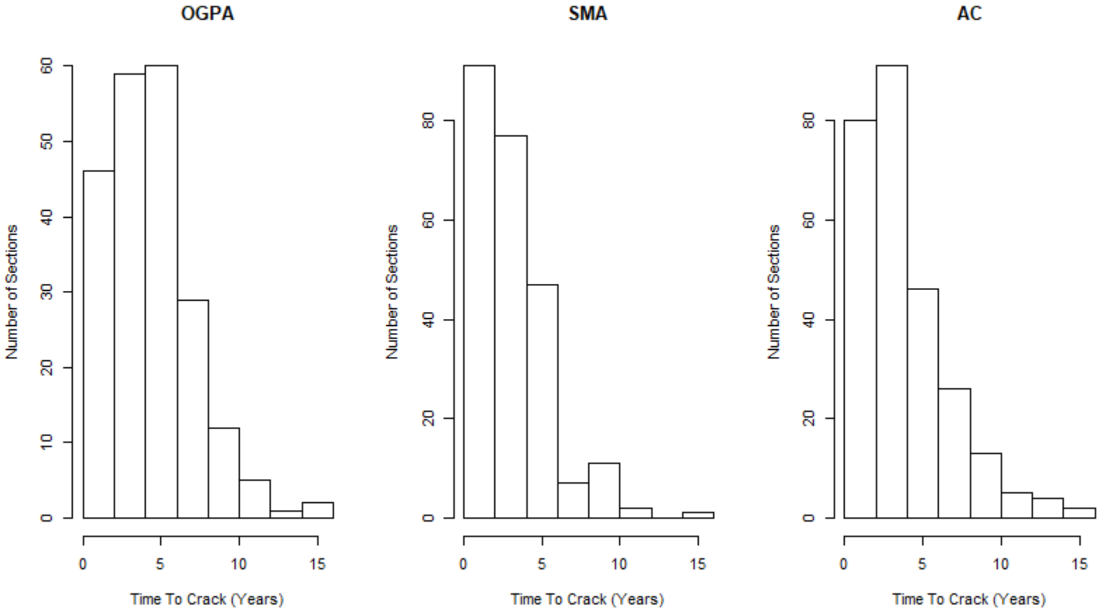
6.3.1 Performance of respective asphalt types

First, an understanding of the relative performance difference between asphalt types was investigated. Both ravelling and cracking were considered as indicators of the surface performance, but some initial analyses revealed that the age at which crack initiation occurs to be the most meaningful performance measure. It is recognised though that ravelling is the main decision driver for OGPA surfaces.

Figure 6.3 illustrates the crack initiation times recorded for three asphalt types. The figures show the age of sections when the first cracks were observed. From a data processing perspective, crack initiation is defined as the point when the crack extent reaches 0.5% of the total surface area, defined by the perimeter bounding all the area covered by a set of cracks as a percentage of the total pavement area. This is consistent with the definition used in the World Bank Highway Development and Management models (Morosiuk et al 2001).

From the observations, it appears that OGPA surfaces are more crack resistant compared with AC and SMA surfaces. It is important to keep in mind though that OGPA surfaces are placed on top of an AC surface, and observing cracks on OGPA is difficult given the open graded nature of the surface. A more significant observation from the figures is the relatively poorer performance of the SMA surfaces with most of these surfaces having crack initiation times of less than five years. This observation confirms the danger of direct comparisons of different surfaces given that a specific technology may be chosen to address specific performance issues. Engineers would only use SMA surfaces for high-stress areas and on pavements with high deflections.

Figure 6.3 Crack initiation time for respective asphalt types



Note: OGPA = open graded porous asphalt
SMA = stone mastic asphalt
AC = dense graded asphalt

Some factors were investigated to understand the relative performance difference between asphalt types. Table 6.2 summarises the outcome from this analysis.

Table 6.2 Trends observed for asphalt type performance

Trend investigated	Outcome from analyses
Traffic loading	No trend
Structural number	No trend
Pavement curvature	No trend
Ratio traffic loading/pavement strength	No trend

Trend investigated	Outcome from analyses
Total loading carried	Expected fatigue trend observed (note co-linearity between age and total loading carried)
Surface thickness	Negative trend (refer to figure 6.4)
Climatic environment/risk[(a)]	No trend
Construction season	Poorer performance outcome for winter construction (refer to figure 6.5)
Cracked status before resurfacing	Insufficient data

[(a)] Note that Cenek's approach to climatic classification (Cenek 2001) has been used as described in Henning (2009).

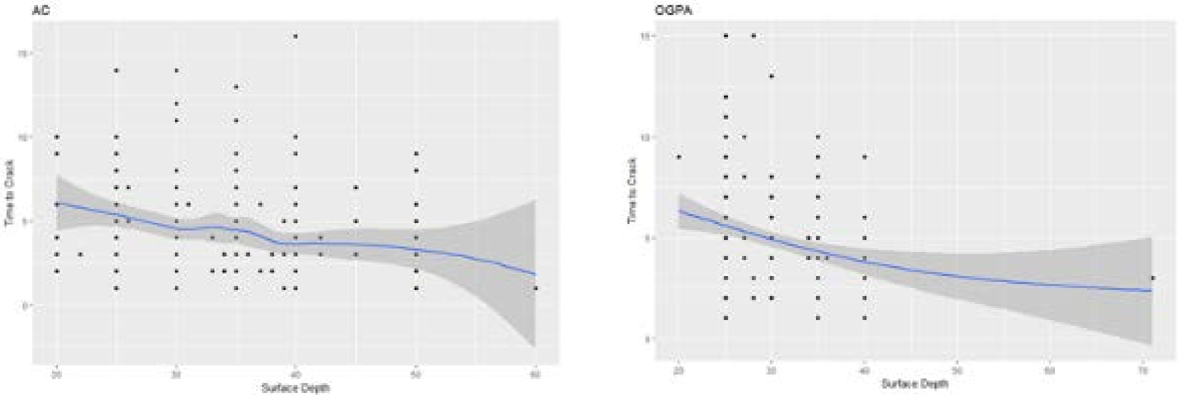
The lack of correlation to both the pavement strength and the traffic loading is not completely surprising given similar observations were made during the development of pavement deterioration models (Mathieson 2014; Henning 2009). The reports have concluded that because the pavement is designed for the traffic it is carrying, the strength and loading do not impact on the performance. This is particularly relevant for asphalt-surfaced pavements.

Crack initiation as a function of surface thickness is shown in figure 6.4. Two factors can explain the impact of the surface thickness:

1 Often surfaces have been overlaid many times. A deterioration of the performance of overlaid surfaces is expected given that subsequent surfaces have been placed on surfaces and pavement that have already displayed some deterioration.

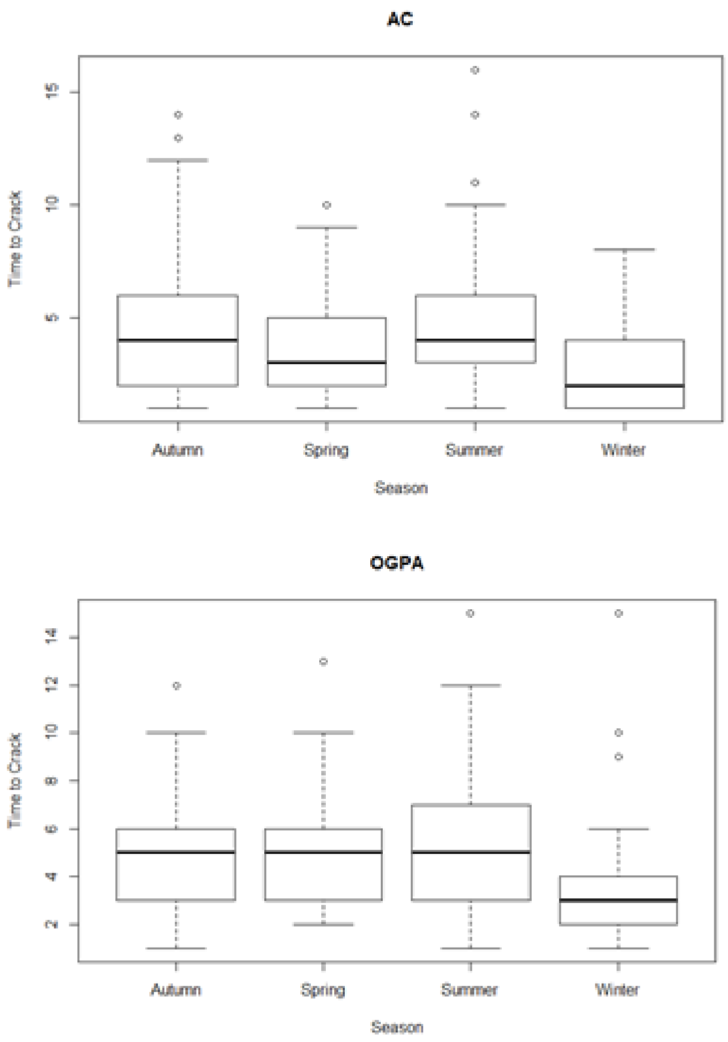
2 In addition to that, the mechanistic behaviour of pavements results in thin asphalt surfaces (<60 mm) lasting longer than thicker asphalt surfaces (>80 mm) on similar flexible pavement layers (Henning 2016). Where thin asphalt surfaces are not considered to be load bearing, thicker asphalt surfaces start carrying bending moments and are prone to cracking due to high tensile strains at the bottom of the asphalt surface.

Figure 6.4 Crack initiation as a function of surface thickness for AC (left) and OGPA (right) surfaces



The impact from the construction season (figure 6.5) is also according to expectations. During cold and often wet winter days or nights, the successful construction of asphalt surfaces is compromised by the ambient temperatures.

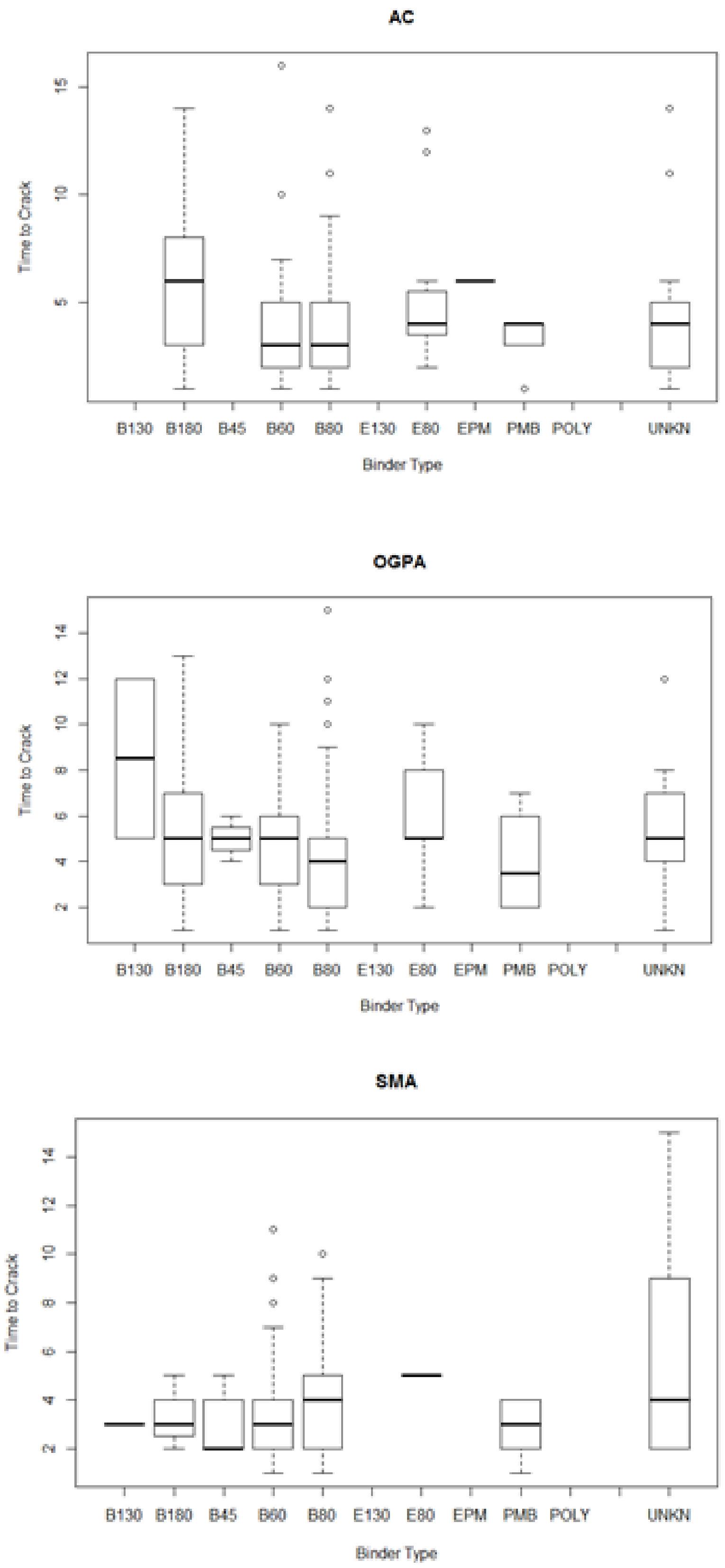
Figure 6.5 Distribution of crack initiation as a function of the construction season



6.3.2 Comparison of performance between different binder types

Figure 6.6 presents a comparison between different bitumen grades. The data in the three graphs in figure 6.6 highlights a problem with the RAMM database in that 180–200 penetration grade bitumen and even bitumen emulsions have been recorded as mix binder types which is highly unlikely (these entries may refer to the tack coat binder instead). Comparing the most commonly used conventional bitumen grades B80 and B60 to PMB modified surfacings, shows they performed similarly.

Figure 6.6 Comparing crack initiation for different surface and bitumen types



To confirm the observations from figure 6.6, further analyses are presented in figure 6.7 which show the relative use of PMB for pavement strength and traffic loading. The number of sections of conventional bitumen are 10 times more than the number of PMB sections. This sample size difference does limit the validity of any observations on the PMB surfaces. The only potential difference in the application of the two bitumen types is that conventional bitumen may be used on lower volume roads, while PMB is only used for higher traffic routes. There is no marked difference in the pavement strength for the two bitumen types.

Figure 6.7 Comparing the use of PMB with conventional bitumen types

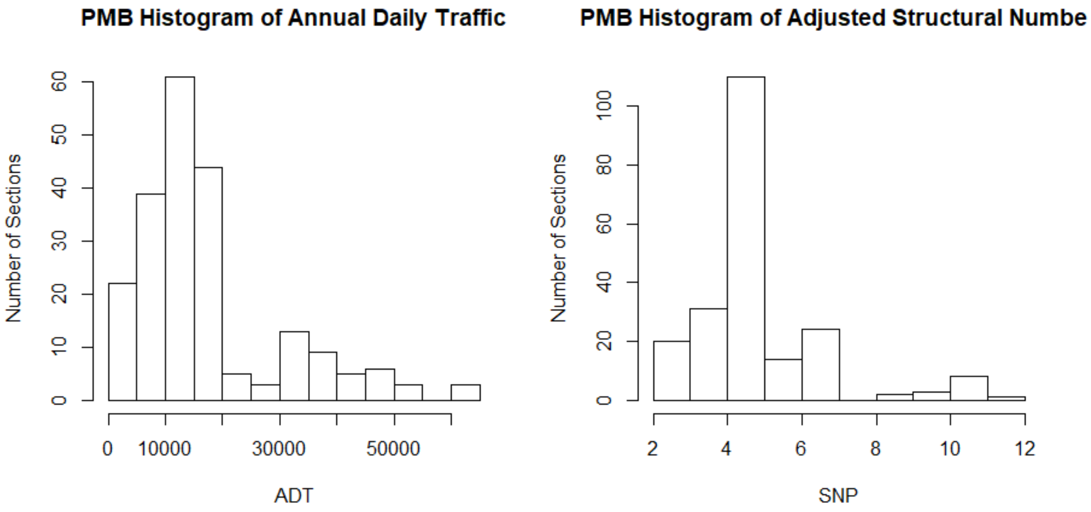
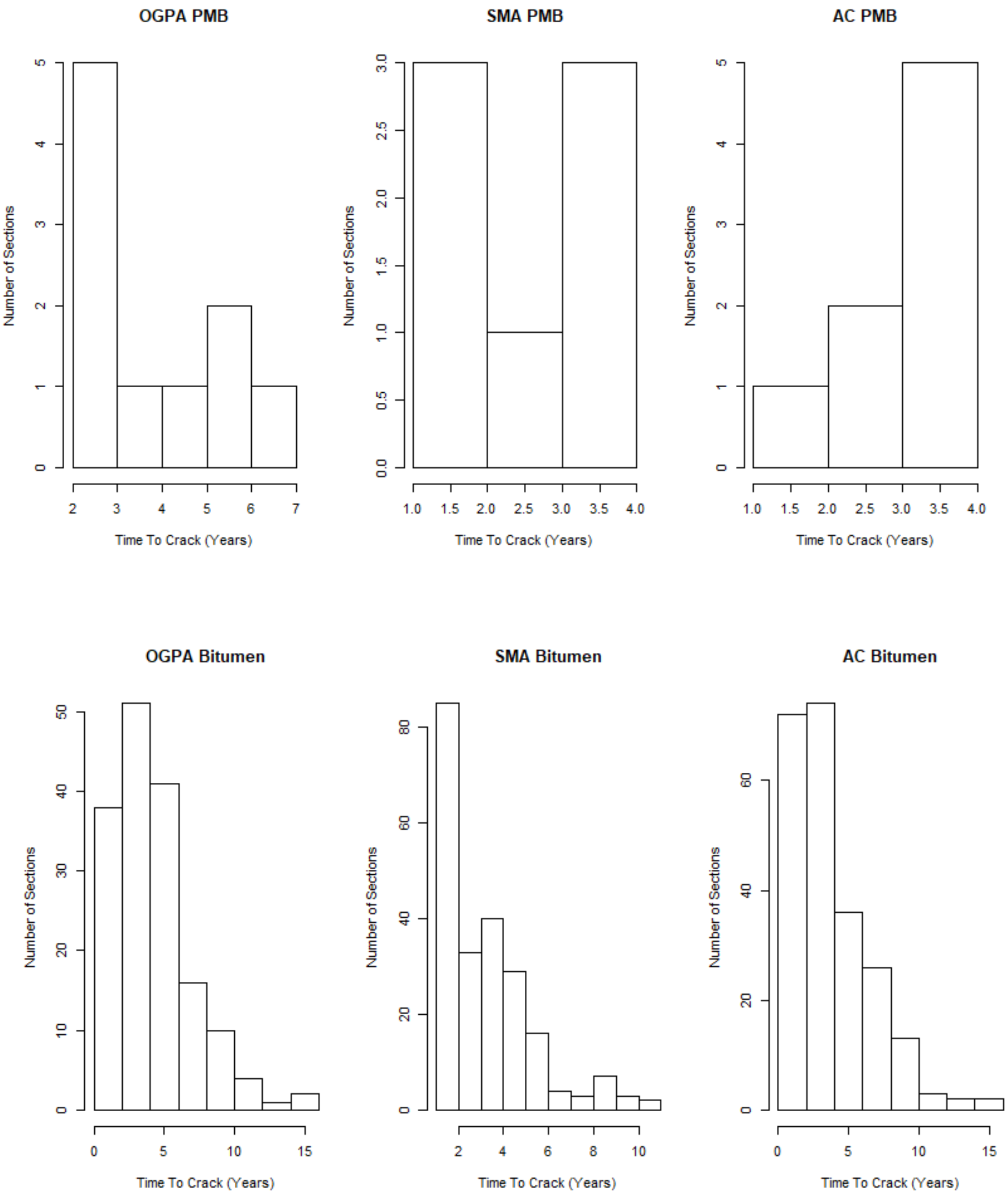


Figure 6.8 shows the performance of the PMB on different surface types compared with the performance of conventional bitumen on the same underlying surface types. Again the sample sizes for the PMB are significantly limited. However, for most of the PMB surfaces the crack initiation time is less than four years, while the conventional bitumen surfaces have a significant number of sections that exceed four years of use before cracking is observed.

In summary, it appears that the majority of the PMB sites have yet to reach their useful lives. Hence, it would be misleading to make any clearcut statement about the cracking resistance of PMB surfaces over conventional bitumen types.

Figure 6.8 Performance of PMB and conventional bitumen surfaces



6.4 Road Science (Downer) surfacings database

This section provides a summary of a cluster of field work carried out by Road Science (Downer) to test the effectiveness of one of their PMBs in conditions where the original unmodified binder/mix design did not fare well. These sites were all constructed between 2008 and 2011 using a SBS modified binder, known as ‘Flexiplus Bind’ (previously ‘RS3 High Strength’) from Road Science. The formulation of this binder was unchanged between 2008 and 2011 and possessed the following properties:

Table 6.3 PMB binder properties

Test	Test method	Typical result
Torsional recovery (%)	AG:PT/T122	65
Softening point (ºC)	ASTM D36-14	90
Viscosity at 165ºC (mPa.s)	AASHTO T316 or ASTM D4402	400
Viscosity at 135˚C (mPa.s)	AASHTO T316 or ASTM D4402	1,200
G*/sin delta (kPa)	AASHTO T315 or ASTM D7175	5.5
jnr$_{3.2}$ at 64ºC (kPa^{-1})	AASHTO T350	0.15

Table 6.4 Mix properties of AC14 mix used at Auckland sites

Binder type	Flexiplus bind (PMB)	Comparative properties using 60/70
Binder content (%)	5.3	5.3
Binder volume (%)	12.8	12.8
Aggregate source	Holcim Bombay	Holcim Bombay
Air voids (%)	2.8	3.0
Resilient modulus at 25ºC (MPa)	2,270	2,986
Fatigue testing results at 20ºC		
initial flexural stiffness (MPa)	2,136	3,239
cycles to failure	>1,000,000	364,443
reduction in flexural stiffness (%)	18.1	50.6
Wheel tracking (mm)	3.2	12.1

It is important to note these were not controlled trial sites. However, due to the lack of controlled trial sites in New Zealand, the data in figure 6.4 is included to supplement the benefits found in adding PMB to asphalt.

The laboratory results from table 6.4 show that the addition of PMB provides a significant increase in both fatigue (cycles to failure) and deformation resistance (wheel tracking) over conventional 60/70. However, it should be highlighted that the wheel tracking experiment was conducted without the standard mix design optimisation. The laboratory experiment was carried out using direct substitution of the binder in the same mix grading. In other words, the mix with 60/70 binder might perform differently if the mix design was optimised.

The following analysis was carried out using information from the Road Science surfacings database for sites in Auckland. Each site represented a road section where an existing (non-PMB) surfacing was replaced with a PMB surfacing and the comparative performance assessed. Most of the sites were surfaced using an AC14 mix designed according to NZTA M/10:2010.

6.4.1 Sites reviewed

Between 2010 and 2012, a total of 10 sites in the Auckland region were resurfaced with 40 mm of AC14 using PMB as the binder (as per tables 6.3 and 6.4). No pavement improvements were undertaken at the sites and therefore any improvement in performance would be attributed to the new surface. All sites were reviewed for defects during June to October 2017. At the time of this research all sites were still in service and had not met the end of their life. The key properties of these sites are listed as follows:

Table 6.5 Site condition upon review

Site	Previous surface	Life of previous surface	Life of PMB AC surface at time of review	Cumulative traffic at end of life of previous surface (ESA)	Cumulative traffic on PMB AC at time of review (ESA)	95th percentile deflection	95th percentile curvature	% of site with cracking
Alpers Ave	Mix 15	6.1	6.8	1.29E+06	7.17E+05	0.131	0.026	0.0%
Kepa Rd	Mix 15	12.0	5.3	2.02E+06	2.44E+06	0.132	0.015	0.0%
Lunn Ave	Unknown	Unknown	7.7	N/A	2.48E+06	0.757	0.226	14.5%
Neilson St	Mix 10 (DG7)	12.3	6.7	1.88E+06	9.85E+06	0.869	0.198	12.0%
Onehunga Mall	Mix 15 (DG10)	2.8	6.0	3.24E+06	1.86E+06	0.866	0.211	6.8%
O'Rorke Rd	Mix 15 (DG10)	12.6	7.0	1.65E+06	2.51E+06	0.73	0.183	5.8%
Somerset Rd	Two coat 3/5	7.2	6.8	7.07E+05	4.25E+05	0.94	0.222	0.0%
Strong St	Mix 15	3.4	6.2	1.85E+04	3.40E+04	1.252	0.399	18.9%
Tamaki Dr	Mix 20 (DG14)	8.5	7.0	3.50E+06	1.39E+06	0.562	0.113	0.0%
Trenwith St	Two Coat 3/5	2.2	6.7	6.53E+04	3.00E+05	1.282	0.301	1.5%

Areas of longitudinal or transverse cracking were omitted from the % cracking metric as the cause of this was more likely due to reflective cracking or joint failures in the underlying pavement. Instead fatigue cracking only was considered as this type of failure could be correlated to the properties of the surface.

Table 6.5 reveals the following findings:

- A number of sites have very high curvatures >0.2 and some as high as ~0.4. Normally 0.15 would be considered the maximum for a standard asphalt (AT 2013). The sites with the highest curvatures also present the highest level of cracking.
- In all cases the cracking is aligned with waste water services running through the pavement.
- Kepa Rd, Alpers Ave and Tamaki Drive all possess very low deflections and curvature with no cracking present on site. Tamaki Dr and Kepa Rd are both placed on structural AC and Alpers Ave is on a cement stabilised base.
- A number of sites have also had sharp increases in traffic after being resurfaced with PMB: Neilson St (950% increase in equivalent standard axles (ESA)/year), Kepa Rd (275%) and Trenwith (153%). This means some of the PMB AC sites have much higher levels of cumulative traffic than the corresponding standard AC surface.
- Strong St and Onehunga Mall have already achieved value for money by lasting 84% and 115% longer than the previous standard AC surfacing.

Overall, none of the PMB AC sites had been replaced at the time of review even though 70% of the sites had weak pavements with curvatures greater than a standard asphalt would be expected to endure.

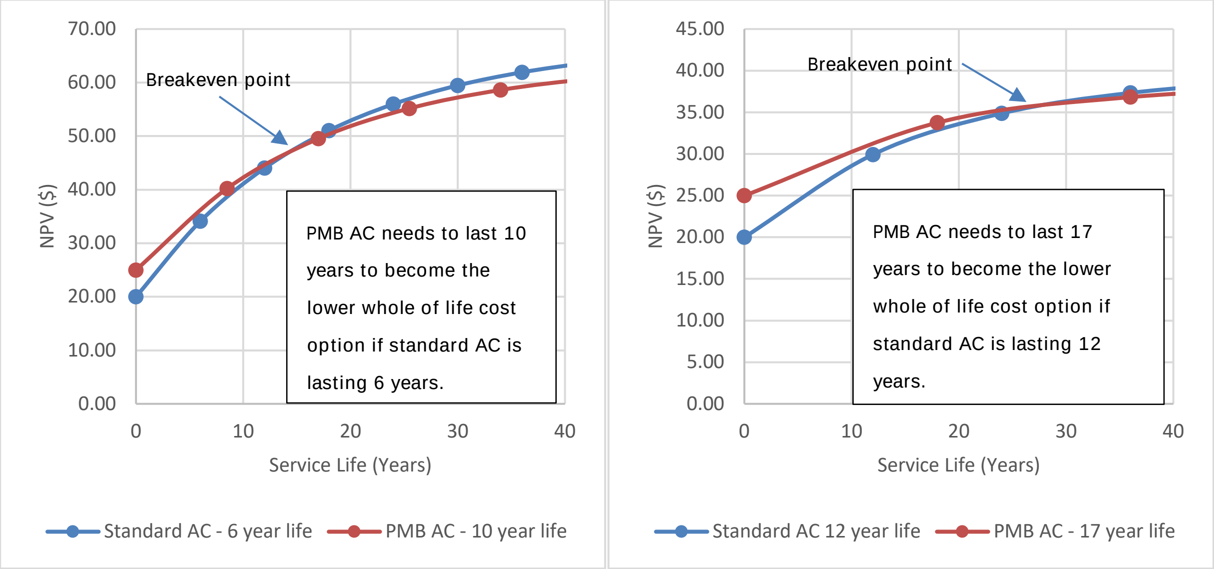
6.4.2 Whole-of-life costs

In order to undertake treatment selections that will reduce the whole-of-life cost of the pavement, a realistic life for the standard option needs to be used to ensure the most favourable treatment is selected. Table 6.5 shows that the life of previous standard asphalts ranged from less than 3 years to 12 years. Of these seven standard asphalt sites, over 40% did not last longer than seven years. This shows that using an optimistically high nominal life (such as the often quoted 12 years) can lead to treatment selection that does not reflect the true whole-of-life cost of the pavement. In order to ensure that the correct cost decisions are being made, whole-of-life costs should be undertaken using lives that are in line with what is actually achieved in practice.

To determine the life required for the PMB AC to achieve favourable whole-of-life cost compared with the standard AC, a net present value (NPV) analysis was undertaken using the following process:

- Nominal costs of $20/m² for standard AC14 and $25/m² PMB AC14 for 40 mm overlays of each.
- Finance discount rate, 6%.
- Annual maintenance was considered to be the same for both asphalt mixes
- Investment period of 40 years was used
- Life for the standard surface varied from 1 to 12 years
- The breakeven point was determined by finding the life of PMB AC option which returned a favourable NPV (over 40 years) when compared with the standard AC option at the lives listed above. An example can be found in figure 6.9.

Figure 6.9 Examples of how the breakeven point for PMB AC is determined for various standard AC lives



Repeating this comparison (as per figure 6.9) with standard AC lives ranging from 1–12 years allows for determination of the minimum life that a PMB AC needs to achieve for it to be considered cost effective compared with the life of the previous surface.

Figure 6.10 below) summarises the results of this analysis by comparing the life required of a PMB AC for it to be cost effective (breakeven) against life achieved by the previous standard AC surface.

Figure 6.10 Increase in life required for a PMB AC to be cost effective compared with standard AC

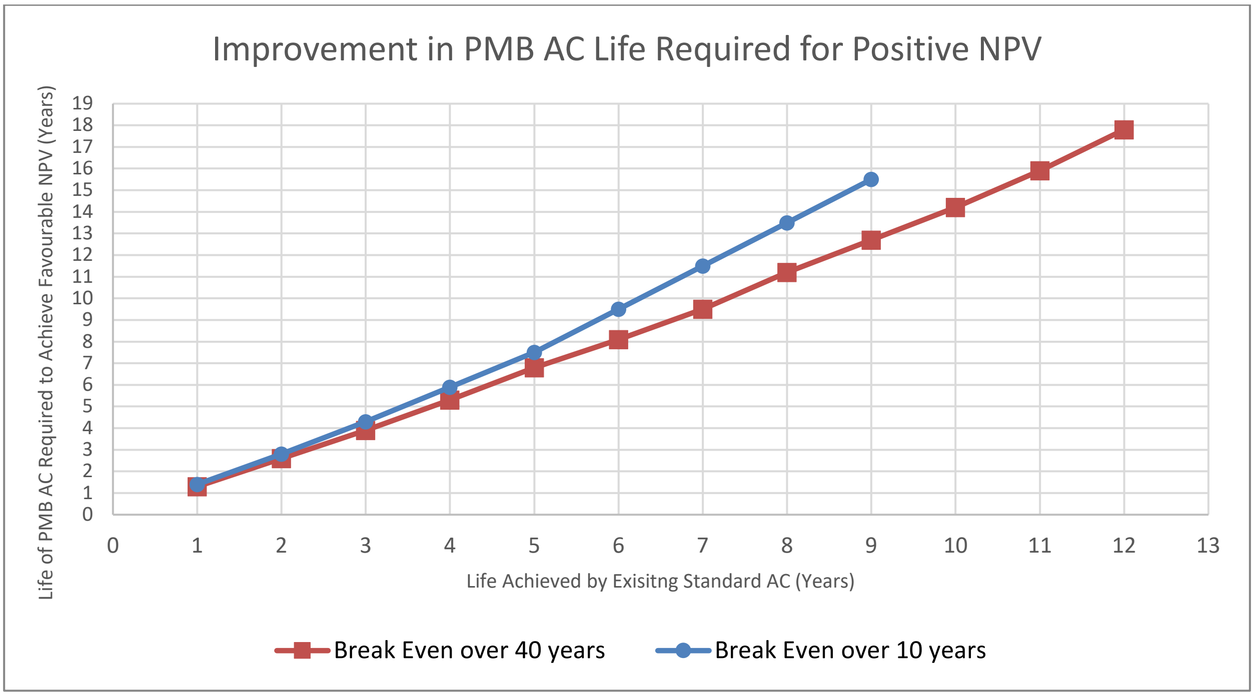


Figure 6.10 shows that if a standard AC lasts six years a subsequent PMB AC needs to last at least eight years for it to be cost effective over 40 years (assuming PMB continues to be used as the resurfacing

option). If a shorter term view of whole-of-life costs is taken (ie analysis period of 10 years), the PMB AC would need to last 9.6 years to be cost effective against a standard AC that lasted six years.

At the time of review all PMB AC sites were still in service and therefore it is still too early to determine the full extent of any whole-of-life cost benefits. Despite this, a number of the previous asphalt surfaces displayed quite short lives and the subsequent PMB AC surfaces have already exceeded the life of the previous AC surface.

Comparisons of whole-of-life cost are normally considered over time (in years); however, damage to the road is determined through the number of axle loadings applied (ESA). A number of sites in table 6.5 have experienced large increases in traffic since being resurfaced with PMB AC, therefore the traffic encountered before and after resurfacing with PMB AC needs to be normalised to allow for a fair comparison of whole-of-life cost. Table 6.6 applies the formulae derived from figure 6.10 (above) to the current life achieved by the PMB AC sites. This comparison establishes how long the PMB AC sites need to last to break even over the 10-year and 40-year NPV analyses. As this comparison was only made between PMB and standard AC, any sites that were previously chipsealed were not considered for this analysis.

Table 6.6 Breakeven points for PMB AC sites compared with previous standard AC adjusted for traffic changes

Site	Previous surface	% change in traffic (ESA/year) after PMB AC resurfacing	Life of previous surface	Adjusted life for standard AC to reflect present traffic conditions (years)	Life of PMB AC surface at time of review (years)	Life required for PMB AC to return favourable NPV (years)	
						Over 10 years (years)	Over 40 years (years)
Alpers Ave	Mix 15	-1%	6.1	6.1	6.8	10.0	8.5
Kepa Rd	Mix 15	175%	12.0	4.4	5.3	6.9	5.9
Neilson St	Mix 10 (DG7)	859%	12.3	1.3	6.7	1.4	1.4
Onehunga Mall	Mix 15 (DG10)	-73%	2.8	10.5	6.0	17.8	15.1
O'Rorke Rd	Mix 15 (DG10)	175%	12.6	4.6	7.0	7.3	6.3
Strong St	Mix 15	0%	3.4	3.4	6.2	5.1	4.5
Tamaki Dr	Mix 20 (DG14)	35%	8.5	6.3	7.0	10.3	8.8

From analysis of table 6.6 the following points can be drawn:

- Significant increases in traffic at Kepa Rd, Neilson St and O'Rorke Rd show that if standard AC was applied in these areas, pavement life would be significantly reduced due to the higher traffic volumes.
- Alpers Avenue, Strong Street and Tamaki Drive show minimal changes in ESA and would therefore offer the best comparison between PMB and standard AC under the same conditions. In this case Strong St has already offered significant benefits in terms of whole-of-life cost.
- Accounting for this increase in traffic, the PMB AC surfaces at Neilson Street, O'Rorke Road and Strong Street are already offering benefits in terms of whole-of-life cost.
- The Onehunga Mall site is the only site that has experienced a significant reduction in traffic loading. The previous standard AC surfacing at this site only lasted 2.8 years whereas the current AC surfacing has lasted over six years. At the time of replacement this would be considered an excellent decision in

terms of treatment selection and would still be so if the traffic had remained at the same level prior to resurfacing with PMB AC.

- The rest of the PMB AC sites are still yet to be replaced with all but the Onehunga Mall site currently within one to three years of the breakeven point.

Overall, three of the seven sites analysed have already returned benefits to the whole-of-life cost of the pavement. Three of the remaining four sites are within one to three years of realising whole-of-life benefits and should be reviewed again at the predicted for breakeven point. The final site (Onehunga Mall) would already be returning a favourable whole-of-life cost if the previous traffic levels had continued.

6.5 Specifications and guidance documents

In New Zealand, there is currently no specific framework or specification for the use of PMBs in road construction. The NZ Transport Agency M1 specification (NZ Transport Agency 2011), covers only unmodified bitumen binders and does not include PMB grades. PMBs are treated as special cases in NZTA P/17 specification (NZ Transport Agency 2012).

The recent M1-A specification for binders used in asphalt (NZ Transport Agency 2016a) provides grades based on traffic levels and also does not include specifications for PMBs. M1-A is ‘blind’ to composition which means that unmodified or PMBs can meet M1-A provided the specification limits are met. In effect polymer modification or other forms of modification are usually needed to achieve the higher grades (V and E). In theory the designer does not need to specify a PMB as any binder meeting the necessary traffic grade should provide satisfactory performance.

The existing design and application practice allow for the use of PMBs but rely very much on the experience of designers and contractors, and is specified on an individual contract basis. Examples of this approach are found in the following specifications covering various surfacing types:

M/10: 2014 – dense graded mixes (AC and DG) and stone mastic asphalt mixes (SMA)

P/11:2007 – open graded porous asphalt (OGPA)

P/17:2012 – reseals

P/23:2005 – performance-based specification for AC, DG, SMA, and OGPA.

Asphalt surfacings are governed by the NZTA M10, P11 and P23 specifications (NZ Transport Agency 2014b; Transit NZ 2005; 2007 respectively). All three specifications currently allow the use of PMBs, with general, qualitative guidance on suitable applications but no details of the necessary physical properties of PMBs.

For example the M10 specification for dense graded and SMA mixes (NZ Transport Agency 2014b) provides some guidance in table N3.6 of the notes (NZ Transport Agency 2014a) to the specification. This is limited to the simple suggestion of PMB for very heavy traffic applications without further information.

Selection of PMBs in asphalt is also driven by fatigue life requirements when designing asphalt pavements according to the Austroads method (Austroads 2012). PMBs in that document though are defined in terms of the Austroads PMB grades discussed above (Austroads 2013).

In New Zealand, seal design is based on volumetrics and traffic level but there is no standard process for binder grade or binder type selection (Transit NZ 2005). The specification of PMBs is done on a contract-by-contract basis. The P17 specification (NZ Transport Agency 2012) requires a minimum softening point to be specified in contract documents when a PMB is to be used (clause 8.3), but no target values are given.

In practice when a designer believes a PMB is required for a given chipseal application, current practice is to specify binder properties in terms of a minimum torsional recovery and softening point. This simple approach is based on experience with SBS modified bitumen and may be misleading if other polymer types are use.

PMBs, in general, have higher viscosities, higher softening points and better torsional recovery. Therefore, from an operational point of view, the specification of PMBs in any application will have an impact on the workability and performance of the material, regardless of whether it is in a hot mix or a chipseal. It would be ideal if such effect is highlighted in the specification and its notes. This presents an opportunity to standardise the PMB practice by providing a more comprehensive and consistent guidance.

The potential issue with the current specifications, namely M10, P11, P17 and P23, is mainly around the lack of specification. All four application specifications currently allow the use of PMBs with very little guidance. The specification of PMBs is done on a contract-by-contract basis. Potential risks can arise due to inadequate specification.

The responsibility currently sits with the manufacturers, suppliers, or contractors to guide the use of PMBs depending on the individual specification. Many of the performance benchmarks in the P11, P17 and P23 are based on unmodified binders.

With a wider uptake of PMBs and introduction of a performance-based binder specification to include the use of PMBs, there is a potential conflict with performance requirements of various mixes using PMBs. This highlights the need for a performance-based binder specification to ensure the binder selection is sound and supported by test data.

In conclusion, the implication for design and application practices with the use of PMBs is that a better understanding of the performance benefits of PMBs need to be in place for more effective use of PMBs. This may be achieved by the introduction of performance-based specifications of binders, including PMBs. Should the binder performance improve significantly due to the polymer modification of the bitumen, then a new class of performance criteria should be included in the binder specification as well as in the surfacing specifications.

7 Conclusions

7.1 Asphalt mixes

Numerous trials and studies have been conducted over the last 30 years aimed at evaluating the benefits of using PMBs in thin asphalt surfacings. Overall these studies support the contention (based on laboratory studies and anecdotal experience) that all else being equal, PMBs improve the rutting resistance, aggregate retention and cracking resistance of thin asphalt surfacings. However, a comprehensive lifecycle cost-benefit analysis is required to quantify the economic benefits of the higher initial costs of PMB modifications.

It must be noted that many reported studies do not demonstrate any clear benefits from the use of PMBs. Further the interpretation of trial findings is complicated by the myriad of different polymer types and concentrations used, differences in mix design, construction techniques, underlying pavement condition, traffic volume and other site factors that can significantly affect surfacing performance. For any specific site, factors other than the binder used can have a more dominant role in determining performance in the field.

7.2 Chipseals

Laboratory studies indicate that PMBs should enhance chip retention and reduce flushing (due to chip embedment) in chipseals but field data supporting the benefits of PMBs in chipseals is much scarcer than for asphalt mixes. Similarly their relatively small number and the fact that PMB seals in New Zealand tend to be used in higher traffic volume/stress situations precludes any meaningful statistical comparison of PMB and unmodified seal performance using the RAMM database.

The most comprehensive field studies have been carried out in the USA comparing emulsion seals. These studies indicate that PMBs (SBS type) do appear to give some improved performance in terms of chip retention and flushing, but the differences are not very large. The trials being conducted in Australia on the benefits of PMBs as stress absorbing membrane layers show that after two years the control (unmodified) seals are performing as well or better than the PMBs, contrary to general expectations. Construction factors that can dominate performance are likely to be even more important in seal construction than for asphalts so drawing definitive conclusions from isolated field trials is difficult.

Overall, there is insufficient field evidence to draw any firm conclusions on whether PMBs provide significant performance benefits in chipseal surfacings and further work is required to quantify the benefits, if any, of using PMBs.

While it was beyond the scope of this project to conduct a comprehensive economic evaluation of polymer modified thin surfacings, the following NPV calculations were carried out in addition to the one calculated for asphalt in section 6.4.2, to provide some understanding of the increase in seal life needed to justify the cost of PMBs. The following assumptions were made:

- Cost of a grade 3 single coat chipseal using conventional binder: \$5.50 m^{-2}
- Cost of a grade 3 single coat chipseal using a 4% SBS binder: \$7.50 m^{-2}
- Finance discount rate: 6%
- Annual maintenance was assumed to be negligible and the same for both seals
- Lifetimes of 5 and 10 years were assumed for the conventional seals
- A 40-year investment period was used.

Based on these assumptions, the results in figure 7.1 indicate that over a 40-year period, the cost of the PMB chipseal becomes economical if an additional 2.5 years is obtained from the use of PMB when compared against the nominal five-year life of a conventional (Grade 3) chipseal.

Figure 7.2 shows that an increase in life of about six years is required if the conventional seal life is assumed to be 10 years.

These examples of NPV calculations demonstrate the potential life increase required to justify the use of PMB economically, which can be significant especially if the average life of conventional surface treatment is reasonably long.

Figure 7.1 Net present value calculation comparing conventional and PMB grade 3 seals with a nominal life of five years

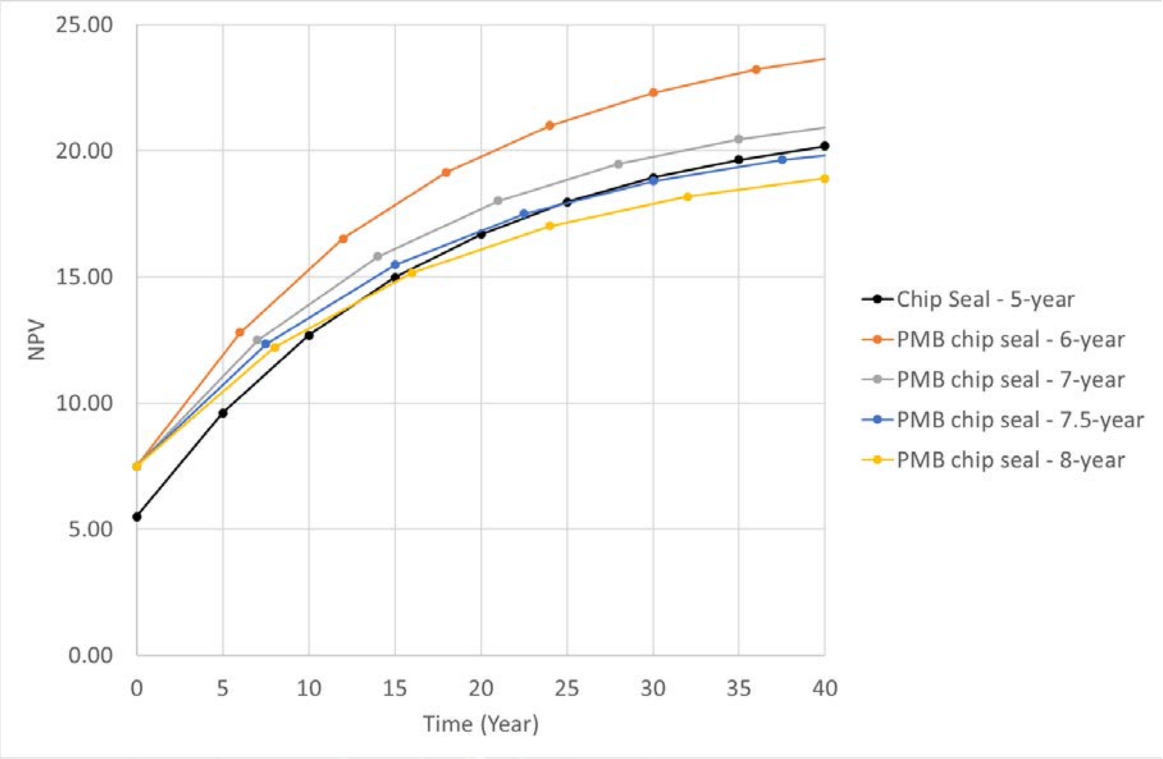
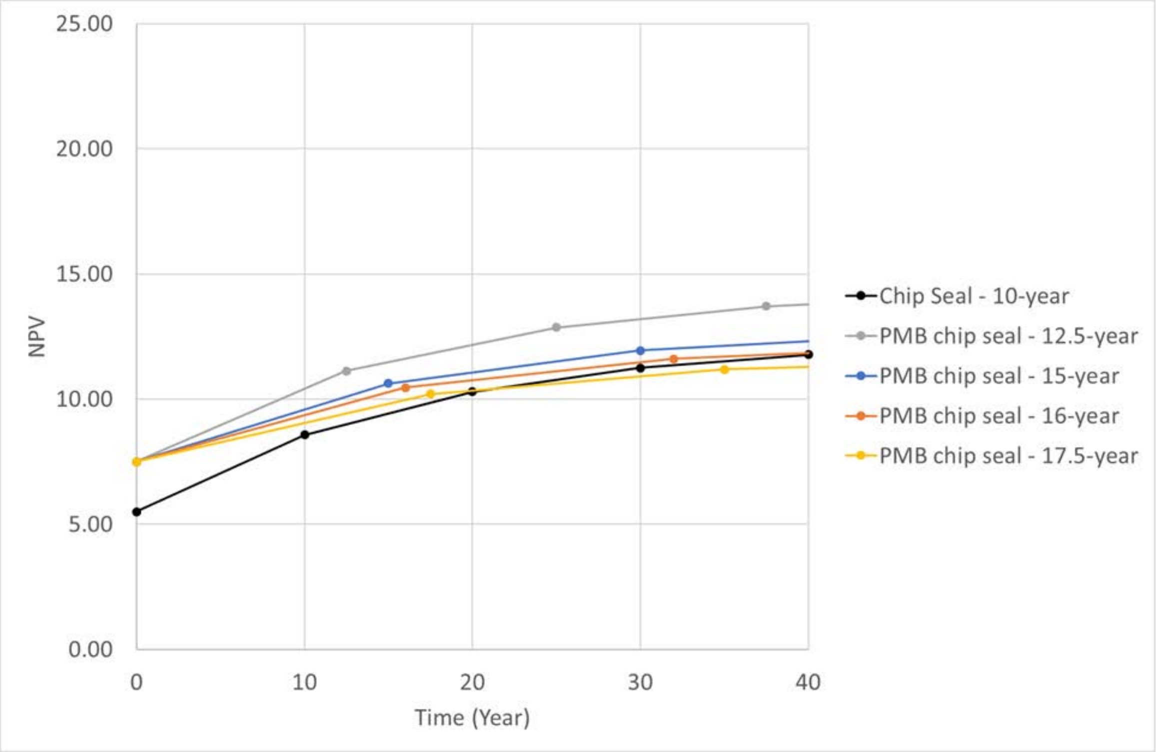


Figure 7.2 Net present value calculation comparing conventional and PMB grade 3 seals with a nominal life of 10 years



8 Recommendations

1. Given the scarcity of robust field evidence supporting the potential performance benefits of PMBs in chipseals it is recommended that further work should be carried out to provide evidence to justify their use, particularly if greater use of crumb rubber from waste tyres is envisioned in the future. It is recommended that trial sites with control sections be constructed across the country to properly assess the performance of PMB seals under various environmental and traffic conditions. Equally, the industry would benefit from more trial sections of thin-asphalt surfacing with control sections to support the reported findings in polymer modified asphalt.
2. Although not controlled trials, the sites identified in the Road Science database are well documented in terms of their construction and the materials used. It would be useful to revisit the sites and continue the monitoring of rutting, texture, and roughness of those sites as they approach the end of their lives to provide more insights into the performance of PMBs.
3. If the RAMM database is to be used to undertake comparative performance assessments of PMB surfacings in the future more detailed data on the materials used must be included to enable valid comparisons. This would include for example physical data on the PMB binders used such as the $J_{nr3.2}$ and percentage recovery from the MSCR test procedure. The accuracy of the data entered also needs to be audited.
4. Modification of the current specifications to enable the most effective use of PMBs in chipseals should the performance benefits be established.

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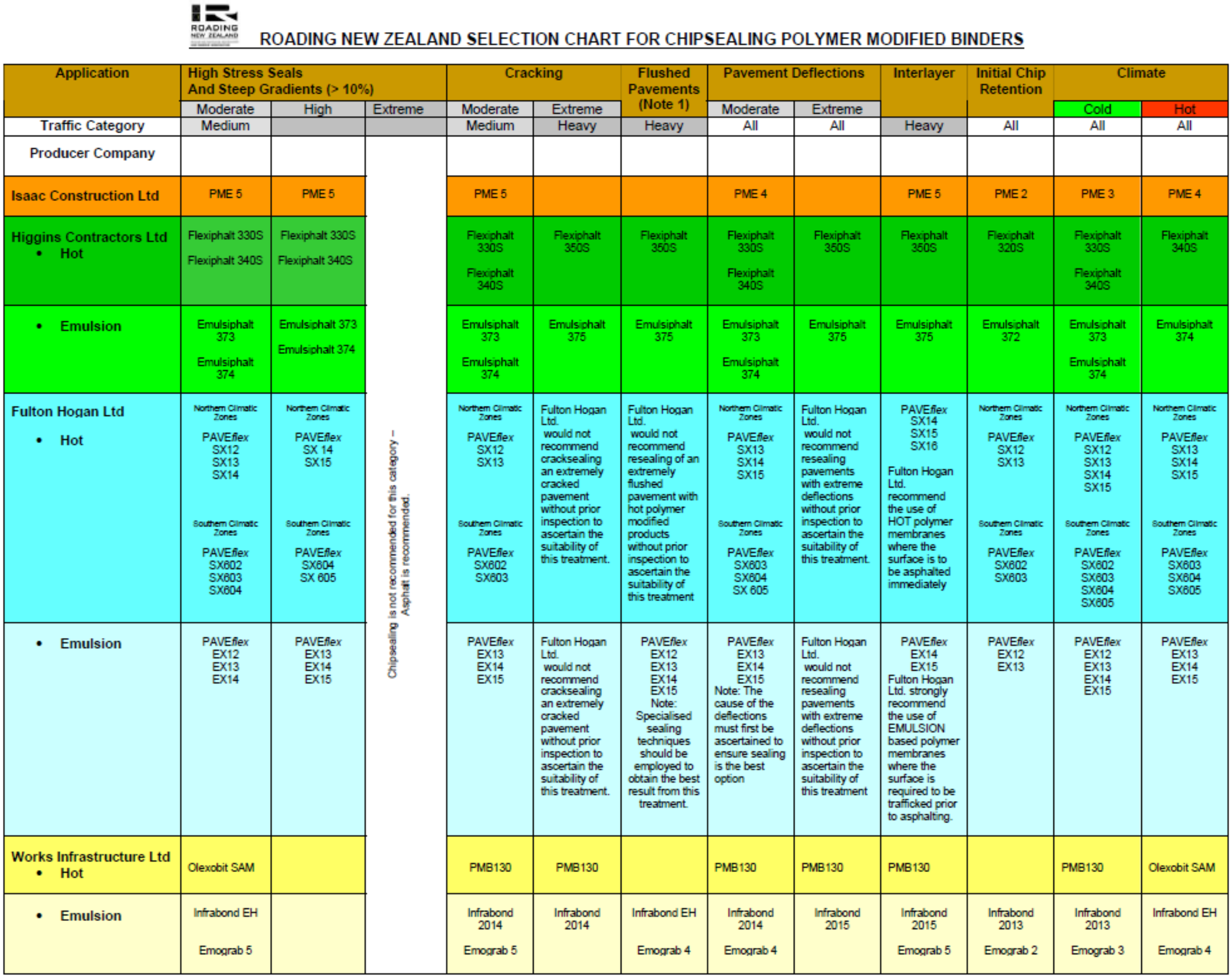
Appendix A: Supplementary tables

Table A.1 New Zealand PMB selection chart (Roading New Zealand 2006)



ROADING NEW ZEALAND SELECTION CHART FOR CHIPSEALING POLYMER MODIFIED BINDERS

Application	High Stress Seals And Steep Gradients (> 10%)			Cracking		Flushed Pavements (Note 1)	Pavement Deflections		Interlayer	Initial Chip Retention	Climate	
	Moderate	High	Extreme	Moderate	Extreme		Moderate	Extreme			Cold	Hot
Traffic Category	Medium			Medium	Heavy	Heavy	All	All	Heavy	All	All	All
Producer Company												
Isaac Construction Ltd	PME 5	PME 5	Chipsealing is not recommended for this category – Asphalt is recommended.	PME 5			PME 4		PME 5	PME 2	PME 3	PME 4
Higgins Contractors Ltd • Hot	Flexiphalt 330S Flexiphalt 340S	Flexiphalt 330S Flexiphalt 340S		Flexiphalt 330S Flexiphalt 340S	Flexiphalt 350S	Flexiphalt 350S	Flexiphalt 330S Flexiphalt 340S	Flexiphalt 350S	Flexiphalt 350S	Flexiphalt 320S	Flexiphalt 330S Flexiphalt 340S	Flexiphalt 340S
• Emulsion	Emulsiphalt 373 Emulsiphalt 374	Emulsiphalt 373 Emulsiphalt 374		Emulsiphalt 373 Emulsiphalt 374	Emulsiphalt 375	Emulsiphalt 375	Emulsiphalt 373 Emulsiphalt 374	Emulsiphalt 375	Emulsiphalt 375	Emulsiphalt 372	Emulsiphalt 373 Emulsiphalt 374	Emulsiphalt 374
Fulton Hogan Ltd • Hot	Northern Climatic Zones PAVE*flex* SX12 SX13 SX14 Southern Climatic Zones PAVE*flex* SX602 SX603 SX604	Northern Climatic Zones PAVE*flex* SX 14 SX15 Southern Climatic Zones PAVE*flex* SX604 SX 605		Northern Climatic Zones PAVE*flex* SX12 SX13 Southern Climatic Zones PAVE*flex* SX602 SX603	Fulton Hogan Ltd. would not recommend cracksealing an extremely cracked pavement without prior inspection to ascertain the suitability of this treatment.	Fulton Hogan Ltd. would not recommend resealing of an extremely flushed pavement with hot polymer modified products without prior inspection to ascertain the suitability of this treatment	Northern Climatic Zones PAVE*flex* SX13 SX14 SX15 Southern Climatic Zones PAVE*flex* SX603 SX604 SX 605	Fulton Hogan Ltd. would not recommend resealing pavements with extreme deflections without prior inspection to ascertain the suitability of this treatment.	PAVE*flex* SX14 SX15 SX16 Fulton Hogan Ltd. recommend the use of HOT polymer membranes where the surface is to be asphalted immediately	Northern Climatic Zones PAVE*flex* SX12 SX13 Southern Climatic Zones PAVE*flex* SX602 SX603	Northern Climatic Zones PAVE*flex* SX12 SX13 SX14 SX15 Southern Climatic Zones PAVE*flex* SX602 SX603 SX604 SX605	Northern Climatic Zones PAVE*flex* SX13 SX14 SX15 Southern Climatic Zones PAVE*flex* SX603 SX604 SX605
• Emulsion	PAVE*flex* EX12 EX13 EX14	PAVE*flex* EX13 EX14 EX15		PAVE*flex* EX13 EX14 EX15	Fulton Hogan Ltd. would not recommend cracksealing an extremely cracked pavement without prior inspection to ascertain the suitability of this treatment.	PAVE*flex* EX12 EX13 EX14 EX15 Note: Specialised sealing techniques should be employed to obtain the best result from this treatment.	PAVE*flex* EX13 EX14 EX15 Note: The cause of the deflections must first be ascertained to ensure sealing is the best option	Fulton Hogan Ltd. would not recommend resealing pavements with extreme deflections without prior inspection to ascertain the suitability of this treatment	PAVE*flex* EX14 EX15 Fulton Hogan Ltd. strongly recommend the use of EMULSION based polymer membranes where the surface is required to be trafficked prior to asphalting.	PAVE*flex* EX12 EX13	PAVE*flex* EX12 EX13 EX14 EX15	PAVE*flex* EX13 EX14 EX15
Works Infrastructure Ltd • Hot	Olexobit SAM			PMB130	PMB130		PMB130	PMB130	PMB130		PMB130	Olexobit SAM
• Emulsion	Infrabond EH Emograb 5			Infrabond 2014 Emograb 5	Infrabond 2014	Infrabond EH Emograb 4	Infrabond 2014 Emograb 4	Infrabond 2015	Infrabond 2015 Emograb 5	Infrabond 2013 Emograb 2	Infrabond 2013 Emograb 3	Infrabond EH Emograb 4

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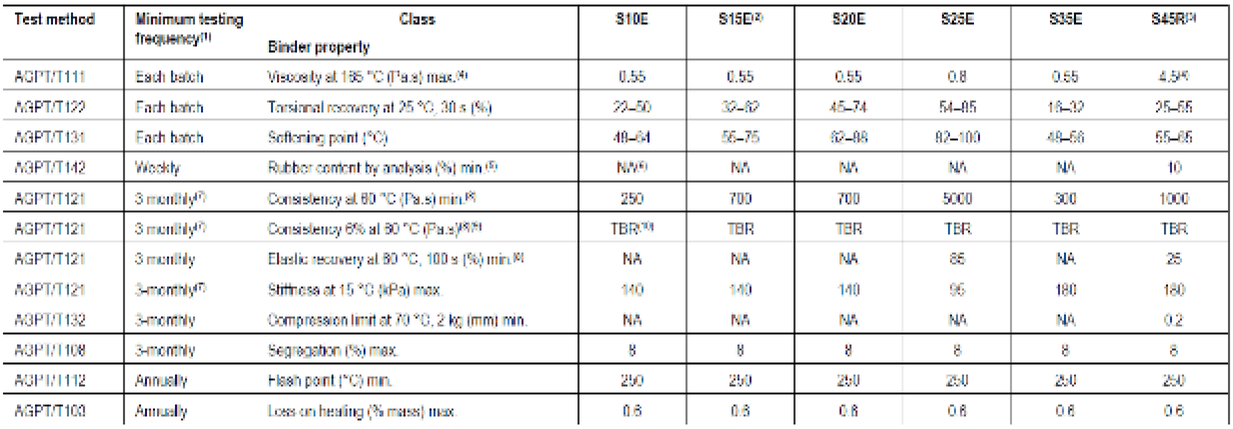
- The recommendation of any product in the above table for use in any particular application is based on information provided by the individual companies and should not be seen as any form of endorsement / guarantee by Roading New Zealand.
- **Note 1**: The use of any recommended PMB over flushed pavements should only be seen as a "holding" treatment and not a long term solution to flushing.

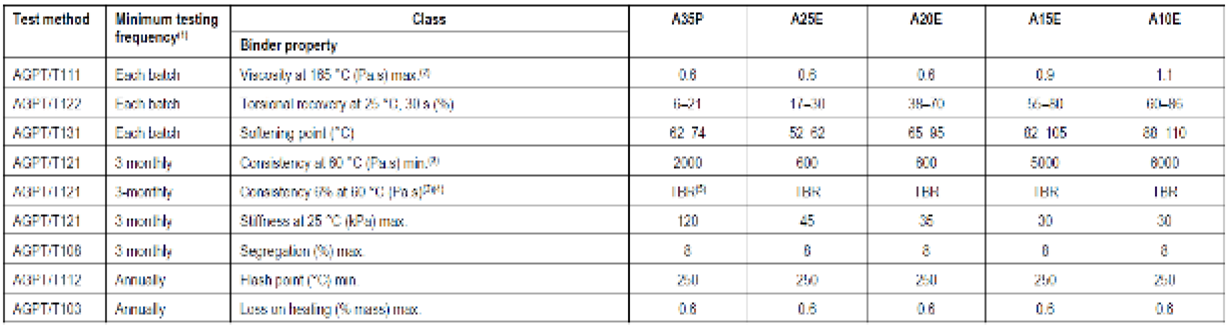
Tables A.2 to A.4 give the Australian PMB specifications.

Table A.2 Properties of polymer modified binders for sprayed sealing applications (Austroads 2014)



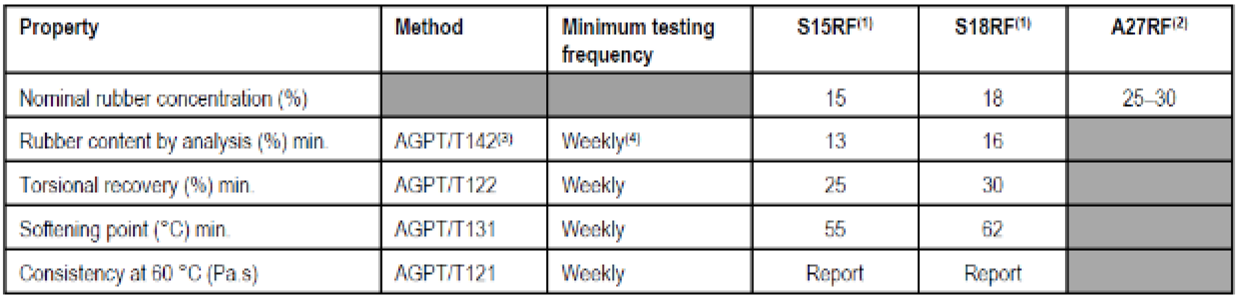
Test method	Minimum testing frequency[1]	Class Binder property	S10E	S15E[2]	S20E	S25E	S35E	S45R[3]
AGPT/T111	Each batch	Viscosity at 165 °C (Pa.s) max.[4]	0.55	0.55	0.55	0.8	0.55	4.5[3]
AGPT/T122	Each batch	Torsional recovery at 25 °C, 30 s (%)	22–50	32–62	45–74	54–85	16–32	25–55
AGPT/T131	Each batch	Softening point (°C)	48–64	56–75	62–88	82–100	48–56	55–65
AGPT/T142	Weekly	Rubber content by analysis (%) min.[5]	NA[6]	NA	NA	NA	NA	10
AGPT/T121	3 monthly[7]	Consistency at 60 °C (Pa.s) min.[8]	250	700	700	5000	300	1000
AGPT/T121	3 monthly[7]	Consistency 6% at 60 °C (Pa.s)[8][9]	TBR[10]	TBR	TBR	TBR	TBR	TBR
AGPT/T121	3 monthly	Elastic recovery at 60 °C, 100 s (%) min.[8]	NA	NA	NA	85	NA	25
AGPT/T121	3-monthly[7]	Stiffness at 15 °C (kPa) max.	140	140	140	95	180	180
AGPT/T132	3-monthly	Compression limit at 70 °C, 2 kg (mm) min.	NA	NA	NA	NA	NA	0.2
AGPT/T108	3-monthly	Segregation (%) max.	8	8	8	8	8	8
AGPT/T112	Annually	Flash point (°C) min.	250	250	250	250	250	250
AGPT/T103	Annually	Loss on heating (% mass) max.	0.6	0.6	0.6	0.6	0.6	0.6

Table A.3 Properties of polymer modified binders for asphalt applications (Austroads 2014)



Test method	Minimum testing frequency[1]	Class Binder property	A35P	A25E	A20E	A15E	A10E
AGPT/T111	Each batch	Viscosity at 165 °C (Pa.s) max.[2]	0.8	0.6	0.8	0.9	1.1
AGPT/T122	Each batch	Torsional recovery at 25 °C, 30 s (%)	6–21	17–30	38–70	56–80	60–86
AGPT/T131	Each batch	Softening point (°C)	62–74	52–62	65–85	82–105	80–110
AGPT/T121	3 monthly	Consistency at 60 °C (Pa.s) min.[3]	2000	600	800	5000	8000
AGPT/T121	3-monthly	Consistency 6% at 60 °C (Pa.s)[3][4]	TBR[5]	TBR	TBR	TBR	TBR
AGPT/T121	3 monthly	Stiffness at 25 °C (kPa) max.	120	45	35	30	30
AGPT/T108	3 monthly	Segregation (%) max.	8	8	8	8	8
AGPT/T112	Annually	Flash point (°C) min.	250	250	250	250	250
AGPT/T103	Annually	Loss on heating (% mass) max.	0.6	0.6	0.6	0.6	0.6

Table A.4 Properties of field produced crumb rubber binders (Austroads 2014)



Property	Method	Minimum testing frequency	S15RF[1]	S18RF[1]	A27RF[2]
Nominal rubber concentration (%)			15	18	25–30
Rubber content by analysis (%) min.	AGPT/T142[3]	Weekly[4]	13	16	
Torsional recovery (%) min.	AGPT/T122	Weekly	25	30	
Softening point (°C) min.	AGPT/T131	Weekly	55	62	
Consistency at 60 °C (Pa s)	AGPT/T121	Weekly	Report	Report	

Tables A.5 to A.11 give the South African PMB specifications (Asphalt Academy 2007).

Table A.5 Modified binder classification system from TG1 (Asphalt Academy 2007)

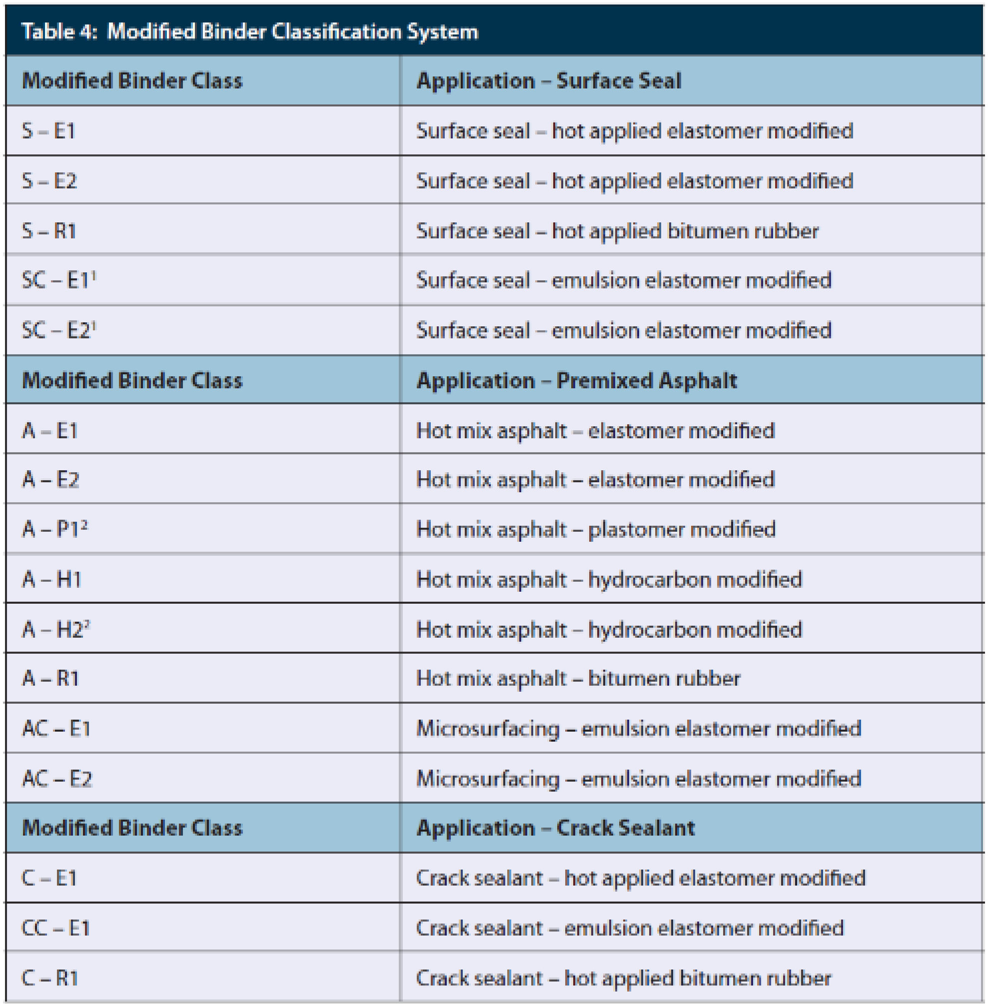


Table 4: Modified Binder Classification System

Modified Binder Class	Application – Surface Seal
S – E1	Surface seal – hot applied elastomer modified
S – E2	Surface seal – hot applied elastomer modified
S – R1	Surface seal – hot applied bitumen rubber
SC – E1[1]	Surface seal – emulsion elastomer modified
SC – E2[1]	Surface seal – emulsion elastomer modified
Modified Binder Class	**Application – Premixed Asphalt**
A – E1	Hot mix asphalt – elastomer modified
A – E2	Hot mix asphalt – elastomer modified
A – P1[2]	Hot mix asphalt – plastomer modified
A – H1	Hot mix asphalt – hydrocarbon modified
A – H2[2]	Hot mix asphalt – hydrocarbon modified
A – R1	Hot mix asphalt – bitumen rubber
AC – E1	Microsurfacing – emulsion elastomer modified
AC – E2	Microsurfacing – emulsion elastomer modified
Modified Binder Class	**Application – Crack Sealant**
C – E1	Crack sealant – hot applied elastomer modified
CC – E1	Crack sealant – emulsion elastomer modified
C – R1	Crack sealant – hot applied bitumen rubber

Table A.6 Properties of hot applied polymer modified binders for surfacing seals from TG1 (Asphalt Academy 2007)

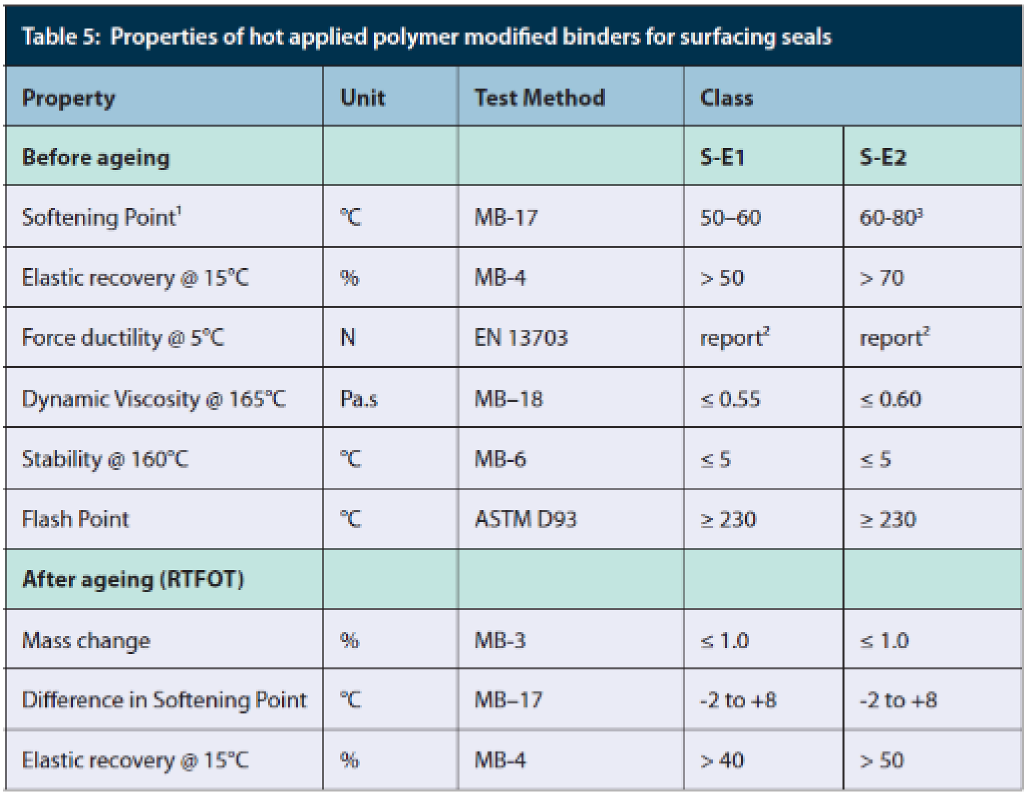


Table 5: Properties of hot applied polymer modified binders for surfacing seals

Property	Unit	Test Method	Class	
Before ageing			**S-E1**	**S-E2**
Softening Point[1]	°C	MB-17	50–60	60-80[3]
Elastic recovery @ 15°C	%	MB-4	> 50	> 70
Force ductility @ 5°C	N	EN 13703	report[2]	report[2]
Dynamic Viscosity @ 165°C	Pa.s	MB–18	≤ 0.55	≤ 0.60
Stability @ 160°C	°C	MB-6	≤ 5	≤ 5
Flash Point	°C	ASTM D93	≥ 230	≥ 230
After ageing (RTFOT)				
Mass change	%	MB-3	≤ 1.0	≤ 1.0
Difference in Softening Point	°C	MB–17	-2 to +8	-2 to +8
Elastic recovery @ 15°C	%	MB-4	> 40	> 50

Table A.7 Properties of polymer modified emulsions for surfacing seals from TG1 (Asphalt Academy 2007)

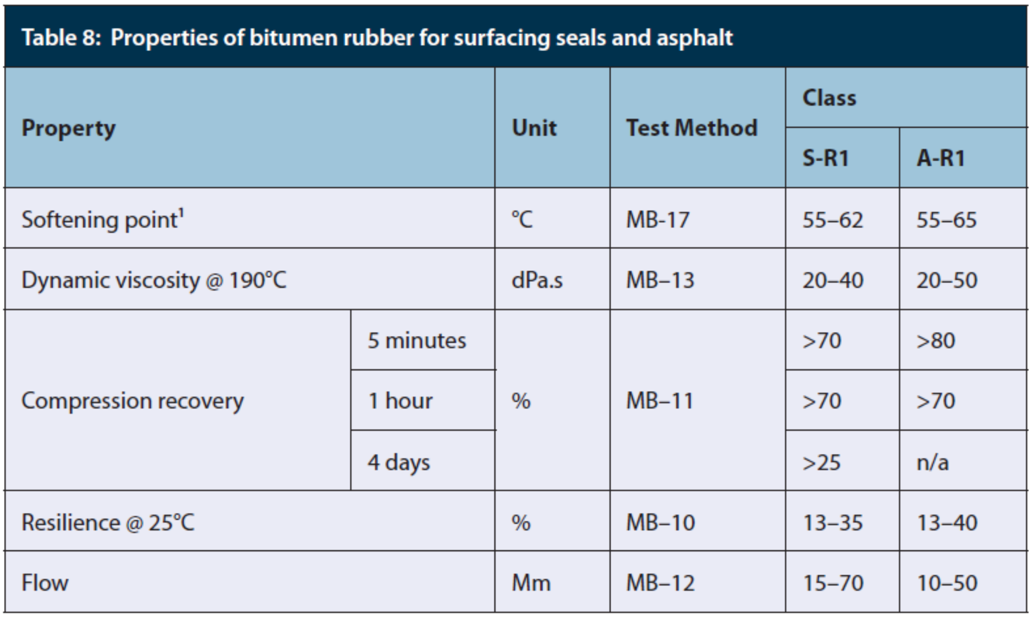


Table 8: Properties of bitumen rubber for surfacing seals and asphalt

Property		Unit	Test Method	Class	
				S-R1	A-R1
Softening point[1]		°C	MB-17	55–62	55–65
Dynamic viscosity @ 190°C		dPa.s	MB–13	20–40	20–50
Compression recovery	5 minutes	%	MB–11	>70	>80
	1 hour			>70	>70
	4 days			>25	n/a
Resilience @ 25°C		%	MB–10	13–35	13–40
Flow		Mm	MB–12	15–70	10–50

Table A.8 Properties of polymer modified binders for hot mix asphalt (Asphalt Academy 2007)

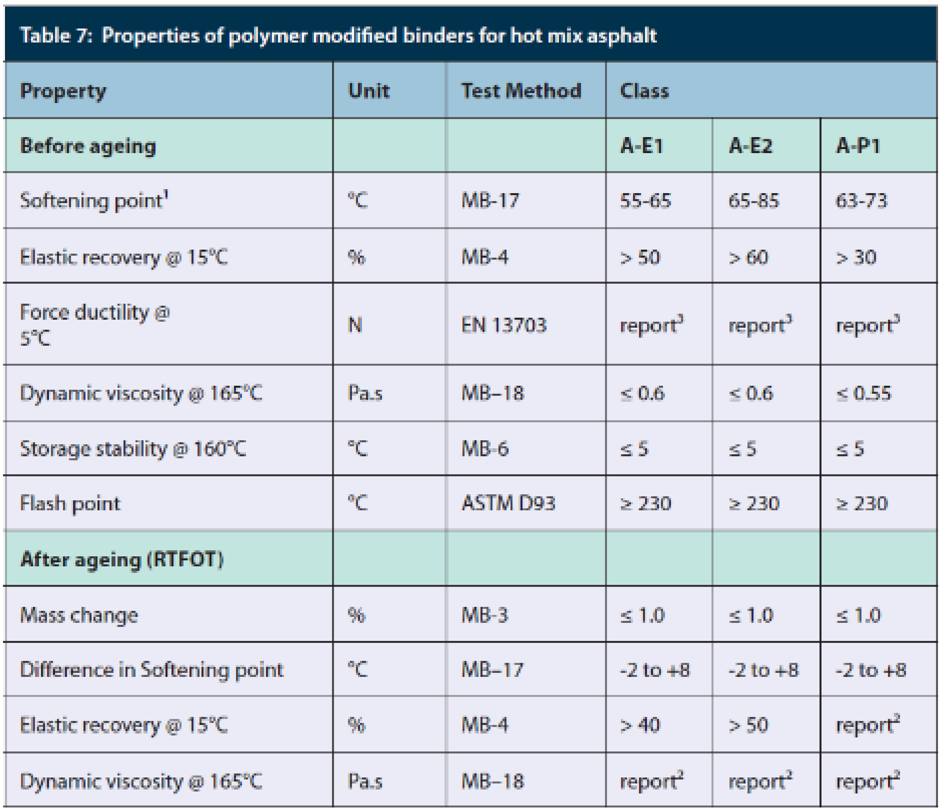


Table 7: Properties of polymer modified binders for hot mix asphalt

Property	Unit	Test Method	Class		
Before ageing			**A-E1**	**A-E2**	**A-P1**
Softening point[1]	°C	MB-17	55-65	65-85	63-73
Elastic recovery @ 15°C	%	MB-4	> 50	> 60	> 30
Force ductility @ 5°C	N	EN 13703	report[3]	report[3]	report[3]
Dynamic viscosity @ 165°C	Pa.s	MB–18	≤ 0.6	≤ 0.6	≤ 0.55
Storage stability @ 160°C	°C	MB-6	≤ 5	≤ 5	≤ 5
Flash point	°C	ASTM D93	≥ 230	≥ 230	≥ 230
After ageing (RTFOT)					
Mass change	%	MB-3	≤ 1.0	≤ 1.0	≤ 1.0
Difference in Softening point	°C	MB–17	-2 to +8	-2 to +8	-2 to +8
Elastic recovery @ 15°C	%	MB-4	> 40	> 50	report[2]
Dynamic viscosity @ 165°C	Pa.s	MB–18	report[2]	report[2]	report[2]

Table A.9 Properties of bitumen rubber for surfacing seals and asphalt (Asphalt Academy 2007)

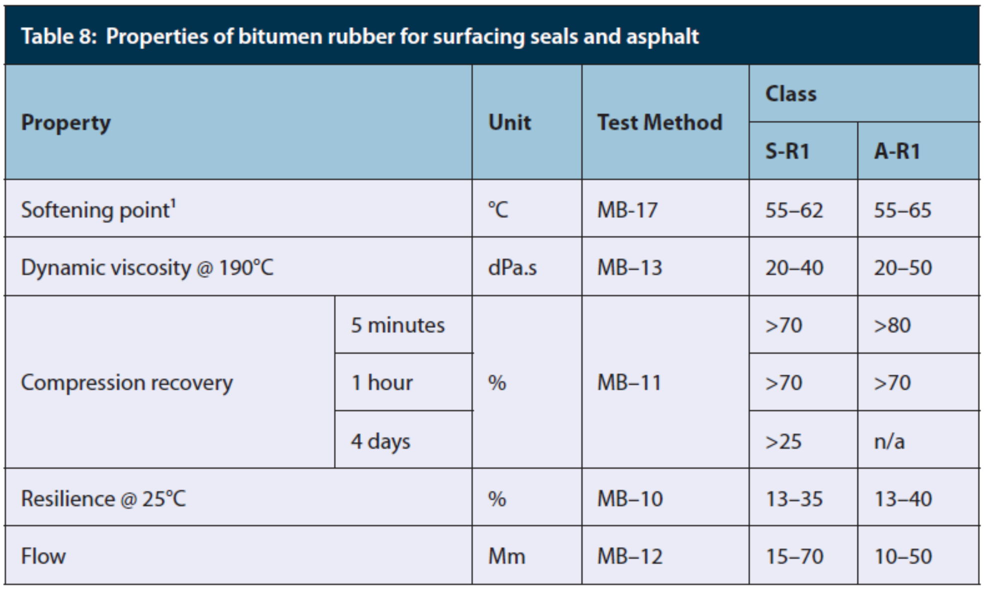


Table 8: Properties of bitumen rubber for surfacing seals and asphalt

Property		Unit	Test Method	Class	
				S-R1	**A-R1**
Softening point[1]		°C	MB-17	55–62	55–65
Dynamic viscosity @ 190°C		dPa.s	MB–13	20–40	20–50
Compression recovery	5 minutes	%	MB–11	>70	>80
	1 hour			>70	>70
	4 days			>25	n/a
Resilience @ 25°C		%	MB–10	13–35	13–40
Flow		Mm	MB–12	15–70	10–50

Table A.10 Properties of hydrocarbon modified binders for hot mix asphalt (Asphalt Academy 2007)

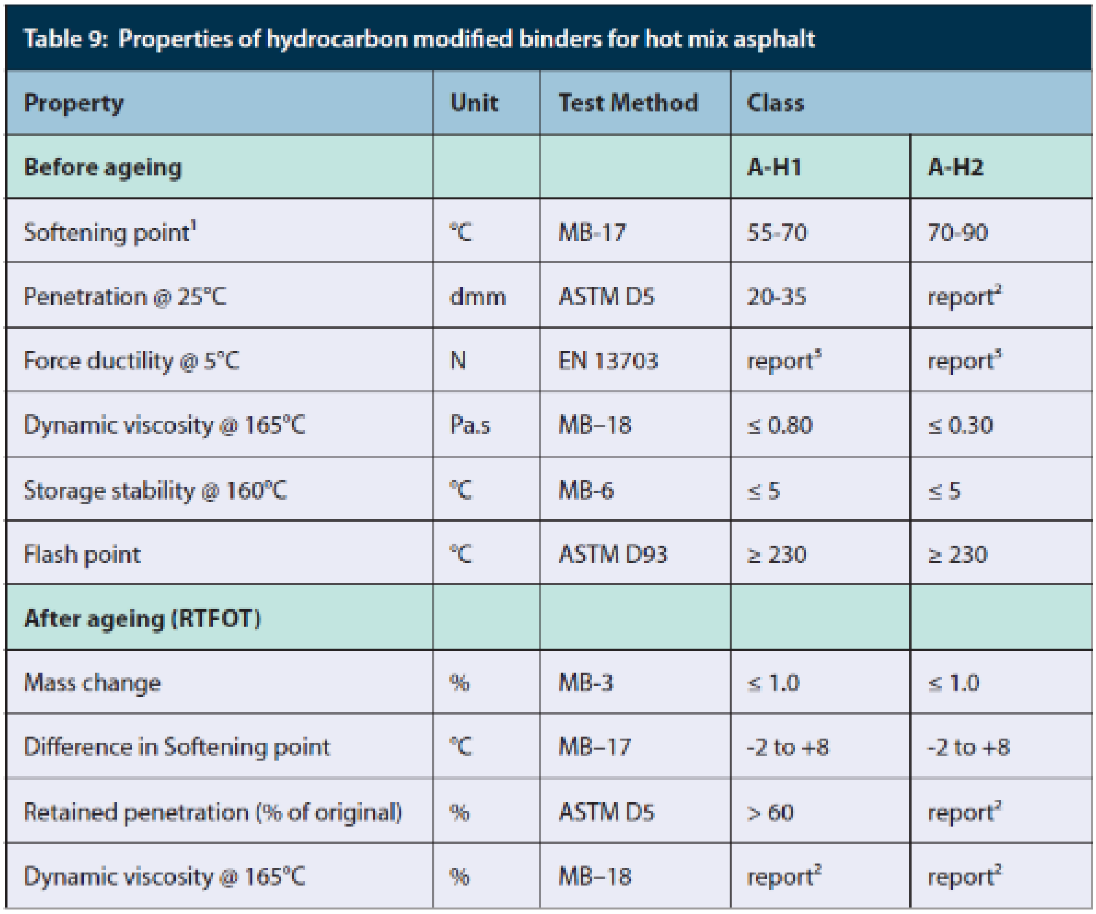


Table 9: Properties of hydrocarbon modified binders for hot mix asphalt

Property	Unit	Test Method	Class	
Before ageing			**A-H1**	**A-H2**
Softening point[1]	°C	MB-17	55-70	70-90
Penetration @ 25°C	dmm	ASTM D5	20-35	report[2]
Force ductility @ 5°C	N	EN 13703	report[3]	report[3]
Dynamic viscosity @ 165°C	Pa.s	MB–18	≤ 0.80	≤ 0.30
Storage stability @ 160°C	°C	MB-6	≤ 5	≤ 5
Flash point	°C	ASTM D93	≥ 230	≥ 230
After ageing (RTFOT)				
Mass change	%	MB-3	≤ 1.0	≤ 1.0
Difference in Softening point	°C	MB–17	-2 to +8	-2 to +8
Retained penetration (% of original)	%	ASTM D5	> 60	report[2]
Dynamic viscosity @ 165°C	%	MB–18	report[2]	report[2]

Table A.11 Properties of modified binder crack sealants (Asphalt Academy 2007)

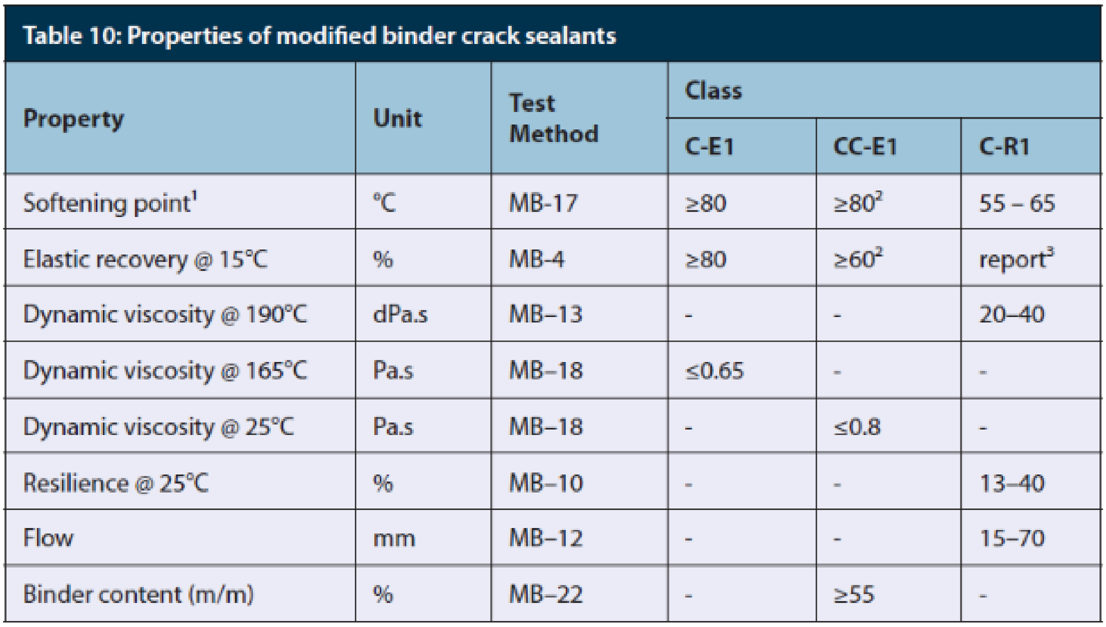


Table 10: Properties of modified binder crack sealants

Property	Unit	Test Method	Class		
			C-E1	**CC-E1**	**C-R1**
Softening point[1]	°C	MB-17	≥80	≥80[2]	55 – 65
Elastic recovery @ 15°C	%	MB-4	≥80	≥60[2]	report[3]
Dynamic viscosity @ 190°C	dPa.s	MB–13	-	-	20–40
Dynamic viscosity @ 165°C	Pa.s	MB–18	≤0.65	-	-
Dynamic viscosity @ 25°C	Pa.s	MB–18	-	≤0.8	-
Resilience @ 25°C	%	MB–10	-	-	13–40
Flow	mm	MB–12	-	-	15–70
Binder content (m/m)	%	MB–22	-	≥55	-

Tables A.12 to A.15 give the EU/UK PMB specifications, taken from EU standard EN 14023: 2010.

Table A.12 Framework specifications for polymer modified bitumens – properties applying to all polymer modified bitumens (European Committee for Standardization 2010)

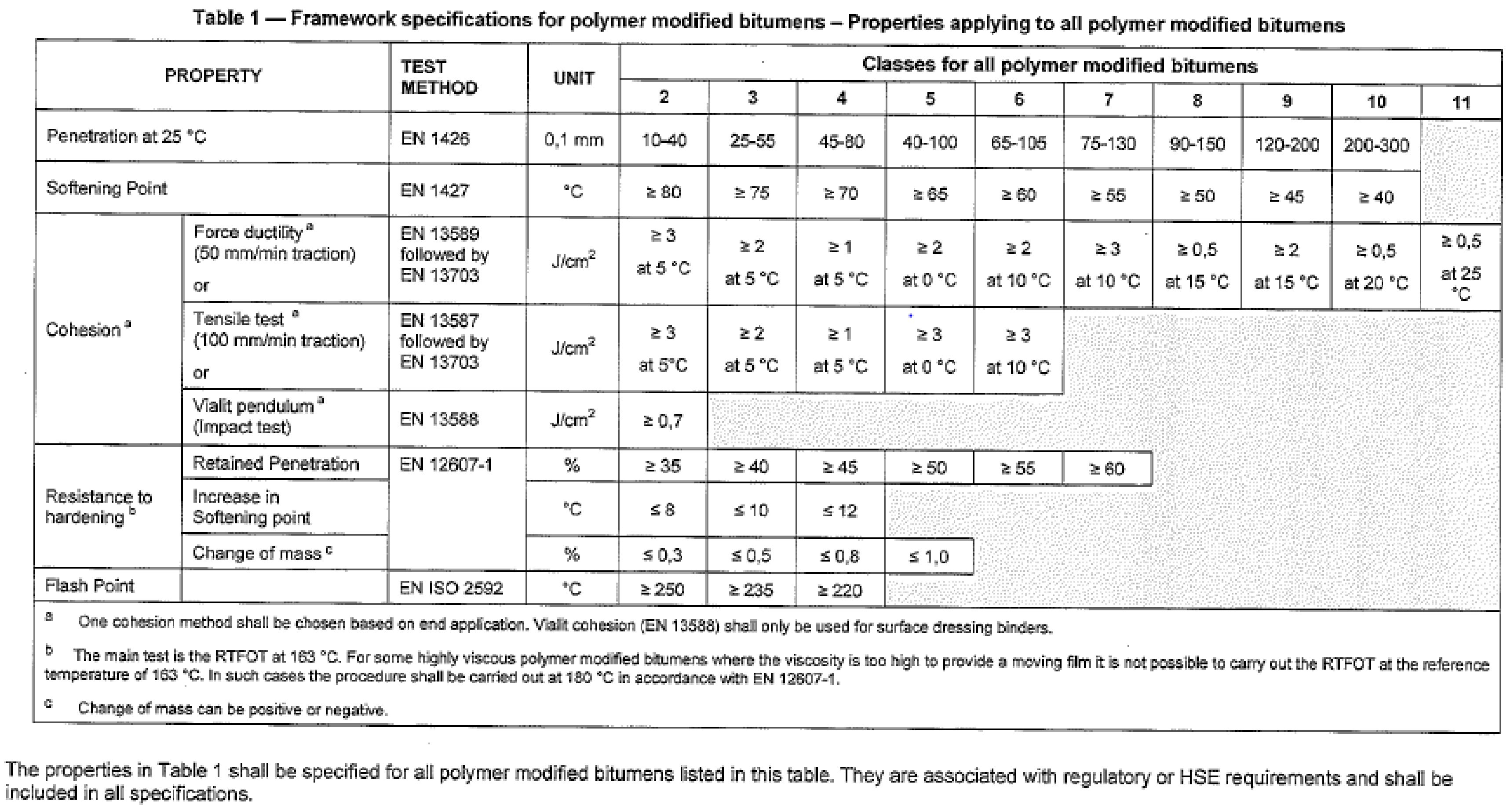


Table 1 — Framework specifications for polymer modified bitumens – Properties applying to all polymer modified bitumens

PROPERTY		TEST METHOD	UNIT	Classes for all polymer modified bitumens									
				2	3	4	5	6	7	8	9	10	11
Penetration at 25 °C		EN 1426	0,1 mm	10-40	25-55	45-80	40-100	65-105	75-130	90-150	120-200	200-300	
Softening Point		EN 1427	°C	≥ 80	≥ 75	≥ 70	≥ 65	≥ 60	≥ 55	≥ 50	≥ 45	≥ 40	
Cohesion [a]	Force ductility [a] (50 mm/min traction) or	EN 13589 followed by EN 13703	J/cm^2	≥ 3 at 5 °C	≥ 2 at 5 °C	≥ 1 at 5 °C	≥ 2 at 0 °C	≥ 2 at 10 °C	≥ 3 at 10 °C	≥ 0,5 at 15 °C	≥ 2 at 15 °C	≥ 0,5 at 20 °C	≥ 0,5 at 25 °C
	Tensile test [a] (100 mm/min traction) or	EN 13587 followed by EN 13703	J/cm^2	≥ 3 at 5°C	≥ 2 at 5 °C	≥ 1 at 5 °C	≥ 3 at 0 °C	≥ 3 at 10 °C					
	Vialit pendulum [a] (Impact test)	EN 13588	J/cm^2	≥ 0,7									
Resistance to hardening [b]	Retained Penetration	EN 12607-1	%	≥ 35	≥ 40	≥ 45	≥ 50	≥ 55	≥ 60				
	Increase in Softening point		°C	≤ 8	≤ 10	≤ 12							
	Change of mass [c]		%	≤ 0,3	≤ 0,5	≤ 0,8	≤ 1,0						
Flash Point		EN ISO 2592	°C	≥ 250	≥ 235	≥ 220							

[a] One cohesion method shall be chosen based on end application. Vialit cohesion (EN 13588) shall only be used for surface dressing binders.

[b] The main test is the RTFOT at 163 °C. For some highly viscous polymer modified bitumens where the viscosity is too high to provide a moving film it is not possible to carry out the RTFOT at the reference temperature of 163 °C. In such cases the procedure shall be carried out at 180 °C in accordance with EN 12607-1.

[c] Change of mass can be positive or negative.

The properties in Table 1 shall be specified for all polymer modified bitumens listed in this table. They are associated with regulatory or HSE requirements and shall be included in all specifications.

Table A.13 Framework specifications for polymer modified bitumens – properties associated with regulatory or other regional requirements (European Committee for Standardization 2010)

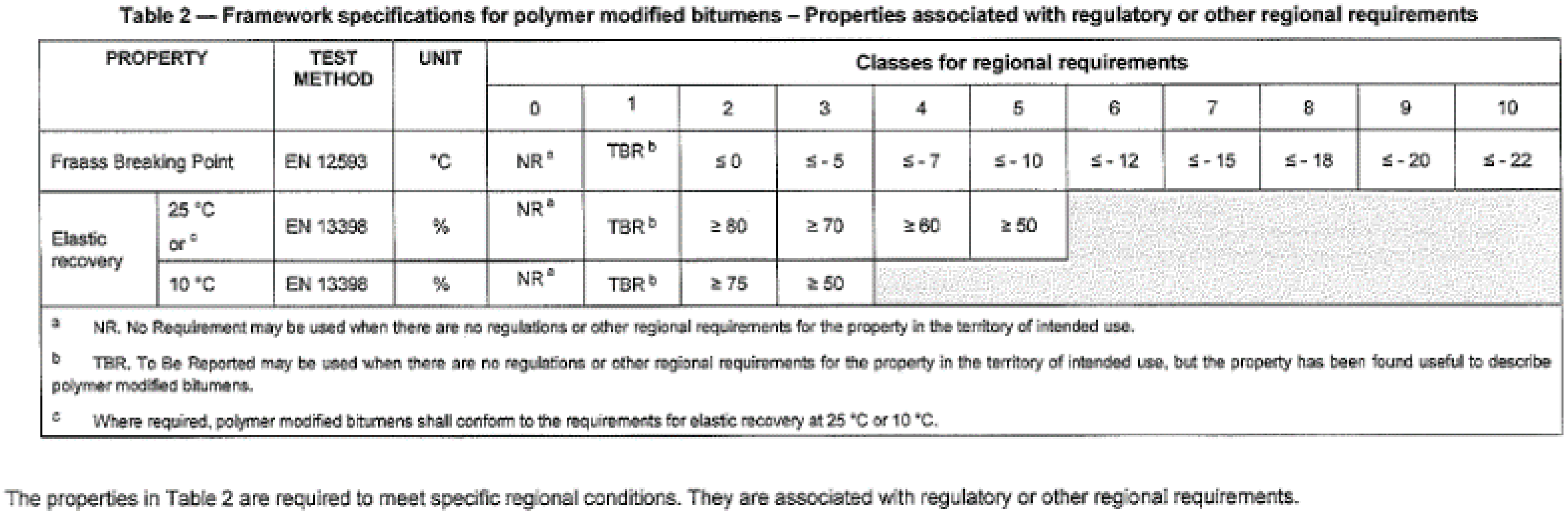


Table 2 — Framework specifications for polymer modified bitumens – Properties associated with regulatory or other regional requirements

PROPERTY		TEST METHOD	UNIT	Classes for regional requirements										
				0	1	2	3	4	5	6	7	8	9	10
Fraass Breaking Point		EN 12593	°C	NR [a]	TBR [b]	≤ 0	≤ - 5	≤ - 7	≤ - 10	≤ - 12	≤ - 15	≤ - 18	≤ - 20	≤ - 22
Elastic recovery	25 °C or [c]	EN 13398	%	NR [a]	TBR [b]	≥ 80	≥ 70	≥ 60	≥ 50					
	10 °C	EN 13398	%	NR [a]	TBR [b]	≥ 75	≥ 50							

[a] NR, No Requirement may be used when there are no regulations or other regional requirements for the property in the territory of intended use.

[b] TBR, To Be Reported may be used when there are no regulations or other regional requirements for the property in the territory of intended use, but the property has been found useful to describe polymer modified bitumens.

[c] Where required, polymer modified bitumens shall conform to the requirements for elastic recovery at 25 °C or 10 °C.

The properties in Table 2 are required to meet specific regional conditions. They are associated with regulatory or other regional requirements.

Table A.14 Framework specifications for polymer modified bitumens – additional properties (European Committee for Standardization 2010)

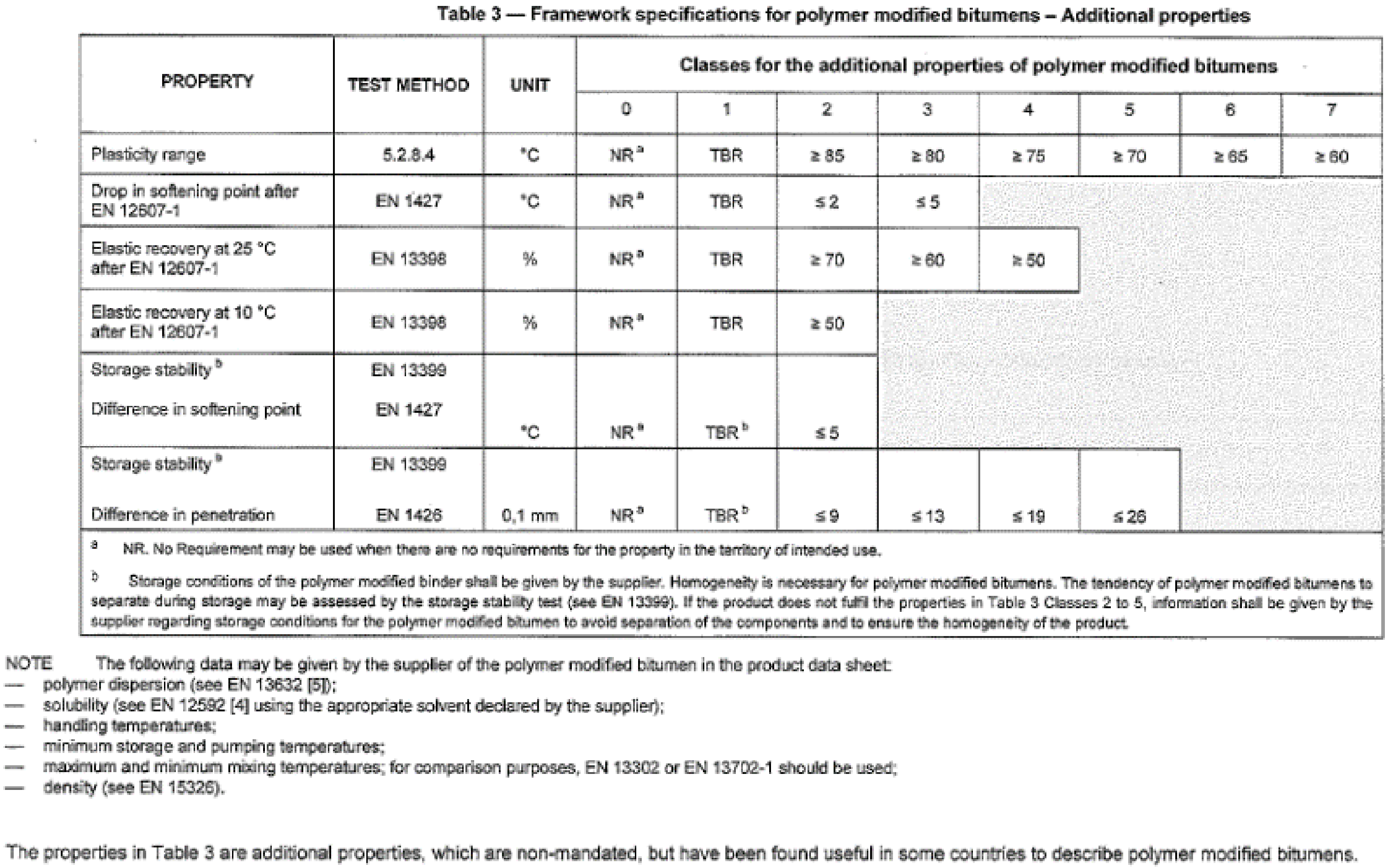


Table 3 — Framework specifications for polymer modified bitumens – Additional properties

PROPERTY	TEST METHOD	UNIT	Classes for the additional properties of polymer modified bitumens							
			0	1	2	3	4	5	6	7
Plasticity range	5.2.8.4	°C	NR [a]	TBR	≥ 85	≥ 80	≥ 75	≥ 70	≥ 65	≥ 60
Drop in softening point after EN 12607-1	EN 1427	°C	NR [a]	TBR	≤ 2	≤ 5				
Elastic recovery at 25 °C after EN 12607-1	EN 13398	%	NR [a]	TBR	≥ 70	≥ 60	≥ 50			
Elastic recovery at 10 °C after EN 12607-1	EN 13398	%	NR [a]	TBR	≥ 50					
Storage stability [b] Difference in softening point	EN 13399 EN 1427	°C	NR [a]	TBR [b]	≤ 5					
Storage stability [b] Difference in penetration	EN 13399 EN 1426	0,1 mm	NR [a]	TBR [b]	≤ 9	≤ 13	≤ 19	≤ 26		

[a] NR. No Requirement may be used when there are no requirements for the property in the territory of intended use.

[b] Storage conditions of the polymer modified binder shall be given by the supplier. Homogeneity is necessary for polymer modified bitumens. The tendency of polymer modified bitumens to separate during storage may be assessed by the storage stability test (see EN 13399). If the product does not fulfil the properties in Table 3 Classes 2 to 5, information shall be given by the supplier regarding storage conditions for the polymer modified bitumen to avoid separation of the components and to ensure the homogeneity of the product.

NOTE The following data may be given by the supplier of the polymer modified bitumen in the product data sheet:

— polymer dispersion (see EN 13632 [5]);
— solubility (see EN 12592 [4] using the appropriate solvent declared by the supplier);
— handling temperatures;
— minimum storage and pumping temperatures;
— maximum and minimum mixing temperatures; for comparison purposes, EN 13302 or EN 13702-1 should be used;
— density (see EN 15326).

The properties in Table 3 are additional properties, which are non-mandated, but have been found useful in some countries to describe polymer modified bitumens.

Table A.15 Inspection scheme for base materials and components (European Committee for Standardization 2010)

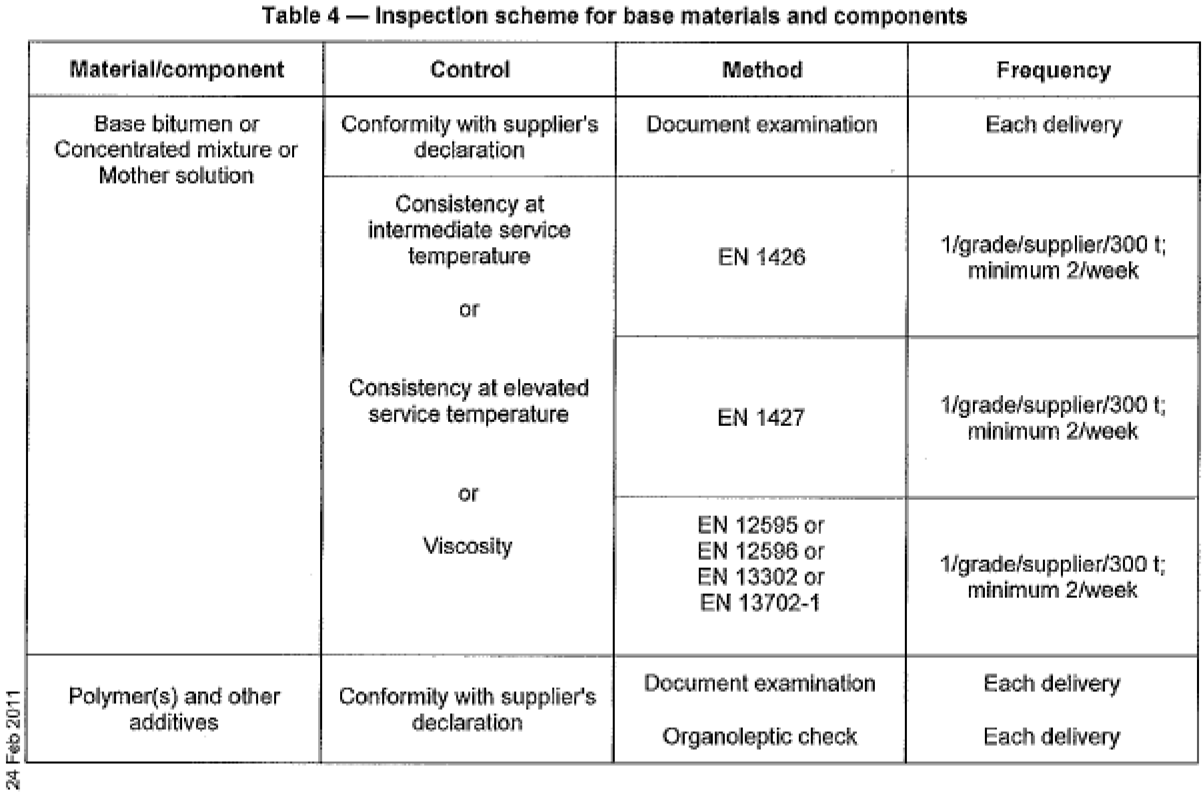


Table 4 — Inspection scheme for base materials and components

Material/component	Control	Method	Frequency
Base bitumen or Concentrated mixture or Mother solution	Conformity with supplier's declaration	Document examination	Each delivery
	Consistency at intermediate service temperature or	EN 1426	1/grade/supplier/300 t; minimum 2/week
	Consistency at elevated service temperature	EN 1427	1/grade/supplier/300 t; minimum 2/week
	or Viscosity	EN 12595 or EN 12596 or EN 13302 or EN 13702-1	1/grade/supplier/300 t; minimum 2/week
Polymer(s) and other additives	Conformity with supplier's declaration	Document examination Organoleptic check	Each delivery Each delivery

Appendix B: Glossary

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
APRG	Austroads Pavement Research Group
ASTM	American Society for Testing and Materials (now ASTM International)
C	centigrade
CR	crumbed rubber modifiers
DG	dense grade
EMA	ethylene-propylene-diene-monomer
EPDM	ethyl-methacrylate
EVA	ethyl vinyl acetate
HDPE	high-density polyethylene
ITF	International Transport Forum
LDPE	low-density polyethylene
MSCR	multiple stress creep recovery
Mt	million tons
NPV	net present value
OECD	Organisation for Economic Co-operation and Development
OGPA	open-graded porous asphalts
PBD	polybutadiene
PE	polyethylene
PMB	polymer modified binders
RAMM	Road Assessment and Maintenance Management (database)
RTFOT	rolling thin film oven test
SANRAL	South African National Roads Agency
SB/SBR	styrene-butadiene
SBS	styrene-butadiene-styrene
SCI	surface condition index
SMA	stone mastic asphalt
wt%	weight percent